Rapid Strain Demodulation Method for Smart Grid Overhead Lines of Distribution Internet of Things in Electricity

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Abstract. An improved quadratic polynomial fitting method is applied to extract Brillouin frequency shift from Brillouin spectrum along optical fiber to improve the real-time performance of strain measurement along optical fiber composite overhead lines in the distribution Internet of Things in electricity. The principle of the improved quadratic polynomial fitting method is to use the median filter algorithm to improve the accuracy of spectrum peak location, and then select the symmetric Brillouin spectrum for quadratic polynomial fitting. The spectrum fitting method based on the Lorentzian model, the original and improved quadratic polynomial fitting methods are used to extract Brillouin frequency shift according to the Brillouin spectra with different signal-to-noise ratios. The results reveal that the improved quadratic polynomial fitting method has the similar accuracy with the spectrum fitting method based on the Lorentzian model, and the computation time is only about 1/100 of that of the latter. This work provides a reference to improve the real-time performance of strain measurement for overhead lines in distribution Internet of Things in electricity.

1. Introduction
There are many optic-electric composite overhead lines in the distribution Internet of Things in electricity [1], such as Optical Fiber Composite Overhead Ground Wire (OPGW) and Opticalphase Conductor (OPPC), so it is very necessary to detect their operating state to ensure its safe and stable operation. The distributed optical fiber sensing technology based on Brillouin scattering can measure the temperature or strain along the optical fiber by detecting the backscattered light. The demodulation of temperature and strain is usually done by calculating the Brillouin frequency shift. There are many methods to calculate Brillouin frequency shift, typical methods are the cross-correlation method [2], the similarity matching method [3] and the spectrum fitting method [4]. It is generally considered that the accuracy of spectrum fitting method is high enough, but the existing problem is relatively slow to compute, which significantly affects the real-time performance of measurement. The quadratic polynomial fitting method, though fast, is susceptible to various disturbances, resulting in low accuracy, and is difficult to be used in the demodulation of the strain in overhead lines of distribution Internet of Things in electricity.

In order to fix this problem, this paper compares the computation time and the influence of frequency sweep span deviation on the spectrum fitting method based on the Lorentzian model and the quadratic polynomial fitting method. Based on this, an improved quadratic polynomial fitting method is introduced. In this method, the accuracy of spectrum peak location is improved through filtering.
Then the symmetrical Brillouin spectrum is selected to improve the accuracy of Brillouin frequency shift by the quadratic polynomial fitting method. The effectiveness of the proposed method is verified by the numerically generated Brillouin spectra along the optical fiber composited with OPGW.

2. **Strengths and weaknesses of quadratic polynomial fitting method**

Generally, the Brillouin spectrum approximately satisfies the following the Lorentzian model.

\[
g_B(v) = g_0\left(\frac{(\Delta v_B/2)^2}{(v - v_B)^2 + (\Delta v_B/2)^2}\right)
\]

where \(g_B\) is Brillouin gain; \(v\) is the frequency shift; \(v_B\) is Brillouin frequency shift; \(\Delta v_B\) is linewidth; \(g_0\) is the peak value of Brillouin gain.

If frequency sweep span is not very large, the Brillouin spectrum approximately satisfies the quadratic polynomial which can be expressed as follows:

\[
g_B(v) = av^2 + bv + c
\]

where \(a\), \(b\) and \(c\) are polynomial coefficients.

The Brillouin frequency shift meets the following linear relationship with the temperature and strain along the optical fiber [5], that is

\[
\delta v_B(z) = C_T^v \delta T(z) + C_s^v \delta \varepsilon(z)
\]

where \(z\) is the optical fiber position; \(\delta T(z)\) and \(\delta \varepsilon(z)\) are the changes of the temperature and strain phase at \(z\) with respect to the reference value, respectively. \(C_T^v\) and \(C_s^v\) are the temperature and strain coefficients of Brillouin frequency shift, respectively; \(\delta v_B(z)\) is the change of Brillouin frequency shift at \(z\) relative to the reference temperature \(T_0\) and in the case of no strain, expressed as follows:

\[
\delta v_B(z) = v_B(z) - v_{B0}
\]

where, \(v_{B0}\) is the Brillouin frequency shift at the reference temperature \(T_0\) and no strain.

If the overhead line temperature is considered as the reference temperature \(T_0\), then the strain along the optical fiber can be demodulated directly by the Brillouin frequency shift variation by Eq. (5).

\[
\delta T(z) = \frac{\delta v_B(z)}{C_T^v}
\]

Brillouin spectra are numerically generated and used to investigate the comparison of the original quadratic polynomial fitting method with the spectrum fitting method based on the Lorentzian model. Spectrum parameters are as follows: \(\Delta v_B=40\text{MHz}\), \(v\) varies in the range of 10.68~10.76GHz, SNR=20dB, frequency step=1MHz; \(10.70 \leq v_B \leq 10.74\text{GHz}\) with a step size of 1MHz. For each combination of the above parameters, 100 Brillouin spectra are numerically generated. In addition, the frequency sweep span deviation is defined as follows:

\[
\Delta v = \left(\frac{v_m + v_M}{2}\right) - v_B
\]

where \(\Delta v\) is the deviation of frequency sweep span; \(v_m\) and \(v_M\) are the minimum and maximum frequencies, respectively.
The relationship between the average error of the Brillouin frequency shift obtained by the two methods and frequency sweep span deviation is shown in Figure 1 (b).

The computation time of the two methods is 40.07 ms and 0.43 ms respectively, which means that the computation time of the quadratic polynomial fitting method is only about 1/100 of the latter. It can be seen from Figure 1 that the spectrum fitting method based on the Lorentzian model can accurately extract the Brillouin frequency shift under different frequency sweep span deviations, and the error is basically less than 0.4MHz. However, the maximum error of the quadratic polynomial fitting method is more than 20MHz, and the error increases with the increase of frequency sweep span deviation. In order to improve the accuracy of the quadratic polynomial fitting method, the degree of symmetry Brillouin spectrum used in fitting should be improved. That is, the frequency sweep span deviation should be small. As can be seen from Figure 1, when the Brillouin frequency shift is in the middle of the frequency sweep span. That is, when the frequency sweep span has no deviation, the quadratic polynomial fitting method has high accuracy. Therefore, in order to improve the accuracy of quadratic polynomial fitting method, it is necessary to improve the symmetry degree of frequency sweep span.

3. Improved quadratic polynomial fitting method

Median filter algorithm can be used to improve the signal-to-noise ratio of the Brillouin spectrum, improve the accuracy of spectrum peak location, and then the Brillouin spectrum symmetrical around the spectrum peak and with the frequency sweep span as far as possible large is selected. Obviously, the selected Brillouin spectrum has a smaller frequency sweep span deviation. Finally Brillouin frequency shift is extracted by the quadratic polynomial fitting method for the selected Brillouin spectrum. The algorithm flowchart is shown in Figure 2.

![Figure 2. Flowchart of improved quadratic polynomial fitting method.](image-url)
3. According to Figure 3, the peak location error for the original Brillouin spectrum is about 2.5 MHz, and the peak location error for the filtered Brillouin spectrum is slightly greater than 1 MHz. Obviously, the peak location of the filtered Brillouin spectrum is more accurate, which lays a foundation for the subsequent selection of Brillouin spectrum with higher degree of symmetry.

**Figure 3.** Brillouin frequency shift error before and after filtering.

4. Validation of quadratic polynomial fitting method

The Brillouin spectrum along an optical fiber composite with an OPGW is numerically generated. The length of OPGW is 4 km and the sampling resolution is 100 m. SNR of Brillouin spectrum is set at 10, and 30 dB respectively. $C_B = 20 \mu \text{e}/\text{MHz}$, $v_{B0}=10.7 \text{GHz}$. The Brillouin frequency shift and strain along the optical fiber are shown in Figure 4. The spectrum fitting method based on the Lorentzian model, the original and improved quadratic polynomial fitting methods are used to calculate the strain along the optical fiber, and the error is shown in Figure 5.

Obviously, Figure 5 shows that the strain errors of the original quadratic polynomial fitting method are much larger than those of the spectrum fitting method based on the Lorentzian model under different signal-to-noise ratios, while the accuracy of the improved method is close to the latter.

**Figure 4.** Brillouin frequency shift and strain along optical fiber.

**Figure 5.** Strain errors along OPGW obtained by different methods.
5. Conclusion
In this paper, the rapid strain measurement of overhead lines of distribution Internet of Things in electricity based on Brillouin scattering technology is studied. A Brillouin frequency shift extraction method based on improved quadratic polynomial fitting is introduced and applied to the strain measurement along OPGW. In the method, the median filter algorithm is used to improve the accuracy of peak location, and then the symmetric and wide range Brillouin spectrum is used for quadratic polynomial fitting. The results show that the error of the improved quadratic polynomial fitting method is close to that of the spectrum fitting method based on the Lorentzian model, but the computation time is only about one hundred times that of the latter.

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