A Fiber-Optic Current Sensor Based on Fuzzy PI Control

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Abstract. The development of power grid has put forward higher requirements on the performance of current sensors. Traditional current sensors already cannot meet these needs of grid metering and protection. This paper proposes a fiber-optic current sensor (FOCS) based on fuzzy PI control strategy which combines fuzzy control with PI control. These parameters of fuzzy PI controller can be adjusted online at different stages of the system response. Simulation results show that the FOCS based on fuzzy PI control has a fast dynamic response and no overshoot, compared with FOCS based on traditional PI control. These advantages of accuracy in metering and rapidity in protection of power grid, can be satisfied simultaneously.

1. Introduction
With the development of the smart grid, especially the construction of high-voltage DC power grid, higher requirements of the current sensor have been put forward for accurate measurement of electric energy and quick protection of circuit breakers. Traditional electromagnetic sensors have been unable to meet these requirements of power grid\cite{1}\cite{2}. Compared with the traditional DC current sensor, the fiber-optical current sensor (FOCS) has many technical advantages, which include high measurement accuracy, wide measurement range, excellent insulation performance, anti-electromagnetic interference, and so on\cite{3}\cite{4}. It has been widely used in the measurement and protection of various high-voltage DC equipment. The FOCS with the traditional PI control strategy, is unable to meet these requirements simultaneously between the measurement accuracy in the case of small current and the response speed in the case of large short-circuit current. In order to solve this problem, the FOCS based on the fuzzy PI control strategy is proposed in the paper, by establishing and analyzing the dynamic model of FOCS. Lastly the simulation result shows the effectiveness of this control strategy.

2. Principle and modeling
2.1. Principle of FOCS
The measurement principle of FOCS is Faraday magneto-optical effect\cite{5}, and the structure of FOCS is shown in Figure 1\cite{6}\cite{7}.
In Figure 1, the SLD source emits light waves, then these light waves pass through the polarizer, the point of 45-degree fusion, the phase modulator, the delay winding of polarization-maintaining fiber, the current sensing fiber in which inducts the Faraday effect by the current. After they are reflected by fiber-optical reflector, these returned light waves with the current information are interfered at the point of 45-degree fusion, and these interference light waves can be shown as:

\[ P = \frac{P_0}{2} (1 + \cos \varphi_s) \quad (1) \]

Where \( P \) is the light intensity after the interference, \( P_0 \) is the light intensity emitted by SLD. \( \varphi_s \) is the phase shift of the Faraday effect, which is expressed as:

\[ \varphi_s = 4VNI \quad (2) \]

Where \( N \) is turns of the sensing fiber, \( V \) is the Verdet constant of the sensing fiber, and \( I \) is the current in the conductor.

2.2. Dynamic model of FOCS

By analysing the principle and structure of FOCS, the nonlinear dynamic model which be shown in Figure 2 can be established\(^{[10][9]}\).

![Figure 1. The structure diagram of FOCS](image)

The Figure 2 shows a nonlinear closed-loop control model with PI controller. The error signal demodulation, the digital ramp generator and the phase modulation are done in the processing unit of FOCS. By linearizing these parts in the structure of FOCS, this model can be simplified into a discrete linear model which is shown in Figure 3\(^{[10]}\).

![Figure 2. The nonlinear dynamic model of FOCS](image)

![Figure 3. The discrete linear model of FOCS](image)
The Faraday phase shift can be expressed as proportional element $K_1$. The detector and preamplifier are expressed as proportional element $K_2$. The sampling, quantization and demodulation process can be replaced by $K_3 z^{-1}$. D/A conversion and the feedback gain corresponding to the post-amplifier are represented by proportional element $K_5$. The modulation process of a phase modulator is $K_4 (1 - z^{-1})$ and $D(z)$ is PI controller. So the closed-loop transfer function of FOCS can be expressed as:

$$H(z) = \frac{C(z)}{R(z)} = \frac{K_1 K_2 K_3 z^{-1} D(z)}{1 + K_1 K_3 z^{-1} D(z) K_5 (1 - z^{-1}) K_3 z^{-1} / (1 - z^{-1})}$$

(3)

$D(z)$ can be expressed as:

$$D(z) = K_p + \frac{K_i}{1 - z^{-1}}$$

(4)

Where $K_p$ is proportional coefficient and $K_i$ is integral coefficient. The error transfer function is:

$$H_e(z) = \frac{E(z)}{R(z)} = \frac{K_i}{1 + K_2 K_3 K_5 z^{-2} D(z)}$$

(5)

Given a step current input, such as:

$$R(z) = A / (1 - z^{-1})$$

(6)

Where $A$ is the amplitude of step current signal. The steady-state error of the FOCS system with PI control is expressed as:

$$e_{ss} = \lim_{z \to 1} (1 - z^{-1}) E(z) = \lim_{z \to 1} (1 - z^{-1}) H_e(z) R(z) = 0$$

(7)

Consequently, FOCS can measure accurately the current in the conductor with these right control parameters of PI controller.

However, these parameters of traditional PI controller are fixed in FOCS. In actual application, FOCS must follow the large change of the current quickly and the steady-state error of FOCS should be zero. The response time and accuracy of FOCS cannot be satisfied simultaneously. For example, when the amplitude of the measured current is small, in order to meet the measurement accuracy and avoid overshoot, we select small parameters which cause a longer response time in FOCS. And when the current changes rapidly such as the short-circuit current, these larger PI parameters are selected to ensure the quick response, which cause the overshoot or oscillation of the system. Therefore, the FOCS with the traditional PI controller cannot meet these requirements of metering and protection at the same time. To solve this problem, we propose the fuzzy PI control strategy of FOCS.

3. Fuzzy PI control

The fuzzy PI controller combines fuzzy control with PI control, which has advantages of simple control, easy implement and parameters to be adjusted online. It takes error $E$ and error change rate $EC$ as input signals of the control system. By fuzzy PI controller, these PI parameters are adjusted at these different stages of the system response according to $E$ and $EC$. The schematic diagram of fuzzy PI controller is shown in Figure 4.
Fuzzy Inference
PI Controller
Object Model

Figure 4. The schematic diagram of fuzzy PI controller
The main part of fuzzy PI controller includes fuzzy input, fuzzy rule base, fuzzy logic reasoning, ambiguity resolution, etc. The basic framework is shown in Figure 5.

Figure 5. The basic block diagram of fuzzy reasoning
Main steps of fuzzy PI controller are as follow\(^{[11][12][13]}\):

1) Fuzzy subset selection
The fuzzy PI controller has two inputs and two outputs. These input variables are the error \(E\) and error change rate \(EC\), these output variables are PI coefficient variable \(\Delta K_p\) and \(\Delta K_i\). Fuzzy field of \(EC, E\) and PI coefficients are expressed as:

\[
E, EC, \Delta K_p, \Delta K_i = \{-3, -2, -1, 0, 1, 2, 3\}
\]  

Elements in the fuzzy subset represent negative large, negative medium, negative small, zero, positive small, positive median and positive large, respectively. So the fuzzy subset can be expressed as:

\[
E, EC, \Delta K_p, \Delta K_i = \{NB, NM, NS, ZO, PS, PM, PB\}
\]  

The subordination functions of \(E, EC\) and \(\Delta K_p, \Delta K_i\) are shown in Figure 6.

Figure 6. Subordination functions of \(E, EC, \Delta K_p, \Delta K_i\)

2) Establishment of fuzzy rules
The proportionality coefficient affects the response speed of the system. The integral coefficient affects the steady-state accuracy of the system. According to different factors, these parameter setting
rules are concluded as shown in Table 1 (each cell contains two fuzzy rules, the left is the fuzzy rule of $\Delta K_p$, the right is the rule of $\Delta K_i$).

### Table 1. Fuzzy control rule library

| $E$ | $EC$ |
|-----|------|
| NB  | PB/NB| NB/NM| NM/NM| NS/NS| ZO/NS| PS/NS| ZO/ZO| ZO/ZO |
| NM  | PB/NB| PB/NM| PM/NM| PM/NS| PS/NS| ZO/NS| ZO/ZO| ZO/ZO |
| NS  | PM/NB| PM/NM| PM/NS| PS/NS| ZO/NS| PS/NS| ZO/ZO| ZO/ZO |
| ZO  | PM/NM| PM/NM| PM/NS| PS/NS| ZO/ZO| NS/PS| NM/PS| NM/PM |
| PS  | PS/NM| PS/NS| ZO/ZO| NS/PS| NS/PS| NS/PS| NM/PS| NM/PM |
| PB  | ZO/ZO| ZO/ZO| NS/PS| NM/PS| NM/PM| NM/PM| NM/PM| PB/PB |

3) Making fuzzy judgement

According to input signals $E$ and $EC$, the fuzzy judgment is made by centroid method through subordination function, and $\Delta K_p, \Delta K_i$ are obtained:

$$K_p = K_p^' + \Delta K_p, K_i = K_i^' + \Delta K_i$$

(10)

Where $K_p$ and $K_i$ are the final PI coefficient, $K_p^'$ and $K_i^'$ are the set value of the PI controller, $\Delta K_p$ and $\Delta K_i$ are the output value of the fuzzy controller.

### 4. Simulation result and analysis

We used Simulink and Fuzzy Logic Toolbox in Matlab for the model simulation. The simulation model of FOCS was carried out by using two control methods: conventional PI control and Fuzzy PI control. These parameters of FOCS are set as following, the number of sensing fiber turns is 10, the Verdet constant is $1.09 \times 10^{-3} \text{rad/A}$. The resolution of A/D converter is 14bit, and the reference voltage is 1.25V. The resolution of D/A converter is 16bit, and the reference voltage is 2.5V. The half-wave voltage of the phase modulator is 3.7V. Thus, the system simulation parameters are as follow:

$$N=10, V = 1.09 \times 10^{-6} \text{rad/A}, K_v = 4.36 \times 10^{-5}, K_i = 1, K_i = 2^{14} / 1.25, K_i = \pi / 3.7, K_i = 2.5 / 2^{16}$$

In fuzzy PI control, the set value of PI controller parameters are $K_p^{'0} = 0.1$ and $K_i^{'0} = 0.6$. The traditional PI control has two sets of parameters, one is $K_p = 0.1$ and $K_i = 0.6$, the other is $K_p = 0.2$ and $K_i = 1.5$.

![Figure 7. Step response curves of two control strategies](image)

The input signal is a step signal of 100A, and simulation results are shown in Figure 7. PI Control 1 is the curve of small parameters of PI control, and PI Control 2 is the curve of big parameters. Another is the fuzzy PI control. From the Figure 7, we can know that the PI Control 1 has a long rising time about
1ms and settling time 1.5ms, but there is no overshoot in the curve. Meanwhile, PI Control 2 has quick response speed, but it has 20% overshoot, with rising time 0.1ms and the settling time 1.5ms. In comparison, the fuzzy PI control has quick response speed, the rising time is about 0.2ms, the settling time 0.5ms, and no overshoot. The performance of the fuzzy PI control is better than that of the traditional PI control in these simulation curves.

5. Conclusion
A FOCS based on fuzzy PI control strategy is proposed in this paper, which has quick response speed and no overshoot by simulating analysis. It solves the contradiction between the measurement accuracy and the response speed of traditional PI control effectively, which can meet the requirement of grid metering and protection at the same time.

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