Magnetic Field Analysis of HTS Transformer Windings With High Currents

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***Abstract*—The leakage magnetic field in HTS transformer windings fabricated by Bi-2223 tapes decreases the critical current and increases the ac losses in the tapes. Because of the anisotropy of the HTS tape, the numerical analysis of the radial component of the leakage field is especially important. In this paper the influence of the core structure and the winding configuration on the stray field is studied by finite element method, and some suggestions for improving the leakage field distribution are presented to make HTS transformers more efficient.**

***Index Terms*—FEA analysis, high-temperature superconducting transformer, magnetic leakage field, winding geometry.**

I. Introduction

THE MAJOR benefits of the high-temperature superconducting (HTS) transformers are reduced sizes, weight, energy losses, and the potential fire and environment hazards [1], [2]. In former studies, we consider the cold core structure of the superconducting transformer neither efficient nor economical since the core losses are more than 20 times those of warm core. Therefore, the warm core structure is adopted to decrease the power losses for cooling system. However, the warm core structure increases the gaps between the warm core and the HTS windings, loosens the electro-magnetic coupling between them, and thus increases the radial component of the stray field, which is perpendicular to the superconducting tapes. Because of the anisotropic properties of the HTS tapes, the behavior of the radial stray field is the crucial factor for critical current degradation and increasing ac loss. The calculation of transformer leakage flux is of fundamental importance for reducing the radial component of the leakage field in the transformer design.

We investigate the effects of the core and winding geometries on the leakage field distribution. The purpose of appropriate choice of the core type and the winding configuration is to decrease the radial field.

II. Tranformer Geometry

A. Design Parameters of the Transformer

We design a 22 kVA single-phase transformer to investigate the question. Because of its high performance, we adopt the silicon sheet steel core operating at room temperature. BSCCO-2223 tapes are used for both the primary and secondary windings. The main design parameters of the transformer are shown in Table I.

TABLE I
Design Arameters of the Transformer

Ratings	Capacity	22kVA
	Voltage	220/20V
	Current	100/1100A
	Frequency	50Hz
	Phase	Single-phase
Core	Materials	27QG110
	Nominal Flux Density	1.7T
	Cross section	5578mm^2
Windings	Material	BSCCO-2223
	Cross Section	4.1mm×0.203mm
	Number of Filaments	55
	Filament twist	No
	Critical Current Density	120A/mm^2
	V/N	2.0V
	Parallel Tapes	3/33

TABLE II
Magnetic Field Varied With the Material Performance of the Flux Diverters

Material	Radial Component BX(T)	Axial Component BY(T)
Without flux diverters	0.0286	0.0397
Powdered iron epoxy composite (μ_r=6)	0.0272	0.0397
Amorphous Metal SA1	0.0267	0.0398
Silicon Steel 27QG110	0.0267	0.0398

B. Transformer Geometry

There are a number of possible choices for the core geometry in a single-phase HTS transformer. The typical core forms are "C-core" core-type with two limbs and "E-core" shell-type with three-limbs as shown in Fig. 1 [3]. With the core-type configuration, the top and the bottom yokes are equal in cross section to the wound limbs; with the shell-type, their cross section area is only 1/2 of that of the wound limb.

The primary and secondary windings have 110 turns and 10 turns, respectively. Three coils are connected in parallel for primary winding, and thirty-three coils for secondary winding to carry the high currents. Both the windings are the type of pancake or helical. The primary and secondary windings can be wrapped either concentrically or adjacently to each

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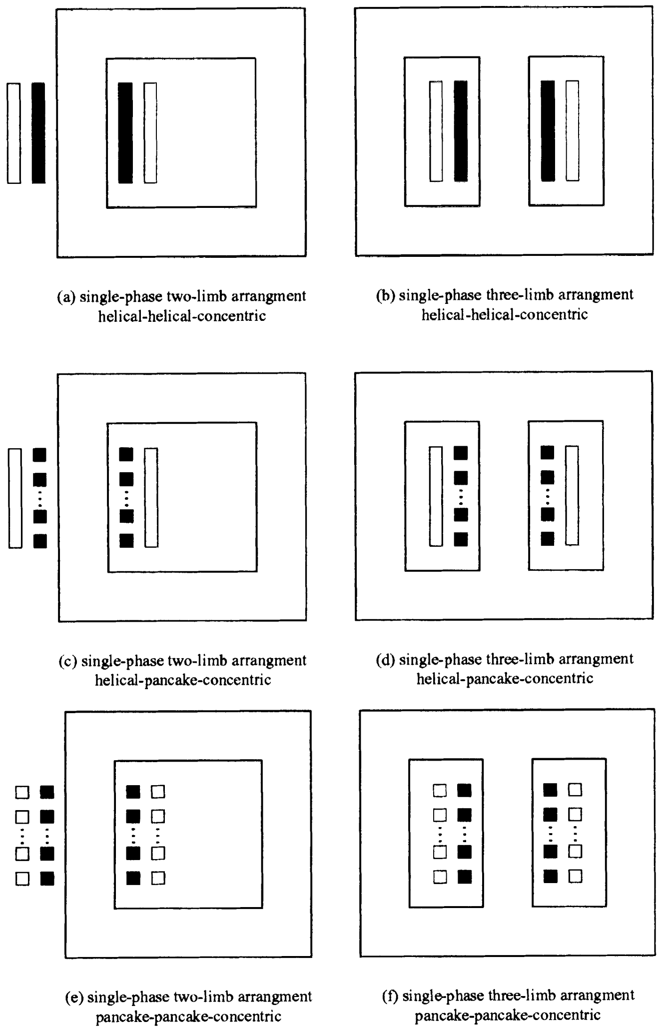


Fig. 1. Typical forms for single-phase transformers. (The black coils represent the secondary coils, and the white ones represent the primary coils. A long bar represents helical coil, a square block represents pancake coil). (a) Single-phase two-limb arrangment helical-helical-concentric. (b) Single-phase three-limb arrangment helical-helical-concentric. (c) Single-phase two-limb arrangment helical-pancake-concentric. (d) Single-phase three-limb arrangment helical-pancake-concentric. (e) Single-phase two-limb arrangment pancake-pancake-concentric. (f) Single-phase three-limb arrangment pancake-pancake-concentric.

other around the core. However, if the primary and secondary windings are located adjacently to each other, the window height increases nearly double that of the concentric structure. The window height is far too large compared with the window width. As a result, we only consider the concentric situation.

HTS transformer windings are usually made of double pancake coils or helical coils. When tapes are wound in parallel to carry the large currents, they should be transposed to obtain a homogeneous current distribution in the helical coil, which is especially difficult in handling due to the brittleness of HTS tapes. No transposition of the tapes is needed in a pancake winding since the pancake coils can be stacked adjacently to each other. To avoid the transposition in a helical winding, paralleled coils can be wound adjacently to each other in the height direction. Apparently, this is not suitable for the secondary winding with 33 parallel coils.

Fig. 1 lists the different geometry types of the HTS transformer. For given geometry shown in Fig. 1(a) and (b), the helical coils are adopted for both primary windings and secondary windings, each helical coil has 11 layers and 10 turns per layer and three coils are wound adjacently for each winding. For the primary windings, the 11 layers are wound in series, for the secondary windings, however, the 11 layers are wound in parallel; in Fig. 1(e) and (f), the double pancake coils are adopted, there are 10 turns for each double pancake coil and 33 coils are needed for each winding; in Fig. 1(c) and (d), the primary coils are made into helical, and the secondary coils are made into pancake, the pancake coils have the same geometry as is in Fig. 1(e) and (f), the helical winding has 5 layers and 22 turns per layer so that the primary windings and the secondary windings are the same in height.

III. Magnetic Field Calculation

In this section, the different types of the HTS transformer as shown in Fig. 1 are analyzed mathematically. The magnetic field distributions are calculated by the finite element method (FEM), assuming homogeneous distribution of the current density in the coil cross section.

A. Performance Comparison

To make full use of the HTS tapes and reduce the power losses, we aim at small circumfluence of currents and small radial stray field component. If the average current in the coils is,

$$I_{\mathrm{avg}} = \frac{1}{n}\sum_{k=1}^{n} i_k \tag{1}$$

the normalized average current can be calculated by,

$$I_{\mathrm{nrm}} = \frac{I_{\mathrm{avg}}}{I_{\mathrm{avg_{theo}}}} \tag{2}$$

the uneven degree of the currents can be expressed as follows,

$$C_e = \frac{1}{nI_{\mathrm{avg}}}\sum_{k=1}^{n} |i_k - I_{\mathrm{avg}}| \tag{3}$$

where, n is the coil numbers, i_k is the current of the kth coil, is the theoretical value when the currents flow uniformly in the coils.

Fig. 2 shows the current unevenness and the normalized average current for different arrangements. Fig. 3 shows the maximal value of radial and axial stray field components.

When the secondary windings (high-current side) are wound helically, although the average current of each coil is similar to the nominal current, the circulating current among the parallel tapes becomes considerably high because of no transposition. As a result, the radial and the axial components of the leakage field are much higher than that of any other arrangements, and the HTS tapes quench quickly.

If the primary windings are made of pancake coils instead of helical coils, circulating current will decrease by about 30%, but the radial component of the leakage field increases by about 40%. The adoption of the e-type core reduces the circulating

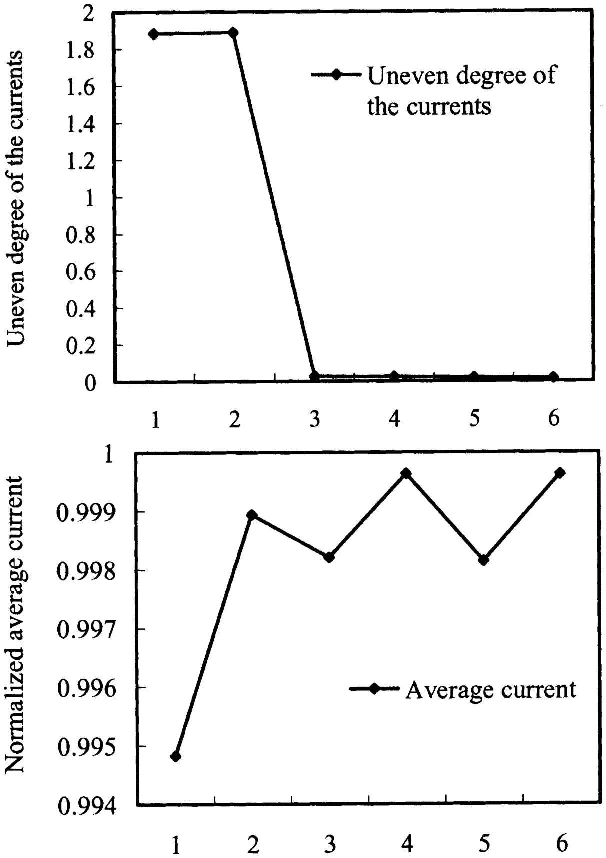


Fig. 2. Current unevenness and normalized average current for different arrangements [in which, 1-(a), 2-(b), 3-(c), 4-(d), 5-(e), 6-(f)]. (a) Uneven degree of the currents. (b) Normalized average current.

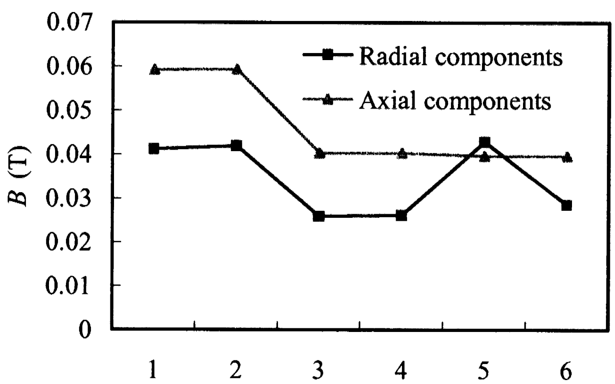


Fig. 3. Maximal values of radial and axial stray field components for different arrangements [in which, 1-(a), 2-(b), 3-(c), 4-(d), 5-(e), 6-(f)].

current by 10%, as well as increases the average level of the current appreciably. The e-type core is also good for reducing the radial component of the pancake coils to an acceptable level because shell-type arrangement provides intrinsically better magnetic shielding.

Although arrangements (c) and (d) show the smallest radial components of the stray field, the differences of their radial field from arrangement (f) are very small. Considering the circulating current and the winding techniques, arrangement (f) is adopted, i.e., both the primary and secondary windings are

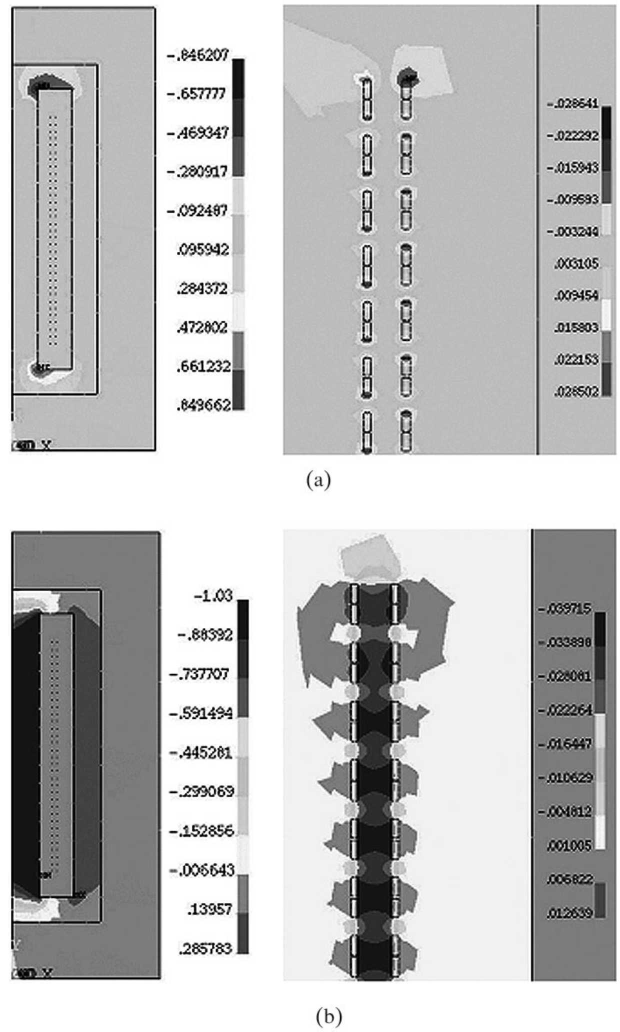
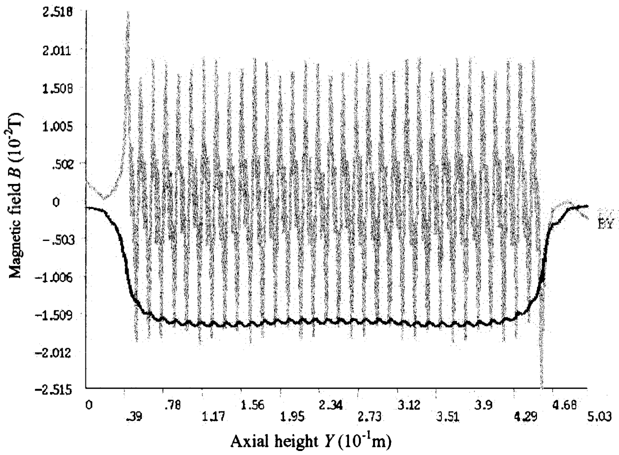


Fig. 4. Magnetic field distribution in the transformer. Left: whole area Right: part of the enlarged coil area. (a) Radial component of the magnetic field distribution. (b) Axial component of the magnetic field distribution.

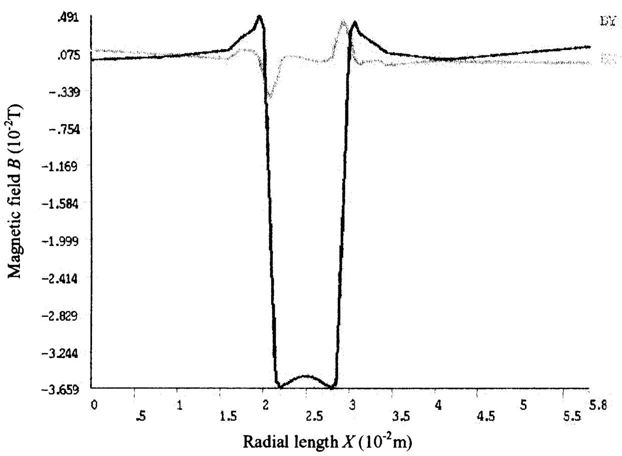
wound double-pancake, and the "E-core" with 3 limbs is applied instead of the "C-core".

B. Magnetic Field Distribution in the Transformer Windings

For the chosen transformer geometry, the magnetic field distribution in the transformer at full load is shown in Fig. 4. The right part of the figure shows the leakage field in the windings. The radial components of the stray field concentrate on the end region of each double-pancake coil, and the axial components concentrate on both inner-side and outer-side of each coil. The radial component values of the magnetic field alternate between the positive maximum and the negative maximum along the axes, and change a little in the radial direction. It attains a maximum at the end edge of the winding. The maximal axial field is attained at the edge of the space between the primary and secondary coils, periodic variations appear along the axes due to the gaps, and its value decreases at the end edge of the coil, as shown in Fig. 5. At the position where the radial field component attains maximum, the axial component is minimal, and vice versa.



(a)



(b)

Fig. 5. Calculated magnetic field distribution. (a) Axial (BY) and radial (BX) component of the magnetic field along the line parallel to coil axis. Radial position X is at the average radius of the secondary windings. (b) Axial (BY) and radial (BX) component of the magnetic field along the line perpendicular to coil axis. Axial position Y is the top of the windings.

C. Effect of the Flux Diverter

Some researchers have reported some methods to reduce the radial component of the leakage magnetic field by flux diverters [4], [5]. The flux diverter rings are placed close to the end edge of the windings inside the cryostat, with rectangular cross section of 20 mm $\times$ 20 mm. In this paper, the influence of the material properties of the flux diverters on magnetic field distribution is investigated. The powdered iron epoxy composite has a relative permeability of about 6. The relative permeability of the amorphous metal or the silicon steel is much higher than it, and each exceeds 3000. The relative permeability of the amorphous metal is the highest. According to the calculation results, the adoption of the different flux diverters decreases the radial stray field by 0.0014 T, 0.0019 T and 0.0019 T, respectively. The material with higher relative permeability will make the reduction larger. It seems that the amorphous metal is suitable for the flux diverters because of its high relative permeability and low power loss. However, the effects of the flux diverters are not obvious for the chosen transformer geometry. The use of the shell-type "E-core" may be one of the reasons. The other possible reason may be that the width of the flux diverters is so small due to the narrow space in the cryostat that its effect does not emerge distinctly.

IV. Conclusion

The effects of the transformer geometry including the core and winding geometries on the leakage field distribution are investigated. According to our calculations, we can draw the conclusion that:

1) An "E-core" shell-type arrangement is helpful to even the currents in the transformer coils connected in parallel, and reduce the radial stray field. It is particularly suitable for HTS transformer with heavy currents.
2) It seems that helical coils are not suitable for the HTS windings carrying large currents, but they are competent to carry currents not so high if there are no need to make any transposition. The pancake winding is suitable to wind the HTS tapes.
3) Amorphous metal is the good candidate for the flux diverters.

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