A Fault Diagnosis System of All-Fiber Optical Current Transformer with Correlation Detection

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Abstract. All-fiber optical current transformer (FOCT) based on Magneto-optical Faraday effect plays a pivotal role in current metering and protection of smart grid. However, the fault diagnosis of FOCT is one of the most critical issues to be solved. In order to ensure the proper functioning of FOCT, a fault diagnosis system is presented by monitoring the intensity variation of the light interference with Square wave bias modulation of FOCT, which is measured by digital signal processing unit using correlation detection technology. Afterwards, the faulty types of FOCT are recognized by the amount of the optical power variation. The experimental results show that the system can effectively detect these kinds of fault types, such as the broken of optical fiber, the increasing loss of optical fiber and the breakdown of light source in FOCT.

1. Introduction

Current transformers based on Magneto-optical Faraday effect play a very important role in metering, controlling and protection of the smart grid. In comparison with conventional transformers, all-fiber optical current transformers (FOCT) are lightweight, immune to electromagnetic interference and compatible with modern control and protection systems with a wide measurement range.

However, the faulty diagnosis of FOCT is one of the most noticeable issues to be solved. As we can see, Wu Zhejun [1] put forward a monitoring system of all-fiber optical current transformers in the patent ‘Optical path condition monitoring system of FOCT’, and Liang Bing [2] demonstrated a way to detect faults in the patent ‘Apply of Segmental optical fault diagnosis in all-fiber optical current transformers’, but the optical fiber coupler used in above both patents would cause too much light lost during transmission which leads to the drop in measurement accuracy of FOCT. This paper presents a system which is able to detect faults without increasing optical loss and influencing measurement accuracy, by monitoring the intensity variation of the light interference with Square wave bias modulation of FOCT using correlation detection technology.

2. Basic principles

The operation of FOCT is based on Faraday magneto-optical effect. As shown in figure 1, when linear polarized light propagates in the magnetic rotation material, the polarization direction is rotated by the magnetic field paralleling with the direction of the optical beams. The deflection angle is proportional to the magnetic field intensity, so it can be utilized to detect the intensity of current which generates the magnetic field [3].
3. System structure and correlation detection

3.1. System structure
The configuration and working process of FOCT used in the polarization reflected interferometric optical way is introduced in figure 2. Polarized reflective interferometric optical fiber current sensor is made up of a light source, optical fiber coupler, fiber polarizer, phase modulator, optical fiber delay coil, quarter-wave wave plate, sensing optical fiber coil, reflector, PIN-FET and digital signal processing(DSP) unit [3].

3.2. Apply of correlation detection
The operation principle of polarized reflective interferometric FOCT is briefly described as follows. After the light emitted by the light source passes through the optical fiber coupler, it is polarized into linearly polarized light by the fiber polarizer. The pigtail of the polarizer and the pigtail of the phase modulator are fused at 45°, and the linearly polarized light is injected into the PM fiber at 45° and transmitted along the delay coil of the PM fiber. After passing through the λ/4 wave plate, the linearly polarized light of the two orthogonal modes becomes left-handed and right-handed circularly polarized light respectively, and propagates into the sensing fiber coil. The current transmitted in the current-carrying wire generates a magnetic field, which generates a Faraday magneto-optical effect in the sensing fiber, causing a phase difference between the two circularly polarized lights. After being reflected by the reflector, the polarization modes of the two beams of circularly polarized light are interchanged (that is to say, the left-handed light becomes right-handed, and the right-handed light becomes left-handed light). After passing through the sensing fiber coil again, the phase difference produced by the 2 beams of light is doubled due to the influence of Faraday magneto-optical effect. After the two beams pass through the λ/4 wave plate again, they return to linearly polarized light and interference occurs at the polarizer. Finally, the light carrying the non-reciprocal phase difference
information generated by the Faraday effect enters the PIN-FET, and the received optical power \( P \) can be expressed as [4]:

\[
P(\varphi_S, \varphi_b) = P_0 \left[ 1 + \cos (\varphi_S + \varphi_b) \right]
\]  

(1)

Where \( \varphi_S \) is the phase shift caused by Faraday magneto-optical effect, \( \varphi_b \) is the square-wave offset phase, and \( P_0 \) as well as \( P \) is optical power.

In the positive period, \( \varphi_b \) is equal to \(+ \pi / 2\), namely

\[
P_+ = P_0 \left[ 1 + \cos (\varphi_S + \pi / 2) \right] = P_0 \left( 1 - \sin \varphi_S \right)
\]  

(2)

In the negative period, \( \varphi_b \) is equal to, namely \(- \pi / 2\), namely

\[
P_- = P_0 \left[ 1 + \cos (\varphi_S - \pi / 2) \right] = P_0 \left( 1 + \sin \varphi_S \right)
\]  

(3)

The A/D converter samples the adjacent positive and negative half-period signals within a period with correlation detection, which is \( P_+ \) and \( P_- \), then converts analog signals into digital signals. The digital signal processing unit adds the positive half-period signal (\( P_+ \)) to the negative half one (\( P_- \)), which is

\[
W = P_+ + P_- = 2P_0
\]  

(4)

Where \( W \) is the output of digital signal processing unit. Consequently, the alternating amount is eliminated and the direct amount obtained reflects the amount of optical power, which is not influenced by the measured current. We can determine whether FOCT is in faulty states according to the output of DSP unit which represents the amount of optical power.

4. Experiments

4.1. Measuring the normal range of optical power

As is known to all, in addition that the optical power in the optical fiber varies because of some faults, such as fiber breakage, light source breakdown, or too small bending fiber radius, it also fluctuates due to the effect of ambient temperature under normal circumstances. In order to rule out the influence of temperature on optical power under normal conditions and cause misjudgment of faults, we first performed a temperature cycling test on FOCT to determine the range of optical power change during normal operation of FOCT from -40°C to 70 °C to determine a normal fluctuation range of optical power.

As shown in figure 3, the FOCT measurement part is placed in the thermostat, and two optical fibers are connected externally, one of which is connected to the optical power meter to measure the optical power output by the DSP unit, and the other is connected to the optical fiber sensor coil, and a stable 500A DC wire passes through the optical fiber sensing coil.

Figure 3. Schematic diagram of temperature cycle test.
The test process is as follows. Put the FOCT at room temperature into the thermostat, raise the temperature to 70 °C, then lower it to -40 °C, and then raise the temperature to normal temperature with temperature changing rate of 20°C per hour. The optical power at -40°C, -30°C, -20°C, -10°C, 0°C, 10°C, 20°C, 30°C, 40°C, 50°C, 60°C, 70°C were recorded[5], and the optical power curve was obtained as shown in figure 4.

As we can see from figure 4, the optical power of the curve is almost unchanged between -20°C and 60 °C, while the optical power decreases sharply at -30 °C, and the optical power increases significantly at 70 °C. Obviously, the effect of low temperature on optical power is large, which is caused by the performance of the polarizer at low temperature. Besides, the minimum optical power is 8.5 μW when the temperature is the lowest, and the maximum optical power is 16 μW when the temperature is the highest.

Figure 4. Optical power curve in temperature cycle test.

Thus, the fluctuation range of the optical power under the influence of temperature is from 8.5 μW to 16 μW. Therefore, it is possible to determine whether the FOCT is faulty by measuring the optical power value output by the DSP. If the measured optical power value is within this range, it is judged to be normal, and if it exceeds this range, it is judged to be faulty.

It should be particularly noted that due to the difference in the manufacturing process and materials of different FOCTs, the range and situation of the optical power variation of different FOCTs at full temperature from -40 °C to 70 °C are different. This article only illustrates a method for judging FOCT failures, but the range of optical power variation in this paper is not applicable to all FOCTs.

At last, we are going to test the reliability of this system through proof tests.

4.2. Proof tests

Based on the possible failures in actual operation, we artificially set up four kinds of faults and observed whether the faults could be detected by the above system of detecting optical power. The four kinds of faults are as follows:

a. Breaking the fiber in delay coil
b. Making the bending radius of the delay coil 1cm
c. Adjusting the light source to half of its normal value
d. Adjusting the light source to double of its normal value

The proof test results are listed in the table 1, from which we can see the four types of faults can be recognized correctly.
Table 1. Proof test results.

| Faulty Types | a     | b     | c     | d     |
|--------------|-------|-------|-------|-------|
| Optical Power(μW) | 1.6 μW | 5.4 μW | 4.6 μW | 25.3 μW |
| Malfunction/Normal | Malfunction | Malfunction | Malfunction | Malfunction |
| Judgment correct/wrong | Correct | Correct | Correct | Correct |

Reference Normal Range[8.5 μW, 16 μW]

5. Conclusion

According to the experimental data, the above four types of malfunction can be detected by monitoring the optical power. This paper introduces a system based on the FOCT aiming to detecting the faults of the FOCT. Through experiments it is verified that the system and method can effectively recognize the faults of FOCT that cause the change of optical power.

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