# Numerical Study on Electromagnetic Field and AC loss of HTS Air-core Transformer


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*Abstract*—**Air-core transformer has advantages of no iron loss, no magnetic saturation, and compact in size, which make them attractive to be studied for practical applications. In this paper, the *H*-formulation is used to numerically analyze the electromagnetic field and AC loss of the HTS air-core transformer and optimize the air gap.**



***Keywords-high temperature superconductor (HTS); HTS air-core transfromer; AC loss; electromagnetic field; H-formulation***


## I. Introduction

With the development of HTS technology, research involving the application of HTS transformers have been actively carried out. Compared with traditional transformers, the main advantages of HTS air-core transformer include no iron loss, no magnetic saturation, a possible reduction of size and weight [1].

This paper briefly introduces the modeling method of HTS air-core transformer and analyze the electromagnetic field distribution, AC loss and efficiency optimization.

## II. Numerical Method

### A. Basic Equations

The primary and secondary sides of the air-core transformer are composed of 8 double pancakes as shown in Fig. 1(a). The PDE module based on the ***H***-formulation in the Comsol is established to numerically study and the governing equations are as follows [2]:

$$\frac{\partial(\mu_0\mu_r H)}{\partial t}+\nabla\times(\rho\nabla\times H)=0 \tag{1}$$

$$\frac{\partial H_r}{\partial z}-\frac{\partial H_z}{\partial r}=J_\varphi \tag{2}$$

$$E_\varphi=\rho J_\varphi \tag{3}$$

$$J_\varphi=J_c(B)=J_{c0}\Bigg/\left(1+\sqrt{\beta^2\left|B_{\parallel}\right|^2+\left|B_\perp\right|^2}\Big/B_0\right)^\alpha \tag{4}$$

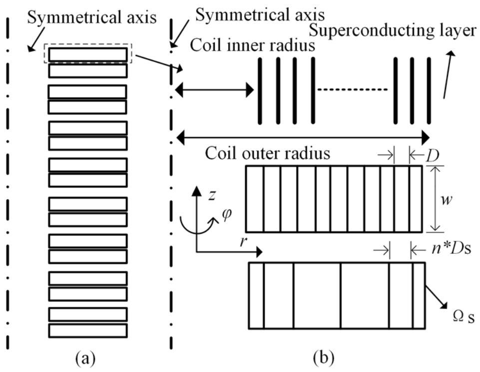


Figure 1. Basic structure and homogenization method.

TABLE I. The Parameters of HTS Air-core Transformer

| Parameters | Value |
|---|---|
| Inner diameter (cm) | 12 |
| Outer diameter (cm)<br>Air gap (cm) | 13.2<br>1 |
| Number of double-pancake | 8 |
| Turn number | 2x20 |
| Tape width (mm) /thickness (mm) | 4.5/0.3 |
| Superconducting layer thickness (um) | 1 |
| Critical current $I_c$ at 77K (A) | 143.96 |

Here the $J_c(B)$ is dependent on the perpendicular and parallel magnetic field, where $B_0$=35mT, $J_{c0}$=7.545 × $10^8$A/m$^2$, $\alpha$=0.6, $\beta$=0.25.The AC loss per cycle is calculated as follows:

$$Q=\sum 2\int_{T/2}^{T} dt\left(\int_{\Omega_s} E\cdot J d\Omega_s\right) \tag{5}$$

### B. Homogenization Method

The homogenization method is briefly shown in Fig. 1(b). First, the superconducting layer is artificially expanded to make tapes fill the space of the entire pancake. Then combine several adjacent turns of a pancake to a new turn because adjacent tapes have similar current density distributions. Note that a new current constraint should be used to ensure the transport current in the new turn is still the same as the original mode.

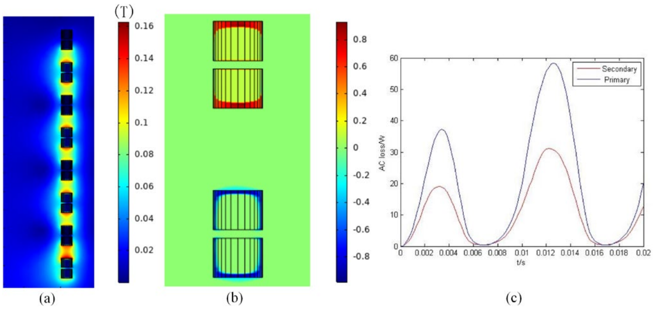


Figure 2. (a) Magnetic field (b) normalized current density (c)AC loss.

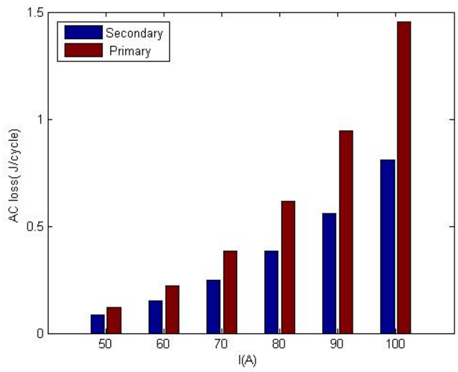


Figure 3. AC loss per cycle when different primary current levels.

## III. Results and Discussion

### A. Electromagnetic Field and AC loss Analysis

When a current of 60A/50Hz passes through the primary side, the electromagnetic field distribution of the double pancake coils at the current peak are shown in the Fig. 2. Coupling occurs between the primary and secondary coils, and an induced current appears on the secondary coils which confirms the correctness of the model. The instantaneous AC loss power of the primary and secondary coils is shown in Fig. 2 (c). Fig. 3 shows the AC loss of the primary and secondary coil at different current level.

### B. Validation of Effect

Assume the load impedance is 10Ω, the system efficiency can be obtained from equation (6). The cryocooler power is calculated as 12 times of the AC loss power of the superconductor at 77K [3]. The system efficiency including cryocooler power loss is defined as equation (7). When different currents are applied on the primary side, the system efficiency $\eta$ and system efficiency $\eta_c$ including cryocooler are shown in Fig. 4.

$$\eta = P_{\text{out}} / \left(P_{\text{out}} + P_{\text{hys}}\right) \tag{6}$$

$$\eta_c = P_{\text{out}} / \left(P_{\text{out}} + P_{\text{hys}} + P_{cy}\right) \tag{7}$$

### C. Air gap optimization analysis

As the air gap changes, the system efficiency changes are shown in Fig. 5. When the air gap of the system is reduced,

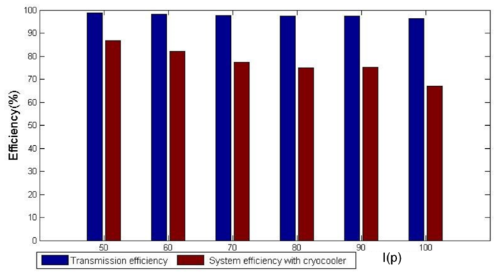


Figure 4. Transmission efficiency varies with current.

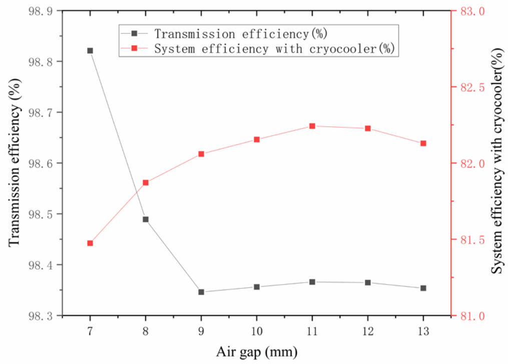


Figure 5. Transmission efficiency varies with air gap.

the induced current of the secondary coil increases and the transmission efficiency of the system increases. However, increasing the current will increase both the AC loss of the system and cryocooler power loss, leading to a decrease in efficiency. Therefore, this system can increase the 1mm air gap, so that the system efficiency including the cryocooler power loss increases and the transmission efficiency does not change much.

## IV. Conclusions

In this paper, the HTS air-core transformer model is established based on the ***H***-formulation. The magnetic field distribution and critical current distribution of primary and secondary coils are obtained. The AC loss of the primary and secondary coils and the efficiency of the system when different currents pass through are analyzed. It is found that increasing the air gap by 1 mm would increase the system efficiency including the cryocooler power loss increases and the transmission efficiency does not change much. The analysis method is provided to optimize the design of HTS air-core transformer.

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