

Retraction

Retracted: Electromagnetic Field Analysis and Optimization Method of High-Temperature Superconducting Transformer under the Influence of Abnormal Voltage

Mobile Information Systems

Received 19 September 2023; Accepted 19 September 2023; Published 20 September 2023

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

- (1) Discrepancies in scope
- (2) Discrepancies in the description of the research reported
- (3) Discrepancies between the availability of data and the research described
- (4) Inappropriate citations
- (5) Incoherent, meaningless and/or irrelevant content included in the article
- (6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

- [1] W. Zhi, Y. Zhang, and H. Yang, "Electromagnetic Field Analysis and Optimization Method of High-Temperature Superconducting Transformer under the Influence of Abnormal Voltage," *Mobile Information Systems*, vol. 2022, Article ID 8256988, 8 pages, 2022.

Research Article

Electromagnetic Field Analysis and Optimization Method of High-Temperature Superconducting Transformer under the Influence of Abnormal Voltage

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Received 1 July 2022; Revised 22 July 2022; Accepted 2 August 2022; Published 29 August 2022

Academic Editor: Fusheng Zhu

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High-temperature superconducting transformers are an important research topic of superconducting technology in power applications, and electromagnetic field analysis and optimization are the basis for the design and application of high-temperature superconducting transformers. The electromagnetic field analysis of high-temperature superconducting transformers should consider the superconducting properties of the materials, that is, the properties of critical current and magnetic field. This paper aims to study the electromagnetic field analysis and optimization method of high-temperature superconducting transformer under the influence of abnormal voltage. Due to the energy loss of high-temperature superconducting transformers, in order to study the economy and reliability of high-temperature superconducting transformers, in this paper, the core loss, winding AC loss, and coil power consumption of high-temperature superconducting transformers are analyzed under normal operation and short-circuit fault conditions, respectively. The power and stress on the windings are analyzed. In order to take into account the current-carrying capacity, short-circuit loss, and short-circuit electromotive force of superconducting windings in normal operation, a concentrically placed double-cake coil structure is selected in this paper, and according to different optimization objectives, a global optimization method is used to evaluate the structure of the coil. The structural parameters of the high-temperature superconducting transformer are optimized, including the structural parameters of the magnetic conducting ring. It is found that that abnormal voltage will affect the electromagnetic field of high-temperature superconducting transformers, including winding circulating current, leakage magnetic field, and current distribution.

1. Introduction

A modern power transformer is a highly reliable, high-efficiency power device. With the rapid development of China's electric power industry and urban construction, the country is implementing the reconstruction and expansion of urban power grids and rural power grids, and the transformer industry has developed rapidly accordingly. Due to the increasing capacity of a single unit, users have higher and higher requirements for transformers. In addition to meeting the technical specifications of electricity, magnetism, force, heat and high efficiency, power transformers should also meet the requirements of small oil-free and low-noise power transformers and the requirements in order to reduce the footprint and reduce environmental

pollution. Due to its inherent defects, the constant conduction transformer is difficult to meet the needs of the development of the modern power industry. Research and development of new superconducting transformers, thereby improving the performance of power transformers, has great theoretical research significance and practical application value [1, 2]. The selection of the core structure of the transformers will affect the performance of the transformer. According to the relative position of the iron core and the coil, the iron core can be divided into two main structural types: core iron core and shell iron core.

From an economic point of view, the low impedance characteristics of superconducting materials are conducive for reducing the total loss of the transformer, and the high current density can improve the efficiency of the power

system. The use of superconducting transformers will greatly save energy and reduce operating costs. From the perspective of insulation operating life, the windings and solid insulating materials of superconducting transformers operate at deep low temperatures, and there is no insulation aging problem. [3, 4]. In an emergency, a superconducting transformer can carry the load originally supplied by two transformers, which improves the safety of the system. From the perspective of its contribution to the power system, the internal resistance of the superconducting transformer is very low during normal operation, and increasing the larger voltage regulation range is conducive for improving the performance of the power system. When it comes to a short-circuited condition, the superconductor quenches into a resistive state, which may limit the current spike. This potential fault current limiting capability separates the transformer impedance requirements from the short-circuit current requirements, and the corresponding power system components are designed according to the limited current, which reduces the investment of the entire system. From the perspective of environmental protection, the superconducting transformer adopts liquid nitrogen for cooling, which replaces the forced oil circulation cooling or air cooling used in the normal conduction transformer, which reduces the noise and avoids the possible fire hazard caused by the transformer and environmental pollution caused by flux leakage. Overall, superconducting transformers have the advantages of small size and light weight, and will become the most ideal energy-saving transformers in this century, with great potential development prospects [5, 6].

The superconducting power device is made of superconducting tape, and its main body is a superconducting coil. From the external geometry, there are many kinds of coils, such as circular coils, yin and yang coils, toroidal coils, saddle coils, etc. [7]. The superconducting axisymmetric coil is the basic coil structure and has a wide range of applications in superconducting engineering technology. It has many advantages, including being easy to manufacture, easier to wind and support the magnetic field force. The magnetic field generated by the winding is the largest. Through the combination of several coils, a highly uniform magnetic field or a magnetic field with a uniform gradient along a certain direction in space can be obtained [8, 9]. The electromagnetic problems of high-temperature superconducting transformers include the magnetic conductive ring at the coil end on the distribution of the transformer leakage magnetic field, the current distribution between the parallel superconducting strips and their influence on the transformer leakage magnetic field distribution.

With the continuous discovery of high-temperature superconducting materials, the critical current continues to increase. It is believed that with the continuous development of science and technology, the emergence of practical superconducting materials in the liquid nitrogen temperature region will certainly make the application of axisymmetric coils more extensive [10, 11]. However, the actual superconducting axisymmetric coils are all made of superconducting wires, so each turn has helicity. Since there is an insulating layer outside the superconducting wire, whether a

square wire or a round wire is used, the current density of the coil is not uniformly distributed. When analyzing the magnetic field of a superconducting axisymmetric coil, the calculation of the magnetic field will be extremely complicated if the helicity and inhomogeneity are taken into account. However, in the engineering application of superconducting power devices, power devices with superconducting spiral coils as the main body appear, such as the spiral winding structure of high-temperature superconducting transformers, and the layered spiral structure of high-temperature superconducting power cables. At this time, it is necessary to analyze the general spiral coil. The magnetic field of the structure, and the constraints of the properties of the superconducting material must be considered, which will have important significance in the design of the electromagnetic parameters of the superconducting power device [12, 13]. High-temperature superconducting tapes do not have the excellent mechanical properties of low-temperature superconducting wires. Bending, twisting, and exposure to minor tensile stress will reduce its current-carrying capacity.

According to the different superconducting materials of the coils, high-temperature superconducting transformers can be divided into hybrid superconducting transformers and high-temperature superconducting transformers. The low-voltage high-current winding of the hybrid transformer adopts high-temperature superconducting winding and operates at the temperature of liquid nitrogen, while the high-voltage winding is composed of low-loss copper coils due to the low current. The high-voltage side copper winding can withstand a larger fault current than normal temperature, and the use of copper winding can also save a certain amount of superconducting wire costs [14, 15]. However, the required structure of the cryogenic container is complex, the radial size of the high-voltage winding cannot be reduced, and the resistance loss of the copper winding affects the efficiency of the transformer. This is a transitional type of superconducting transformer, while the high-temperature superconducting transformer operates at the temperature of liquid nitrogen, and the high- and low-voltage windings use high-temperature superconducting windings. According to whether there is an iron core, high-temperature superconducting transformers can be divided into iron core transformers and air-core transformers. In terms of loss, the transformer has an optimal core section. If the section is increased, the increase in core loss will exceed the reduction in winding loss and cooling loss. Conversely, the increase in winding loss and cooling loss will exceed the reduction in core loss [16, 17]. Therefore, iron-core transformers are often used in large power transformers, and air-core transformers are only used when there are special requirements for weight and structural simplicity. For core transformers, the use of superconducting materials can reduce the optimal core section by about 4 times, thereby reducing the weight of the transformer and core loss. For air-core transformers, the low-loss characteristics of superconducting materials make it possible to greatly increase the excitation current, thereby making it possible to manufacture large air-core power transformers. Due to the cancellation of the iron core, the air-core transformer has the

advantages of light weight and small volume, and there is no problem of no-load loss, electrical insulation between the winding and the iron core, inrush current caused by magnetic saturation and higher harmonics of the excitation current. High temperature superconducting transformers have inherent low impedance characteristics, and the AC loss of the winding is much smaller than that of the iron core. The empirical formula for the optimum capacity of conventional transformers is not suitable for high-temperature superconducting transformers.

Specifically, the critical current and external magnetic field of the high-temperature superconducting tape have the characteristics of anisotropy, and the critical current will be reduced to a certain extent under the influence of the external magnetic field. For superconducting transformers, the current-carrying capacity of the device windings must be attenuated by the influence of the leakage magnetic field inside the windings. Therefore, the current-carrying capacity of high-temperature superconducting tapes plays an extremely important role in the design, economic performance, and operational stability of high-temperature superconducting electrical devices. The study of the electromagnetic properties of the superconducting electrical device must be based on the anisotropy of the critical current and magnetic field of the high-temperature superconducting tape, and the analysis of the magnetic field distribution of the high-temperature superconducting electrical device is the basis for the analysis and design of the electromagnetic properties of the high-temperature superconducting electrical device [18, 19].

2. Electromagnetic Field Finite Element Analysis of Leakage Magnetic Field of High-Temperature Superconducting Transformer

High-temperature superconductors are nonideal second-class superconductors, and they are all changing during the excitation process of their magnet applications or superconducting power applications such as superconducting transmission cables, superconducting current limiters, superconducting transformers, superconducting motors, and other power equipment. In the magnetic field. Compared with conventional transformers, superconducting transformers have inherent low impedance characteristics, and their AC losses are also much smaller than the copper losses of conventional transformers, so the number of turns of the windings can be increased, thereby reducing the cross-sectional area and volume of the core. And no-load loss. Superconducting transformers also have a much higher operating current density than conventional transformers, which greatly increases the ampere-turns of the transformer windings, thereby increasing the electrical load of the transformer. In proportion to the square, when the transformer fails, the problem of short-circuit force and thermal stability will be more prominent. At the same time, since the average radius of the winding decreases with the cross-sectional area of the iron core, the width of the winding is reduced due to the high current density of the

superconducting tape. The electromagnetic problems of high-temperature superconducting transformers include the influence of core operating temperature, core type, coil type, and others such as magnetic field, electric field, and so on.

Electromagnetic field optimization is the goal that electromagnetic engineering technicians strive to pursue. On the premise of meeting the requirements of electromagnetic characteristics, our design goals are either to minimize the volume of the device, minimize the loss, and minimize the amount of materials, or to make the device economical and technically superior. High-temperature superconducting devices have unique electromagnetic properties, that is, the critical current and magnetic field of high-temperature superconducting wires are anisotropic, which must be considered when analyzing the electromagnetic properties of high-temperature superconducting devices. At present, high-temperature superconducting devices are mainly composed of high-temperature superconducting coils, and their structures may be very complex, such as hybrid spiral coils, which make full use of the different advantages and characteristics of various coils to meet the special requirements of engineering electromagnetic fields. Based on the latest optimization technology of electromagnetic field, electromagnetic field optimization technology has a very important position in electromagnetic engineering design. (1) According to the law of mechanics, it is extended to the field of electromagnetic field, and the stress distribution optimization technology of the hybrid coil is proposed, that is, the virial theorem of electromagnetic field. (2) By using the genetic algorithm toolkit of Matlab, the corresponding method can be realized.

The leakage magnetic field of a high-temperature superconducting transformer can be expressed by Maxwell's equations:

$$\begin{aligned}\nabla \times H &= J_0 + \frac{\partial D}{\partial t}, \\ \nabla \cdot B &= 0, \\ \nabla \times E &= -\frac{\partial B}{\partial t},\end{aligned}\tag{1}$$

where B is flux density, E is electric field, H is magnetic field strength, and J is current density.

In an isotropic electromagnetic medium, the relationship between the field quantities E and D , B and H , J and E in the electromagnetic field is represented by the auxiliary equation of the electromagnetic field. Its relationship is

$$\begin{aligned}D &= \varepsilon E, \\ B &= \mu H, \\ J &= \sigma E,\end{aligned}\tag{2}$$

where μ is permeability and ε is conductivity.

The equivalent conductivity of the high-temperature superconducting tape can be expressed as

$$\sigma = \lambda_{sc}\sigma_{sc} + (1 - \lambda_{sc})\sigma_{ag}.\tag{3}$$

Among them, λ is the silver-to-super ratio, and σ is the electrical conductivity. In practical engineering calculations, the equivalent electrical conductivity of high-temperature superconducting tape is often given by the E-J characteristic curve of the high-temperature superconducting tape measured experimentally:

$$\sigma = \frac{J}{E}. \quad (4)$$

Under normal working conditions, that is, when the current in the high-temperature superconducting coil satisfies $J < J_c$, then

$$E = E_c \left(\frac{J}{J_c} \right)^n. \quad (5)$$

In this way, the equivalent conductivity of the high-temperature superconducting tape under normal working conditions can be expressed as

$$\sigma = \frac{J_c^n}{E_c} J^{1-n}, \quad (6)$$

where J_c is the critical current density of the high-temperature superconducting tape. In order to describe the basic properties such as the magnetization characteristics of high-temperature superconductors, some scholars have proposed different critical state models. The most commonly used is the critical state model proposed by (7), which assumes that the current density in the superconductor is independent of the applied external field, namely,

$$J_c = C. \quad (7)$$

It is proposed as a model of the critical state, arguing that the critical current varies with the external field, namely,

$$J_c(H) = \frac{J_0}{(1 + |H|/H_0)}. \quad (8)$$

The calculation of the electromagnetic force in the high-temperature superconducting transformer has a guiding role for the winding design and fixing of the transformer. It is considered a prerequisite for designing HTS transformer protection devices.

3. Abnormal Voltage Analysis

In a power transformer, the coil completes the transmission and conversion of electrical energy through an electromagnetic field. The electrical energy of the system is introduced into the transformer by the primary coil and transmitted by the secondary coil. Common coil forms are continuous, tangled, and spiral. The gaps between the wire cakes directly lead to the uneven distribution of the magnetic field near the inner diameter of the wire cakes. In order to study the effect of the air gap on the magnetic field distribution, we compare it with the magnetic field produced by the helical winding.

3.1. Continuous Coil. The continuous coil is composed of several continuously wound wire cakes distributed along the

axial direction. This structure can adapt to the requirements of various voltage levels and capacities in a wide range. It has high mechanical strength and good manufacturability, but the impulse voltage distribution is not good.

3.2. Tangled Coil. Tangled coils are mainly used on high-voltage coils of transformers of 220 kV and above. As for the tangled continuous coil, it is often divided into several areas, some areas adopt a tangled structure, and some areas adopt a continuous structure. This kind of coil is called a tangled continuous coil.

3.3. Spiral Coil. The helical coil is the simplest form of coil structure. It is formed by winding one or more wires in the form of a solenoid, usually multiple wires are wound in parallel.

3.4. Double-Layer Spiral Coil. Also known as U-shaped coil, it combines the characteristics of helical coils and layered coils. Each layer of helical type adopts multi-helix, and the second layer is wound through the lifting process. There are both axial oil gaps and radial oil gaps; the head positions are all on the same side.

Alternating magnetic fields or transport currents cause energy losses in the second type of superconductors, which are called AC losses. It should be noted that the AC loss is different from others since it is influenced by the frequency. The coil height refers to the dimension occupied by the coil in the axial direction. In addition, there is a concept of electrical height, which refers to the height of pure copper wire after removing the upper and lower end rings or electrostatic rings. The radial dimension is also called the width dimension, which refers to the width occupied by the wire cake on the plane perpendicular to the axis along the radial line of the center of the circle. The wire is wound around the mold for one turn, which is called a turn. For tangled or continuous coils, there are integer turns and fractional turns, full turns and unsatisfactory turns. The winding direction of the coil refers to the advancing direction of the turns during winding, which is divided into left winding direction and right winding direction.

There are many factors that cause abnormal voltage, and the common reasons are as follows:

3.5. Treatment of Winding Short-Circuit Point. There are actually many ways to wind multiple flat copper wires in parallel. The most common method is to produce flat copper wires into composite wires, winding a single composite wire or winding multiple composite wires in parallel. This belongs to the category of parallel winding of multiple flat copper wires. We can use a 500 V megohmmeter to check for shorts in parallel wires. If there is a short circuit between the wires, the pointer of the megohmmeter will indicate very little or zero. The method of determining the short-circuit point with multiple wires is parallel: if it is not at the outgoing position, we can calculate and analyze the internal position of the short-circuit point on the line segment.

3.6. The Number of Turns. When the test result of the semi-finished transformer is the wrong number of turns, it is not possible to accurately determine which line segment has wrong turns, but only to determine that there is an error in a certain winding tap area. Many turns and few turns may be in the normal line segment or in the special line segment, but from experience, the situation of how many turns is likely to occur in the special line segment, and it is very likely to occur in the first few lines of the special line segment.

3.7. Poor Winding Insulation Condition. When there is moisture in the transformer winding or abnormal changes in temperature and electric field environment, the insulation performance of the transformer winding will be reduced. Since the insulation performance of the windings is greatly reduced after being damp, moisture is the most important factor affecting the insulation performance of the transformer windings. When the transformer is not tightly sealed, it is easy to cause moisture to enter the transformer and affect the winding insulation.

3.8. Transformer Windings Are Deformed by Short-Circuit Electromotive Force. The short-circuit current flows through the transformer windings, and acts together with the leakage magnetic field to make the windings subject to the short-circuit electromotive force. Taking the double-winding transformer as an example, when the amplitude-direction electromotive force acts on the high-voltage winding, the high-voltage winding is subjected to outward pulling force, and the deformation trend is outward expansion. When the amplitude-direction electromotive force acts on the low-voltage winding, the low-voltage winding is subjected to inward tension, and the deformation trend is concave deformation. The abnormal voltage and current are shown in Figures 1 and 2.

4. Electromagnetic Field Analysis and Optimization Method of the High-Temperature Superconducting Transformer under the Influence of Abnormal Voltage

Generally speaking, the electromagnetic field problem is the problem of solving Maxwell's equations. There are usually two methods: one is the direct method, which is solved directly from Maxwell's equations; the other is the indirect method, which is solved by the potential function.

4.1. Winding Circulation. Compared with the normal conduction transformer, the superconducting transformer winding design has two obvious characteristics: one is to minimize the leakage magnetic field in the winding area, especially its radial component, so as to increase the critical current and reduce the AC loss; the other is to minimize the leakage field. A small unbalance of leakage reactance between branches of windings may cause considerable circulating current. In recent years, research on

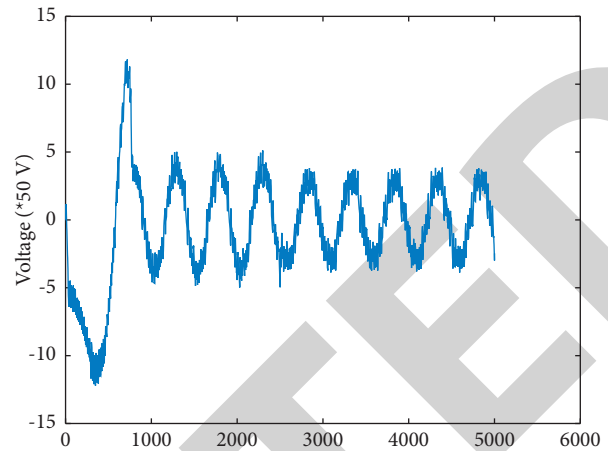


FIGURE 1: Abnormal voltage.

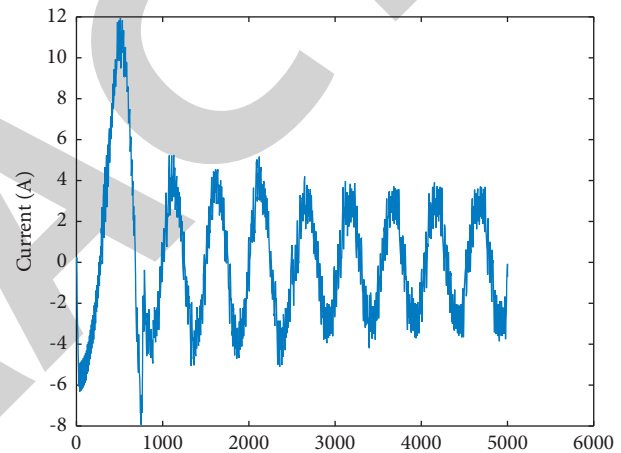


FIGURE 2: Abnormal current.

superconducting transformers, such as the influence of winding form on leakage magnetic field, AC loss calculation, quench test and protection, performance of insulation and core materials at low temperature, optimization design and hollow superconducting transformers, etc., are rather common. Much literature has been published but relatively few studies have been done on circulation.

Figures 3 and 4 list the calculation results of the circulating current in various situations, namely, with or without abnormal voltage. We can see the following: ① The difference in the circulating current is obvious in various situations, and whether the wire is transposed or not has a great influence on the circulating current. ② In terms of the circulating current distribution, among the three types of windings, the layered winding is the most suitable for the situation where multiple wires are wound in parallel, the spiral winding is the second, and the pie winding is the worst. It can be seen that from the perspective of reducing the circulating current, the layered winding is most suitable for the situation where multiple wires are wound in parallel, because it can better balance the reactance of each branch by transposing the wires between the winding layers. However, considering the circulating current and the manufacturing

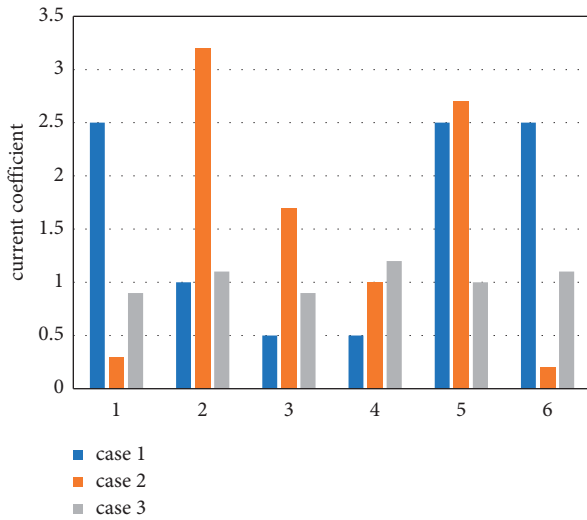


FIGURE 3: Current distribution of each branch.

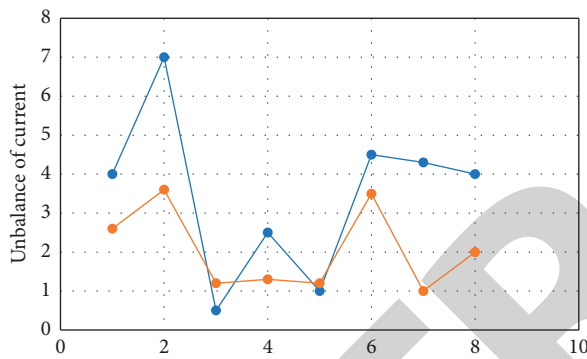


FIGURE 4: Unbalance of current.

process, the spiral winding should be used, because if the conductors are properly transposed, the circulating current of the spiral winding can be controlled to be smaller. It is also important that the welding points required by the spiral winding are far more than that of the layered winding. Winding is less. At the same time, it is proved that from the consideration of circulating current distribution, it is impossible to short-circuit the two ends of each layer of the secondary side layer winding and then use copper wire to transition to the adjacent layer to replace the transposition of the superconducting wire between the layers.

4.2. Nonlinear Harmonic Analysis of Leakage Magnetic Field of the High-Temperature Superconducting Transformer. The magnetic field problem of superconducting current conductors is a boundary value problem, which can be summed up in three categories: analytical method, numerical method, and semi-analytical numerical method. The magnetic field of the high-temperature superconducting transformer changes with the sinusoidal current under normal working conditions, and the iron core of the transformer is in a saturated state. Since the core and windings of the transformer are axisymmetric structures, the 3D model can be simplified into

a 2D model for calculation. The calculation process is basically similar, with the following differences: 1. Thanks to the iron yoke, it is no longer necessary to divide the far-field region. 2. With the presence of a saturated core, the analysis becomes nonlinear and the B-H curve of the core needs to be defined in the material properties. 3. Since the winding is composed of one wire cake, and each wire cake has a small cross section, the mesh should be divided as carefully as possible. 4. Since the high-temperature superconducting tape is in the superconducting state, the voltage is very small, but the current is very large, so we choose the current density as the excitation.

4.3. Current Distribution. When the cable conductor of the high-temperature superconducting cable passes through the AC current, the current-carrying capacity of the conductor is significantly reduced, the current distribution of each layer is extremely uneven, and the AC loss increases, thus affecting the stable operation of the cable conductor, or greatly reducing the ideal of the cable conductor. It can be inferred that the sinusoidal AC waveform passing through the cable conductor must be distorted at this time. According to Ohm's law, the current distribution of conductors in each layer is determined by joint resistance, flow resistance, self-inductance and mutual inductance. The inductive reactance per unit length of each layer of the conductor is about two orders of magnitude larger than the joint resistance or flow resistance. Therefore, in the case of AC, the actual current-carrying capacity of each layer of tape is mainly determined by the self-inductance and mutual inductance of each layer. Self-inductance and mutual inductance are structural parameters, which are determined by physical characteristics such as the shape, structure size, and winding arrangement of each layer of tape.

In addition, the contact resistance also has a certain influence on the current distribution. Assuming that the high-temperature superconducting cable does not have a helical structure, but has an n-layer parallel conductor structure, the current will be distributed in the outer layer of the cable as much as possible. When the outer layer current exceeds its critical current value, the electric field will increase and the outer layer will be rapidly saturated, resulting in the AC loss increases, but little current flows through the inner layer, resulting in extremely uneven current distribution in the cable. Foreign experiments show that increasing the contact resistance between the power supply and the superconducting tape can also make the current distribution as uniform as possible, but it will increase the ohmic loss of the current lead and increase the cooling cost. Therefore, the factors of uniform current distribution are generally analyzed from the structural parameters of the high-temperature superconducting cable.

When the current $I = 40A$ is applied to the winding, the magnetic field distribution on the vertical path at the inner diameter of the winding is obtained as shown in Figures 5 and 6. It can be seen that the maximum value of the axial radial magnetic field experienced by the helical winding and the pie winding is approximately equal. However, the

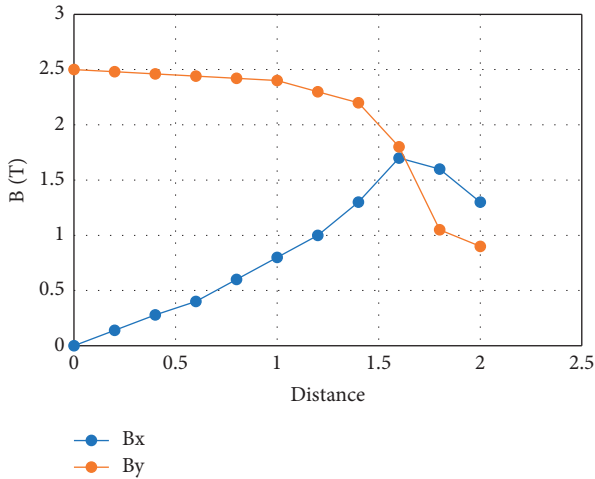


FIGURE 5: Flux density vs distance in helical winding.

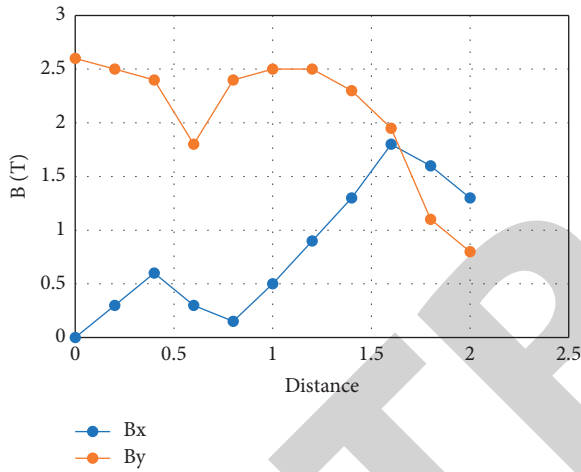


FIGURE 6: Flux density vs distance in pie winding.

magnetic field distribution of the pie winding shows obvious periodicity, the peaks always appear near the wire pie, and the troughs appear at the gap between the wire pie and the wire pie. Although the critical current attenuation under the influence of the magnetic field is roughly equal for the two winding methods as a whole, for the wire cake located in the middle of the entire winding, since the position of the wire cake is in the peak section of the magnetic field, they are affected by the magnetic field. Pie winding is larger than spiral winding, and the relative current margin is also lower. Due to the difference in the magnetic field distribution, there must also be a difference in the AC losses of the two windings. By expanding the length of the air gap between the high-voltage winding and the low-voltage winding, it is hoped that the leakage magnetic field near the high-voltage winding and the low-voltage winding can be reduced. It expands the air gap between the high- and low-voltage windings from 35 mm to 70 mm and 105 mm, respectively, and then we can obtain the magnetic field distribution near the low-voltage winding, as shown in Figure 7. The warm superconducting tape has anisotropy, and the increased

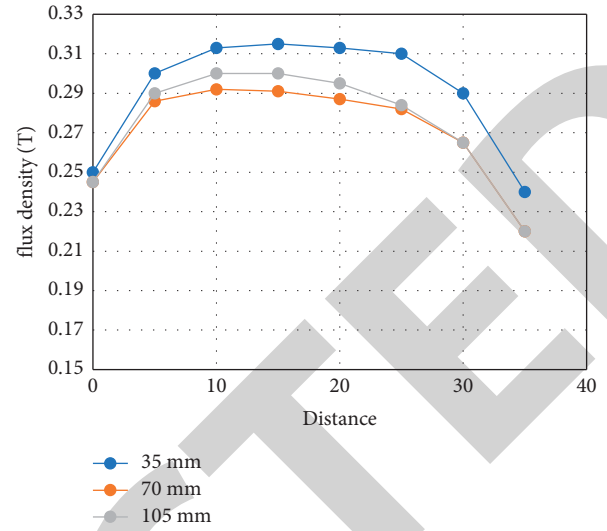


FIGURE 7: Flux density vs distance in different gaps.

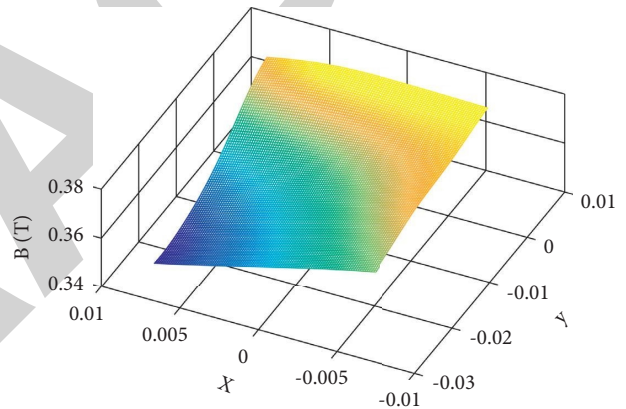


FIGURE 8: Flux density vs position.

radial leakage magnetic field due to the inconsistency between the iron core and the coil will reduce the critical current of the superconducting tape and increase the AC loss of the superconducting winding.

As shown in the figure, increasing the length of the air gap between the high-voltage winding and the low-voltage winding can reduce the leakage magnetic field near the winding, but the effect is not very obvious. When the air gap is increased to three times the original air gap, it takes up a lot of space and increases the volume of the entire transformer, but the radial component of the leakage magnetic field is reduced by less than 10%. It can be seen that this optimization method is too inefficient and not desirable. Besides, the flux density versus different position is shown in Figure 8.

5. Conclusion

In this paper, the core loss, the AC loss of the winding, the electric power received by the coil, and the stress on the winding of the high-temperature superconducting transformer are analyzed under the normal operating state and

the short-circuit fault state, respectively. In order to take into account the current-carrying capacity, short-circuit loss, and short-circuit electromotive force of superconducting windings in normal operation, a concentrically placed double-cake coil structure is selected in this paper, and according to different optimization objectives, a global optimization method is used to evaluate the structure of the coil. It is found that abnormal voltage will affect the electromagnetic field of high-temperature superconducting transformers, including winding circulating current, leakage magnetic field, and current distribution.

However, many aspects are not considered in this paper, and the work to be continued in the future is as follows: (1) Measurement of AC loss of high-temperature superconducting transformer. (2) Electromagnetic-thermal-mechanical coupling analysis of high-temperature superconducting transformer. (3) Overall optimization design method of high-temperature superconducting transformer.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

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