Optik 126 (2015) 2180–2183

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

On-line temperature monitoring in power transmission lines based on Brillouin optical time domain reflectometry

Yun-qi Hao [a,*], Yu-long Cao [b], Qing Ye [b], Hai-wen Cai [b], Rong-hui Qu [b]

[a] College of Physics and Electronics Engineering, Zhengzhou University of Light Industry, Zhengzhou, 450002, China
[b] Shanghai Key Laboratory of All Solid-state Laser and Applied Techniques, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, 201800, China

ARTICLE INFO

Article history:
Received 13 April 2014
Accepted 23 May 2015

Keywords:
Brillouin optical time domain reflectometry
Three-phase power transmission lines
On-line temperature monitoring

ABSTRACT

The Brillouin frequency shift in single-mode fiber is linear to the temperature change around the sensing fiber, so on-line temperature monitoring of three-phase cables could be realized through measuring the Brillouin frequency shift of contained fiber used for fiber communication. Electrifying 100 m compound transmission lines with different time, and monitoring the temperature variation, experimental results shows that the temperature along the lines increases generally with the time lengthening, presenting monotonic increasing property. Moreover, the temperature distribution across the line section is analyzed, and the temperature difference between the cable line and the fiber is 0.018 °C. All the results shows that the BODTR sensing system could be used for the on-line temperature monitoring on the power transmission lines and provide technical support for the smart grid.

1. Introduction

With the development of power system; the transmission voltage and current have been improvement greatly. Consequently the on-line monitoring on the transmission lines plays a vital role for secure and stable running [1,2]. Fast and accurate measurements of temperature along the transmission cables could provide reliable information for decision-making by real-time monitoring the status of the lines; and maximize the capacity of transmission paths; etc. [3]. Currently; the temperature measurement of transmission lines includes non-contact infrared technology [4] and direct measurement through the surface electronic thermometer [5,6]. Above methods are the electrical measurements and are vulnerable to strong electromagnetic interference of transmission lines which will induce instability to measurement results. In addition; the electronic measure equipment also requires additional power supply [7,8]. Therefore; it is urgent to develop a new type of on-line monitoring technique with stable and reliable operation performance.

Fiber sensor technique is insensitive to the electromagnetic interference [9]. The unification development of power, optical fiber communication and digital television promotes the progress of power cables. So the fiber contained in the transmission lines could be utilized for fiber sensor. Recently, a number of studies have focused on long-distance distributed fiber sensing technologies based on the Raman [10,11] and Brillouin scattering [12,13]. The former needs multi-mode fiber; and generally speaking, the sensing distance is less than 10 km [10,14]. The latter needs single-mode fiber, and the sensing distance is more than 30 km [15,16]. Fiber in the compound transmission lines aims at optical fiber communication, and the fiber is single-mode. Therefore it could be used for the Brillouin distributed fiber sensing conveniently. Two branches of distributed sensing based on Brillouin scattering in optical fibers are Brillouin optical time domain reflectometry (BOTDR) [12] and Brillouin optical time domain analyzer (BOTDA) [13]. The focused subject is BOTDR, for the reason that it accesses one fiber end only [12] and offer simple implementation. The BOTDR sensing instrument could be set in the apparatus room of the power cables, realizing the long distance sensing and on-line monitoring.

In this paper, we investigate the application of BOTDR sensing system on the on-line temperature monitoring, and the transmission line is the three-phase power lines compounded with the optical fibers. Firstly the Brillouin frequency shift (BFS) is measured when the electrical line is not on load; and then the BFS is recorded with the time lengthening when the electrical line is electrified; at different time the on-line temperature is calculated; finally the temperature of the optical fiber in the transmission line is studied at the fixed sensing position and time. The experimental results present that the BOTDR sensing technique could provide the technical reference for establishing the load-temperature picture, and realizing the on-line temperature monitoring for the power lines.

* Corresponding author. Tel.: +86 037163556807.
E-mail address: haoyunhaoqi@126.com (Y.-q. Hao).

http://dx.doi.org/10.1016/j.ijleo.2015.05.111
0030-4026/

2. Experimental principle and setup

In the optical fiber sensing system, fiber is the transmission medium and at the same time it is also the sensor element. In the single-mode optical fiber, the Brillouin scattering is backward and its frequency shift between the incident pump light is proportional to the temperature change and the strain variance, as following:

$$\nu_B(t,\varepsilon) = \nu_B(t_0,\varepsilon_0)[1 + c_{\nu T}(t - t_0) + c_{\nu\varepsilon}(\varepsilon - \varepsilon_0)] \quad (1)$$

where, $\nu_B(t,\varepsilon)$, $\nu_B(t_0,\varepsilon_0)$ is the Brillouin frequency shift at temperature t and strain ε, t_0, ε_0; $c_{\nu T}$ and $c_{\nu\varepsilon}$ are coefficient of Brillouin frequency shift with the temperature and strain; $t - t_0$ and $\varepsilon - \varepsilon_0$ are the temperature and strain change.

The backscattered Brillouin light detected at the incident port carries related temperature and strain information along the long-distance sensing fiber. The Brillouin frequency shift is related to the temperature and strain, that's to say, cross-sensitivity. But in our experiment, the optical fiber in the power transmission line is packaged in the isolative tube full with fiber grease, used for optical fiber communications. The international standards require that the optical fiber performance is not influenced when the applied strain is more than 4500 N. Therefore in this paper the strain change could be neglected; so

$$\nu_B(t) = \nu_B(t_0)[1 + c_{\nu T}(t - t_0)] \quad (2)$$

$c_{\nu T}$ is about 1.1 MHz/°C for the single-mode optical fiber. If the primary temperature t_0 is known and the corresponding Brillouin frequency shift $\nu_B(t_0)$ is set as the reference, the temperature to be measured t could be obtained according to the measured Brillouin frequency shift $\nu_B(t)$ with the BOTDR sensing system:

$$t = t_0 + \frac{\nu_B(t) - \nu_B(t_0)}{c_{\nu T}} \quad (3)$$

The BOTDR sensing system in the experiment is shown as Fig. 1. A short-cavity single-frequency stable linear-polarization fiber laser (SFFL) [17] at 1548.976 nm is used as the primary light source in the sensing system. Part of the laser beam is amplitude modulated by an acousto-optic modulator (AOM, Model MT160-IIR10-FIO, AA Inc.) to generate pulse sequence with repetition rate of 4 kHz and pulse width of 200 ns. For 1550 nm wavelength band, the Brillouin frequency shift is about 11 GHz. In order to detect the Brillouin scattering with the conventional detector (bandwidth <800 MHz), the other part of the source is applied to pump a compact single-frequency Brillouin fiber laser (BFL) with about 11 GHz frequency shift, which is used as local oscillator (LO) for coherent detection. The modulated pulse is appropriately amplified (avoiding stimulated Brillouin scattering) by an Erbium doped fiber amplifier (EDFA) and then launched into the long sensing fiber to generate the backscattered spontaneous Brillouin signal. The spontaneous Brillouin scattering signal can be detected by the coherent heterodyne detection. The beat signal between SBS and LO are injected into a double balanced photodetector (DB-PD, New Focus 1617-AC, Newport) through a 1:1 coupler, and then amplified by a micro-wave amplifier (MWA, ALPHALAS BBA-100-VG, bandwidth 0.01–2 GHz). All the data is collected by high-speed data-acquisition card (DAQ, Gage, Model CS82G, 3 GS/s sample rate), where the data acquisition is synchronized with the signal generator for the AOM. Acquisition and analysis of sensing signal are real-time processed by a customized LabVIEW program. The data algorithm is discrete Fast Fourier Transformation (FFT), and the central frequency of every unit is the Brillouin frequency shift.

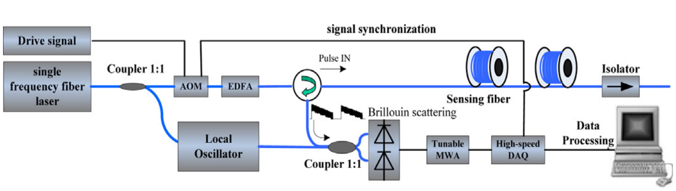

Fig. 1. Configuration of BOTDR sensing system.

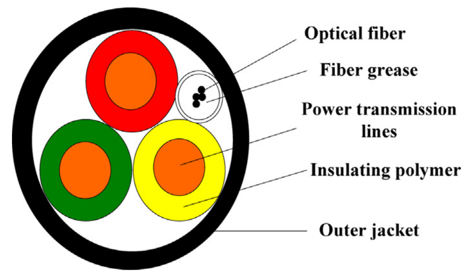

Fig. 2. Schematical cross-section of three phase cable.

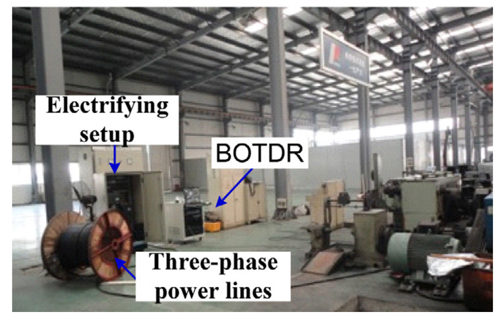

Fig. 3. Experimental scence of on-line temperature monitoring.

In the three-phase power transmission cables, the long distance optical fiber is parallel to power lines. For different products model, their geometric positions in the cross-section are also not the same, which need paying special attention when calculating the temperature field in the cross-section. In this paper the compound power cable is SGIT-4B1 + 0.6/1kV−3 × 6, and its cross-section is shown as Fig. 2. As mentioned above, the Brillouin frequency shift is only influenced by the temperature change. Therefore, the temperature distribution along the optical fiber and the power transmission line could be obtained through measurement of the Brillouin frequency shift.

The experimental scene is presented in Fig. 3, where one fiber in the three-phase line is connected to the tail-fiber of BOTDR sensing system, constructing the long distance sensing fiber. The electrification equipment is turned on and the electrical current and voltage is applied on the lines. The applied voltage is 385 V and the current is less than 1 A in the experiment, as shown in Fig. 4. It needs to note that the two values are not the actual voltage and current in the power system, but the experimental results could also represent the temperature monitoring function of BOTDR sensing system.

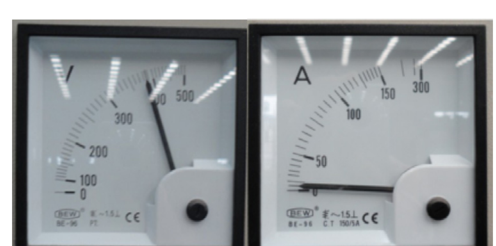

Fig. 4. Voltage and current applied on the power line.