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Magnetic Field Analysis of 1 MVA HTS Transformer Windings

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Abstract-- **In a HTS transformer, the perpendicular component of magnetic flux density (B_r) applied to HTS tapes of pancake windings becomes larger than that of solenoid winding, thereby decreasing the critical current in the HTS tapes. This paper introduces several methods to reduce B_r applied to the HTS tapes in the transformer with double pancake windings by changing winding arrangements and the relative permeability of flux diverters. We have conducted a winding design for a single-phase 1MVA 22.9kV/6.6kV HTS transformer. We observed a change of B_r due to a variation of gap-length between the high voltage windings and the low voltage windings, reciprocal arrangement and an increase of the number of the high voltage pancake. We also observed a change of Br on the HTS tapes due to variation of the relative permeability of flux diverters placed between the high voltage winding and the low voltage winding. Finally, we have designed a 1MVA 22.9kV/6.6kV HTS transformer winding using suggested methods and calculated transformer parameters by the 3D finite element method.**

1. INTRODUCTION

High Temperature Superconducting(HTS) transformers are more attractive than conventional transformers because they are more energy efficient, lighter in weight, smaller in size, and environment friendly[1]. Hence there are lots of international interests on the development and commercialization of HTS transformers. For example, ABB/American Superconductor (ASC) in Europe developed a three-phase 630kVA HTS transformer cooled by LN_2 at 77K in 1997 [2]. In America, Waukesha Electric Systems (WES)/Oak Ridge National Laboratory (ORNL) developed a single-phase 1MVA HTS transformer in 1998 [3], and Fuji Electric Corporation/Kyushu University in Japan developed a single-phase 1MVA HTS transformer cooled by liquid nitrogen and worked at real load test [4].

These transformers have windings of a solenoid type. But a conventional high voltage transformer generally needs windings of a pancake type for electrical insulation. So we have done a winding design and magnetic field analysis of a single-phase 1MVA 22.9kV/6.6kV HTS transformer composed of several double pancake windings.

In general, when the superconducting devices are wound with Bi2223/Ag tapes, it is necessary to consider perpendicular component of magnetic flux density (B_r) because of anisotropy characteristic of Bi2223/Ag tape [5]. In fact, B_r on the HTS tapes in the transformer with double pancake windings is higher than that of solenoid windings having the same current capacity. The increase of B_r applied to the HTS tapes decreases the critical current density of the HTS tapes. In this paper, several methods to reduce the B_r applied to the HTS tapes in the transformer with double pancake windings by using changes of winding arrangement and flux diverters are introduced. First, we observed a variation of the B_r applied to the HTS tapes by changing gap length between the high voltage winding and the low voltage winding. Second, we observed a variation of the B_r by various reciprocal arrangements and an increase of the number of high voltage pancakes. Third, we observed a variation of B_r on HTS tapes by a variation of relative permeability of flux diverters placed between the high voltage winding and the low voltage winding. Finally, we have designed a 1MVA 22.9kV/6.6kV HTS transformer winding using suggested methods and calculated transformer parameters by the 3D FEM.

2. TRANSFORMER WINDING DESIGN BY ELECTROMAGNETIC FIELD ANALYSIS

2.1. Standard Design of a 1MVA HTS Transformer Winding

A conceptual design of a single-phase 1MVA 22.9kV/6.6kV HTS transformer with Bi2223/Ag HTS tapes was made. We adopted double pancake winding type that is mostly used in conventional high voltage transformers. The high voltage and low voltage sides are composed of 4 double pancake windings. Four HTS tapes are wound in parallel for the windings of the low voltage side with the rated secondary current of 152A and are transposed in order to distribute the currents equally in each conductor. Fig. 1 shows the configuration of a 1MVA HTS

TABLE I Specification of Standard Design Model of A 1MVA HTS TRANSFORMER

Specification	Value
Phase Number	1
Capacity	1 MVA
Rated Prim./Second. Voltage	22.9 kV / 6.6 kV
Rated Prim./Second. Current	44 A / 152 A
Number of Turns	Primary 888 / Secondary 256
Volt / Turn	25.8 V/T
Prim./Second. Tape Length	1212 / 1332 m
Number of Bobbins	4 / 4
inner dia. of Coils	378 / 378 mm
outer dia. of Coils	450 / 489 mm
Strand Cross Section	Bi-2223/Ag tape(4.1mm×0.21mm)

transformer standard design model with conventional pancake winding arrangement and Table I shows specification of the transformer. Fig. 2 shows B_r distribution on the high voltage and the low voltage side. We can see that maximum B_r on high voltage and low voltage side are 0.298 [T] and 0.337 [T]. In the case of Bi-2223 HTS tapes, the critical current decreases below 50% if B_r on the tapes is 0.337[T].

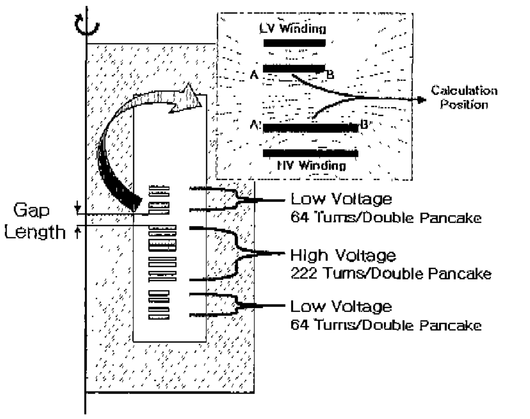


Fig. 1. Configuration of a 1MVA HTS transformer standard design model with conventional pancake winding arrangement.

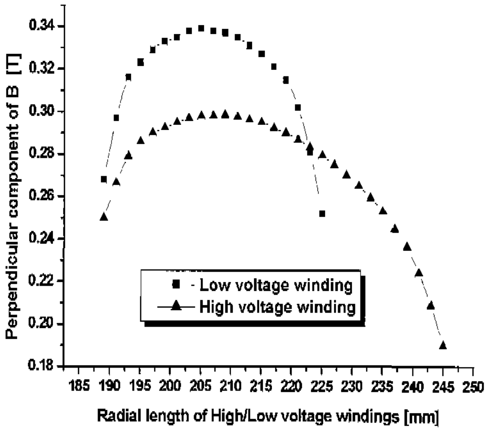


Fig. 2. B_r distribution on the high voltage and the low voltage side of a 1MVA HTS transformer standard design model with conventional pancake winding arrangement.

2.2. B_r distribution on the winding by a variation of gap between the LV winding and the HV winding In general, the no-load current of large power transformers is less than 3% of the rated current. So we assumed that phase difference between the primary current and the secondary current is about 180° when we analyze the magnetic field of the transformer.

From this point of view, when the primary current and the secondary current of a HTS transformer reach peak value during operation, magnetic leakage flux concentrates on the space between the high voltage winding and the low voltage winding. In this case, B_r applied to tapes of the double pancake windings is high and the critical current density of the tapes decreases sharply. So we calculated a change of B_r on the transformer winding by a variation of gap length between the high voltage winding and the low voltage winding. Fig. 3 shows B_r distribution on the low voltage coil of a 1MVA HTS transformer. In Fig. 3, we can see that B_r on the transformer winding is not greatly influenced by the gap length between the high voltage winding and the low voltage winding.

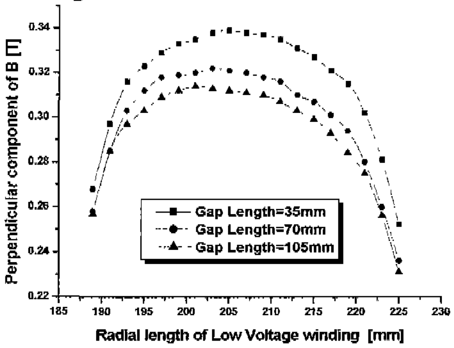
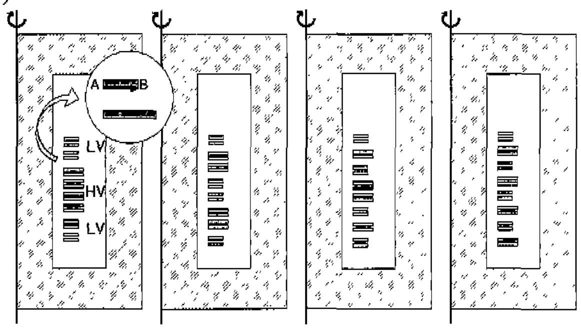


Fig. 3. B_r distribution on the low voltage winding of a 1MVA HTS transformer by a variation of gap length between the low voltage winding and the high voltage winding.

2.3. B_r distribution on the winding by reciprocal arrangement and an increase of the number of the high voltage pancakes

The windings of reciprocal arrangement are usually adopted to make low impedance voltage for large power transformers [6]. One of the advantages of double pancake winding is that it is easier to realize reciprocal arrangement of windings than solenoid winding. On a transformer with double pancake windings, leakage flux concentrates on the space where the high voltage winding and the low voltage winding meet. But it is possible to divide leakage flux using reciprocal arrangement on the transformer with double pancake windings. Fig. 4 shows various reciprocal arrangements of the low voltage pancakes and the high voltage pancakes of a 1MVA HTS transformer. Fig. 5 shows B_r distribution on the low voltage winding by reciprocal arrangement. In Fig. 5, we can see that it is possible to reduce B_r about 35% using reciprocal arrangement on the transformer windings.

Fig. 6 shows various reciprocal arrangements of a 1MVA HTS transformer of which the number of the high voltage pancakes is increased two times. Fig. 7 shows B_r distribution on the low voltage winding by various reciprocal arrangements of a 1MVA HTS transformer of which the number of the high voltage pancakes is increased two times. In Fig. 7, we can see that maximum B_r applied to the tapes is about 0.15 [T] in the case of Fig. 6 (c).



(a) (b) (c) (d)

Fig. 4. Various reciprocal arrangements of 1MVA HTS transformer windings. (a) Conventional arrangement (L-H-L). (b) L-H-L-H-L arrangement. (c) L-H-L-H-L-H-L arrangement. (d) L-H-L-H-L-H-L-H arrangement

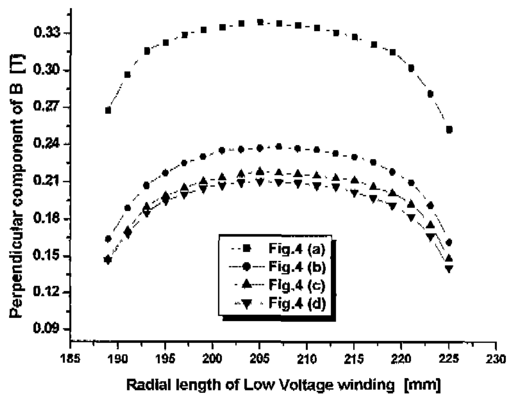
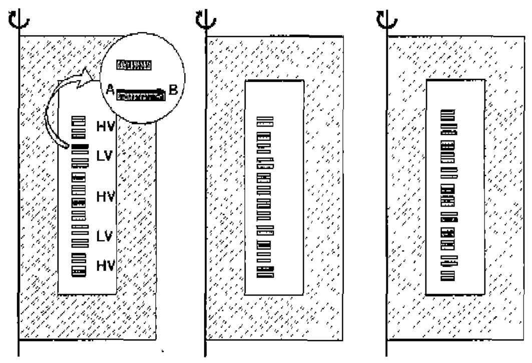


Fig. 5. B_r distribution on the low voltage winding of a 1MVA HTS transformer by reciprocal arrangements of the low voltage pancakes and the high voltage pancakes.



(a) (b) (c)

Fig. 6. Various reciprocal arrangements of a 1MVA HTS transformer of which the number of the high voltage pancakes is increased two times. In this figure, long bars represent the low voltage windings and short bars represent the high voltage windings.

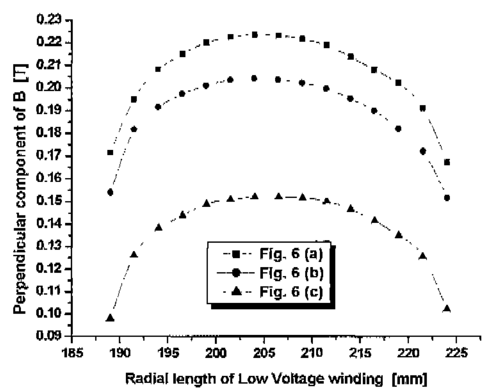


Fig. 7. B_r distribution on the low voltage winding by various reciprocal arrangements of a 1MVA HTS transformer of which the number of the high voltage pancakes is increased two times.

3. Transformer Winding Design using Flux Diverters

It is important to reduce the radial component of leakage flux in the superconducting transformer with double pancake windings. So we have considered the use of magnetically permeable flux diverters to reduce B_r in the HTS tapes [7]. Fig. 8 shows an arrangement of windings and flux diverters in the standard design model of a 1MVA HTS transformer winding. Flux diverters are located between the low voltage windings and the high voltage windings inside the cryostat. Fig.9 shows variations of B_r on the low voltage winding and B in flux diverters of a 1MVA HTS transformer standard design model by changing the relative permeability of flux diverters. B_r on the tapes decreases from 0.236 [T] to 0.159 [T] as the relative permeability of the flux diverter increases from 5 to 1500. It is possible to reduce B_r about 50 % as compared with B_r on a standard design model without flux diverters. Fig.10 also shows variations of B_r on the low voltage winding and B in flux diverters of a 1MVA HTS transformer that is considered reciprocal arrangement and is increased the number of the high voltage pancakes. B_r on the tapes decreases from 0.137 [T] to 0.107 [T] as relative permeability of flux diverter increases fro m 5 to 1500. It is possible to reduce B_r about 70 % as compared with B_r on a standard design model without flux diverters.

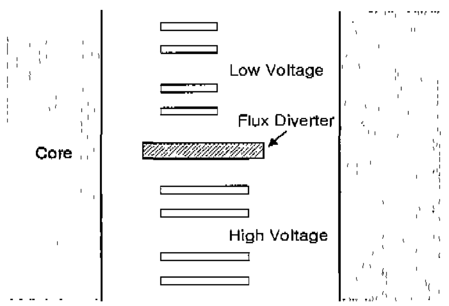


Fig. 8. An arrangement of windings and flux diverters on the standard design model of a 1MVA HTS transformer winding.

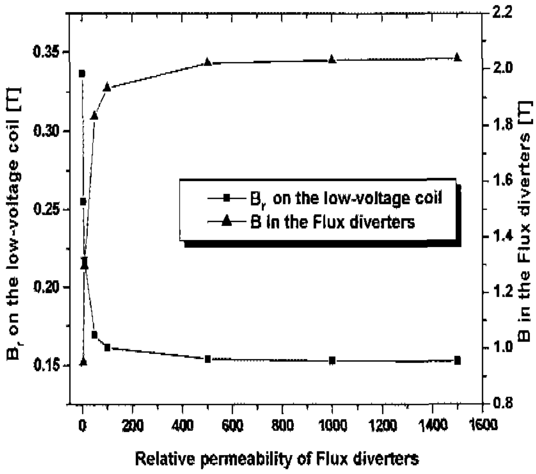


Fig. 9. Variations of B_r on the low voltage winding and B in flux diverters of a 1MVA HTS transformer standard design model by changing the relative permeability of flux diverters.

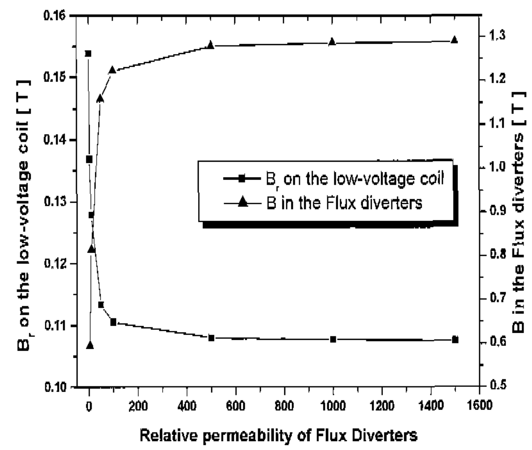


Fig. 10. Variations of B_r on the low voltage winding and B in the flux diverters of a 1MVA HTS transformer that is considered reciprocal arrangement and is increased the number of the high voltage pancakes.

4. 3D Analysis of a 1MVA HTS Transformer

We have designed a 1MVA 22.9kV/6.6kV HTS transformer winding considering suggested methods and calculated transformer parameters by the 3D FEM. Table II shows specification of a 1MVA HTS transformer standard design model. Fig. 11 shows distribution of B_r on the low voltage winding of a 1MVA HTS transformer with flux diverters. Fig. 12 shows distribution of B_r between position A and position B in Fig. 11. In Fig. 12, we can see that maximum B_r on the tapes is about 0.117 [T]. It is possible to reduce B_r about 65 % as compared with B_r on a standard design model without flux diverters. Secondary current of this HTS transformer reaches about 215A during operation. The B_r, 0.117 [T] limits the critical current of HTS tapes when the operation temperature is 77K. But This B_r is enough to flow 215 A under the subcooled operation of 65K.

TABLE II
SPECIFICATION OF A 1MVA HTS TRANSFORMER

Specification		Value
Rating	Capacity	1 MVA
	Voltage	22.9 kV / 6.6 kV
	Current	44 A / 152 A
HTS windings	No. of turns	888 / 256
	Voltage/turn	25.8 V/T
	Length of tape	1,248 m / 1,454 m
	No. of bobbin	8 / 4
	Outer diameter	472 mm / 488 mm
	Inner diameter	416 mm / 416 mm
Flux Diverter	Material	Silicon steel plate
	No. of Flux diverter	8
	Thickness	10 mm
	Inner /Outer diameter	398 mm / 508 mm
Iron Core	Material	Silicon steel plate
	Height / Width	1,384 mm / 998 mm
	Cross section area	590 cm^2
	Max. flux density	1.7 T
Cryostat	Material	FRP
	Inner / Outer diameter	698 mm / 300 mm
	Height	1,089 mm

5. Conclusion

In general, pancake type windings are preferred in conventional high voltage transformers because of ease o f electrical insulation. However, in windings of pancake type, high perpendicular component of B greatly decreases the critical current. Studies to reduce B_r applied to the HTS tapes in the transformer with double pancake windings are conducted. First, we calculated variations of B_r on the low voltage coil by a variation of a gap between the high voltage winding and the low voltage winding and found out that B_r is not greatly influenced by the gap. Then we calculated a variation of B_r by various reciprocal arrangements and division of voltage per pancake on the high voltage side. We confirmed that it is possible to reduce B_r on HTS tapes by the reciprocal arrangements and division of voltage per pancake. We also observed that flux diverters is effective to reduce B_r. Finally, we have designed a 1MVA 22.9kV/6.6kV HTS transformer winding considering suggested methods and calculated transformer parameters by the 3D FEM. As a result, we could drop B_r applied to the HTS tapes about 65 % compared with B_r on a standard design model without flux diverters.

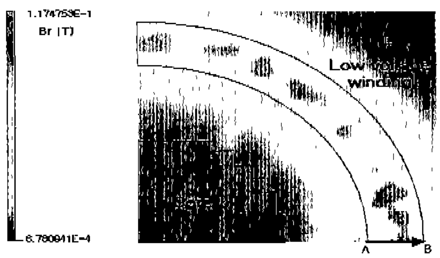


Fig. 11. Distribution of B_r on the low voltage winding of a 1MVA HTS transformer with flux diverters.

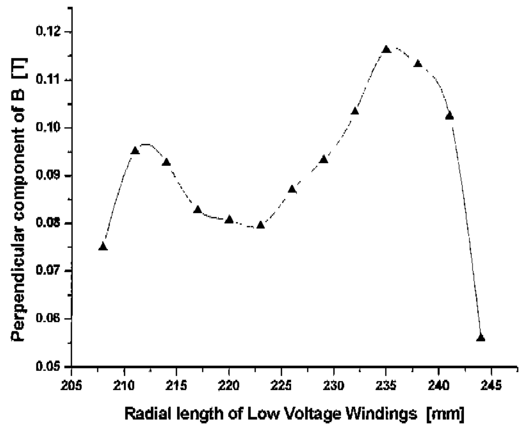


Fig. 12. Distribution of B_r from A of the low voltage winding to B of that on a 1MVA HTS transformer.

ACKNOWLEDGMENT

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REFERENCES

[1] S. P. Metha, N. Aversa, and M. S. Walker, "Transforming Transformer," *IEEE Spectrum*, pp. 43–49, July 1997.

[2] H. Zueger, "630kVA high-temperature superconducting transformer," *Cryogenics*, vol. 38, pp. 1169-1172, 1998.

[3] S.W. Schwenterly, B.W. McConnell et al., "Performance of a 1MVA Demonstration Transformer," *IEEE Trans. Appl. Supercond.*, vol.9, no.2, pp.680-684, June 1999.

[4] K. Funaki, *et al.*, "Development of a 22kV/6.9kV Single-phase Model for a 3MVA HTS Power Transformer," *IEEE Trans. Appl. Supercond.*, vol. 11, no.1, pp.1578-1581, March 2001.

[5] So Noguchi, Makoto Yamashita, Hideo Yamashita, and Atsushi Ishiyama, "An Optimal Design Method for Superconducting Magnets using HTS Tape," *IEEE Trans. Appl. Supercond.*, vol. 11, no.1, pp.2308 -2311, March 2001.

[6] K. Karsai, D. Kerényi, and L. Kiss, "Large Power Transformers," *New York, NY: Elsevier*, pp. 81-92, 1987.

[7] Maitham K. Al-Mosawi, Carlo Beduz, and Yifeng Yang, "The Effect of Flux Diverters on AC Losses of a 10kVA High Temperature Superconducting Demonstrator Transformer," *IEEE Trans. Appl. Supercond.*, vol. 11, no.1, pp.2800- 2803, March 2001.