Identification and Filtering of Random Error in Fiber Optic Current Transducer

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Abstract. With the advantages of excellent insulation performance, wide dynamic measurement range, good frequency response characteristics and high sensitivity, fiber optic current transducer (FOCT) has become the mainstream of current measurement technology. The structure of fiber-optic current transformer is complex, and random error becomes one of the major problems that affect the application of fiber-optic current transformers in power engineering. It is urgent to study the random error characteristics of fiber current transformers and propose effective measures to suppress random errors. The characteristics of random error in FOCT are analyzed, and time series model is established by preprocessing and statistical inspection of FOCT output data. Based on the random error characteristics of the FOCT output signal, it makes prerequisite preparation for the signal filtering optimization modelling and the construction of the state function equation. With the derived random error state function of FOCT, the Wavelet filtering algorithm combining with Kalman filtering algorithm is proposed, then, the time domain and frequency domain local area transforms are used to detect the random error characteristics and identify various types of random error information accurately. Real-time multi-scale decomposition and optimal estimation of random error in FOCT are realized. Experimental results demonstrate that the time series modelling and Wavelet filtering algorithm can accurately identify the random error characteristics of the FOCT and automatically match the parameter filtering to improve current measurement accuracy.

1. Introduction
As a new type of current measurement device, Fiber Optic Current Transducer (FOCT) is more advanced than traditional electromagnetic current transformers. FOCT has the advantages of high measurement accuracy, large dynamic range, wide frequency response range, and excellent insulation performance \[1, 2\]. The current transformer is important equipment for providing current information for relay protection, measurement and control, metering and other power devices. Its accuracy and reliability are closely related to the safe and stable operation of the power system \[3\]. The structure of fiber-optic current transformers is complex. The composition of the fiber-optic current transformers involves factors such as optical, electrical, mechanical, and environmental preservation. The error factors are numerous. The random error of optical fiber current transformers seriously affects the engineering application of fiber-optic current transformers. The random error of the fiber current transformer comes from the time-varying noise caused by various factors such as coherent noise of the light source, noise intensity of the light source, shot noise of the photodetector, thermal noise of the electronic device, environmental noise, and aging of the device \[4\]. Although there are many sources of noise, after the FOCT signal processing section performs filtering, conversion and signal processing on the interference signal containing non-reciprocal phase, the characteristics reflected by the FOCT
output data mainly include angled random walk noise, and unstable bias value. Sex, rate random walk noise, rate slope noise, quantization noise, and sinusoidal noise, among others, angular rate random walk noise, bias instability, and rate slope noise content are large.

The random error problem faced by FOCT has become one of the main factors limiting its large-scale application in power engineering. This paper focuses on the random error problem of FOCT output data, starting from the FOCT output data preprocessing and statistical test, establishing a time series feature analysis model, and using Wavelet transform, using time domain and frequency domain local transformation, can accurately detect random error characteristics. Identify various types of random error information. By obtaining the random error feature of the FOCT output signal, it lays a foundation for the optimization of signal filtering modelling, state equations and output equation modelling.

2. Principle of FOCT
Fiber-optic current transformer is an optical sensor based on Faraday magneto-optical effect and Sagnac effect [7]. It measures the intensity variation of light waves caused by the non-reciprocal phase difference of light waves in real-time through a closed-loop feedback system. After signal processing and data processing, it acquires current information. According to the structure of the fiber-optic sensor head [8], FOCT is divided into reflective FOCT and circular FOCT. Although the two structures are not the same, the principle of light-wave sensing and signal processing are similar, and the noise characteristics are basically the same.

Figure 1 is a schematic of a FOCT with a reflective structure. The light emitted by the light source passes through the coupler and is deflected by the polarizer to form linearly polarized light; the linearly polarized light is injected into the polarization-maintaining fiber at an angle of 45°, and is transmitted into the X-axis and Y-axis of the polarization-maintaining fiber on average; when the two beams are transmitted After passing through the λ/4 wave plate, the light in the cross mode is transformed into left-handed and right-handed circularly polarized light and enters the sensing fiber; the Faraday effect of the magnetic field generated by the transmission current in the sensing fiber is the two circularly polarized lights. After the mirror reflection from the sensing fiber end face, the polarization modes of the two circularly polarized lights are interchanged and passes through the conductive fiber again.

Figure 2 is a schematic of the FOCT of the Sagnac structure. The light passing through the polarizer becomes linearly polarized. After the coupler is divided into two, all the way to the 1/4 wave plate into a left-handed circularly polarized light, all the way to the right-handed circularly polarized light, the two sides into the sensor head in the opposite direction. The Faraday effect rotates the polarization planes of the two circularly polarized lights. Then the second time it passes through another 1/4 wave plate and then becomes linearly polarized back to interfere.

![FOCT with a reflective structure](image-url)
The reflective type adopts the common optical path design to overcome the interference caused by factors such as vibration and temperature, and avoids the gyro effect, and has become the current mainstream structure.

3. Data Characteristics of FOCT
The performance of the fiber-optic current transformer is affected by many factors such as temperature, electromagnetic interference, mechanical deformation and various effects [9-10]. The gain error compensation technology of the four-state square wave modulation can adjust and reduce the error caused by temperature within a certain range. The noise level of the FOCT determines the signal-to-noise ratio (SNR) of the signal detection process and therefore causes errors in the FOCT measurement with the highest accuracy.

According to the entire detection of the signal of the reflective fiber current transformer, any process will generate unknown noise. According to the difference of noise sources and the requirements of the power system on the performance of fiber current transformers, the noise characteristics of fiber-electric power transformer data mainly include angled random walk noise, bias instability noise, rate random walk noise, and rate slope noise. Quantization noise, sine noise.

The angle random walk (ARW) represents the white noise level of the fiber current transformer. Photon detector (PIN) photon shot noise in fiber-optic current transformers results in the inability to determine the amount of Faraday phase shift measurements of the fiber current transformer, resulting in a limit value for the current measurement.

The angular random walk noise results from the integrated broadband rate power spectral density. This noise is caused by shot noise, amplifier noise, electronic device thermal noise, and some high-frequency noise whose sampling duration is longer than the relevant duration.

Bias Instability (BI) reflects the biased low-frequency fluctuations of fiber current transformers. Discharge instability, such as discharge components, plasma discharge, circuit noise, ambient noise, and some devices that may create random flicker, can occur in fiber-optic current transformers.

Rate Random Walk (RRW) represents the extreme case of exponentially correlated noise with long correlation time. RRW is the result of the integration of the phase-valued power spectral density due to the current change, which is accompanied by the long-term effect of the resonator, resulting from white noise passing through the integrator.

Rate Ramp (RR) is essentially a fixed error. RR is caused by the monotonous change of the light source intensity of the fiber current transformer which is extremely slow and lasting for a long time. The change of the external environment temperature also causes RR.

Quantization Noise (QN) represents the minimum resolution of the current information of the fiber current transformer. When the fiber current transformer is used for current measurement, the sampled
value of the interference signal is converted from A/D to digital data and sent to the FPGA (or DSP) for signal processing.

4. Time Series Modelling Method of FOCT Signal

The FOCT output data is an ordered random signal, which cannot be modeled by the traditional modelling method based on the input and output. It can be processed by the timing analysis method [11]. That is, the output signal of the system is used to establish the system operating status based on statistical theory. The parametric model establishes the FOCT time series model.

Time series models are often used to fit stationary and normal sequences. In a certain degree of approximation, the appropriate order can be used to describe any generalized stationary stochastic process. Let be a smooth, normal, zero mean time series, the model can be expressed as follows

\[ x_k = \phi_1 x_{k-1} + \phi_2 x_{k-2} + \ldots + \phi_p x_{k-p} + a_k - \theta_1 a_{k-1} - \ldots - \theta_q x_{k-q} \]  

where \( x_k \) is the time series, \( \phi_p \) is the autoregression coefficient, \( \theta_q \) is the moving average coefficient, \( a_k \) is the residual, and \( p \) and \( q \) are the orders of the model. Equation (1) represents the value of the time series at the \( k \) time, which can be used to estimate the values of the past \( n \) periods. The error is

\[ e = a_k - \theta_1 a_{k-1} - \ldots - \theta_q x_{k-q} \]  

The premise of establishing the time series model is that the original FOCT signal satisfies the requirements of stationarity, normality, and zero mean value. Generally, these FOCT output data do not possess these conditions. It is necessary to perform preprocessing operations on the sample data and check the corresponding characteristics.

Reverse order test is usually used to check the stationarity of the FOCT data sequence. If the stationarity requirement is not satisfied, the trend items are extracted from the FOCT random sequence. Reverse order test method is defined as follows: \( \{ x_n \} \) will be divided into \( l \) subsequences, and after obtaining the mean \( \mu_l \) of each subsequence, the mean value constitutes a sequence \( \mu_1 \mu_2 \mu_3 \ldots \mu_l \). When \( i > j \), \( \mu_i > \mu_j \). \( \mu_j \) is defined as a reverse order. The total number of reverse order of the sequence is:

\[ A = \sum_{j=1}^{l-1} A_j \]  

The theoretical mean and variance of the total number of inverse orders are given by

\[ E[A] = \sum_{j=1}^{l-1} E[A_j] = \frac{l(l-1)}{4} \]  

\[ \sigma_A^2 = \frac{l(2l^2 + 3l - 5)}{72} \]  

Construct statistics is given by

\[ u = \left[ A + \frac{1}{2} - E[A] \right] / \sigma_A \]  

The differential processing method can be used to extract trend items. Usually, the random sequence that does not meet the stationarity requirements can satisfy the stationarity requirements after the first differential processing. After processing, the stationarity is checked, and if the stationarity requirements are not satisfied, the secondary differential processing is performed. The data sequence is differentially processed to obtain a new sequence, and the mean value is subtracted from the mean sequence.
value of the new sequence to complete the trend item extraction.
For the normal observed FOCT data sequence normality test, standard deviation coefficient $\xi$ and the
standard kurtosis coefficient $\nu$ are tested.
Standard deviation factor is obtained by
\begin{equation}
\xi = \sqrt{\frac{1}{6n} \sum_{i=1}^{n} \left( \frac{x_i - \bar{x}}{S} \right)^3}
\end{equation}

Standard kurtosis coefficient is obtained by
\begin{equation}
\nu = \sqrt{\frac{n}{24} \left[ \sum_{i=1}^{n} \left( \frac{x_i - \bar{x}}{S} \right)^4 \right] - 3}
\end{equation}
when $\xi \approx 0$ and $\nu \approx 0$, the random sequence satisfies the normality requirement.

5. Experiments
According to the FOCT application system architecture, an experiment platform is built, as shown in
Figure 3. The experimental platform consists of a current generator, a clock synchronization unit, a
high-accuracy current transformer, a merging unit, and a signal processing system. Preprocess the
data, and further verify the effectiveness of the time series model and Kalman / Wavelet transform
algorithm in the identification and filtering of FOCT signal characteristics.
Figure 5. Random error characteristics in FOCT before filtering

Figure 6. Random error characteristics in FOCT after filtering

Figure 4 is the time series of the FOCT current data recorded. Figure 5 shows the result of the time series modelling and further data optimization according to the Wavelet algorithm to obtain the result of Figure 6.

The experimental results demonstrate that the FOCT mainly includes angular random walk noise, bias instability, and rate ramp, Kalman filtering algorithm/Wavelet transform algorithm can effectively extract the characteristics of the random error signal after time-series modelling, and after filtering, the three random errors of random walk noise, bias instability, and rate slope all dropped by 40%.

6. Conclusions

Focused on the characteristics of non-stationary and non-normal distribution of FOCT random errors, the Kalman filter based on Wavelet transform is used for filtering. This method combines the multi-scale characteristics of Wavelet transform based on the traditional Kalman filter. This method not only has the function of de-correlation and multi-resolution analysis of the self-similar process by the Wavelet transform, but also maintains the characteristics of the Kalman filter for estimating the linear unbiased minimum variance of unknown signals. The Kalman filtering method based on Wavelet transform has introduced the Wavelet decomposition and reconstruction process. The output of the filter is the minimum variance estimation for low-frequency information and high-frequency information in the Wavelet domain, which can effectively remove the autocorrelation and non-stationary of random error. In the process of filtering, the algorithm can output the estimated low-frequency information and high-frequency information online, analyze the random error characteristics online, and have real-time filtering effects. Kalman filter based on Wavelet transform achieves real-time multi-scale decomposition and optimal estimation of FOCT random errors.

7. References

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