SPONTANEOUS RAMAN POWER AND BRILLOUIN FREQUENCY SHIFT METHOD BASED DISTRIBUTED TEMPERATURE AND STRAIN DETECTION IN POWER CABLES

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ABSTRACT

The high temperature regions occurred along the cable limit the transmittable load capacity in power cables. The strains generated on XLPE insulation of a power cable shorten the cable operation time due to their ageing effects on insulation. Therefore it is clear that detecting the 'hot spots' and strain information along the cable is important. In this study, temperature and strain data have been obtained along a 380 kV power cable by using a 1550 nm single mode fiber. To detect temperature data along the cable, distributed temperature detection method based on Raman scattering has been used. In order to obtain strain data, Brillouin frequency shift information of the backscattered signal at the scattering point has been utilized. Under the occurrence of simulation conditions such as cable connection points, cross-connection points and passing through ducts, temperature and strain profiles have been obtained along a 5 km cable. Simulations have been performed with a spatial resolution of 1.5 m, a temperature resolution of 1.25 ºC and a strain resolution of 50 με.

I. INTRODUCTION

An underground power cable is exposed to electrical, thermal and mechanical strains damaging the cable insulation. The function of insulation, beside being a good electrical insulation, is to conduct the heat of the cable conductor. Cross-linked polyethylene, or shortly XLPE, structure is used in power cables as insulation material. One of the most important effects threatening the cable insulation is the maximum operating temperature. Other important factor is the presence of hot spots at bending points along the cable. Since the thermal interaction at hot spots accelerates the ageing process, the operating time of the cable will be shorter than estimated if these hot spots are not detected or neglected. The maximum load that can be transmitted at a certain voltage level is limited by the maximum allowable current, operating temperature and the losses occurred along the cable insulation [1].

There are several methods used to detect the temperature changes along the cable insulation. In conventional point temperature measurement method, a thermocouple or a platinum resistance probe is used [2]. Since this method requires numerous sensing and connection elements, it is expensive and is not suitable under difficult environmental conditions. Furthermore, temperature values obtained by using mathematical models such as finite elements methods approach to real values with a maximum accuracy of 80-90 % [3, 4]. The distributed sensing method used in this study, is capable of receiving thousands of data along a single optical fiber by using the characteristic properties of optical fiber in sensing. This method is more advantageous in terms of cost-effectiveness, data detection capacity and reliability [5].

In this study, distributed sensing has been used to obtain the temperature and strain profiles along a 380 kV power cable. There are various distributed sensing methods such as spontaneous Raman power and Brillouin frequency shift method, Brillouin frequency shift and Brillouin power change method [6, 7, 8]. In this study, spontaneous Raman power and Brillouin frequency shift method has been used. The temperature information has been obtained from Raman power changes along the cable and strain data have been obtained from the Brillouin frequency shift of the backscattered signal. Using this method and a 1550 nm single-mode optical fiber model, simulations have been performed for a 5 km power cable with a spatial resolution of 1.5 m, a temperature resolution of 1.25 ºC and a strain resolution of 50 με.

In the second section, scattering mechanisms used in distributed sensing and the parameters that determine the sensor performance are described. In the third section, simulation conditions and results are presented and interpreted.

II. SCATTERING MECHANISMS AND PARAMETERS USED IN SENSING

In distributed optical fiber sensing, the variation between the pumping light power and backscattered light power is determined as a function of temperature and/or strain.

Raman scattering results from the interaction between the pumping light and the molecular vibration modes existing in the molecular structure of the medium. A variation occurs between the frequency of incident photons and the frequency of scattered photons. The scattering components whose frequency decreases form Raman Stokes signals while the scattering components with increasing frequency form Raman anti-Stokes signals as shown in Fig. 1 [9].

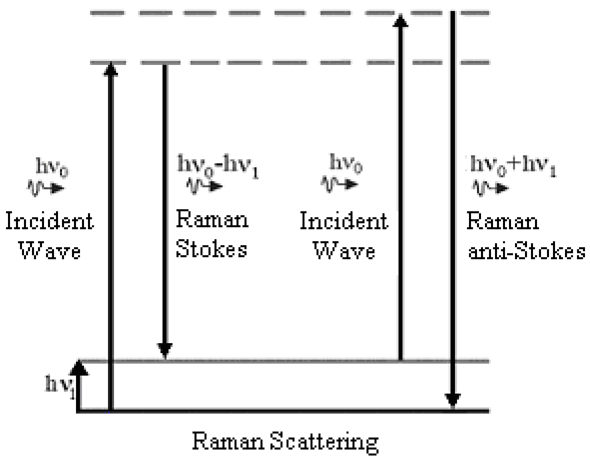

Fig. 1. Raman Stokes and anti-Stokes scattering

Since Raman power is sensitive to temperature, it can be used in detecting the distributed temperature. The ratio of Raman Stokes power to Raman anti-Stokes power is given by

$$R(T) = \left[\frac{\lambda_s}{\lambda_{as}}\right]^4 e^{-(\frac{h\Delta v}{kT})} \quad (1)$$

where, λ_s and λ_{as} are Raman Stokes and anti-Stokes wavelengths, respectively, h is the Planck constant, Δv is the frequency variation between the Raman anti-Stokes signal and the pumping signal, k is the Boltzmann constant and T is the temperature in terms of Kelvin. The sensitivity of Raman power to temperature can be obtained from (1) as shown in (2).

$$\frac{1}{R(T)}\frac{dR(T)}{dT} = \frac{hcv_r}{kT^2} = \frac{h\Delta v}{kT^2} \quad (2)$$

Considering the values Δν = 13.5 THz and T = 293 °K, the percentage change in Raman power due to the temperature change will be 0.80 % /ºK.

Brillouin scattering results from the interaction between the incident light wave and spontaneous acoustic waves thermally generated in the fiber [9]. In Brillouin scattering, a variation occurs between the frequency of incident photons and the frequency of reflected photons called as the Brillouin frequency shift. Brillouin frequency shift is expressed as

$$\upsilon_b = \frac{2n}{\lambda_p}\upsilon_a(\sin\frac{\theta}{2}) \quad (3)$$

where υ_b is the Brillouin frequency shift, n is the refractive index, υ_a is the acoustic frequency, λ_p is the pumping wavelength and θ is the scattering angle. Since the velocity of acoustic wave is sensitive to the fiber temperature and the strain applied on the fiber, Brillouin frequency shift information includes both temperature and strain data. Brillouin scattering is shown in Fig. 2.

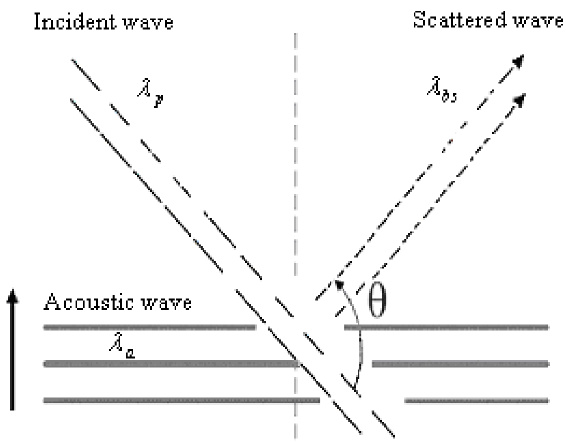

Fig. 2. Brillouin scattering (λ_{bs}) as a result of interaction between the acoustic wave (λ_a) and the pumping light (λ_p)

Parameters affecting the performance of the sensing system based on distributed sensing method can be listed as follows:

- **Fiber Length (Spatial Range):** The spatial range can be defined as the maximum fiber length on which required performance criteria are obtained. It is determined by the total two-way loss in the fiber.
- **Spatial Resolution and Sampling Interval:** Spatial resolution is the distance between 10 % and 90 % of the temperature change in the temperature vs. distance graphic. The response of distributed temperature sensing system to local temperature variations is determined by this parameter. Spatial resolution is given by

$$\Delta z = \frac{c.\tau}{2n} \quad (4)$$

where c is the speed of light in vacuum, τ is the pulse duration and n is the refractive index of the fiber. Sampling interval is the minimum detectable distance between two scattering points and specifies the total number of measurement points on the fiber sensor.

- **Temperature and Strain Resolutions:** Temperature and strain resolutions can be described as the minimum difference between two measurand values that the sensing system can interpret accurately. Temperature and strain resolutions are given by equations (5) and (6) respectively.

$$\delta T = \frac{\left|K_{\varepsilon}^{P}\delta\nu\right| + \left|K_{\varepsilon}^{V}\delta P\right|}{\left|K_{\varepsilon}^{V}K_{T}^{P} - K_{\varepsilon}^{P}K_{T}^{V}\right|} \tag{5}$$

$$\delta\varepsilon = \frac{\left|K_{T}^{P}\delta\nu\right| + \left|K_{T}^{V}\delta P\right|}{\left|K_{\varepsilon}^{V}K_{T}^{P} - K_{\varepsilon}^{P}K_{T}^{V}\right|} \tag{6}$$

where $\delta\nu$ and δP are RMS noises on the Brillouin frequency shift and the power change, respectively, K_{T}^{P} and K_{ε}^{P} are temperature and strain coefficients of the Brillouin power change, respectively, K_{T}^{V} and K_{ε}^{V} are temperature and strain coefficients of the Brillouin frequency shift, respectively. Temperature and strain coefficients are given in Table 1.

Table 1. Temperature and strain coefficients of Brillouin power change and frequency shift

Coefficients	Corresponding Values
K_{T}^{P}	0.36 ± 0.030 %/(°C)
K_{ε}^{P}	-9x10^{-4} ± 1x10^{-5} %/(με)
K_{T}^{V}	1.07 ± 0.06 MHz/(°C)
K_{ε}^{V}	0.048 ± 0.004 MHz/(με)

- **RMS (Root Mean Square) Noise:** RMS noise is defined as the square root of the mean of squares of the noise values detected at every sampling point on the frequency and power plots of the Brillouin signal. It can be written as

$$F_{RMS} = \sqrt{\frac{S_1^2 + S_2^2 + ... + S_m^2}{m}} = \sqrt{\frac{\sum_{m=1}^{m} S_m^2}{m}} \tag{7}$$

where s_1, s_2, s_3 …… s_m denote the noise values at each sampling point and m is the sampling number.

- **Measurement Time:** It is the time required to obtain the temperature profile with a specific resolution. It includes detection and processing times of the backscattered signal.
- **Thermal Response Time:** It is closely related to structures of the cable and the cladding as well as the thermal connection quality between the sensing system and the object whose temperature will be measured. The thermal response time in optical fibers is smaller than 0.5 seconds.

III. SIMULATIONS

In order to obtain temperature and strain profiles along 380 kV power cable, simulations that have been based on the model of 1550 nm single mode fiber integrated to the power cable have been performed by using Matlab 6.5 program. Different medium conditions have been defined along the cable for simulations. They can be listed as follows:

- There are cable connection points repeated in every 500 m along the cable.
- Cable is passing through a 145x5 mm (inner diameter x thickness) PVC duct between 1500th and 1525th meters.
- Passing through a 145x5 mm PVC duct between 2200th and 2300th meters, strain occurs on the cable because of the longitudinal stress due to a landslide.
- Passing through a 145x5 mm PVC duct between 3700th and 3800th meters, another strain occurs on the cable.
- Cable is passing through two 145x5 mm PVC ducts between 4600th and 4625th meters and between 4675th and 4700th meters. It is passing through another PVC duct with dimensions of 180x7 mm between 4625th and 4675th meters and it is cross-connected with another cable inside this duct at 4650th meter.

In simulations, since the pulse duration and the fiber length have been taken as τ = 15 ns and L = 5 km, respectively, the spatial resolution and the number of measurement points have been computed as Δz = 1.5 m and L/Δz = 3333, respectively. The backscattered Raman Stokes and anti-Stokes signal components have been obtained with the help of (8)

$$\frac{h_S(t)}{h_{AS}(t)} = \left(\frac{\lambda_{AS}}{\lambda_S}\right)^4 \exp\left(\frac{\Delta E}{kT(z)}\right)\exp(\Delta\alpha_p z) \tag{8}$$

where $h_S(t)$ and $h_{AS}(t)$ are the Raman Stokes and anti-Stokes pulse responses, respectively, ΔE is the energy difference between the molecular energy states occurred as a result of Raman scattering and z is the distance between the scattering point and the input of the optical fiber (z=0). The value of $\Delta\alpha_P$ is 1.3x10^{-6} for single-mode fibers [5]. The temperature profile along the cable obtained from backscattered Raman Stokes and anti-Stokes signals is shown in Fig. 3.

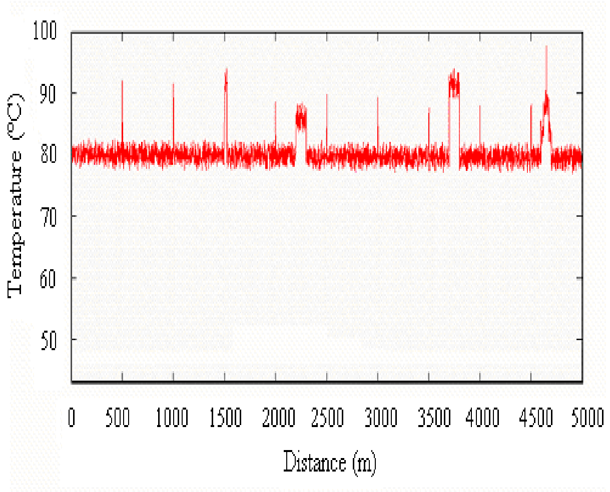

Fig. 3. Temperature profile along 5 km power cable

As shown in Fig. 3, there are increments in the temperature due to cable connection points, cross-connection points and passing through the ducts. Excluding these hot spots, the average temperature along the cable is 80 ºC. At 500th meter and 1000th meter cable connection points and while passing through the ducts between 1500th and 1525th meters, between 3700th and 3800th meters and at 4650th meter, critical temperature value of 90 ºC for XLPE insulation has been exceeded. Maximum temperature value along the fiber has been obtained at 4650th meter. At this point, where the cable cross-connected to another cable while passing through a duct, the temperature has been detected as 98ºC.

Using the known temperature $\Delta T_R(L)$ and the Brillouin frequency shift $\Delta \nu_B(L)$, it is possible to obtain the strain data. The strain profile along the fiber has been obtained by using (9).

$$\Delta\varepsilon(L) = \frac{\Delta\nu_B(L) - K_T^V \Delta T_R(L)}{K_\varepsilon^V} \tag{9}$$

The strain profile of the power cable is shown in Fig. 4. In simulations, the reference strain has been taken as zero. As shown in Fig. 4, the cable experiences strains due to the longitudinal stresses caused by a landslide between 2200th and 2300th meters and between 3700th and 3800th meters. Maximum strain value along the fiber has been detected as 950 με in the range of 3700-3800 m.

Using strain and temperature data, the Brillouin power change can be obtained by (10).

$$\Delta P = K_\varepsilon^P \Delta\varepsilon + K_T^P \Delta T \tag{10}$$

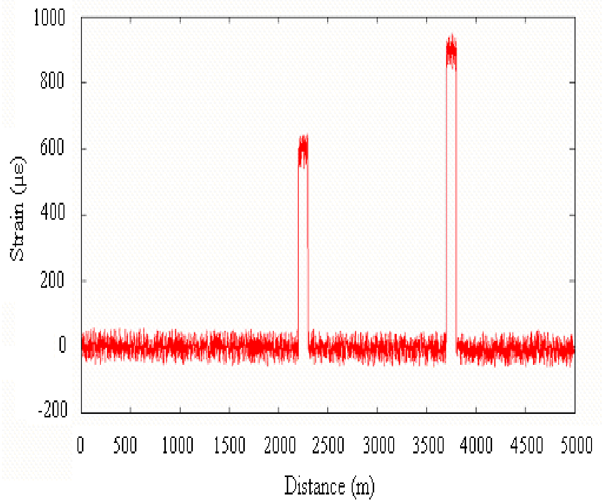

Fig. 4. Strain profile along 5 km power cable

The Brillouin power change along the power cable is shown in Fig. 5. Although the strain variations reach to their maximum values in the ranges of 2200-2300 m and 3700-3800 m, since the temperature changes in these ranges are lower than that in other ranges along the fiber, maximum power change has been detected at 4650th m. At this point, the value of Brillouin power change is 5.79 %.

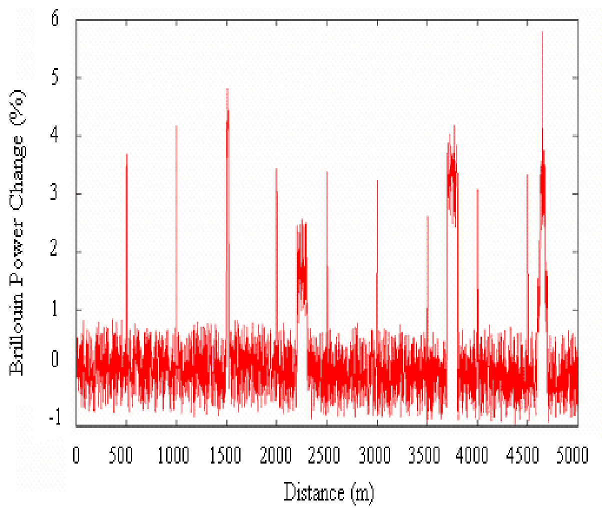

Fig. 5. Brillouin power change along 5 km power cable

The RMS noise values on the Brillouin power change and the frequency shift occurred at various sampling points along the cable are shown in Figs. 6 and 7, respectively.

From Fig. 6, the RMS noise on the Brillouin power change along 5 km power cable have been obtained as ~ 0.45 %.

From Fig. 7, the RMS noise on the Brillouin frequency shift along 5 km power cable have been obtained as ~ 1.20 MHz

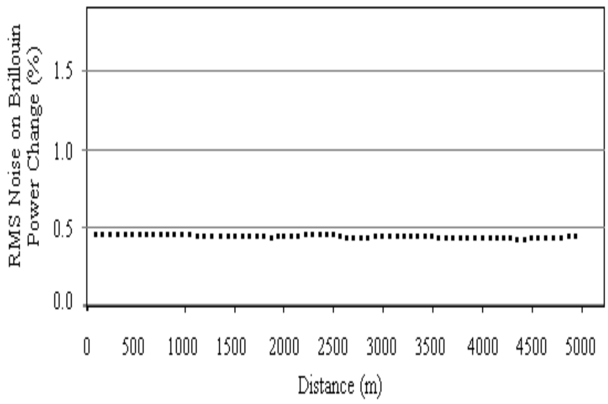

Fig. 6. RMS noise values on the Brillouin power change at various sampling points along 5 km power cable

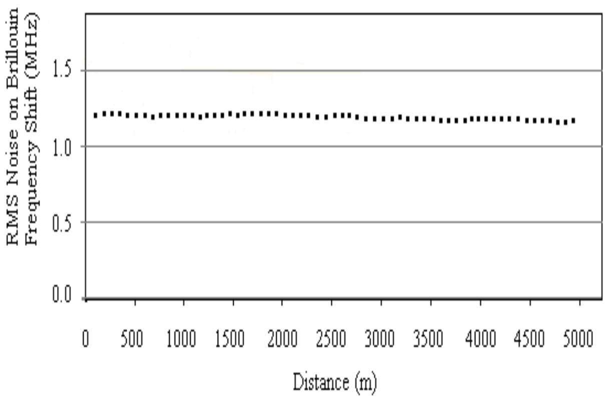

Fig. 7. RMS noise values on the Brillouin frequency shift at various sampling points along 5 km power cable

Using the RMS noise values obtained along the cable in equations (5) and (6), the temperature and strain resolutions have been computed as 1.25 ºC and 50 $\mu\varepsilon$, respectively. According to the results obtained from the computations, the RMS noise on the Brillouin power change is responsible for 95 % of the temperature resolution and 53 % of the strain resolution. That is, power measurements are the dominant factors affecting the accuracy of temperature and strain detection. However the performance of such a sensing system can be improved by using Raman amplification.

IV. CONCLUSION

In this paper, temperature and strain profiles along a 380 kV XLPE insulated power cable have been simulated by using distributed optical fiber sensing method under different environmental conditions. The distributed sensing method based on spontaneous Raman and Brillouin scattering and the parameters determining the performance of such a sensing system have been explained. In simulations, temperature and strain profiles along a 5 km power cable have been obtained with a spatial resolution of 1.5 m, a temperature resolution of 1.25 ºC and a strain resolution of 50 $\mu\varepsilon$.

Results obtained from theoretical computations and simulations show that spontaneous Raman power and Brillouin frequency shift method can be used in sensing temperature and strain data along power cables with high resolutions. One of the most important points that has to be paid attention in applications is the RMS noise values occurred on the Brillouin frequency shift and the power change. RMS noise values are dominant factors affecting both temperature and strain resolutions and hence the performance of the sensing system.

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