Iron Core Design of 3-Phase 40MVA HTS Power Transformer Considering Voltages per Turn

Chan-joo Lee* and Bok-yeol Seok*

Abstract - This paper presents the iron core design method of a high temperature superconducting (HTS) transformer considering voltages per turn (V/T). In this research, solenoid type HTS coils were selected for low voltage (LV) winding and double pancake coils for high voltage (HV) winding, just as in conventional large power transformers. V/T is one of the most fundamental elements used in designing transformers, as it decides the core cross sectional area and the number of primary and secondary winding turns. By controlling the V/T, the core dimension and core loss can be changed diversely. The leakage flux is another serious consideration in core design. The magnetic field perpendicular to the HTS wire causes its critical current to fall rapidly as the magnitude of the field increases slowly. Therefore in the design of iron core as well as superconducting windings, contemplation of leakage flux should be preceded. In this paper, the relationship between the V/T and core loss was observed and also, through computational calculations, the leakage magnetic fields perpendicular to the windings were found and their critical current decrement effects were considered in relation to the core design. The % impedance was calculated by way of the numerical method. Finally, various models were suggested.

Keywords: critical current, HTS transformer, leakage, magnetic field, voltage per turn (V/T)

1. Introduction

The high temperature superconductor is an amazing discovery in the field of science and engineering. Moreover, HTS materials, in which the critical temperatures are above 77K, enable the cooling system to be simplified. This aspect makes it very advantageous when compared with the LTS cooling system. However, HTS materials have a very weak magnetic property related with the critical current. The critical current of HTS materials decreases steeply as the magnetic field, especially the perpendicular component of the field, is applied. To overcome this weakness, the HTS materials must be cooled down below 77K and even to 20K to increase the critical current. This means that the cooling advantage is reduced and that the cooling system is more complicated. Recently the subcooled LN_2 system was introduced and is used worldwide. It cools down the temperature to about 65K so that the HTS critical current at the zero applied field may be up to about 1.5 times of the critical current in 77K. In the case of 20K cooling, the system becomes more complex because it employs the use of cryocoolers and the critical current of HTS material at the zero applied field is up to about 6 times that of the critical current in 77K. Nevertheless, HTS power transformers are developed by many advanced transformer makers such as ABB, Waukesha [1], etc. And yet, their capacities are not sufficient to be commercialized. Siemens has developed a HTS traction transformer with a capacity of 1MVA. In Korea, the maximum capacity of a manufactured HTS transformer is 10kVA [2]. Currently, 21^{st} century frontier research and development activity is taking place with the goal of developing a 3Φ 100MVA HTS transformer in 2011. Hyundai Heavy Industries Co. LTD is researching the HTS power transformer to develop a prototype in 2005. In this paper, the iron core of the HTS power transformer was designed considering the V/T and other various factors. The core loss, the perpendicular leakage flux to winding and the number of LV layers were considered and calculated for the core design.

2. Iron Core Design

The HTS transformer has a similar structure to conventional ones and is composed of iron core and windings. Additionally, the cryogenic system is needed in this case to cool down the superconducting windings. In this paper, the iron core of a 40MVA Δ-Y transformer, specifications of which are shown in Table 1, was designed through the basic core design diagram in Fig. 1.

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Generally in a superconducting power transformer, the V/T tends to be smaller than that of a conventional transformer in order to reduce the core loss [3, 4]. However, small V/T causes the core to be unreasonably tall. To reduce the height of the core, the number of LV layers should be increased, allowing the perpendicular leakage field winding to be enlarged so as to weaken the magnetic property of HTS winding and lessen its critical current. As the number of LV layers increases, % impedance also increases beyond a reasonable level. Because these three factors depend upon each other in this way, various core sizes should be observed through analysis considering these factors in order to properly design iron core.

For this research, automatic calculation sheets for transformer design were developed. When certain fundamental parameters, partially shown in Table 1, are entered, other transformer parameters such as core height, core window size, and proper number of HV layers are automatically calculated.

2.1 Core loss

From now, some researches were performed regarding the superconducting transformer without an iron core as a way of reducing its size and core loss. But, it was found that in the model without an iron core, very high current density or over-dimensioned primary winding with respect to secondary winding is needed to reduce leakage flux, which causes very large % impedance [5]. In this study, we introduced an iron core as a flux path to prevent the generated flux from over leakage into the air, and to achieve the proper % impedance.

The iron core in the time-varying magnetic field is accompanied by loss, which is called iron core loss. The iron core loss is composed of hysteresis loss and eddy current loss. In our core design of the HTS transformer, 30G130, the steel widely used for the iron core was introduced and its loss was about 1.63W/kg at 1.7T and 60Hz.

Core parameters such as core width, core height, core volume and core weight were calculated with respect to the V/T and number of LV layers. The amount of loss was determined from the core loss curve, which is an experimental data of steel makers. Table 2 shows an example of core parameters when the V/T is 20 and the highlighted row is the case of minimum core loss. In Fig. 2, core losses are presented according to the number of LV layers when the V/T is 20, 50, 80 and 100, respectively. The core size, as can be seen in Fig. 2, is not linearly related with the number of LV layers and in a certain number of LV layers, the core loss is minimized. The core loss becomes smaller as the V/T decreases.

Generally in a 30 to 40MVA conventional transformer with tap windings, the core loss is about 30kW. As shown in Fig. 2, losses in all simulated cases are under 30kW. To make the core loss below half that of a conventional transformer, the V/T should be lower than 50.

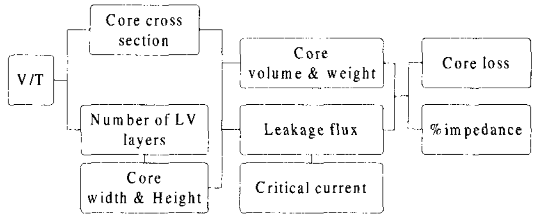

Fig. 1 Basic core design of HTS transformer

Table 1 Parameters of HTS transfomer design

Specifications	
Capacity	40MVA
Primary voltage/current	154kV/86.6A
Secondary voltage/current	23kV/1004.1A
Core material	
Material	Silicon steel
Type	30G130
Thickness	0.3mm
Core loss	1.63W/kg @ 1.7T and 60Hz
Saturation magnetic field	1.91T at 2,500A/m

Table 2 Core parameters according to number of layers

V/T	No. of LV layers	Core width [mm]	Core height [mm]	Core volume [m^3]	Core weight [ton]	Core loss [kW]
20	1	1686	5704	1.066	6.4813	10.56
	3	1931.6	2566	0.567	3.4474	5.619
	5	2177	1941	0.49	2.9792	4.856
	7	2418.6	1671	0.471	2.8637	4.667
	9	2680.4	1515	0.474	2.8819	4.695

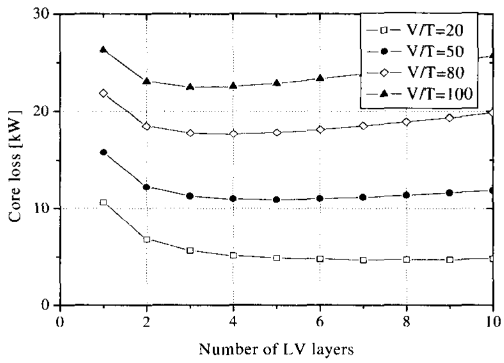

Fig. 2 Core loss according to number of layers

2.2 % impedance

Because there is no copper loss in superconducting transformers, the voltage drop is mostly dependent on the leakage reactance. The approximated equation for the induced voltage by leakage flux is [6]

$$\%impedance = 2\pi f \mu_o \frac{P_{n1}}{U_w^2 l_s g}(l\delta + \frac{a_1 l_1 + a_2 l_2}{3})R \qquad (1)$$

where, μ_o is the permeability of the air, P_{nl} is the nominal capacity of one limb in VA, U_w is the V/T, g is the number of coil groups of balanced ampere-turns on each limb, l_s is the length of leakage channel, l is its mean circumference, δ is the gap between LV and HV winding, l_1 and l_2 are the respective mean turn lengths of two windings, a_1 and a_2 are the winding size in radial direction, and R is the Rogowski coefficient.

The relationship between % impedance and number of LV layers in each V/T is shown in Fig. 3. As can be seen, large V/T signifies small % impedance and as the number of layers increases, % impedance also increases almost linearly with different slopes according to the V/T. In a conventional transformer of 30~40MVA, % impedance is about 10 to 13% and its major component is reactive impedance in large power transformers. In the HTS transformer, the gap between iron core and LV layers is larger than that of conventional ones, so that it may have relatively large % impedance. To satisfy the % impedance condition of the conventional transformer in the HTS transformer, the number of LV layers should be one and the V/T should be over 50.

2.3 Leakage flux

As mentioned above, the leakage flux, especially the perpendicular component to the HTS windings, is one of the most important factors in the design of the HTS transformer. From the positional point of view, the maximum perpendicular field appears in the upper side of winding. Therefore, we investigated the field in (A) and (B) of Fig. 4 with great interest. To observe magnetic field tendency in various V/T and number of layers, 2 dimensional FEM was executed with Flux2D®. Fig. 4 shows part of an example of the analysis model, in which the V/T is 50 and the number of LV layers is 4. LV winding is solenoid type and HV winding is double pancake type, just as in a conventional large power transformer. The double pancake winding has some advantages in size and electrical insulation. However, the magnitude of magnetic flux in double pancake winding is larger than that in the solenoid type. Fig. 5 displays the analysis result of Fig. 4. The maximum perpendicular field in the double pancake type is 0.28T. Many other results with various V/T and number of LV layers are depicted in Fig. 6. The number of layers is closely related with the perpendicular field and the minimum field is 0.09T when the number of LV layers is 1 in all cases of V/T. If the number of LV layers is 2, the perpendicular field is about 0.15T and at that value, the critical current of HTS wire is about 28.3A_{dc}, 24.6% at 77K with no applied field according to the AMSC data.

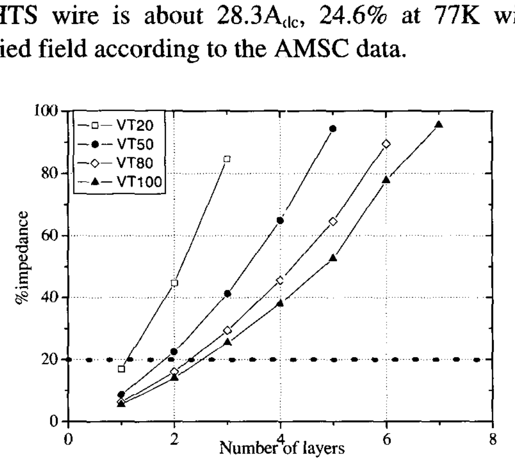

Fig. 3 % impedance according to number of LV layers

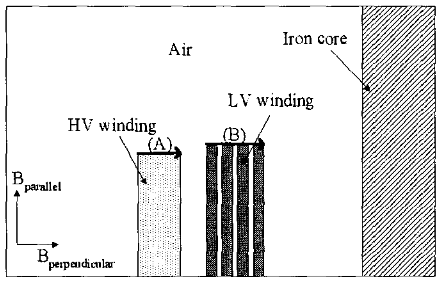

Fig. 4 Analysis model

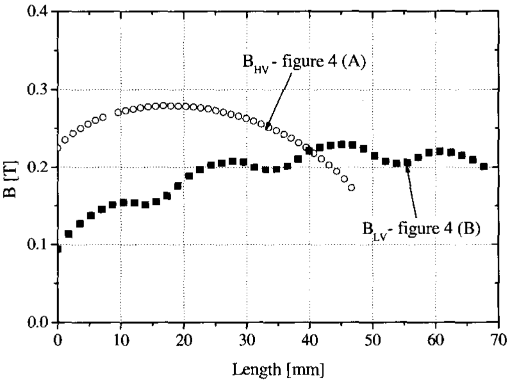

Fig. 5 Perpendicular magnetic field distributions(V/T=50, number of LV layers=4)

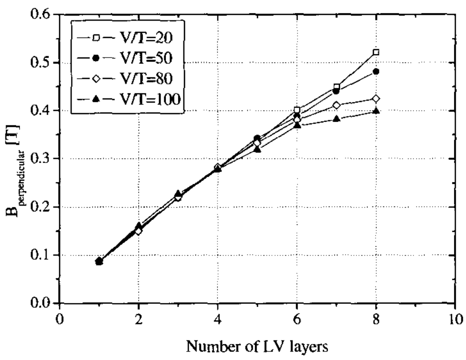

Fig. 6 Maximum perpendicular field to HTS winding according to number of LV layers

Generally in a conventional transformer, shunt structures are used to reduce the leakage flux that causes eddy current in winding, one of the sources of transformer loss and oil temperature rise. These shunt structures are also adoptable in a HTS transformer, and in that case, are often referred to as flux diverters. But, the shunt should be installed in the cryogenic system, which may be a factor of instability. So, shunt installation should be preceded by careful consideration. To reduce the leakage flux without use of a shunt, certain winding methods such as controlling the current density of winding were developed in this research. It was discovered that the maximum perpendicular field of 0.15T was reduced to 0.12T in the case that the number of LV layers is 2 and the V/T is 50.

2.4 Suggestion of iron core

Finally, considering the three factors mentioned above, we suggested iron cores for the 40MVA HTS transformer when compared with a conventional one, which was designed without tap windings, in Table 3.

The designed conventional transformer has a core loss of 34.2kW. On the other hand, the HTS transformer I has a core loss of 19.6kW and the HTS transformer II has a core loss of 22.1kW. % impedance of the conventional transformer, HTS transformer I and HTS transformer II is 10.8%, 10.5% and 9.2%, respectively. Core volume of HTS transformer I and II is about 57% and 64% of that of the conventional transformer, respectively. Since core loss and % impedance have an inversely proportional relationship with each other, it's very important to determine the proper V/T for suitable values.

In considering the amount of HTS wire, HTS transformer I consumes 25.3km and HTS transformer II consumes 22.3km. Considering the present cost of HTS wire, the difference may be large enough to cover the disadvantage of the large volume of HTS transformer II.

Table 3 Core dimensions of 40MVA transformers

	Conventional transformer*	HTS transformer I	HTS transformer II
	Core		
Diameter [mm]	568.5	402	440
Width [mm]	2740	2171	2286
Height [mm]	2576	3119	2880
	Core window		
Width [mm]	545	502	504
Height [mm]	1496	2356	2043

*The conventional transformer has no tap winding.

3. Conclusion

In this paper, the iron core design of a HTS transformer was presented. The core loss, % impedance and leakage flux were considered according to various V/T and number of LV layers. Core loss is proportional to the V/T and % impedance is in inverse proportion to it. Leakage flux has little relationship with the V/T when LV layers are small and is strongly dependent on a large number of LV layers. Finally, two iron core models were suggested and compared with a conventional transformer core.

According to the core design results, core loss and volume were reduced to 57% of the conventional transformer in case of HTS transformer I, which has almost identical % impedance with the conventional one. For smaller core loss or core volume, small V/T is needed, but this causes % impedance and the cost of HTS wire to increase too much. This trade-off relationship will be the base of iron core design in the HTS transformer.

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