Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.10, No.2, (2008), pp.34~37

Fabrication and Test of Multiple HTS Wire with Transposition for HTS Power Transformer

Woo-Seok Kim[1], Chan Park[1,*] and Kyeong-Dal Choi[2]

[1]Seoul National University, 599 Gwanakro Gwanakgu, Seoul 151-742, Korea
[2] Korea Polytechnic University, 2121 Jeongwang-dong, Siheung-si, Gyeonggi-do 429-793, Korea

Abstract-- **According to the recent design of an HTS (High Temperature Superconducting) power transformer whose capacity is hundreds MVA, the rated current values of the low voltage side are generally over thousands amps. Considering the performance of the recent HTS wires, it is inevitable to use several HTS wires in parallel for large rated current. Lots of stacked HTS wires were fabricated and tested so far, and the results have showed that we have to transpose each wire in order to reduce the AC losses as well as to increase the current capacity. But many development programs about HTS transformers reveal that the transposition of the several wires during the winding process is quite difficult not only in case of the layer windings but also in case of the pancake type ones. So, we need transposed multiple HTS wire which we can handle like single wire or cable for the HTS windings of large capacity power transformer. We fabricated several kinds of samples of multiple HTS wire with transposition to apply it to the HTS windings of power transformer. The electrical characteristics such as critical currents or AC losses are analyzed by experiments in case by case. Finally we present the best design of a multiple HTS wire for power transformer.**

1. INTRODUCTION

According to recent trends of development programs about HTS power devices such as a transformer, current limiter, motor, or cable, rated values such as current and voltage are getting larger and higher which means that the realization of power device models for commercialization is being considered now from all over the world. The operating conditions such as current, voltage, magnetic field, or AC losses of the HTS power devices are tough, but a transformer is the one which should endure the toughest conditions [1]. When we consider an HTS transformer for power transmission, this device should be able to endure high voltage like over 154 kV, and large current like over thousands amps for large capacity. Moreover, a strong leakage magnetic flux density may be applied directly to the HTS wires which may generate very high AC losses. So the large current, the high voltage, and the high magnetic field give troubles the HTS transformer all the times.

* Corresponding author: pchan@snu.ac.kr

An HTS transformer gets its advantages over the conventional ones when the rated capacity of the HTS transformer becomes 30 MVA or more [2]. The standard capacity of the recent 154 kV/ 22.0 kV power transformer development in Korea is 3 phase 60 MVA which means that the rated current of the secondary becomes mort than 1,500 amps. Considering the current capacities of the HTS wires being developed recently, it is inevitable to use the HTS wires in parallel in order to be applied to the power transformer like above. But unbalanced current distribution and large AC losses are major problems in parallel HTS windings aside from the difficulties of making parallel windings. Lots of stacked HTS wires were fabricated and tested so far, and the results have showed that we have to transpose each wire in order to reduce the AC losses as well as to increase the current capacity of the parallel HTS wire. But many development programs about HTS transformers reveal that the transposition of the several wires during the winding process is quite difficult not only in case of the layer windings but also in case of the pancake, or disk type ones. It becomes more and more difficult to transpose the HTS wires in the procedure of winding when the rated current increase, so we need transposed multiple HTS wire which we can handle like single wire or cable for the HTS windings of large capacity power transformer.

In this paper, we fabricated several kinds of samples of multiple HTS wire with transposition to apply it to the HTS windings of power transformer. The electrical characteristics such as critical currents or AC losses are analyzed by experiments in case by case. Finally we present the best design of a multiple HTS wire for power transformer.

2. MULTIPLE HTS WIRE

Most of the problems of the parallel THS wire arise when it is used for windings such as solenoid or pancake which is also known as layer type and disk type for a transformer. The unbalance of the distribution of currents arises in winding forms, so we have to make transpositions in the procedure of the windings. In case of the layer type winding, transpositions are used to be made between wires

TABLE I
SPECIFICATION OF HTS WIRE FOR MULTIPLE WIRE SAMPLE

Specification	Value
Thickness	0.21 mm
Width	4.1 mm
Critical Current density	13.5 kA/cm^2
Critical Current	126 A
Max. Stress	75 MPa
Max. Strain	0.15 %
Min. Bending Dia.	100 mm

several times at layer [3]. When the disk type windings are adopted, we used to make transpositions at the joints between disks [4]. Both method of transposition for HTS windings are not so efficient, and it becomes more and more difficult according to increase of the number of the parallel HTS wires. So we like to make multiple transposed HTS wire which has 500 amps of current capacity for the primary side of the 154 kV HTS transformer. Several different kinds of multiple HTS wire samples were fabricated for experimental verification.

2.1. Fabrication of the samples of multiple HTS wires

The objective of the work was more than 500 A of critical current of the multiple HTS wire, so we decided to stack 8 BSCCO wire in parallel considering degradation from stack and winding. The specification of the BSCCO wire is shown in Table I. Four kinds of samples which have or do not have insulation and transposition between HTS wires were designed. The specifications of sample multiple HTS wire is described in Table II and the cross section with the analysis of magnetic field distribution from transport current are shown in Fig. 1. Three same samples of each combination will be fabricated to confirm the performances of the multiple HTS wires.

2.2. Characteristic analysis of the multiple HTS wire

The critical current shown in Table I is critical current of single BSCCO wire at self field, but this value used to be affected by magnetic field applied to the HTS materials when we stacked or make windings with it. Because of the anisotropic characteristics of the HTS wire, the critical current of it is strongly affected by the magnetic field applied perpendicularly to the surface of the HTS wire [5]. In case of stacking HTS wire as presented in this paper, the magnetic field from the adjacent wire is directly applied to another wire, and makes degradation of the critical current

TABLE II
SPECIFICATION OF SAMPLES OF MULTIPLE HTS WIRE

Samples	Insulation	Transposition	Length	No. of Conductor
Sample A	No	No	100 cm	8
Sample B	No	Yes	100 cm	8
Sample C	Yes	No	100 cm	8
Sample D	Yes	Yes	100 cm	8

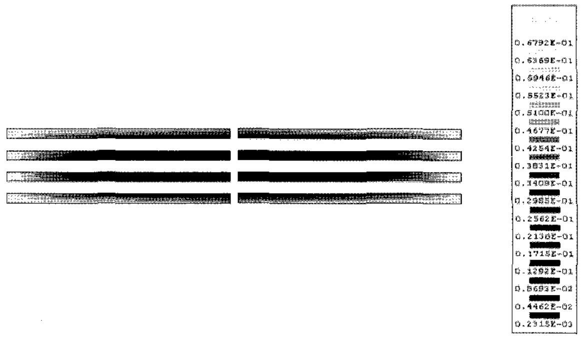

Fig. 1. Magnetic field analysis of the cross section of multiple HTS wire.

of it. So the critical current of the multiple HTS wire should be less than the arithmetic sum of the critical current of each HTS wire. This value can be estimated roughly from the calculation of distribution of magnetic flux density at each HTS wire. 2-dimentional numerical magnetostatic analysis was performed at the cross section of the multiple HTS wire assuming the perfect transposition and uniform distribution of the transport current density. Fig. 1 shows one of the result distributions of the magnetic flux density at the regions of conductors. The maximum or average value of the perpendicular component of the magnetic flux density according to the transport current can be calculated from numerical analysis, and represented as load line in Fig. 2 from which we can estimate the critical current of the multiple HTS wire. Fig. 2 shows that the critical current might be higher than 656 amps which are calculated by the average magnetic flux density, and lower than 880 amps which are from the maximum value of the magnetic flux density.

3. CHARACTERISTIC TEST OF MULTIPLE HTS WIRE

3.1. DC critical current test

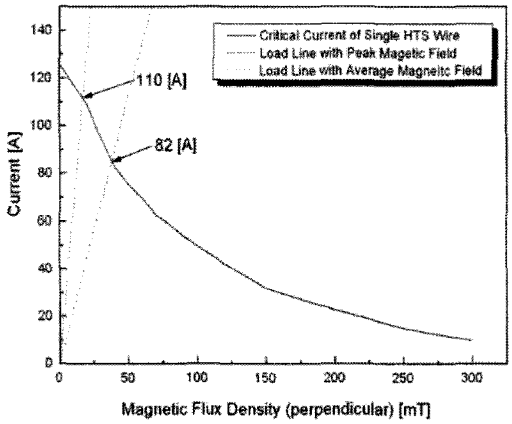

Fig. 2. Estimation of the critical current of multiple HTS wire.

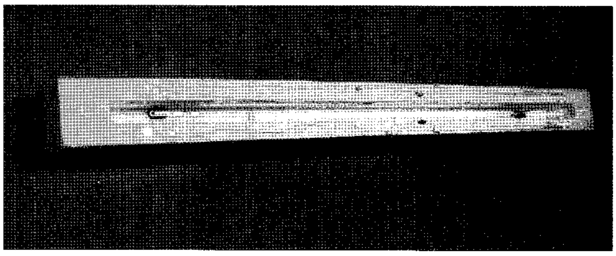

Fig. 3. Fabrication of a sample of multiple HTS wire for Experiment.

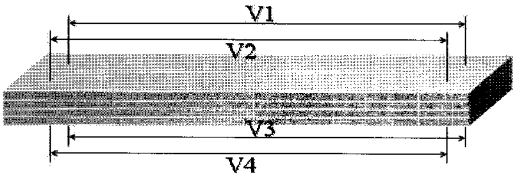

Fig. 4. Configuration of voltage taps for measurement.

The effect of the transpositions is expected to be great in case of an HTS winding, but prior to the winding test, the samples in a straight form of the multiple HTS wire were analyzed by experiment. Fig. 3 shows one of the samples with a vessel for liquid nitrogen as coolant, and the configuration of taps for measurement of voltage difference is shown in Fig. 4.

While DC transport current was applied, four pairs of voltage difference were exactly same, which means that there were no unbalanced leads of transport current from the terminals caused by difference of contact resistances between the HTS wires and the copper terminals. Fig. 5 shows the results of measuring the voltage difference between taps of all samples, and the measured critical currents are listed in Table III.

Even the samples which have the same configuration shows a little deviations but it seems to be from the intrinsic partial difference of the performance of HTS wires or a little degradation from treatment of those. And the measured values are within bounds of numerical estimation from Fig. 2, and close to the upper boundary. The reason of this is supposed to be from the shield effect

TABLE III
EXPERIMENTAL RESULTS OF CRITICAL CURRENT OF SAMPLES

Sample	Critical Current
Sample A-1	780 A
Sample A-2	800 A
Sample A-3	800 A
Sample B-1	790 A
Sample B-2	750 A
Sample B-3	775 A
Sample C-1	860 A
Sample C-2	800 A
Sample C-3	865 A
Sample D-1	850 A
Sample D-2	770 A
Sample D-3	870 A

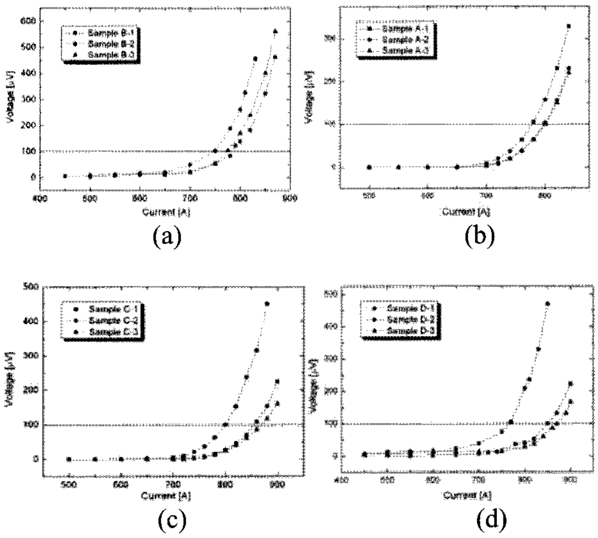

Fig. 5. Results of critical current test for each samp les of multiple HTS wire (a) sample A (b) sample B (c) sample C (d) sample D.

of the HTS materials which can lower the magnetic flux densities at the HTS wires inside. From the results shown in Table III, sample C and sample D which have the insulations between the HTS wire shows higher critical currents over the others which means that the insulations affect the dc critical current of the multiple HTS wires in short straight positions at self fields.

3.2. AC current test

We picked four best ones among the same type samples to apply AC current and measure voltage difference between voltage taps which means the AC performance and also means AC losses. The voltage differences were measured for four best samples according to the AC transport current from 0 to 700 amps in the same conditions. Unlike the case of DC tests, these AC voltage differences include the reactive voltages, the voltages caused by AC loss, and the flux flow voltages. The reactive voltage does not represent the performance of the sample, so we excluded these reactive voltages by compensating using a cancel coil and a lock-in amplifier so just the resistive component remained.

There is no clear definition about AC critical current but this resistive voltage actually can represent the AC performance of the multiple HTS wire. The resultant AC voltages of the samples are shown in Fig. 6. The vertical axis represents the root mean square values of the resistive voltage differences of the samples compared with the calculated estimation by Norris's equation for the transport current loss. These voltages also mean the AC losses of the samples if the transport current is small enough, so there is no flux flow in the HTS materials.

According to the results represented in Fig. 6, the samples with the insulation between the HTS wires still shows better performances compared with the others. In the case of no insulation, the transposition between the

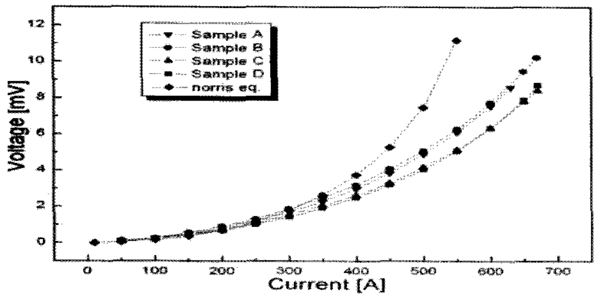

Fig. 6. AC loss measurement of samples of multiple HTS wires with a calculation result from Norris's equation.

HTS wires even made slight more AC loss than no-transposition does. But with the insulations, the transposition improved the AC performance a little especially at low current region. Actually, the transposition is supposed to show remarkable effects in case of a winding form which has some differences of the impedance of each HTS wires. To show these effects, we fabricated a disk type winding using the multiple HTS wire which has a configuration of sample D. Fig. 7 shows the fabricated disk winding and the characteristic test of the winding is going to performed in near future.

4. CONCLUSION

According to the recent development programs about the HTS power devices, the HTS winding for large current like thousands amps is needed. So it is inevitable to use the HTS wires in parallel for large current especially for the power transformer, because it should endure very tough conditions such as high voltages, high magnetic field, and large current. In this paper, we present a multiple HTS wire with transposition using BSCCO wire. In order to decide the best configuration for large current, several short samples which have different kind of configuration were designed and fabricated for experimental verification. Finally we suggested the best configuration for a large current and fabricated a disk type winding using the multiple HTS wire which has the chosen configuration. The characteristic test of the disk winding will be performed in near future.

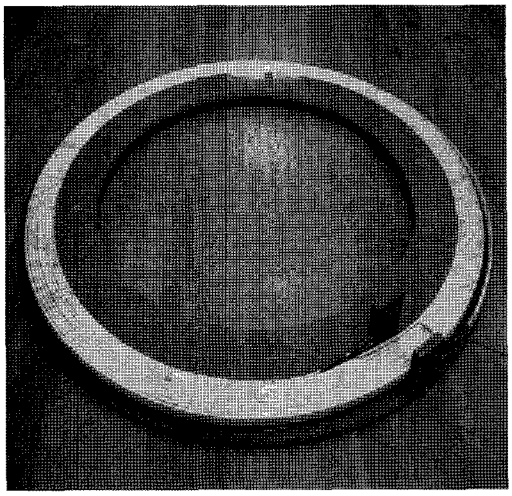

Fig. 7. A disk winding using the multiple HTS wire.

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 Education, Science and Technology, Republic of Korea.

REFERENCES

[1] Sam P. Mehta, Nicola Aversa, and Michael S. Walker, "Transforming transformer," IEEE Spectrum, Vol. 34, No. 7, pp. 43-49, July 1997.

[2] S.H. Kim, W.S. Kim, S. Hahn, K.D. Choi, H.G. Joo, and G.W. Hong, "Feasibility study of an HTS transformer," Conference of KIASC, pp.229-232, February 2002.

[3] W. Funaki, et al., "Development of a 22 kV/ 6.9 kV single-phase model for a 3 MVA HTS power transformer," IEEE Transactions on Applied Superconductivity, Vol. 11, No. 1, pp.1578-1581, March 2001.

[4] W.S. Kim, S. Hahn, K.D. Choi, H..G. Joo, and G.W. Hong, "Design of a 1 MVA high Tc superconducting transformer," IEEE Transactions on Applied Superconductivity, Vol. 13, No. 2, pp.2291-2293, June 2003.

[5] S.H. Kim, W.S. Kim, W.G. Min, C.B. Park, S.J. Lee, J.T. Kim, D.K. Lee, K.D. Choi, H.G. Joo, G.W. Hong, J.H. Han, and S. Hahn, "Analysis of perpendicular magnetic fields on a 1 MVA HTS transformer windings with flux diverters," IEEE Transactions on Applied Superconductivity, Vol. 14, No. 2, pp.932-935, June 2004.