Оптический журнал

Оптическое приборостроение

DOI: 10.17586/1023-5086-2022-89-06-64-72

UDC 535.4

Research on the performance of fiber optical current transformer for high voltage filtering capacitor unbalanced current measurement

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Abstract

Subject of study. A fiber-optic measurement scheme for unbalanced current of high-voltage filtering capacitor is proposed, where an all-fiber temperature sensor based on temperature birefringence is presented to realize the real-time correction of temperature errors. **Method.** The prototypes of the all-fiber filter unbalanced fiber optical current transformer type and magneto-optical crystal type with a rated current of 1 A and rated voltage of 258 kV have been developed and performance tested. **Main results.** After temperature correction, the accuracy of all-fiber filter unbalanced fiber optical current transformer type in the range of –40 °C to 70 °C meets the error limit requirements of class 0.2 specified in the Chinese Standard: GB/T 20840.8-2007 (Instrument transformers — Part 8: Electronic current transformers standard), whose accuracy, integration, reliability and anti-interference ability are better than magneto-optical crystal type. Instrument transformers — Part 8: Electronic current transformers standard whose accuracy, integration, reliability and anti-interference ability are better than magneto-optical crystal type. **Practical significance.** The proposed scheme has the ability of small current (less than 20 mA) measurement in high voltage (more than 110 kV) scenarios.

Keywords: high-voltage filtering capacitor, fiber optical current transformer, fiber temperature sensor, temperature correction, accuracy

Acknowledges: Aeronautical Science Foundation of China (2019ZH069003); Scientific research projects of ministry and provincial key laboratories in China (2242020k30035).

For citation: Jun Zhao, Shengguo Xu, Baofeng Wu, Xiaohan Sun. Research on the performance of fiber optical current transformer for high voltage filtering capacitor unbalanced current measurement // Оптический журнал. 2022. Т. 89. № 6. С. 64–72. DOI 10.17586/1023-5086-2022-89-05-64-72

OCIS codes: 060.2370.

Исследование характеристик волоконно-оптического трансформатора тока для измерения тока дисбаланса высоковольтного фильтрующего конденсатора

Jun Zhao, Shengguo Xu, Baofeng Wu, Xiaohan Sun

Аннотация

Предмет исследования. Предложена волоконно-оптическая схема измерения тока дисбаланса высоковольтного фильтрующего конденсатора, в которой реализована коррекция температурных ошибок в реальном времени, использующая полностью волоконный датчик температуры на основе температурного изменения двойного лучепреломления. **Метод.** Разработаны прототипы волоконно-оптического трансформатора тока цельноволоконного (AF-FU-FOCT) и магнитооптического кристаллического (MOC-FU-FOCT) типов на номинальный ток 1 А и номинальное напряжение 258 кВ, выполнены испытания этих устройств. **Основные результаты.** После температурной коррекции точность цельноволоконного устройства (AF-FU-FOCT) в диапазоне от –40 °C до 70 °C соответствует требованиям к пределу погрешности класса 0,2, указанным в стандарте GB/T 20840.8-2007 (Китай), причём точность, удобство интеграции в схемы, надёжность и помехоустойчивость его оказалась лучше, чем у магнитооптического кристаллического устройства (MOC-FU-FOCT). **Практическое значение.** Предлагаемая схема даёт возможность измерения малых токов (менее 20 мА) в высоковольтной (более 110 кВ) аппаратуре.

Ключевые слова: высоковольтный фильтрующий конденсатор, волоконно-оптический трансформатор тока, волоконный датчик температуры, температурная коррекция, точность

1. INTRODUCTION

The unbalance protection of high-voltage capacitors is one of the important measures to ensure the safe and reliable operation of AC filters [1, 2]. Among them, the unbalanced current transformer is a key device for measuring the unbalanced current of high-voltage capacitors and realizing AC filter fault monitoring [3, 4].

With the increase of grid voltage level and the large-scale use of smart electrical equipment, traditional electromagnetic current transformers (ECT) have gradually exposed many shortcomings such as poor insulation, large size, and difficulty in power supply [5]. Chen et al. [6] introduced a novel magnetic sensor array based current measurement method with a clamp-like structure, which can alleviate the magnetic interference from random sources, however, the solution can only test a few hundred amperes of current. Wang et al. [7] proposed a time-domain feedback calibration method to relieve the dependence of the calibration file on the input signal when the air coil sensor is calibrated, but it cannot solve the problem of limited bandwidth and output signal distortion of the air coil sensor.

Fiber optical current transformer (FOCT) uses fibers as sensitive material and signal transmission medium, which is immune against electromagnetic interferences and provides the absence of saturation effects. Due to the extremely low absorption loss of fiber, it allows remote detection. In addition, FOCT measures the magnetic field generated by the electric current rather than the current itself, thus avoiding the electric hazards that the high voltage measurements imply. Thus, the inherent advantages of FOCT are very attractive for high-voltage applications [8–10].

However, FOCT based on the Faraday effect have an intrinsic temperature dependency of the current sensitivity caused by the natural drift of the Verdet constant as well as birefringence in the sensing medium [11]. In order to reach high class accuracy of up to 0.2%, these effects have to be compensated. Muller and Bohnert *et al.* [12–15] use the temperature dependence of birefringent fiber phase retarders to balance the temperature dependence of the Faraday Effect. However, in the actual FOCT system, this method is difficult to completely eliminate the temperature error due to the process consistency and other issues. In this case, it is feasible to use a separate temperature measurement to compensate for the temperature dependency.

Depending on the ratio between the temperature effect and the desired accuracy of the current measurement, a certain accuracy of the temperature measurement of the current sensing element should be achieved. Electrical temperature sensors such as PT100 or thermocouples are cost effective solutions, but the signal transmission cables are susceptible to electromagnetic interference. Hence, optical temperature sensors are suitable for this purpose. Willsch et al. [16] presented a GaAs type optical temperature sensor based temperature compensation scheme, but this semiconductor absorption theory and spectral analysis method based transmission-type fiber temperature sensor has the problem of low accuracy and resolution. As a result, a functionaltype high integration polarization maintaining fiber temperature sensor (PMF-TS) based on 45° tilted fiber Bragg grating (TFBG) in-fiber polarizer [17, 18] is proposed [19], which has the advantages of simple structure, high accuracy and high resolution comparing with the existing mature temperature measurement methods such as fluorescent fiber temperature sensor [20] or FBG sensor [21, 22].

On this basis, the high-voltage and small-current filter unbalanced FOCT (FU-FOCT) based on PMF-TS is designed. In addition, the 258 kv prototypes of all-fiber type and magneto-optical glass type were developed, whose performances was tested in detail.

2. SYSTEM SCHEME

The architecture of FU-FOCT is shown in Fig. 1, which is composed of FOCT and PMF-TS. Among them, FOCT and PMF-TS share the super light emitting diode (SLD) and signal processing unit.

FU-FOCT is based on Faraday magneto-optical effect and adopts a reflective in-line structure, which has good reciprocity and anti-interference ability, whose working principle is shown in [15]. In this article, we designed two types of FU-FOCT probes, the all-fiber type (AF-FU-FOCT) and the magneto optical crystal type (MOC-FU-FOCT).

The temperature dependence of FU-FOCT is mainly caused by the temperature dependence of the Verdet constant and the birefringence effect of the sensing fiber material [15].

Fused silica fiber has the inherent temperature dependence of Verdet constant, with the change rate $(1/V_0)\delta V/\delta T$ equals to 0.7×10^{-4} K^{-1} [13]. Here, V_0 is the Verdet constant at room temperature. The quarter-wave plate are short sections of elliptical-core fiber with the length corresponding to a quarter of the fiber beat length, and the retardation ρ decreases essentially linearly at a rate of $(1/\rho_0)\delta\rho/\delta T = (-2.2 \pm 0.1)\times10^{-4}$ K^{-1} [13], where, ρ_0 is the retardation at the room temperature.

According to the test results, without temperature compensation, for the rated 1 A FU-FOCT, the ratio error (RE) usually fluctuates in the range of ±0.5% – ±1.5% from −40 to 70 °C, which far exceeds the error limit of class 0.2.

A. AF-FU-FOCT architecture

Since the rated value of the unbalanced current of filtering capacitor is mostly 1–2 A, in order to improve the sensitivity and accuracy, the AF-FU-FOCT with a double spiral type current sensing unit is designed (Fig. 2).

The rotation angle θ_1 of the transmitted polarized light is proportional to the product of the magnetic field strength B and the optical path L, as shown in Eq. (1), and the proportional coefficient is the Verdet constant V and the vacuum permeability μ.

$$\theta_1 = \mu V \int_L H dl = NMVI, \qquad (1)$$

where, N is the turns of sensing fiber, M is the turns of cable, I is the current to be measured.

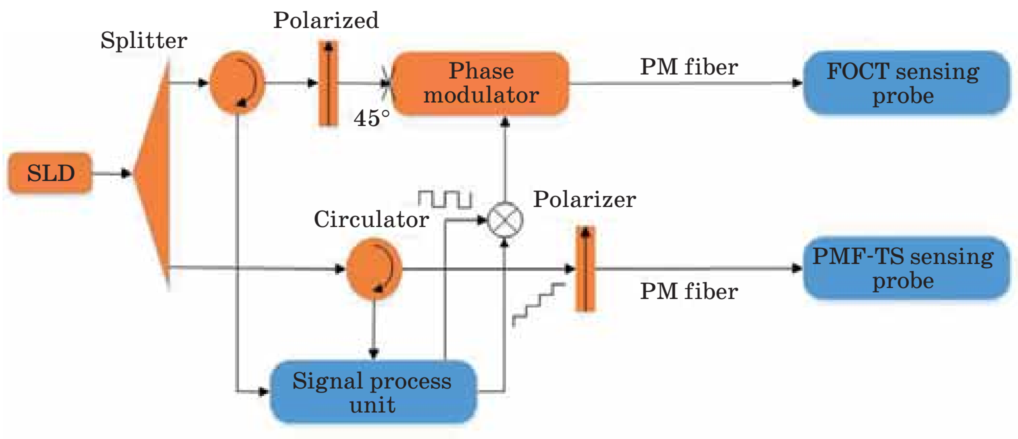

Fig. 1. The FU-FOCT system architecture

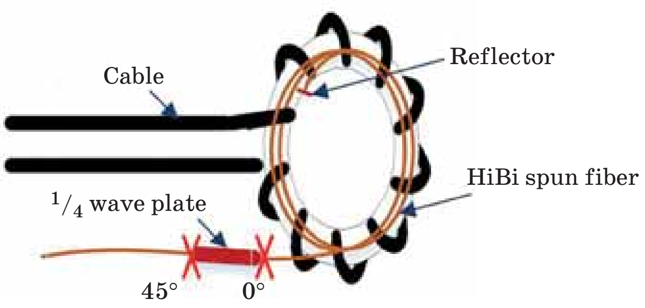

Fig. 2. Schematic diagram of AF-FU-FOCT sensing ring

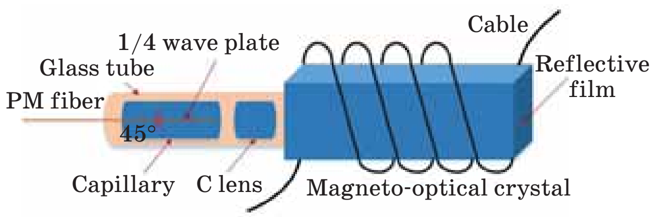

Fig. 3. Schematic diagram of MOC-FU-FOCT sensing probe

B. MOC-FU-FOCT architecture

For the purpose of comparative study, the MOC-FU-OCT is proposed, as shown in Fig. 3. The PM fiber and the quarter-wave plate are fused at 45 degrees and packaged in a capillary. The incident light enters the magneto optical crystal after collimated by the C-lens, and the end of the magneto-optical glass is plated with a total reflection film. The MOC-FU-FOCT sensor probe is placed into a solenoid, and then the magnetic field in the solenoid can be measured according to the Faraday magneto optical effect.

Obviously, the rotation angle θ_2 of the transmitted polarized light in the magneto optical crystal can be shown as follows:

$$\theta_2 = MVI. \quad (2)$$

C. TFBG polarizer based PMF-TS

PMF-TS is presented to measure the temperature of the current sensing probe, whose working principle is shown in [19].

As shown in Fig. 4, the TFBG polarizer and temperature sensing fiber are made of panda-type PM fiber and are welded at a 45° angle. All components of PMF-TS are welded together which can improve the integration, reliability

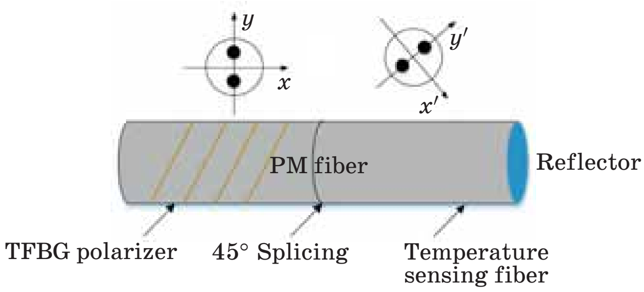

Fig. 4. Schematic diagram of PMF-TS sensing probe

and anti-interference ability. The test results show that the accuracy and resolution of PMF-TS can reach ±0.1 °C and 0.01 °C, respectively, which has higher resolution than PT100, 18B20, and optical fiber temperature sensor based on fiber Bragg grating or Raman/Brillouin scattering effect [19].

3. EXPERIMENTAL PROTOTYPE

As shown in Fig. 5a, a AF-FU-FOCT prototype with the rated primary current (*In*) of 1 A and rated voltage (*Un*) of 258 kv was developed. Where, the multi-turn current sensing fiber is tightly wound on the epoxy framework, whose outside is wound with multiple turns of wires. Here, the current sensing fiber is SHB1250 high birefringence spun fiber of Fibercore Ltd.

Figure 5b shows the probe of the MOC-FU-FOCT, where, the size of the magneto-optical crystal is 3×3×20 mm^3, and the Verdet constant is 0.092 min/oe*cm@1310 nm.

Under the sensor head is a suspended optical fiber insulator whose function is to meet the performance requirements of insulation and light transmission. As shown in Fig. 6, the 900 µm fiber pigtails for temperature sensing probe (SM fiber) and current sensing ring (PM fiber) pass through the insulator, which is filled with insulating paste.

Figure 7 shows the developed PMF-TS, whose length is about 3 mm, and packaged with ceramic sleeve.

4. EXPERIMENTAL TESTS

The accuracy test scheme is designed and shown in Fig. 8. Among them, the Omicron CMC256plus relay protection tester is used as

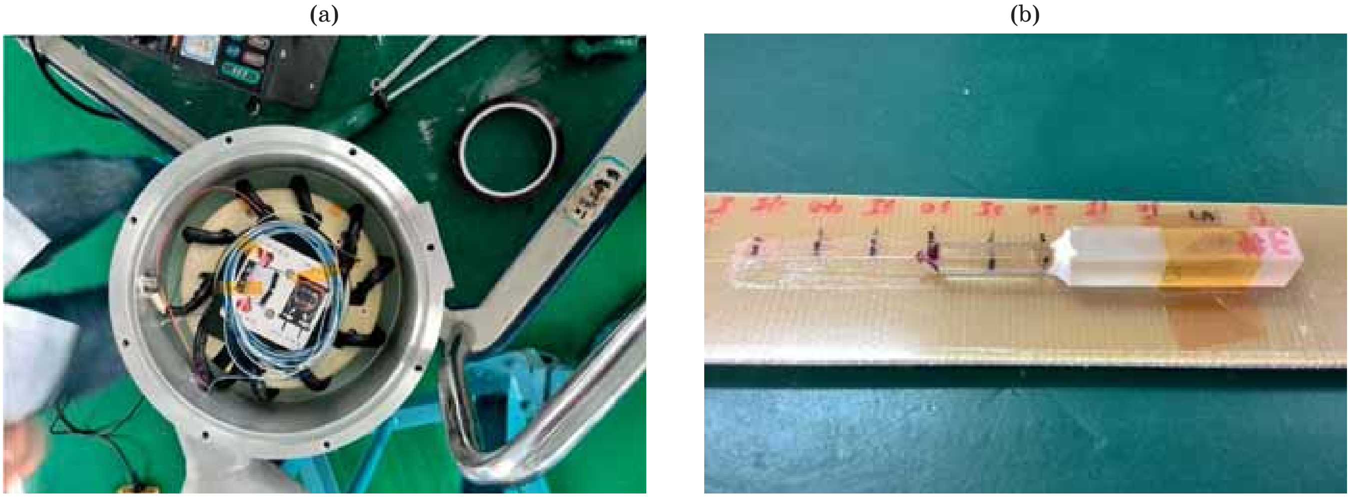

Fig. 5. Photos of the AF-FU-FOCT sensing head (a) and the MOC-FU-FOCT sensing head (b)

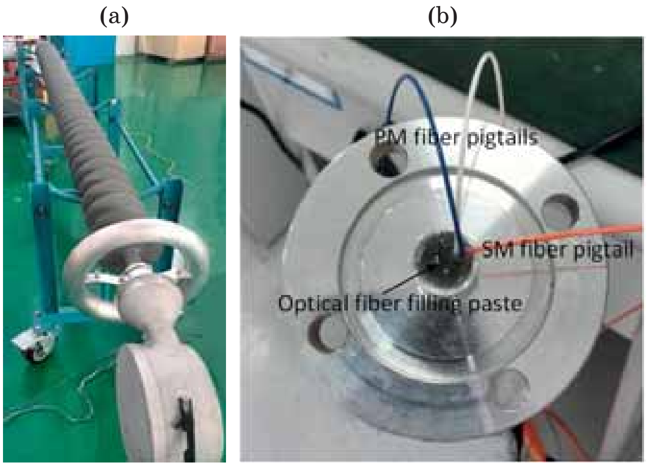

Fig. 6. Photos of suspended optical fiber insulator (a) and transmission fibers (b)

Fig. 7. The PMF-TS sensing probe

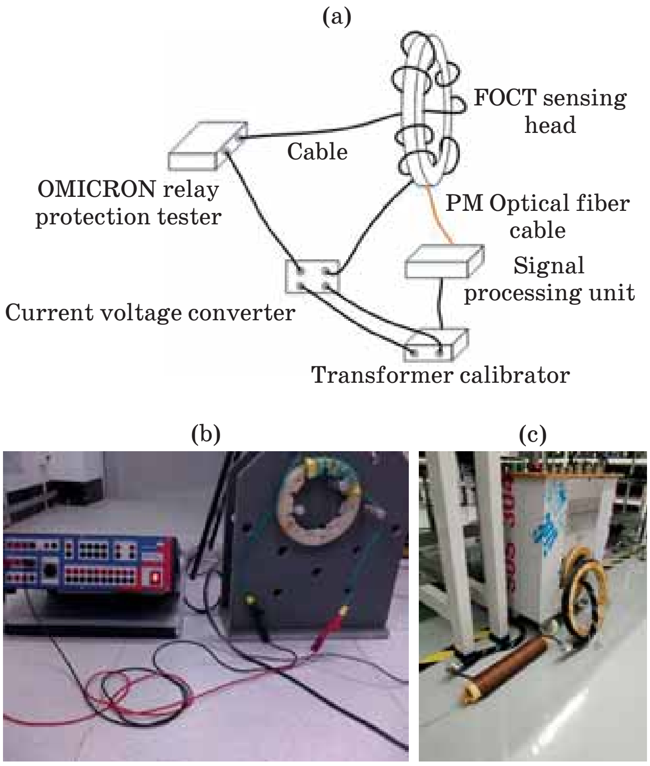

Fig. 8. The accuracy test scheme (a) and the accuracy test photos of AF-FU-FOCT (b) as well as MOC-FU-FOCT (c)

the current source to generate the primary currents of different frequencies (50–1200 Hz) and different amplitudes (50 mA — 1.2 A). The current is converted into the voltage by a current-to-voltage converter, and sent to the transformer calibrator together with the FU-FOCT demodulation signal to calculate the measurement error.

In order to improve the accuracy and stability, Kalman filter algorithm is used to enhance the noise reduction effect. Figure 9 shows the accuracy test results of FU-FOCT at 1 A after Kalman filtering (the covariance of process noise (Rvv) and measurement noise (Rww) are 0.000001 and 0.1, respectively). For AF-FU-FOCT, when $N = 35$ and $M = 10$, the fluctuation ranges of *RE* and phase error (*PE*) are −0.16–0.18% and −3.78′–2.62′ respectively, which meets the error limit requirements of class 1 specified in GB/T 20840.8-2007, while when $N = 60$, $M = 10$, the fluctuation ranges of *RE* and *PE* are −0.042–0.08% and −0.15′–0.17′ respectively, reaches the accuracy level of class 0.2.

Put the MOC-FU-OCT sensor probe into a solenoid made of 60 turns of cable, and test its accuracy under 1 A. As shown in Fig. 9c, the fluctuation range of *RE* is about –1.5–1.5%, which is much higher than AF-FU-FOCT.

The put FU-FOCT sensor heads into the environmental experiment box, and perform the temperature performance test according to the temperature cycle curve are shown in Fig. 10b.

As shown in Fig. 11, in the temperature range of −40 °C to +70 °C, the system error changes monotonously with the ambient temperature. Here, *T* is the temperature measured by PMF-TS, RE_a and RE_b represent the ratio-errors after and before the temperature compensation, respectively.

For AF-FU-FOCT, the *RE* fluctuation range is about −0.52–0.86%, and after the error correction by PMF-TS, the *RE* can be reduced to less than ±0.2%. While for MOC-FU-OCT, because of its low accuracy, it is difficult to improve its performance to the level of AF-FU-FOCT.

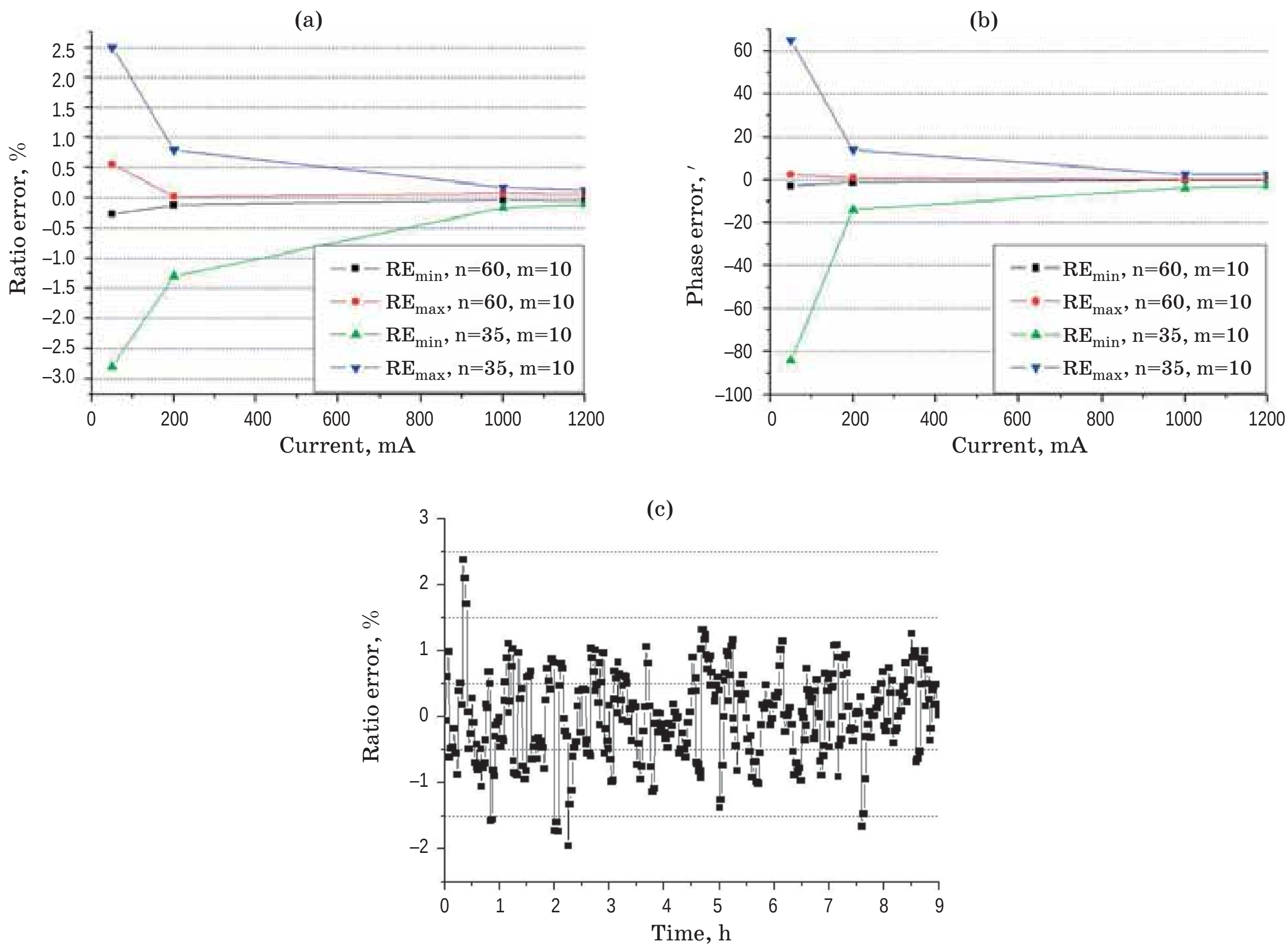

Fig. 9. RE (a) and PE (b) test data for AF-FU-FOCT, the accuracy test results for MOC-FU-OCT (c)

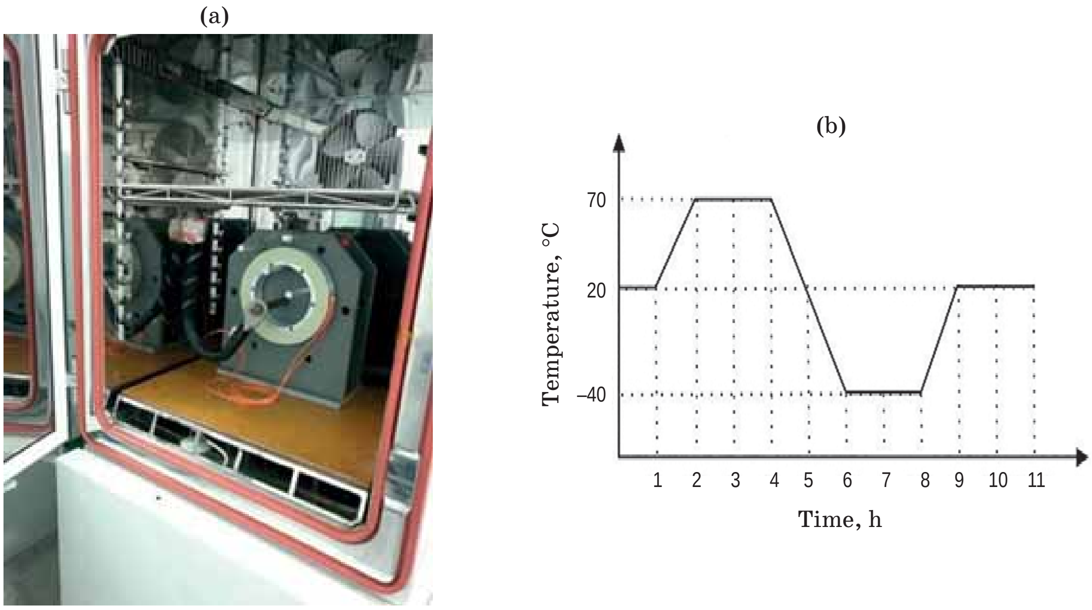

Fig. 10. Experimental photo (a) and temperature cycle curve of the temperature performance test (b)

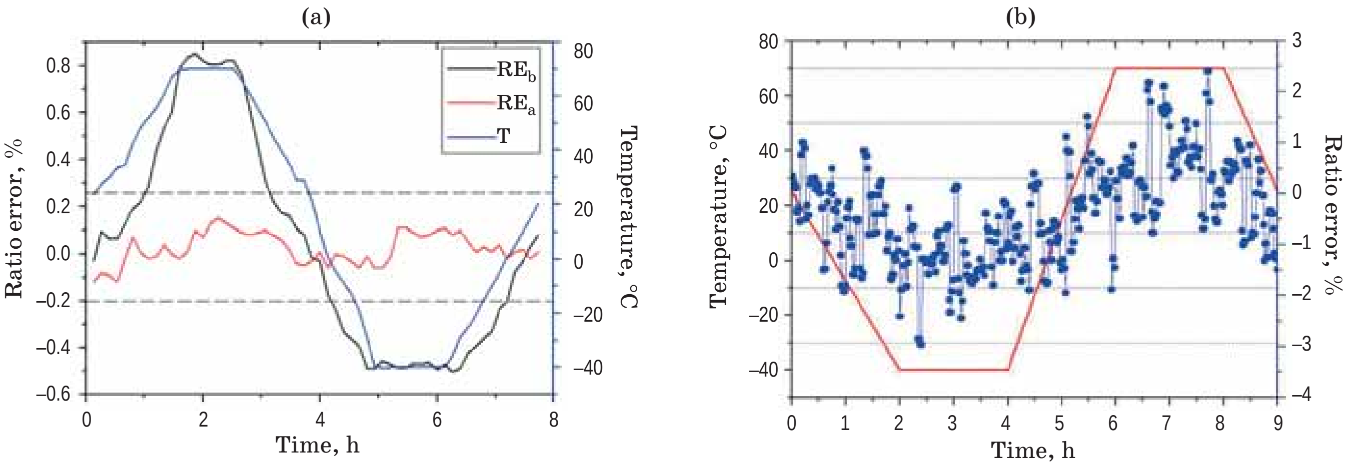

Fig. 11. The temperature performance test results for AF-FU-FOCT (a) and MOC-FU-OCT (b)

5. CONCLUSION

The FU-FOCT for high-voltage filtering capacitor unbalanced current measurement is proposed, where the real-time temperature correction is realized by the PMF-TS based on the 45 degree TFBG, and the sensitivity and accuracy can be improved by using a double spiral structure. The prototype of AF-FU-FOCT with a rated current of 1 A and rated voltage of 258 kv has been developed. The performance test results show that, it not only has better connection reliability, but also has higher measurement accuracy compared with MOC-FU-FOCT, which can meet the error limit requirements of class 0.2.

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The article was submitted to the editorial office 01.12.2020, approved after review 10.03.2022, accepted for publication 25.04.2022