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Conceptual Design of a Single Phase 33 MVA HTS Transformer with a Tertiary Winding

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3차 권선을 고려한 단상 33 MVA 고온초전도 변압기의 개념설계

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Abstract

We have proposed a 3 phase, 100 MVA, 154 kV class HTS transformer substituting for a 60 MVA conventional transformer. The power transformer of 154 kV class has a tertiary winding besides primary and secondary windings. So the HTS transformer should have the 3rd superconducting winding.

In this paper, we designed conceptually the structure of the superconducting windings of a single phase 33 MVA transformer. The electrical characteristics of the HTS transformer such as % impedance and AC loss vary with the arrangement of the windings and gaps between windings. We analyzed the effects of the winding parameters, evaluated the cost of each design, and proposed a suitable HTS transformer model for future power distribution system.

Keywords : High Temperature Superconductivity, Transformer, Tertiary Winding, AC loss

I. Introduction

High Temperature Superconducting (HTS) transformers have many benefits over the conventional transformers. At the early stage of the development of the HTS transformer, energy saving and operating cost reduction due to the high efficiency were considered as the major advantages.

Reduced weight and size of the HTS transformer can be more advantageous than the high efficiency in some situations.

The size effect of the HTS transformer is the most important merit in Korea. The standard of power capacity of the 3 phase transformer for 154 kV power line is 60 MVA in Korea and most of them are installed in basements of buildings in downtown of major cities. Though 150 % increase of current

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power load in 2017 is predicted, it is hard to find a solution for increasing the capacity of facilities, especially for the power transformer. If an HTS transformer substitute for the conventional one, its size can be reduced to 1/3 or 1/2 of the conventional one. Even if it is not so critical benefit for the substations which are built on the field or in the mountain far away from metropolis, but there are about 50 underground substations at the basements of large buildings in Seoul. There is no way to increase the power capacity of the substations in Seoul except constructing new buildings.

In Korea, 154 kV class three phase power transformer is composed of 3 individual single phase ones. The design criteria which is considered for the single phase one can be directly applied to the three phase one.

This paper presents the design of 33 MVA single phase HTS transformer with YBCO coated conductor considering a tertiary winding. The rated primary and secondary voltages of the transformer are 154 kV and 22.9 kV respectively. Generally, power transformer of 154 kV class has a tertiary winding besides primary and secondary windings. So, we considered the third superconducting winding in the design of the transformer.

II. Design targets of HTS transformer

In order to evaluate the design of HTS transformer system, a target specification is needed and Table 1 shows the specification of the target HTS transformer. We adopted shell type for the core and continuous disk type for windings in order to limit the voltage stress within them. The transformer windings are cooled using liquid nitrogen which has the boiling point of 77 K at normal pressure. Decreasing the temperature yields an increase of the HTS wire current capacity. Operating temperature of HTS transformer is 65 K. By sub-cooling liquid nitrogen the temperature down to 65 K can be reached [1].

An FRP cryostat with a room temperature bore was designed in order to separate the HTS windings from the room temperature iron core. The cryostat has vacuum layers outside and inside of that for thermal insulation.

Table 1. Specification of the HTS transformer.

Specifications	value	Unit
Phase	Single phase	
Capacity	33	MVA
Rated voltage (rms)	154/22.9/6.6	kV
Phase voltage (rms)	88.9/13.2/6.6	kV
Rated current (rms)	0.37/2.5/1.6	kA
Connection type	Y - Y - Δ	

III. HTS transformer winding

A. Specification of coated conductor

According to the expectations of the industrial manufacturers, 300 A/cm of critical current at liquid nitrogen (LN_2) temperature is the goal for commercialization.

To design the HTS transformer, we determined the coated conductor specifications based on the trend of development as shown in Table 2.

The HTS windings of the transformer we designed will be cooled by using sub-cooled LN_2 at 65 K. The local temperature of the HTS windings could be somewhat different from the temperature of the coolant, so the maximum operating temperature is assumed to be 67 K. Fig. 1 shows the critical current of coated conductor at different operating temperature and magnetic fields.

For the magnetic field we assumed a maximum value of 0.18 T would be applied as a perpendicular component of magnetic field at the coil ends. In order to achieve large operating current several tapes have to be connected in parallel. This yields the design results 5 tapes in parallel for the primary winding operated at 371.2 A and 30 tapes in parallel for the secondary winding operated at 2,502 A of rated currents.

Table 2. Specification of coated conductor.

Specification	Value	
Thickness of wire	200 μm	
Width of wire	4 mm	
Stabilizer	Cu, thickness 75 μm	
YBCO layer	2 μm	
Critical current	120	@ 77 K, 0 T
	228	@ 69 K, 0 T

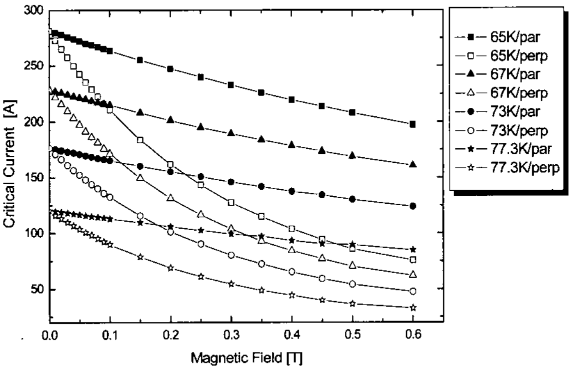

Fig. 1. Critical current of coated conductor.

The operating current of coated conductor was determined to have the current margin of 30 %. But non-uniform distribution of currents and large AC losses are major problems of parallel HTS windings setting aside difficulties of making parallel windings. It requires manufacturing technology for fully transposed conductors.

B. HTS windings

Perpendicular magnetic field generates large AC losses in HTS windings which cannot be accepted because of very expensive cooling system and the poor transformer efficiency. Therefore primary, secondary and tertiary windings have to be arranged as concentric cylinder type. Radial gap length has to be adjusted according to the voltage stress between windings and leakage percent impedance. Primary winding is continuous disk type and secondary is layer type. Fig. 2 shows the arrangement of windings for the HTS transformer. Tertiary winding is

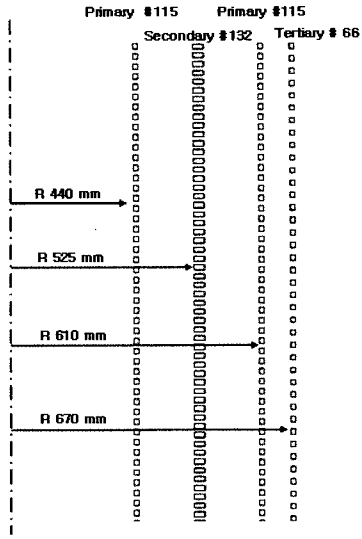

Fig. 2. Winding arrangements of HTS transformer.

necessary to suppress the third harmonics component and to compensate for asymmetric loads of the secondary.

IV. AC loss of HTS transformer

In most of HTS windings for power applications, the main property to be considered is the AC loss due to the perpendicular component of the magnetic field, except for the case of transmission cable where the main component of the external magnetic field is parallel to the surface of the HTS wire.

We were able to estimate the AC losses generated from the coated conductor which will be used for the HTS windings of the transformer using the same technique of calculation of AC losses for BSCCO windings. Numerical calculation is carried out to figure out the parallel and perpendicular magnetic field components in the winding. The AC loss from perpendicular magnetic fields and parallel fields is calculated by the strip and slab model equation [2, 3]. Calculated AC loss consists of magnetization loss and transport current loss.

The AC losses in the winding have been analyzed for the case of primary and secondary at rated currents and tertiary winding with no current.

V. Design of HTS transformer

Basic structure of the HTS transformer is not greatly different from that of conventional transformer. Like general transformer, an iron core that accomplishes a magnetic circuit between primary HTS windings and secondary HTS windings should be installed and designed by the same method as a conventional one.

HTS transformers were designed according to the voltage per turn (V/T) of winding and they were compared with the 60 MVA, 154 kV/22.9 kV conventional transformer.

The comparisons are shown in Table 3. The size of transformer can be reduced to about 87 % of 60 MVA conventional transformer at V/T of 80. The operation loss of transformer can be reduced to about 54 % of that of conventional transformer at 140 V/T. As V/T decreases, the weight and size are reduced. This is desirable from the original view point of 100 MVA HTS transformer. Smaller V/T causes long length of HTS wire. On the other hand, the weight and loss decrease as the V/T increases.

The required quantity of HTS wire and loss decreases as the V/T increases as shown in Fig. 3. In the economic sense, the large V/T is desirable. When the V/T is 70 and 140, the necessary HTS wire is

Table 3. Result design of 100 MVA HTS transformer and 60 MVA conventional transformer (per phase).

Conventional transformer

Capacity	Width [m]	Height [m]	Weight [ton]	TR loss [kW]
60 MVA	2.4	5.5	46.7	90

HTS transformer

Capacity	V/T	Size [m^2]	Weight of core [ton]	Cost of windings [$]	TR loss [kW]
100 MVA	80	11.7	8.6	47,250	230
	100	12.2	10.7	39,958	125
	120	12.7	12.9	34,840	75
	140	13.2	15.3	31,376	48

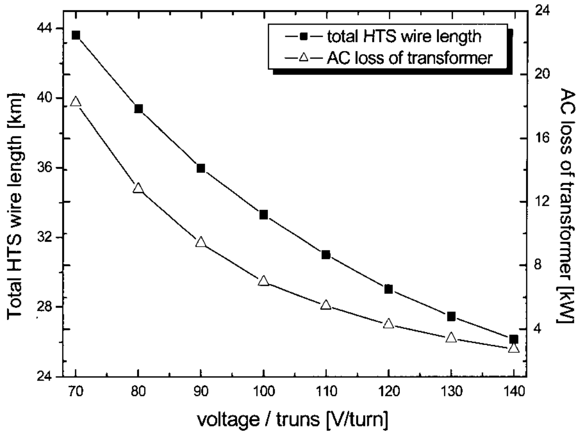

Fig. 3. HTS wire length and AC loss of transformer according to the V/T (per phase).

about 43.6 km and 26.2 km. Also AC loss is about 18.24 kW and 2.7 kW, respectively.

The cost differences between them will be about $20,000 in 2015, when the price of HTS coated conductor wire is expected to $20/kA-m.

VI. Conclusion

In this paper, we designed single phase 33 MVA HTS transformer with tertiary winding. Due to limits of road transportation it is required that a three phase 100 MVA transformer system is made of 3 individual single phase transformer. And the tertiary winding requires for suppression of third harmonics and compensation of asymmetric load. We analyzed the effects of the V/T parameters, evaluated the cost of each design, and proposed a suitable HTS transformer model for future power distribution system.

Acknowledgments

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