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Conceptual Design of an HTS large power transformer with continuously transposed coated conductors

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Abstract-- **This paper shows results of a design work of a program that is to develop a large power single phase high temperature superconducting (HTS) transformer. The program forms a part of a national project in Korea. A target of the design work is an HTS power transformer with rated voltages of 154 kV/22.9 kV and material for windings is supposed to be coated conductor. The design results presents in this paper will include: 1) HTS winding structures for high voltage in liquid nitrogen, 2) design result of continuously transposed coated conductor (CTCC), 3) conceptual design of high voltage bushings, 4) cooling system. A feasibility study will succeed to this design work for construction of a prototype HTS power transformer with capacity/voltage of 33 MVA/154 kV.**

TABLE I
SPECIFICATIONS OF DESIGN TARGET.

Specification		Value
Capacity		33 MVA
Voltages	Primary	88.912 kV, Y-connection
	Secondary	13.221 kV, Y-connection
	Tertiary	6.6 kV, delta-connection
Impedance		20 %
Core magnetic field		1.59 T
Operating temperature		69 K
Load factor HTS conductor		0.7
Tab voltage step for OLTC		88.912 kV ±1.25%, 17 tabs

1. INTRODUCTION

Though a superconducting power transformer has quite a few advantages over a conventional one such as high efficiency, reduced size, and environmentally cleanness, but lots of R&D programs are showing very slow progress world widely [1]. The reason is two folds. First, the conductor is still expensive and the performances are not good enough yet. In case of a power transformer, by virtue of the superconductor's zero resistances, it is possible to make a transformer small by increasing the number of turns of windings. However, the cost of the superconductor, especially HTS wires such as YBCO CC, is one of main obstacles to a practical use of the HTS devices. Too much AC loss density from an HTS wire is also big problem to be solved. The other reason is an insulation problem in a cryogenic environment. An electrical device for power grid such as a transformer should stand very high voltages [2]. but insulation materials for very high voltage in low temperature are still limited to a couple of materials. In fact, some institutes are concentrating on development of new cryogenic materials for high voltage insulation or construct a database for cryogenic characteristics of existing ones [3]. Although we have much of problems to be solved right now for developing the HTS transformer, there are still couples of R&D programs in progress, and DAPAS program in Korea is one of them. The final goal of this national project of the HTS transformer is to develop key techniques such as a design technique, high voltage bushings, continuously transposed HTS conductor for the power transformer, HTS winding structure, and cryogenic system. This paper presents a conceptual electric design for a 3 phase, 100 MVA, 154 kV HTS transformer, which is expected to substitute a 60 MVA conventional one at the same space. It is well known that the size effect should be one of the major advantages for HTS power devices, so the design work on this project will be based on the premise that the 100 MVA HTS transformer should occupy the same room as a 60 MVA conventional one does. This conceptual design will focus on the electric parts including conductors, windings, and bushings. Although end terminal for HTS power cable has been developed recently by one of the electric company in Korea [4], but the bushing for a transformer is much more difficult than that for a cable because they will be operated in gas nitrogen or helium, which are poor insulators for high voltages like 154 kV.

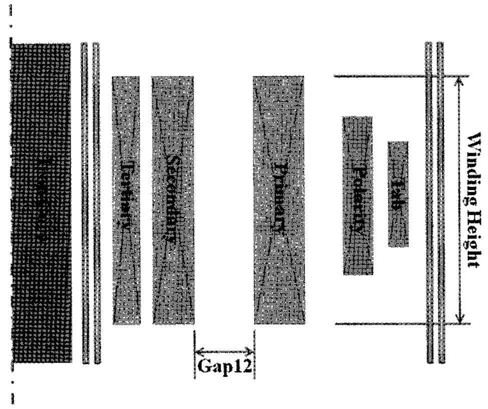

Fig. 1. Configuration of the HTS windings and iron core of the transformer.

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2. SPECIFICATIONS OF AN HTS POWER TRANSFORMER

Table I shows the specifications of the 33 MVA, 154 kV single phase HTS transformer. Three of identical transformer can be put together with proper connections to make 3 phase 100 MVA transformer bank. Primary and Secondary windings of the transformer will be joined together in Y-connection, so the rated phase voltage of the primary winding will be 88.912 kV. Secondary and tertiary winding's connections between the phases will be Y and delta-connection respectively, so the phase voltages of each will be 13.221 kV and 6.6 kV. All the HTS conductors for the windings are supposed to be continuously transposed coated conductor (CTCC) with 2G wire, and the load factor of the CTCC at the operating temperature of 69 K should be around 0.7 under the condition of the perpendicular magnetic flux density of 0.2 T. The primary winding of this transformer should have 17 taps which cover ±1.25 % of the rated voltage as an industrial standard from the Korea Electric Power Co. (KEPCO).

3. RESULTS OF DESIGN WORK

The design parameters presented in this paper include just a part of electrical design works. Each part of the results of design will be verified by experiments later.

3.1. HTS windings

The HTS winding part for the transformer consists of primary, secondary, tertiary, polarity, and tap windings. The primary and secondary windings are essential windings for the transformer, and tertiary winding is generally required for the power transformer in order to suppress the 3rd harmonics in the essential windings. The tertiary winding is also very useful for the internal power supply for the substation. The high voltage transformer for power distribution also requires some special windings for a compensation of the voltage drop on the secondary winding caused by the load variation. The tap changing is usually realized by the combinational tap changing between the tap windings and the polarity windings shown in Fig. 1. We used to have a previous design of HTS windings for another

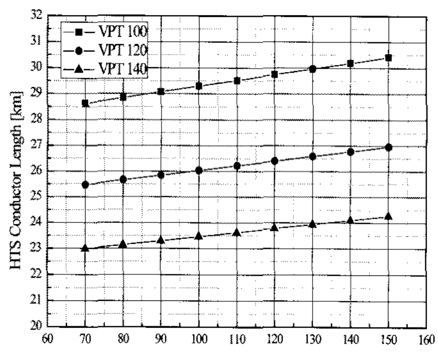


Fig. 2. Total demands of HTS conductor vs. distance between primary and secondary windings and voltage per turn.

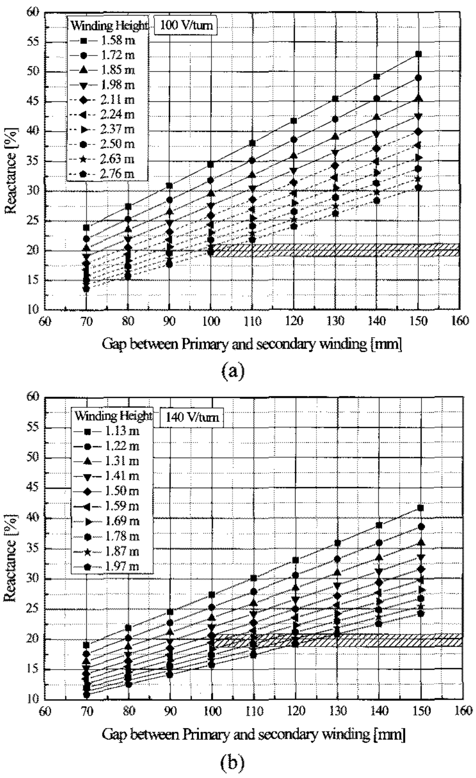


Fig. 3. Impedance calculation according to the height of the coil parts and the distance between the primary and the secondary windings. (a) a case with 100 V/turn and (b) a case with 140 V/turn.

similar transformer which had separated primary windings to minimize magnetization loss from the primary and secondary windings. The secondary HTS winding was located between the separated primary windings in the previous design, which made the diameter of the HTS winding parts too big because of the distance it needs for high voltage insulation between the primary and secondary windings. The separated primary winding is merged together in this design work that results in a smaller size and higher loss density. Even though the loss density may

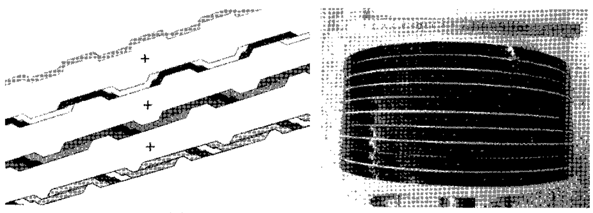
TABLE II
LINE VOLTAGES AND NUMBER OF TURNS FOR TAB VOLTAGES OF THE PRIMARY WINDING.

No.	Line voltage [V]	No. of turns	Error[%]
1	154000 + 8 x 1925 = 169400	703	0.035585
2	154000 + 7 x 1925 = 167475	695	0.033952
3	154000 + 6 x 1925 = 165550	687	0.032281
4	154000 + 5 x 1925 = 163625	679	0.030570
5	154000 + 4 x 1925 = 161700	671	0.028819
6	154000 + 3 x 1925 = 159775	663	0.027025
7	154000 + 2 x 1925 = 157850	655	0.025187
8	154000 + 1 x 1925 = 155925	647	0.023304
9	154000 + 0 x 1925 = 154000	639	0.021374
10	154000 - 1 x 1925 = 152075	631	0.019395
11	154000 - 2 x 1925 = 150150	623	0.017365
12	154000 - 3 x 1925 = 148225	615	0.015282
13	154000 - 4 x 1925 = 146300	607	0.013144
14	154000 - 5 x 1925 = 144375	599	0.010950
15	154000 - 6 x 1925 = 142450	591	0.008695
16	154000 - 7 x 1925 = 140525	583	0.006379
17	154000 - 8 x 1925 = 138600	575	0.003999

be higher than before but the total loss might be not so high because of reduced volume of HTS windings. Gap12 in Fig. 1 denotes the distance for the high voltage insulation, which affects leakage magnetic field and mainly the impedance of the transformer. Other distances between windings except the main coils do not show any direct effects on the impedance of the transformer so we could set those distances according to the insulation requirements. Fig. 2 shows the demand of HTS conductor according to the Gap12, the distance of the primary and secondary windings. It is very clear total demand of the conductor is in proportion to the Gap12 and inverse proportion to voltage per turn as shown in Fig. 2.

The impedance of the transformer should be around 20% considering the standard of 154 kV, 60 MVA power transformers in Korea, which is 15 %. Fig. 3 shows the impedance of the transformer vs. Gap12 and the height of the winding parts. The calculation results are quite understandable because the impedance of the transformer is usually proportional to the leakage flux between the primary and the secondary windings. Obviously, the leakage flux should be proportional to the Gap12 and inversely proportional to the height of the windings. For our design work, we set a height limitation for HTS winding parts to 2 meters, considering producibility. A test for the sample HTS winding in liquid nitrogen says the Gap12 should be more than 100 mm [5], so the possible design candidate should be located in hatched area of each graph in Fig. 3. Obviously there is no possible model with the 100 V/turn as shown in Fig.3 (a), so we decided that the voltage per turn should be around 140 V/turn.

First of all, to determine the number of turns of windings, we have to decide the number of turns for tap winding. The voltage step of the tap winding should be 1.25 % of the primary rated voltage, which is 1111.4 V. When the number of turns for each tap is set to 8 turns, an assumed voltage per turn will be 138.925 V. It makes the number of turns of the secondary winding about 95 turns, so the final decision of the voltage per turn will be changed to 139.172



(a) (b)

Fig. 4. (a) Configuration of CTCC and (b) sample CTCC of 10 meters using stainless steel tape with epoxy coating.

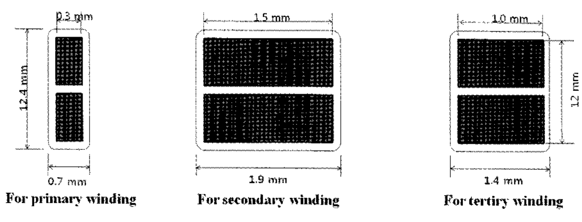


Fig. 5. Design of CTCCs for the HTS transformer windings.

TABLE III
DESIGN PARAMETERS OF WINDINGS AND CORE.

Specification	turns	layers	Disks
Primary main winding	575	5.75	100
Primary polar winding	64	1	64
Primary tab winding	64	1	8
Secondary winding	95	1	95
Tertiary winding	47	1	47
Iron Core	H 400 cm, W 239 cm, D 67.2 cm		
Cryostat	H 323 cm, OD 166 cm, ID 70 cm		
Width of HTS Conductor	12 mm,		
Critical Current	300 A t 77K, 0 T		

V. Table II shows the determined number of turns, line voltages for the taps, and the error caused by the slight change of the voltage per turn. The summary of the winding design is shown in Table III. All the windings will be wound as layer windings with the maximum diameter of the outermost winding, tap winding, is 1.37 m and the height of the primary and the secondary winding is 1.65 m.

3.2. CTCC for large rated currents

Twist or transposition of the filamentary wire is indispensible for the use of any conductor for AC power devices. Because of the special tape shape of the YBCO CC, it is not easy to realize the twist of the filaments but transposition can be done using specially tailored coated conductor, as shown in Fig. 4 (a). It may help to make an even distribution of current as well as reduce the AC loss from the conductor [6]. Each strand needs an insulation to isolate the strands from each other, so we put an epoxy coating around each strands. Fig. 4 (b) shows a sample CTCC of 10 m length produced with epoxy coating and it was tested under the similar condition of the operation of the transformer. Configuration of designed CTCCs for each HTS windings of the transformer are shown in Fig. 5, and specifications of CTCCs and the YBCO CC used for the design of the conductor are summarized in Table III. The final CTCCs for each winding will be insulated with Nomex® tape over 3 times for the voltage per turns.

Big AC loss is actually the most serious problem with the YBCO CC itself, and so as with CTCC too. Although the transposition of the CTCC may prevent the magnetic coupling of each strand, but the cross section of the strand itself still has a very large aspect ratio which may results in huge AC losses. We consider the striation of the HTS layer would be the only solution for reducing the AC loss, so we are working on the striation on the strand for CTCC with laser cutting. Successfully fabricated with very short sample of CTCC and same process for long length of the CTCC is now on going.

3.3. Bushings for high rated voltages

The technique of high voltage insulation in cryogenic environment is main bottleneck in development of HTS power devices. A Bushing for the rated voltage of more than 154 kV is essential for realization of the HTS power transformer. In order to test the HTS windings with high voltages, we tried to just modify a conventional bushing for voltage of 60 kV. Fig. 6 shows the modified bushing and insulation scheme with various gas states. We will put mixed SF_6 gas with nitrogen gas in the middle part of the bushing to prevent from freezing by heat conduction through the current leads. The bottom part of it will be filled with nitrogen gas with pressure of 3 atm. to secure the space for insulation from the frame. A big cryostat made of G10 was built for the test of busing, and the high voltage experiment will be performed shortly. A similar insulation scheme for 154 kV will also be prepared.

3.4. Cryogenics

The operating temperature of the transformer is 69 K, a sub-cooled liquid nitrogen circulation system will be required for a stable operation. Fortunately, a similar cooling system had been already constructed a few years ago, and the system could be used for the HTS power transformer. It had been designed for 65 K operation of the previous HTS transformer, and it consists of 2 sets of refrigerator and a cryogenic pump which has a capacity of 19 liter/min. The system is shown in Fig. 7, and supposed to be applied to the transformer system to keep the operating temperature of 69 K and the nitrogen gas pressure of 3 atm. in the cryostat of the transformer.

3.5. Configuration of the iron core and the cryostat

The dimension of the HTS transformer with iron core and the cryostat presented in this paper is shown in Fig. 8. The height of the transformer itself is about 4 meter, still a bit tall, and the bushings may add more height, but with an effort to make an optimal insulation design, it is expected to be a little bit shorter than now. Right now, we are also focusing upon the successful striations on the strands for long CTCC to make the AC loss about one tenth of that of non-striated conductor.

4. CONCLUSION

Basic electric design parameters for 154 kV, 33 MVA single phase HTS power transformer are presented in this paper. A configuration of 60 kV cryogenic bushing for a HTS transformer was proposed in this paper and will be tested soon. Hopefully, it will work well, then we will move on to 154 kV class. More detail design work including the On Load Tab Changer (OLTC) interface is now in progress.

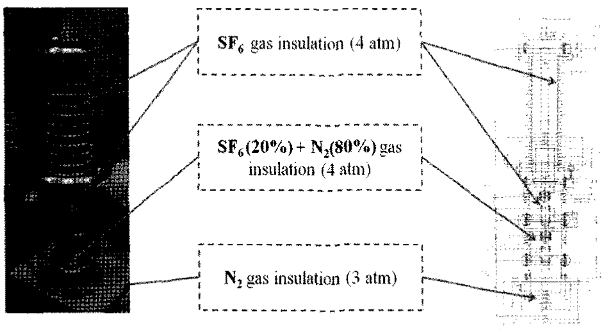


Fig. 6. Insulation scheme for the modified 60 kV bushing for the HTS power transformer.

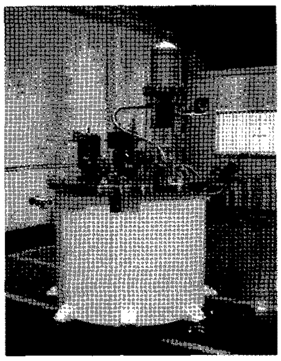


Fig. 7. Cooling system for the 69 K operation of the HTS transformer.

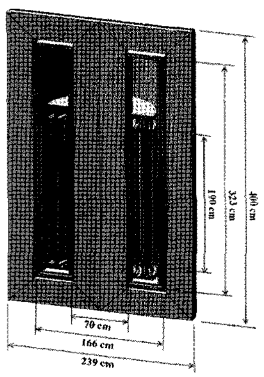


Fig. 8. Configuration of the HTS windings, iron core, and the cryostat for the HTS power transformer with the primary rated voltage of 154 Kv.

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REFERENCES

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

[2] C. S. Weber, C. T. Reis, D. W. Hazelton, S. W. Schwenterly, M. J. Cole, J. A. Demko, E. F. Pleva, S. Mehta, T. Golner, and N. Aversa, "Design and operational testing of a 5/10-MVA HTS utility power transformer," *IEEE Transactions of Applied Superconductivity*, Vol. 15, No. 2, June 2005.

[3] Isidor Sauers and Enis Tuncer, "Strategic dielectrics R&D for HTS and other OE application," *2009 DOE Peer Review*, August 2009.

[4] S. H. Sohn, J. H. Lim, S. W. Yim, O. B. Hyun, H. R. Kim, K. Yatsuka, S. Isojima, T. Masuda, M. Watanabe, H. S. Ryoo, H. S. Yang, D. L. Kim, and S. D. Hwang, "The results of installation and preliminary test of 22.9 kV, 50 MVA, 100 m class HTS power cable system at KEPCO," *IEEE Transactions on Applied Superconductivity*, Vol. 17, No. 2, June 2007.

[5] H. G. Cheon, D. S. Kwag, J. H. Choi, C. H. Min, T. S. Park, H. H. Kim, and S. H. Kim, "Insulation design and experimental results for transmission class HTS transformer with composite winding," *IEEE Transactions on Applied Superconductivity*, Vol. 18, No. 2, June 2008.

[6] J. K. Lee, et al., "Effects of striations on magnetization loss of transposed coated conductors," *Physica C 468*, August 2008.