Slope-assisted Based Fast Strain Measurement Method for Power Overhead Lines of Distribution Internet of Things in Electricity

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Abstract. A distributed optical fiber sensor based on Brillouin scattering can measure the strain along the optical fiber. In order to improve the real-time performance of strain measurement for optic-electric composite overhead lines in the distribution Internet of Things in electricity, the slope-assisted technique is introduced into the demodulation of Brillouin frequency shift. In this technique, the Brillouin frequency shift can be calculated according to the Brillouin gain corresponding to a single frequency and then the strain along the optical fiber can be obtained. The least squares technique based on the pseudo-Voigt model and the slope-assisted technique are implemented, and the Brillouin frequency shift along the optical fiber with different signal-to-noise ratios (SNRs) is calculated by using the two methods. The results reveal that the slope-assisted technique has high accuracy at high SNR and at the same time both the computation time and the spectrum measurement time of this method are far less than that of the least squares technique based on the pseudo-Voigt model.

1. Introduction
Optic-electric composite overhead lines are widely used in distribution Internet of Things in electricity, and their condition state needs to be detected. The distributed optical fiber sensing technology based on Brillouin scattering can measure temperature or strain along the optical fiber without additional sensors. The key problem in temperature or strain measurement is the estimation of Brillouin frequency shift [1]. Most existing methods use the least squares technique [2]. Although the accuracy is high, it is computationally expensive, which affects the real-time performance and even reliability of the overhead lines condition detection.

In order to fix this problem, the slope-assisted technique [3] is introduced into the strain measurement along the optic-electric composite overhead line in this work. Unlike the least squares technique, which usually requires a relatively complete Brillouin spectrum, the slope-assisted technique only needs to measure the single-point Brillouin gain to calculate the Brillouin frequency shift, and the spectrum measurement time is shorter. The least squares technique and the slope-assisted technique based on the pseudo-Voigt model are implemented, and the Brillouin spectra along optical phase conductor (OPPC) with different signal-to-noise ratios (SNRs) are numerically generated. The two methods are compared from the aspects of strain measurement accuracy, spectrum measurement time and computation time for Brillouin frequency shift extraction. According to the
results, the slope-assisted technique for the strain measurement of overhead lines of distribution Internet of Things in electricity is validated.

2. Overhead lines strain measurement based on Brillouin scattering

2.1. Distributed optical fiber sensing technology based on Brillouin scattering

Generally, the Brillouin spectrum approximately satisfies the following pseudo-Voigt model [4].

\[ g_B(v) = g_1 \frac{(\Delta v_B/2)^2}{(v-v_B)^2 + (\Delta v_B/2)^2} + g_2 e^{-(4\ln 2)(v-v_B)^2/(\Delta v_B)^2} \]  (1)

where \( g_B \) is Brillouin gain; \( v \) is the frequency shift; \( v_B \) is Brillouin frequency shift; \( \Delta v_B \) is linewidth; \( g_1 \) and \( g_2 \) are the peaks of Brillouin gain in the Lorentzian and Gaussian models, respectively.

If the temperature along the whole optical fiber is considered to be a constant value \( T_0 \) during Brillouin spectrum measurement, then the strain of the optical fiber can be calculated by Eq. (2).

\[ \varepsilon = \frac{v_B - v_{B0}}{C_{vc}} \]  (2)

where \( \varepsilon \) is the strain of the optical fiber; \( v_{B0} \) is the Brillouin frequency shift at \( T_0 \) and no strain; \( C_{vc} \) is the strain coefficient of Brillouin frequency shift. Obviously, the key problem of strain measurement is the rapid and highly accurate extraction of Brillouin frequency shift. There are some optical fibers in OPPC. Therefore, the strain of OPPC can be obtained according to the strain of the composited optical fiber.

Let \( z=0 \) at the optical fiber incident end and \( z=l \) at the measuring point, then \( l \) can be calculated by Eq. (3).

\[ l = \Delta t c/(2n) \]  (3)

where \( \Delta t \) is the time difference between the incidence of pulse light and the backscattered light returning to the incident end; \( c \) is the speed of light in a vacuum; \( n \) is the refractive index of optical fiber.

2.2. Least squares technique

The least squares technique is used to fit the Brillouin spectrum according to a spectrum model, and then the Brillouin frequency shift is calculated. The objective function corresponding to the least squares technique is shown in Eq. (4).

\[ E = \frac{1}{2} \sum_{n=0}^{N-1} e_n^2 = \frac{1}{2} \sum_{n=0}^{N-1} (g_B(v_n) - g_{B,n})^2 \]  (4)

where \( E \) is the sum of squares of errors; \( v_n, g_{B,n} \) and \( e_n \) are the \( n^{th} \) frequency, the corresponding Brillouin gain and error respectively. \( N \) is the number of sweeps. More details about the corresponding initial value algorithm, optimization algorithm and convergence criterion can be found in Ref. [2].

2.3. Slope-assisted technique

Assume that \( v_0 \) is the working point frequency. The slope-assisted technique only measures the gain corresponding to \( v_0 \). Let \( v_0=10.69 \text{GHz}, \Delta v_B = 50 \text{MHz}, g_1=g_2=0.5 \), then the relationship between the working point gain and the Brillouin frequency shift is shown in Figure 1.
In this way, the Brillouin frequency shift can be obtained according to the Brillouin gain at the actual working point and the above relationship. $v_{BM}$ is set to, and the working point frequency is generally chosen as

$$v_0 = v_{BM} - \frac{\Delta v_B}{2}$$

(5)

where $v_{BM}$ is the mean value of Brillouin frequency shift along the optical fiber. That is, the working point is selected in the left part of the spectrum.

3. Comparison of slope-assisted technique and least squares technique

The Brillouin spectra along the optical fiber composited with OPPC are generated numerically based on Eq. (1). The length of OPPC is 4km, the sampling resolution is 10m, the SNR of Brillouin spectrum is 10-40dB with a step of 5dB, $\Delta v_B = 50$MHz, $g_1 = g_2 = 0.5$. The frequency sweep span is 10.675-10.775GHz, and the frequency step is 1MHz. Assume that $C_v = 20 \mu e$/MHz and $v_{BO} = 10.70$GHz. The Brillouin frequency shift and strain along the optical fiber are shown in Figure 2. Brillouin spectra at different SNRs are shown in Figure 3. Since $v_{BM} = 10.725$GHz and $\Delta v_B = 50$MHz, the working point frequency is set to 10.7GHz according to Eq. (5). The strain errors along the optical fiber obtained by the two methods under different SNRs are shown in Figure 4. The influence of SNR on strain error obtained by the slope-assisted technique is shown in Figure 5.

Figure 1. Relationship between working point gain and Brillouin frequency shift.

Figure 2. Brillouin frequency shift and strain along optical fiber.
As can be seen from Figure 4, the errors of the least squares technique under different SNRs are always smaller than those of the slope-assisted technique. From Figures 4 and 5, we can see that the
error of the two methods decreases with SNR. A high SNR requires a large average times which results a poor real-time performance. In the meantime, the maximum and average errors of the slope-assisted technique are 35.83με and 11.61με respectively at 30dB. Considering that the slope-assisted technique is a fast measurement method, the accuracy of the slope-assisted technique should not be too high. Therefore, it can be considered that the slope-assisted technique can meet the accuracy requirements. Because the spectrum measurement time is proportional to the number of sweeps [5], the measurement time of the slope-assisted technique is only 1/101 of the least squares technique. In addition, the computational time of the Brillouin frequency shift of the two methods is 36.01ms and 34.41μs, respectively. Obviously, the real-time performance of the slope-assisted technique is significantly greater than that of the least squares technique.

4. Conclusion
In this work, the rapid strain measurement of overhead lines of distribution Internet of Things in electricity is studied. The least squares technique and slope-assisted technique are used to measure the strain along the optical fiber for generated numerically Brillouin spectra with different SNRs. The results reveal that the accuracy of the slope-assisted technique can basically meet the requirements when SNR is not less than 30 dB. The time of spectrum measurement and Brillouin frequency shift extraction of the slope-assisted technique are far less than that of the least squares technique.

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References
[1] W. Zou, Z. He, K. Hotate, Complete discrimination of strain and temperature using Brillouin frequency shift and birefringence in a polarization-maintaining fiber, Optics Express 17 (3) (2009) 1248-1255.
[2] Z. Xu, L. Zhao, H. Qin, Selection of spectrum model in estimation of Brillouin frequency shift for distributed optical fiber sensor, Optik 199 (2019) 163355.
[3] R. Bernini, A. Minardo, L. Zeni, Dynamic strain measurement in optical fibers by stimulated Brillouin scattering, Optical Letters 34 (17) (2009) 2613-2615.
[4] X. Bao, A. Brown, M. Demerchant, J. Smith, Characterization of the Brillouin-loss spectrum of single-mode fibers by use of very short (<10-ns) pulses, Optics Letters 24 (8) (1999) 510-512.
[5] X. Tu, Distributed fiber sensing technique employing vector Brillouin optical time domain analyzer, Changsha: National University of Defense Technology, 2015.