TEST Engineering & Management
July-August 2020
ISSN: 0193-4120 Page No. 964 - 972

Comparison of Optical Current Transformers with Iron Core under Different Structural Parameters Based on Magnetic Field Distribution

Zhengang Shi[1], Wenjie Fu[1], Chong Sun[1], Linhao Zhang[1], Han Li[1], Chaofei Wu[1], Can Ding[2]
[1] State Grid Hebei Marketing Service Center.
[2] College of Electrical Engineering & New Energy, China Three Gorges University.
Email: dingcan@ctgu.edu.cn

Article Info
Volume 83
Page Number: 574 - 585
Publication Issue:
July-August 2020

Article History
Article Received: *06 June 2020*
Revised: *29 June 2020*
Accepted: *14 July 2020*
Publication: *25 July 2020*

Abstract

The application of optical current transformers in the power system will be affected by the interference of the external environment and the accuracy will be affected. One of the important methods to improve the accuracy of the optical current sensor is to increase the magnetic field strength where the magneto-optic glass is located. In this paper, the magnetic field distribution of the optical current sensor with iron core is calculated by simulation, the influence of its structural parameters on the magnetic field distribution is studied, and compared with the magnetic field distribution of the optical current transformer of the commonly used magnetic ring structure. It is found that under the same current, the magnetic field strength of the magneto-optical material with iron core optical current sensor is much greater than that of the commonly used optical current transformer with magnetic ring structure. The geometric structure parameters of the optical current sensor with iron core have a great influence on its magnetic field distribution, and the magnetic field strength in the magneto-optical material can be improved by optimizing the structure parameters, thereby improving the measurement accuracy. This article can provide a basis for the design optimization of optical current transformers.

Keywords: *Optical current sensor, iron core, structure parameters, magnetic field distribution*

1.INTRODUCTION

Traditional electromagnetic current transformers have matured and are widely used in power systems. However, as the scale of the power system continues to increase, it gradually exposes some shortcomings, such as low safety, poor environmental friendliness, difficulty in installation, and the presence of magnetic saturation to reduce the accuracy of the measurement**Error! Reference source not found.-Error! Reference source not found.**. Optical current transformers theoretically have the function of electromagnetic current transformers, and do not have the disadvantages of electromagnetic current transformers. However, optical current transformers have other problems, such as the low sensitivity of magneto-optical sensing materials to the current magnetic field, which requires a larger magnetic field strength to improve accuracy. This becomes the main reason restricting the optical current transformer **Error! Reference source not found.-Error! Reference source not found.**. Magneto-optical materials, as sensing materials for optical current transformers, are affected by magnetic fields. In the harsh electromagnetic environment, the magneto-optic medium will make the magnetic field unevenly distributed along the optical path of the medium **Error! Reference source not found.**. The problem of non-uniform magnetic field complicates the optical medium model and will inevitably affect the measurement accuracy of the optical current transformer. Therefore, generating a large and uniform magnetic field becomes a necessary condition for the optical current transformer to improve the measurement accuracy. There are many literatures that study the magnetic field distribution of commonly used magnetic ring type optical current transformers **Error! Reference source not found.-Error! Reference source not found.**, and some literatures analyze the influencing factors of magnetic field distribution**Error! Reference source not found.-Error! Reference source not found.**. But there is almost no analysis of the magnetic field distribution and influencing factors of the optical current transformer with iron core.

In this paper, the magnetic field distribution of the optical current transformer with iron core is studied, and compared with the commonly used magnetic ring type optical current transformer. Finally, the influence of the structural parameters of the optical current transformer with iron core on the magnetic field distribution is studied.

2.FARADAY EFFECT MAGNETO-OPTIC SENSING MECHANISM MODEL

The Faraday Effect is mainly due to the external magnetic field magnetizing the optical material, which makes the material itself have a magnetic moment. The effect, which affects the electric field distribution of the light wave, is reflected in the macroscopic rotation of the polarization state of the light wave. Considering that the sensing material is only affected by the modulation of the magnetic field, and the effect of the magnetic field on the sensing material is uniform everywhere, the Faraday rotation angle is proportional to the magnitude of the magnetic field in the optical path direction.

$$\varphi_c = VHL \quad (1)$$

In the formula, V is the field constant of the magneto-optical material (rad/A); H is the magnetic field strength parallel to the direction of the optical path (A/m); L is the length of the optical path of polarized light through the magneto-optical medium (m). Faraday magneto-optical rotation effect is shown in Figure 1.

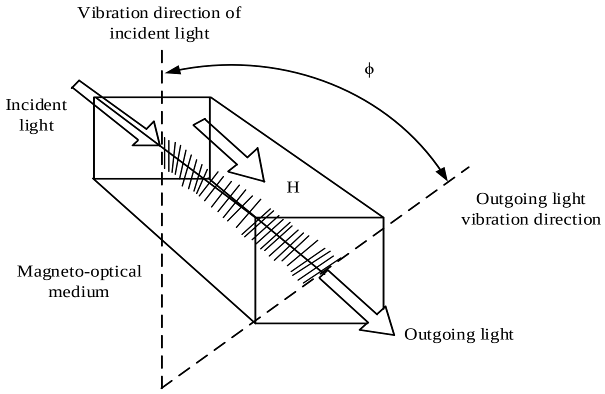


Figure 1. Faraday magneto-optical effect

Considering that the sensing material is only modulated by the magnetic field, When the effect of the magnetic field on the magneto-optical material is not the same everywhere, the Faraday rotation angle is proportional to the integral of the magnetic field in the direction of the optical path.

$$\varphi_c = V\int_L H(L)dL \quad (2)$$

Faraday's magneto-optical effect connects light and magnetic field. In the power system, magnetic field and current are closely related, that is, the conductor current generates a magnetic field, so the principle of magneto-optical rotation can be used to measure current. The current is proportional to the strength of the magnetic field it generates. The relationship between the two can be expressed as:

$$i = \frac{1}{k}\int_L H(L)dL \quad (3)$$

In the formula, k represents the ratio coefficient of the magnetic field strength integral to the current along the optical path. It can be seen from the combination of formulas (2) and (3) that the Faraday rotation angle is constantly proportional to the measured current and is expressed as:

$$\varphi_c = Vki \qquad (4)$$

The magnetic field environment of the optical current transformer is complex and changeable, and the magnetic field on the sensing optical path is almost impossible to be the same everywhere. For the sensor shown in Figure 2. The magneto-optic glass material is rectangular, and the magnetic field distribution generated by the conductor is circular, the shape of the magneto-optic glass and the shape of the magnetic field distribution are different, so that the magnetic field is unevenly distributed along the optical path. The uneven distribution of the magnetic field along the optical path is an objective physical fact, and the problem of uneven magnetic fields will adversely affect current sensing.

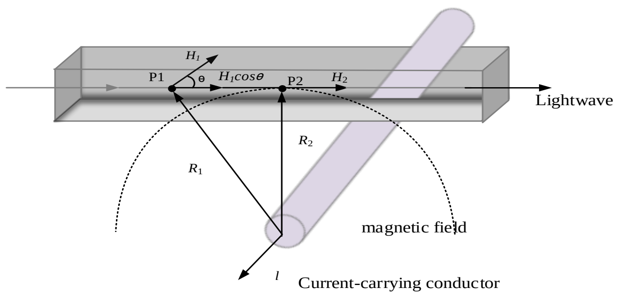


Figure 2. Schematic diagram of the magnetic field distribution of the optical current sensor

3.MAGNETIC FIELD SIMULATION OF THE SENSING PART OF THE OPTICAL CURRENT TRANSFORMER WITH IRON CORE

The schematic diagram of the sensing part of the common magnetic ring optical current transformer is shown in Figure 3, and the optical sensing unit is placed in the solenoid. The core of the magnetron technology is to strengthen the magnetic field of this phase, and the multi-turn solenoid is used to greatly increase the magnetic field generated by the current, and the purpose of anti-magnetic field interference of the optical current transformer is better achieved.

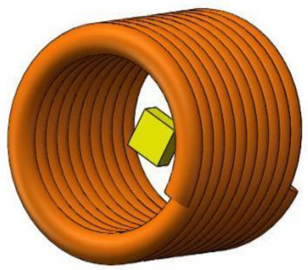


Figure 3. Schematic diagram of common magnetic ring optical current sensor

The schematic diagram of the sensing part of the optical current transformer with iron core is shown in Figure. 4. One end of the coil is the input end of the current, and the other end of the coil is the output end of the current. A fiber is connected to both ends of the magneto-optic glass, so that through the Faraday Effect, different magnetic field strengths can be measured.

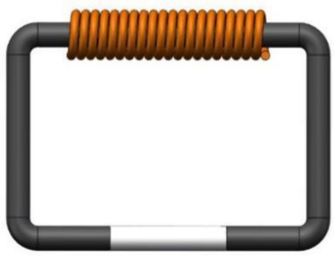


Figure. 4 Schematic diagram of optical current sensor with iron core

The surrounded iron core is a ferrite magnetic ring, and the coil surrounds the ferrite wall. A ferrite magnetic ring is selected, which is shaped into a rectangular parallelepiped, and a coil surrounded by a single wire is wound on its arm. Compared with the traditional common structure, there are more ferrite magnetic rings. The specific material values are shown in **Error! Reference source not found.**.

Table 1. Material properties of each part of optical current transformer with iron core

July-August 2020
ISSN: 0193-4120 Page No. 964 - 972

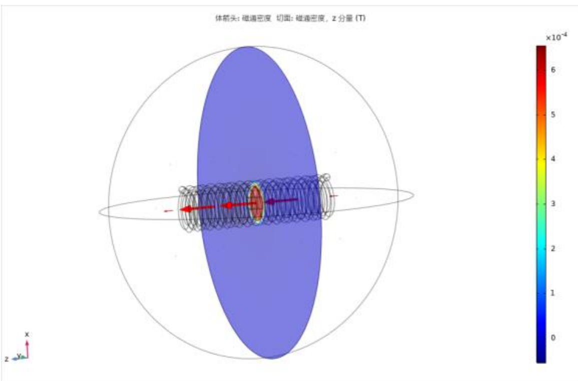
Component	Material	Relative permeability	Conductivity/(S/m)	Relative permittivity
Space	air	1	1	1
Current-carrying conductor	copper	1	59980000	12400000
Magnetic material	Manganese zinc ferrite	5000	0.004	12400000
Magneto-optical material	ZF-3 glass	1	0	3.8

In order to make the magnetic field distribution of the sensors of the two structures comparable, the geometric parameters of the two sensor coils are exactly the same, and the passing current is 1A. The geometric parameters of the coil are shown in Table 1.

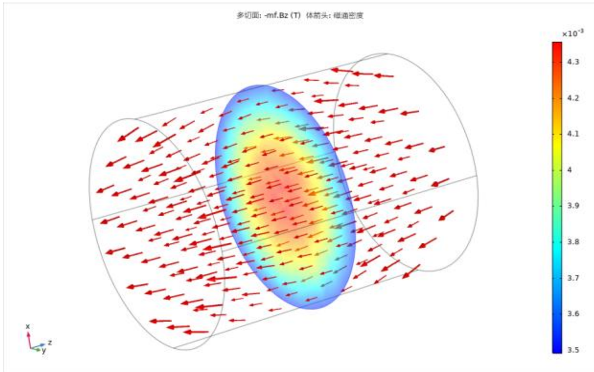
Table 1. Geometric parameters of coil structure

Axial pitch/ mm	Radial pitch/ mm	Number of turns	Large radius /mm	Small radius /mm
2	0	20	5	0.9

The calculation results of the sensor magnetic field distribution of two different structures of optical current transformers are shown in **Error! Reference source not found.**, in which the width, radius and length of the iron core are 30mm, 2mm and 45mm, the length of the magneto-optical glass is 5mm and the radius is 2mm.



(a) Magnetic field distribution of magnetic ring type optical current sensor



(b) Magnetic field distribution of optical current sensor with iron core

Figure. 5 Magnetic field distribution of two optical current trans-formers with different structures

It can be seen from the above figure that the magnetic field intensity distribution of both structures is very uniform. However, the magnetic field distribution intensity of the sensing part of the optical current transformer with the iron core structure is obviously stronger than that of the common structure. The magnetic field strength of the optical current transformer with the iron core structure can reach 6 times that of the common structure transformer. This is because the iron core is a paramagnetic material, and the magnetic permeability is very large, so that the magnetic induction intensity inside the iron core is greatly increased, thereby greatly increasing the strength of the magnetic field in the magneto-optic glass.

4.INFLUENCE OF GEOMETRIC STRUCTURE PARAMETERS OF OPTICAL

July-August 2020
ISSN: 0193-4120 Page No. 964 - 972

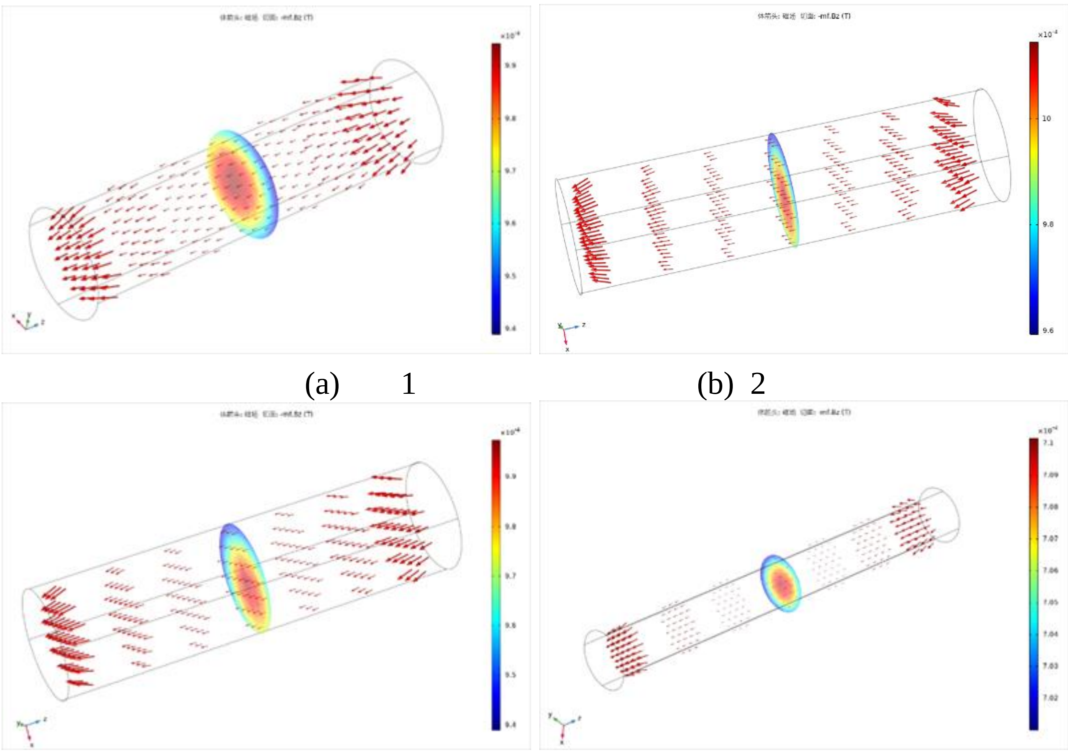
CURRENT SENSOR WITH IRON CORE ON MAGNETIC FIELD DISTRIBUTION

Because the optical current transformer with iron core is essentially a magnetic ring sensor, but the structure becomes complicated due to the existence of the iron core. The geometric parameters of the structure have a great influence on the distribution of the magnetic field strength. It can be seen that both the geometric parameters of the coil and the core have an effect on the magnetic field distribution. Assuming that the geometric parameters of the coil are exactly the same as those of the magnetic collector structure, we analyze the influence of the width, radius and length of the iron core on the magnetic field distribution, When the length of the iron core is changed, the length of the magneto-optical glass is kept unchanged, and the length of the magneto-optical glass is kept at 15mm. The calculation case is shown in **Error! Reference source not found.**.

Table 3. Iron core structure parameters with iron core optical current sensor

	Width / mm	Length / mm	Radius / mm
1	30	45	2
2	40	55	2
3	30	55	2
4	30	55	1

After calculation, the simulation results of the magnetic field distribution in the 1 to 4 cases are shown in Figure 5.



(a) 1 (b) 2 (c) 3 (d) 4

Figure 5. Magnetic field distribution of optical current transformers with different geometric parameters

It can be seen from Figure 5 that if the length of the magneto-optical glass is kept constant, when the length of the iron core increases, the magnetic field strength is almost unchanged. When the radius of the iron core becomes smaller, the magnetic field strength becomes smaller. When the width of the iron core increases, the magnetic field strength becomes larger. It can also be seen from the figure that changing the radius of the iron core has the greatest effect on the strength of the magnetic field

July-August 2020
ISSN: 0193-4120 Page No. 964 - 972

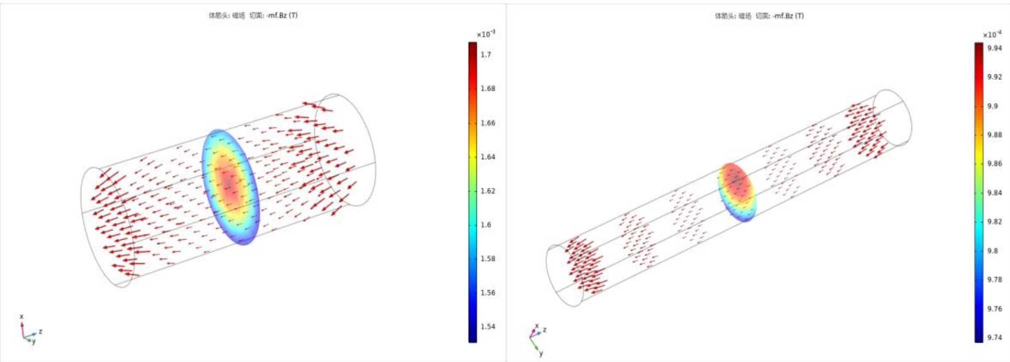
distribution, while changing the length and width has a small effect, which can be ignored. Therefore, the radius parameter of the iron core can be optimized to increase the magnetic field strength.

The geometric parameters of magneto-optic glass also have an influence on the distribution of the magnetic field. In order to study the influence of magneto-optic glass on the distribution of the magnetic field, the geometric parameters of the magneto-optic glass shown in **Error! Reference source not found.** were used for simulation calculation.

Table 4. Geometric parameters of magneto-optic glass

	Width / mm	Length / mm
1	5	2
2	10	2
3	15	2
4	15	1

After calculation, the magnetic field simulation results in the 2 and 4 cases are shown in Figure 6, and the calculation results in the first and third cases are shown in **Error! Reference source not found.**(b) and Figure 5 (a).



(a)2 (b) 4

Figure 6. Magnetic field distribution of optical current transformer under different geometric parameters of magneto-optic glass

It can be seen from Figure 6 that changing the length of the magneto-optical glass greatly changes the magnetic field strength. When the length becomes smaller, the magnetic field strength becomes larger. The magnitude of the magnetic field under different magneto-optical glass lengths is shown in Figure 7.

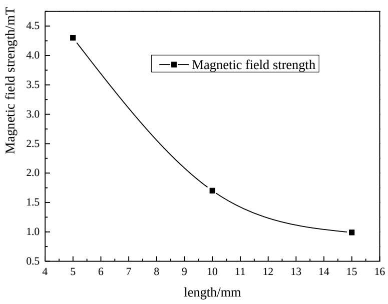


Figure 7. Magnetic field distribution under different magneto-optical glass lengths

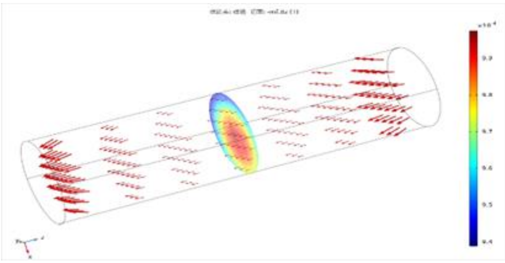
It can be seen from Figure 7 that changing the radius of the magneto-optical glass will also change the magnetic field strength. When the radius becomes smaller, the magnetic field becomes larger, but the change is smaller and can be ignored. The length of magneto-optical glass is affected by the number of turns of the coil and the axial pitch. The more the number of turns of the coil, the greater the magnetic field strength and the greater the axial pitch. At the same number of turns, the length of the coil will become larger, and the length of the corresponding magneto-optical glass will also change. Therefore, the geometric parameters of the coil need to be combined for further analysis.

Changing the geometric parameters of the coil may have a greater impact on the magnetic field distribution, because the length of the iron core is closely related to the geometric parameters of the coil. It changes the geometric parameters of the coil for simulation. Since the axial pitch and the number of turns of the coil are the main factors affecting the length, the main influence of the changes of these two parameters on the magnetic field distribution of the transformer is considered. The width, radius and length of the iron core are 30mm, 2mm and 55mm, the length of the magneto-optical glass is 15mm and the radius is 2mm. The geometric parameters of the coil structure are shown in Table 2.

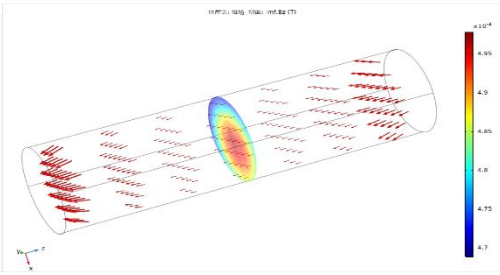
Table 2. Geometric parameters of coil structure

	Axial pitch/mm	Number of turns
1	2	20
2	2	10
3	2.5	20
4	2.5	10

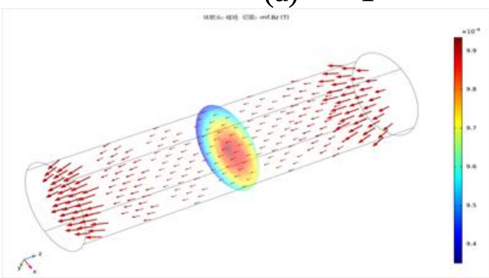
After calculation, the magnetic field simulation results in the 1 to 4 cases are shown in Figure 8.



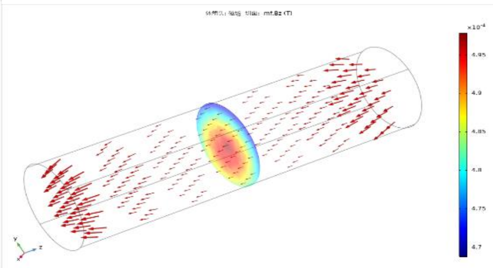
(a) 1



(b) 2



(c) 3



(d) 4

Figure 8. Magnetic field distribution of optical current sensor under different coil structure geometric parameters

It can be seen from Figure 8 that since the number of turns is reduced by 1/2, the second case is 1/2 of the first case, but the length of the coil is also reduced by half. If the length of the magneto-optical glass is also reduced. Therefore, the magnetic field strength will not be reduced to 1/2, so this provides the possibility of miniaturization of the iron core type optical current transformer. Changing the axial pitch does not change the strength of the magnetic field, but it will change the length of the coil, so the length of the iron core needs to be changed appropriately. If the axial pitch becomes 3mm, the length of those coils will be greater than the length of the core, so the core length must be increased, but this does not necessarily affect the length of the magneto-optic glass. The optimal parameter of the coil should be the minimum axial pitch. The minimum axial pitch is related to the small radius of the coil. The smaller the radius, the smaller the length of the coil, but the greater the loss. Therefore, it can be seen that the magnetic field distribution of the sensing part of the iron core type optical current transformer will be affected by various factors. The main factors affected are the length of the magneto-optical glass and the number of turns and radius of the coil.

5.CONCLUSIONS

Through the above analysis and calculation, this article can draw the following conclusions:

(1) The optical current transformer with iron core can make full use of the parameters of the coil, iron core and magneto-optic glass to adjust the intensity of the generated magnetic field. Compared with the commonly used magnetic ring type optical current transformer, the generated magnetic field strength is greater;

(2) The magnetic field distribution of the sensing part of the optical current transformer with iron core is mainly affected by the length of the magneto-optical glass. The larger the length, the smaller the magnetic field strength, and the smaller the length, the greater the magnetic field strength, which is conducive to miniaturization design;

(3) The magnetic field distribution of the sensing part of the optical current transformer with iron core will also be affected by the number of turns and radius of the coil. When the number of turns of the coil becomes larger, the magnetic field strength also becomes larger. However, the length of the corresponding iron core should also become larger, and the radius affects the minimum axial pitch, thereby affecting the length of the coil, which is not conducive to miniaturization design;

(4) For the above analysis, the structural parameters of the sensing part of the optical current transformer with iron core can be optimized based on the magnetic field distribution.

ACKNOWLEDGEMENTS

The authors acknowledge project supported by State Grid Hebei Electric Power Co., Ltd. (Grant No. SGHEDK00DYJS1900100)

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results

REFERENCES

1. Linghao ZHANG, Jiankun LIU, Jing BU. Research on improved current transformer saturation recognition method based on floating threshold. Electric Power Engineering Technology, 2019 (3), pp. 115-120.
2. Zhiqiang YANG, Wei CHEN. Research on Measuring Method of Core Remanence of Current Transformer. Power Engineering Technology, 2018, v.37; No.179 (03), pp. 44-48.
3. Lin CHENG, Anxiang GUO, Weidong QI, et al. Research on the output characteristics of electronic current transformer in complex electromagnetic environment. Shaanxi Electric Power, 2017, 045 (008), pp. 64-69.
4. Zhanfeng FAN, Shenyi BAI, Zhide YANG, et al. Research on key technologies of optical current transformers. Power system protection and control, 2008, 46 (03), pp. 67-74.
5. Yamaguchi Tatsushi, Shiozawa Daigoro, Rokunohe Toshiaki, et al. Development of Independent Type Optical CT. Electronics and Communication in Japan, 2014, 97(1), pp. 28-36.
6. Xuanhe BAO. Key technology analysis of optical current transformer. Shandong industrial technology, 2018 (20), pp. 162.
7. Shuyun MU, Mei HUANG, Dezhong WANG. Analysis of the development trend of electronic transformer technology. Shaanxi Electric Power, 2012 (09), pp. 78-83.
8. Zhihong XIAO, Zhizhong GUO, Guoqing ZHANG, et al. Study on Faraday optical rotation effect of non-uniform magnetic field. Chinese journal of electrical engineering, 2017, 37 (08), pp. 2426-2436.

9. Dai WAN, Lisheng ZHONG, Fei QI, et al. Structural design and simulation of a new type of optical current sensor. Hunan Electric Power, 2015 (08): 9-13.
10. Anlan MAO, Guoxiong YE, Shipu WU, et al. Detection method of compound error of Rogowski structure electronic current transformer. Electrical Measurement and Instrumentation, 2011 (04), pp. 36-41 + 50.
11. Shen YAN, Helu YUN, Liu ZHAO, et al. Performance of magneto-optical glass in optical current transducer application. Journal of Magnetism and Magnetic Materials, 2015,33(2), pp. 389.
12. Xun Wan, Jianlin Zhao, Meirong Wang. A novel design of the sensor head for avoiding the influence of the reflection phase shift in optical current transducer. Optics and Lasers in Engineering, 2009, 48(3), pp. 39-45.
13. Zhengping WANG, Chong KANG, Zongjun HUANG, et al. Faraday mirror-typed optical current transformers and its theoretical analysis. Optics and Laser Technology, 2005, 39(2), pp. 42-48.
14. Hongpeng HE. Multiphysics research and design of OCT sensor unit based on COMSOL[D]. Beijing, North China Electric Power University, 2014.
15. Orr Philip, Fusiek Grzegorz, Niewczas Pawel, et al. Distributed Photonic Instrumentation for Power System Protection and Control. IEEE Transactions on Instrumentation and Measurement, 2015, 64(1), pp. 19-26.