A High-order Harmonic Based Demodulation Method for Fiber Optic Current Sensors

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***Abstract*—An improved demodulation method using the first to fourth harmonic component of the output signal is demonstrated. The simulation results indicate that the demodulation performance is independent of modulation coefficient.**

***Keywords*—fiber optic current sensors, phase modulator, modulation coefficient, demodulation method**

I. INTRODUCTION

As smart grids move towards ultra-high voltage (UHV) and high capacity, current measurement has become an important factor in protecting the security of power transmission. However, the traditional electromagnetic current sensors have exposed many issues, including large size, bulky, poor insulation performance and susceptibility to electromagnetic interference, making them unsafe and impractical [1]. Compared with the traditional current sensors, fiber optic current sensors (FOCS) based on the Faraday effect have the advantages of smaller size, larger dynamic range, light weight, and non-magnetic saturation, and have widely used in the transmission grids in recent years [2].

PZT piezoelectric ceramic are generally used as phase modulators in FOCS systems because of their good cost performance. However, the characteristics of PZT phase modulators are susceptible to temperature fluctuations and piezoelectric ceramic deterioration, which will lead to increasing measurement errors and even worse system failures. One study [3] has only investigated the modulation performance of the PZT phase modulator variation, but the impact on the output of FOCS system is not considered. Meanwhile, another work [4] proposed a method to compensate for changes in modulation coefficients, however, this method requires complex control circuits. Therefore, it is necessary to further investigate the effect of modulation coefficient variation on FOCS and eliminate it to enhance the output accuracy of the system.

In the paper, the influence of the modulation coefficient variations on the FOCS output error is numerically simulated. In order to eliminate the effect of the PZT phase modulator factor, an improved demodulation method is proposed to improve the output accuracy of the system. The simulated results show that the improved demodulation method can efficiently enhance the stability of FOCS and enable its accuracy to meet the 0.2S class requirement.

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II. CONFIGURATION AND PRINCIPLE

The schematic diagram of reflection structure fiber optical current sensor is shown in Fig.1. And the upper part of Fig. 1 ideally illustrates the evolution of polarization state [5].

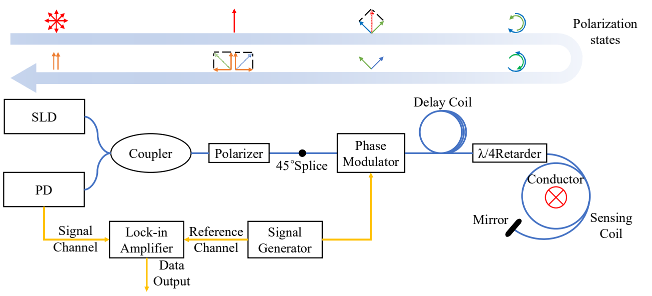

Fig. 1. Reflective fiber optic current sensor schematic diagram and evolution of polarization states.

Based on the system Jones transmission equation, the I_{out} obtained by photodetector can be expressed as:

$$I_{out} = \frac{E_x^2}{2} \cdot \left[1 + \cos\left(\varphi_F + 2K_\omega V_\omega \sin\left(\frac{\omega\tau}{2}\right) \cos\left(\omega\left(t - \frac{\tau}{2} \right)\right)\right)\right] \tag{1}$$

Where, $I_0 = E_x^2$ is the input light intensity, $\varphi_F = 4NVI_0$ is the phase change caused by Faraday magneto-optical effect, N is the number of sensing coils wrapped around the conductor, V is the Verdet constant of optical fiber, K_ω is the modulation coefficient of the phase modulator, V_ω is the operating voltage of the phase modulator, ω is the angular frequency of the modulated signal, and τ is the time difference between two passes of polarized light through the phase modulator. For ease of analysis, $\phi_e = 2K_\omega V_\omega \sin(\omega\tau / 2)$ is defined as the modulation depth.

According to the expanded form of the Bessel function [6], the expression of the detector output signal can be further obtained by:

$$
\begin{aligned}
I_{out} &= \frac{E_x^2}{2}\left(1+J_0\left(\phi_e\right)cos\varphi_F\right) \\
&+E_x^2 cos\varphi_F \sum_{n=1}^{\infty}\left(-1\right)^n J_{2n}\left(\phi_e\right)cos2n\omega\left(\mathrm{t}-\frac{\tau}{2}\right) \\
&-E_x^2 sin\varphi_F \sum_{n=0}^{\infty}\left(-1\right)^n J_{2n+1}\left(\phi_e\right)\cos\left(2n+1\right)\omega\left(\mathrm{t}-\frac{\tau}{2}\right)
\end{aligned}
\tag{2}
$$

Where, J_n $(\cdot)$ represents the nth order first class Bessel function.

The amplitudes of the first to fourth harmonic components of the output signal are extracted by lock-in amplifier (LIA), which can be expressed as:

$$S_1 = -E_x^2 J_1\left(\phi_e\right)sin\varphi_F \tag{3}$$

$$S_2 = -E_x^2 J_2\left(\phi_e\right)cos\varphi_F \tag{4}$$

$$S_3 = -E_x^2 J_3\left(\phi_e\right)sin\varphi_F \tag{5}$$

$$S_4 = -E_x^2 J_4\left(\phi_e\right)cos\varphi_F \tag{6}$$

Combining (3) and (4), the current measured is calculated by:

$$I = \frac{1}{4NV}arccot\frac{S_2 J_1\left(\phi_e\right)}{S_1 J_2\left(\phi_e\right)} \tag{7}$$

As shown in (7), the measured current I is determined by the harmonics (S_1, S_2) and the modulation coefficient, which is independent of the input light intensity. However, the modulation coefficient can greatly be influenced by environmental disturbance, leading to instability and output errors of the FOCS. Thus, it is necessary to improve demodulation method to eliminate the effects of the modulation coefficient.

Based on the properties of Bessel function:

$$J_{n-1}\left(\phi_e\right)+J_{n+1}\left(\phi_e\right)=J_n\left(\phi_e\right)\frac{2n}{\phi_e} \tag{8}$$

Therefore, the first to fourth order Bessel functions can be calculated by:

$$J_1\left(\phi_e\right)+J_3\left(\phi_e\right)=J_2\left(\phi_e\right)\frac{4}{\phi_e} \tag{9}$$

$$J_2\left(\phi_e\right)+J_4\left(\phi_e\right)=J_3\left(\phi_e\right)\frac{6}{\phi_e} \tag{10}$$

Substituting (3), (4), (5) and (6) into (9), (10), and the simplification results are given by:

$$tan\varphi_F = \frac{\phi_e\left(S_1+S_3\right)}{4S_2} \tag{11}$$

$$tan\varphi_F = \frac{6S_3}{\phi_e\left(S_2+S_4\right)} \tag{12}$$

Combining (11) and (12) and eliminating the modulation depth ϕ_e, the current is calculated by:

$$I = \frac{1}{4NV}arctan\sqrt{\frac{3S_3\left(S_1+S_3\right)}{2S_2\left(S_2+S_4\right)}} \tag{13}$$

It's clearly shown in (13) that the measured current is independent of the modulation depth ϕ_e (i.e., modulation coefficient K_ω), indicating that the improved demodulation method is unaffected by modulation coefficient variation.

III. Simulation Results and Analysis

As shown in (7) and (13), the two demodulation methods are based on the harmonics of the output signal (S_1-S_4), modulation depth ϕ_e, and the constant number of sensing coils. In order to investigate the influence of modulation coefficient variation on the output, the error of the FOCS with different modulation coefficient is simulated by MATLAB. The error of the FOCS can be defined by:

$$\varepsilon = \frac{\left|I_0 - I\right|}{I_0}\times 100\% \tag{14}$$

Where, I_0 is the input current and I is the output current demodulated by (7) or (13) during the numerical simulation.

Combining with the actual engineering situation of FOCS in smart grids, the current is with a rated of 1000 A and the rest of the simulation parameters are listed in Table I. Moreover, the parameters of the LIA are also listed below.

TABLE I. Simulation Parameters

	Parameters	Value
Simulation parameters of FOCS	Photoelectric parameters $\boldsymbol{E_x^2}$	1.7 V
	Transmission delay $\boldsymbol{\tau}$	1 μs
	Verdet constant $\boldsymbol{V}$	1.2×10^{-6} rad/A
	Modulation frequency	70 kHz
	Delay coil length	150 m
	Sensing coils number $\boldsymbol{N}$	100
	Loading voltage $\boldsymbol{V_\omega}$	5 V
	Modulation coefficient K_ω	1 ~ 4 rad/V
Demodulation parameters of lock-in amplifier	Sample rate $\boldsymbol{f_s}$	10 MHz
	Passband attenuation $\boldsymbol{\delta_{pass}}$	0.5 dB
	Stopband attenuation $\boldsymbol{\delta_{stop}}$	80 dB
	Passband cut-off frequency $\boldsymbol{f_{pass}}$	0.01 Hz
	Stopband cut-off frequency $\boldsymbol{f_{stop}}$	0.1 Hz

Referring to GB/T 20840.8-2007, the requirements of 0.2S class current sensor accuracy, the errors at 1%, 5%, 20%, 100% and 120% (10A, 50A, 200A, 1000A and 1200A) of the rated current 1000A are simulated respectively.

The simulation results are shown in Fig. 2, and the error curves are plotted for different current, respectively. The red line in each plot represents the output error, and the blue dashed lines show the first and second order Bessel function.

The gray dashed line marks the position where the Bessel function equals zero.

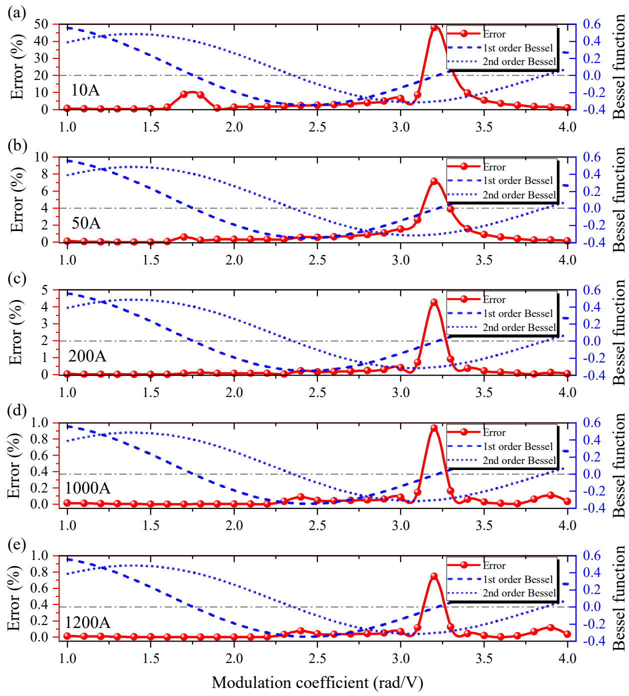

Fig. 2. Simulation results at different modulation coefficient.

It is obviously shown in Fig. 2 that the error suddenly increases when ϕ_e is at the zero point of the Bessel function, causing the sensor no longer meets the accuracy requirement of 0.2S class. The reason is that the properties of the arccot functions close to the zero point. Therefore, it's necessary to eliminate the influence of the modulation depth ϕ_e to improve the stability of the system.

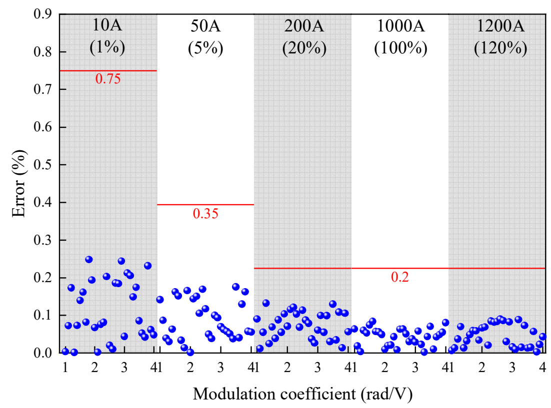

Fig. 3. FOCS error using the improved demodulation method.

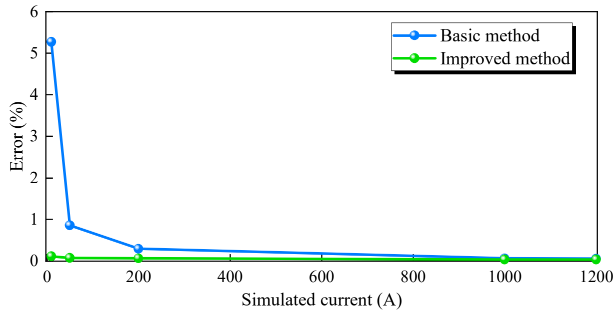

Fig. 4. FOCS error between the basic and improved demodulation method.

Then, the error of FOCS is calculated by the improved demodulation method, and the results are displayed in Fig. 3. It can be seen that the error is reduced, which can meet the 0.2S class requirement consistently. However, there are still some error fluctuations because the low-pass filter in the lock-in amplifier does not perfectly filter out the AC signal except for the DC signal. The comparison of the error between the basic and improved demodulation method is illustrated in Fig. 4, indicating that the error can effectively reduce through the improved method.

IV. Conclusion

In summary, the improved demodulation method extracts the first to fourth harmonic amplitudes, and eliminates the modulation coefficient. The simulation results show that FOCS can meet the requirement of 0.2S class accuracy, which provides the foundation for FOCS apply in complex environments.

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