Design and validation of broadband calibration system for fiber-optical current transformers

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Abstract. With the rapid development of the energy system, new requirements are put forward for the current measurement equipment, including fiber-optical current transformer (FOCT), which is a vital instrument for measuring the current of high voltage direct current (HVDC) system. Nowadays, the broadband measurement performance of FOCT requires higher technical indicators, yet the existing calibration system of FOCT cannot meet the actual engineering needs. This paper developed a broadband calibration system for FOCT, which can accurately verify the broadband performance of FOCT in the frequency range from 50Hz to 2500 Hz. The impedance of the secondary circuit of the lifter in the calibration system is calculated; the power supply selection requirements of the FOCT calibration system were proposed. The broadband calibration of FOCT prototype with rated current 1000A was calibrated in the frequency range from 50Hz to 2500Hz. Further, the validity of the system was verified.

1. Introduction
With the rapid development of the energy system, the traditional electromagnetic current transformer cannot meet the requirements of power grids [1-2]. So it is essential to develop a new type of current transformer [3]. Fiber-optical current transformer (FOCT) has gradually entered a practical stage with incomparable advantages. It has attracted wide attention of researchers. [4-6]. However, there are still some technical problems for a vast practical application of FOCT [7]. For example, the harmonic frequency is much higher than the requirement of the national standard (GB/T26216.1-2010) [8], which not only needs higher requirements for the broadband measurement ability of the transformer, but also needs to improve the calibration frequency range of the broadband calibration system of FOCT.

At present, many scholars have done some research on the broadband measurement performance of FOCT. Reference [9] built a test platform to test the broadband measurement performance of FOCT. The test results showed that the measurement error of FOCT was less than 0.55% and the bandwidth was more than 10 kHz in the range of 50 - 1200 Hz. Document [10] introduced the mechanism of harmonic measurement error of FOCT, and built a DC FOCT harmonic current measurement error test platform. The experimental results showed that within the range of 50 - 1200 Hz, the measurement error of the prototype was less than 0.5%, and the bandwidth was more than 10 kHz. At present, the broadband calibration of FOCT mainly carries out frequency response experiments at 50 - 1200Hz according to the national standard, lacking the calibration ability to measure the performance of FOCT under higher frequency harmonics.
Given the deficiency of FOCT broadband calibration capability, this paper developed a FOCT broadband calibration system. The system can accurately verify the broadband performance of FOCT in the frequency range from 50Hz to 2500Hz. This system verified the accuracy of the FOCT prototype in the range from 50Hz to 2500Hz.

2. Design of broadband calibration system for FOCT
FOCT has been widely used due to its high measurement accuracy and large dynamic range. However, the accuracy of FOCT has not been paid enough attention when measuring high-order harmonics in actual operation. Besides, the corresponding researches on FOCT broadband calibration system are also less. In order to meet the requirement of measuring higher harmonics in power system, a FOCT broadband calibration system was developed. The primary circuit impedance of the broadband calibration system was analysed and tested, and the power design was optimized according to the test results. The optimized calibration system can accurately verify the measurement performance of FOCT in the frequency range of 50 - 2500Hz.

2.1. Operating principle of broadband calibration system
FOCT is a new type of electronic current transformer based on Faraday magneto-optical effect and Ampere circuit law. The system structure consists of three parts: optical fiber sensing ring, polarization maintaining optical fiber delay ring and signal processing unit. According to Faraday magneto-optical effect and Ampere circuit law, the magnitude of the current transmitted in the current-carrying wire is proportional to the phase difference caused by Faraday effect. Therefore, the measured current can be calculated by detecting the optical phase difference signal. (Figure 1)

The calibration system of FOCT adopts direct measurement method, and the basic principle is shown in Fig. 2. The measured current was supplied by the signal generator amplified by power amplifier and broadband lifter. The standard transformer and FOCT were connected in series to the measured current circuit. The output signal of FOCT was transmitted to the merging unit through the acquisition unit, then it was converted into TCP/IP signal by the protocol converter, further it was input to the DC electronic transformer calibrator. The second output of standard current transformer was converted into voltage signal through standard resistance of 1 Ω. Besides, it was also input to DC electronic transformer calibrator. The DC electronic transformer calibrator based on LabVIEW platform sent out synchronous clock signals to ensure the synchronization of FOCT and standard transformer output signals, and obtained error signals such as ratio error and angle difference through programming calculation. In order to improve the measurement accuracy, the average values of the ratio error and angle difference of 10 cycles were selected as the final results.

![Figure 1. Operating principle of broadband calibration system.](image-url)
2.2. Power supply design of calibration system

The theoretical inductance of rectangular circuit was calculated by formula (1) and formula (2), where \( h \) is the width of a rectangular circuit, \( w \) is the length of the rectangular circuit, and \( d \) is the diameter of the wire. Formula (3) was used to calculate the theoretical inductance of the circular circuit, in which \( D \) is the equivalent diameter of the circuit and \( d \) is the diameter of the conductor. The theoretical calculation values are shown in Table 1.

At the same time, the impedance of the primary current loop was measured and analyzed. The principle diagram of the impedance measurement of the primary current loop is shown in Fig 2. As can be seen from Fig.2, the primary winding turns are 20 turns and the secondary winding turns are single turns. A 100A current conductor constitutes the secondary winding of the lifter. Its length is 5m, theoretical DC resistance is 4.5mΩ, and it was arranged in a circle with a diameter of about 1.6m. Resistance \( R \) is a high accuracy broadband shunt (0.8V/100A), with a 8 mΩ theoretical resistance. Its stray capacitance and inductance can be neglected in this test. \( U \) is the secondary output voltage of the elevator, namely, the primary current loop voltage. Its amplitude was measured by a digital multimeter. \( U_R \) is the voltage drop of resistor \( R \). When the voltage \( U \) and \( U_R \) were input to the reference input and single input of PLA respectively, the phase angle difference and amplitude of \( U_R \) relative to \( U \) can be measured, also, the current and inductance of primary current loop can be calculated.

\[
L_{rec} = \frac{\mu_0 \mu_r}{\pi} \left[ -2(w+h) + 2\sqrt{h^2 + w^2} + \text{temp} \right] \\
\text{temp} = -h \ln \left( \frac{h + \sqrt{h^2 + w^2}}{w} \right) - w \ln \left( \frac{w + \sqrt{h^2 + w^2}}{h} \right) \\
+ h \ln \left( \frac{2h}{d} \right) + w \ln \left( \frac{2w}{d} \right) \\
L_{cir} \approx \mu_0 \mu_r \left( \frac{D}{2} \right) \left[ \ln \left( \frac{8 \cdot D}{d} \right) - 2 \right]
\]

Table 1. Theoretical inductance calculation.

| Circuit | parameters         | Theoretical inductance (μH) |
|---------|--------------------|-----------------------------|
| Circle  | D=1.6m, d=10mm     | 5.2                         |
| Rectangle | w=1.25m, h=1.25m, d=10mm | 4.8                     |
| Rectangle | w=1.5m, h=1m, d=10mm | 4.7                       |
| Rectangle | w=2m, h=0.5m, d=10mm | 4.3                       |
| Rectangle | w=2.45m, h=0.05m, d=10mm | 2.3                     |
| Rectangle | w=2.47m, h=0.03m, d=10mm | 1.8                     |
Figure 2. Primary current loop impedance test.

Use the test circuit as shown in Fig. 2 to measure the circuit resistance and inductance of the primary current loop with a single conductor and twisted conductor. The measurement results were as shown in Fig. 3.

Figure 3. Impedance test results.

Where lines a, b, c and d are the calculated figures of resistance, inductive reactance, inductance and impedance in primary current loop with single conductor. Dotted lines A, B, C and D were the calculated figures of resistance, inductive reactance, inductance and impedance in primary current loop with twisted conductor.

Lines in Fig. 3 show that when the current frequency is 2500Hz, the impedance of the circuit is close to 60mΩ. It is an immense value, which may affect the output capability of the calibration system, so that the output frequency range of the broadband calibration system cannot reach 2500Hz. Based on the reason, the primary current circuit was twisted to minimize the area of the circuit. At the same time, the circuit was approximately rectangular. The above tests were carried out again, and the circuit resistance and inductance were calculated. As can be seen from dotted lines in Fig.3, the inductance of the circuit was reduced by nearly half, and the impedance of the circuit was 33 mΩ at the current frequency of 2500 Hz. As can be seen from Fig. 3, the impedance of the circuit depended mainly on the DC resistance of the circuit at low frequency, and the inductance of the circuit at high frequency.

Comparing figures in Table 1 and Fig. 3, the maximum error between theoretical and measured values of loop inductance is about 20%. Considering that the conditions of actual measurement were not wholly consistent with the theoretical assumptions, this error is acceptable. The circuit parameters of the last line of Table 1 (The rectangular circuit width is minimal) were roughly equivalent to the case of twisted conductors (Fig. 3), when the error was small. The theoretical analysis and experimental measurement of primary circuit impedance showed that the primary circuit impedance of FOCT
broadband calibration system would reach the minimum as long as the area of the primary current loop was reduced as much as possible and the conductor was twisted. Therefore, the broadband calibration system can realize the ability to output 2500Hz primary current as long as the appropriate power supply scheme was selected.

3. Validation of broadband calibration system for FOCT

According to the analysis above, a prototype of FOCT with rated current 1000A was verified. AE Techron’s 7796 power amplifier was used for the power amplifier of this calibration system. It can provide 400 Vrms output voltage. The THD (harmonic distortion rate) of the output signal in the range of 20 Hz-20 kHz is less than 0.0015%. It can operate in voltage or current mode and can output over 5000W power range. It experienced very low noise and fast swing rate, and can drive all kinds of resistive inductance loads safely. The signal generator adopted XL-221 single-phase dynamic waveform power source of Xinglong Technological Company. It can output single-phase AC/DC voltage and current; DC, square wave, triangle wave, sine wave, and 129 superimposed harmonics. It also has the functions of a custom waveform, various types of waveform splicing output and so on. It can be used in situations requiring complex waveform signal output, such as transformer detection, harmonic analysis, etc. When the AC signal was selected, the AC voltage in the frequency range from 0.001 kHz to 5 kHz can be output, and the stability and accuracy can reach less than 5/10000. It can be used as a standard AC voltage source. The wide-band current elevator was used to verify the current transformer, which was used as a power supply for the primary current of the current transformer or other 50Hz single-phase current power supply equipment. Output current: 10 - 120A, permitting long-term operation under rated current and 1.5 times overload for 30 minutes.

What is more, the active broadband current transformer was selected as the standard current transformer in the calibration system. Its frequency range is 50 Hz to 2500Hz, and its accuracy level is 0.002. It is 2 orders of magnitude lower than the accuracy (0.2 level) of the tested FOCT prototype, which can meet the calibration requirements and achieve the calibration effect. The standard resistance was made of manganese copper with a precision of 0.01 and a resistance value of 1Ω. The NI PXIe-1062Q chassis produced by NI Company was selected as the hardware of data acquisition unit. Its high bandwidth backplane can provide a dedicated bandwidth of up to 1 GB/s per slot to meet the needs of efficient operation. At the same time, it enjoyed high sampling accuracy, strong anti-interference ability, and low noise.

The prototype of FOCT (rated current 1000A) was connected to the calibration system, and the input current was set to 100A (10% rated current). The ratio and angle difference between 50Hz and 2500Hz were measured. The measurement results are shown in Fig. 4. From the measurement results, it can be seen that within the range from 50 Hz to 2500 Hz, the maximum ratio error of the FOCT prototype was 0.52%, and the maximum angle difference was 54 μs, which meets the requirements of the national standard "GB/T 26216.1-2010", in the amplitude error should not exceed 0.75% and the phase error should not exceed 500 μs. In the range from 50 Hz to 2500 Hz, the calibration system can meet the requirement of frequency response test accuracy of FOCT.
4. Conclusions
This paper designed a broadband calibration system for FOCT. To realize a primary current output up to 2500 Hz by the broadband calibration system, it is suggested by this paper that, the area of the primary current loop should be reduced as mush as possible, the conductors should be twisted-pair processed, and the power supply scheme should be appropriately matched.

By using the designed system, the calibration of a certain FOCT prototype in the frequency range from 50 Hz to 2500 Hz was made. The maximum ratio error of the calibrated FOCT prototype was 0.52%, meaning that the system could accurately calibrate the broadband performance of FOCT in the frequency range from 50 Hz to 2500 Hz.

5. References
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