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Extended Characterization of an Optical Sag Sensor for High-Temperature Low-Sag Lines

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Abstract—This paper reports on the extended characterization of an optical sag sensor to verify its suitability for monitoring sag and temperature in high-temperature low-sag (HTLS) overhead lines. The sensor utilizes fiber Bragg grating (FBG) technology and can be integrated with the photonic voltage and current sensors that were previously developed by the authors. The response of the sag sensor was evaluated experimentally in the laboratory for temperatures from -20 ˚C to 180 ˚C and for forces up to 3 kN. The sensitivities of the sag sensor to force and to temperature estimated from the experiments were around 0.116 nm/kN and 30 pm/˚C, respectively. The change in the sag sensor sensitivity to force was approximately 25% within the considered temperature range and the change in the sag sensor sensitivity to temperature was 2% within the considered force range. It was demonstrated that the proposed sensor can provide force and temperature measurements within the considered ranges and should be suitable for HTLS lines.

Index Terms— Fiber Bragg gratings, high temperature low-sag conductors, optical sag sensor, power grids

I. INTRODUCTION

In 2021, energy demand around the globe increased by 5.8% exceeding the levels from 2019 by 1.3%, while the electricity generation alone increased by 6.2% [1]. The statistics indicate that electricity is the major factor for infrastructural developments around the globe [2], as growing energy demand enforces the need for upgrading the existing network systems.

The important components of the electrical grid are overhead lines (OHLs) that are used for energy transmission and distribution to the users. Since constructing new transmission lines is time consuming and highly expensive, there is a push towards the increase in the current carrying capacity of the existing lines [3].

Dynamic line rating (DLR) systems to monitor current carrying capacity in transmission lines have been used by network operators. Such systems measure atmospheric climatic conditions and the overhead line parameters, such as conductor's temperature and sag to determine current carrying capacity at any given moment [4].

One way to improve the transmission capacity of overhead lines is to use high-temperature low-sag (HTLS) conductors, which can replace original aluminum conductor steel- reinforced (ACSR) conductors that have a similar diameter. High temperature conductors are defined as conductors which are designed to operate at higher temperatures, above 100 ˚C due to weather conditions and high ampacity. HTLS conductors can endure continuous operation at high temperatures of up to 180 °C with short-time operation up to 250 °C without any significant decrease in tensile strength or increase in sag [5]–[7].

However, the HTLS conductors, like other overhead lines, are exposed to environmental conditions such as Sun's radiation, wind or ice loads, which can affect the conductor performance. For example, wind and ice loads can cause vibrations of varying frequencies and loading that may potentially damage conductors through fretting [3]. Also, excessive forces in the conductor may lead to its damage while excessive temperature may limit the conductor current carrying capabilities. Therefore, in addition to the electrical parameters, measuring mechanical parameters of the line is of great importance.

The current state of the art in OHL monitoring involves a range of different technologies. For example, a hybrid optoelectronic system has been reported in [8] to measure temperature and current of an OHL to calculate sag. Vibration detection sensor [9] has been used to measure vibration on transmission line. Image processing has been used by [10] to measure sag by taking aerial pictures of transmission line using UAV rotors. A magnetoresitive (MR) sensor is used in [11] to measure sag by using magnetic field of transmission line. The method calculates magnetic field from a line conductor at the ground level and measure current to determine sag. An IoT based sag measurement system [12] uses a sensor module which is installed on the transmission line and can measure several parameters such as humidity, illumination etc. However, wireless electronic sensors are generally not suitable for adverse temperature conditions or long-distance coverage. Moreover, there is reticence to use wireless technologies by network operators due to cybersecurity concerns.

Fiber-optic sensors seem to be an attractive proposition as optical fiber is already integrated in the transmission lines. Tension based measurement of sag is reported by [10] using an FBG-based load sensor anchored between the tower and insulator holding the transmission line. Another FBG-based sag sensor was reported in [13], [14]. In this design, the authors used a chirped FBG to deliver both strain and temperature in order to derive line tension. However, none of these solutions enable sag monitoring at elevated temperatures.

To offer a holistic measurement system allowing for monitoring

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both OHL electrical and mechanical parameters, a range of optical sensors were previously proposed by the authors [15], [16]. Apart from the optical voltage and current sensors, the authors proposed optical sensors for sag, temperature and vibration monitoring of standard low-temperature OHLs that could be integrated with the sensors measuring electrical parameters [17], [18].

In this paper, the extended characterization of an optical sag sensor previously developed by the authors in [17], [18] is reported. The sensor performance was tested in the laboratory conditions for temperatures from -20 ˚C to 180 ˚C and for forces up to 3 kN. The proposed sensor capability to measure sag and temperature on HTLS lines was assessed based on the experimental results.

II. OPTICAL SAG SENSOR

A. Conductor's Parameter

The details of the optical sensor design were previously presented by the authors in [17] and a preliminary characteristic of the sensor for monitoring low temperature OHL conductors was presented in [17], [18]. The sag D of the conductor as a function of the distance between the poles S and the actual length of the conductor L, can be expressed by the following equation [13], [17].

$$D = \sqrt{3S(L-S)/8} \quad (1)$$

where the difference between the conductor length L and span length S is defined as the conductor slack.

The conductor sag D can be related to the measured strain in the conductor by the following equation [17].

$$D = \sqrt{[3S(L_c(1+\varepsilon)-S)]/8} \quad (2)$$

where L_c is the initial conductor length and ε is the strain measured by the sensor equal to the change in the distance between the clamps used to clamp the sensor to the conductor (a relative elongation of L_c). It is assumed that the sag sensor is attached to the conductor before line tensioning. If the sensor is fitted after the conductor has already been tensioned, only the difference in strain $\Delta\varepsilon$, and consequently the difference in sag ΔD from the installation moment can be measured. To allow for calculations of the absolute sag and clearance to the ground, the initial horizontal tension in the conductor, as well as its initial sag and length at the conductor installation must be known [17].

B. Optical Strain and Temperature Sensor

The proposed sag sensor utilizes a commercial strain sensor T220, Technica SA [19]. As FBGs are sensitive to strain and temperature, the T220 sensor comprises a second embedded absolute FBG temperature sensor (decoupled mechanically) which serves as both an independent absolute temperature sensor and precise temperature compensator [19]. Therefore, strain and temperature measurements can be performed simultaneously by the sag sensor. FBGs in the T220 sensor are terminated with 3 mm high temperature cables suitable for operation up to 200 °C.

C. Optical Sag Sensor

To construct the sag sensor, the T220 strain and temperature sensor was spot-welded to a 2 mm thick stainless steel (SS304) mounting plate with narrow sections as per the designs discussed by the authors in [18]. The plate with the sensor was then secured between 2 sets of metal clamps made of SS304 that could be fastened to the conductor with bolts. For the purpose of the sensor characterization, the sag sensor was installed on a solid rod made of hard drawn copper (HDC) with flat ends to allow installation in the machine as shown in Fig. 1 [18].

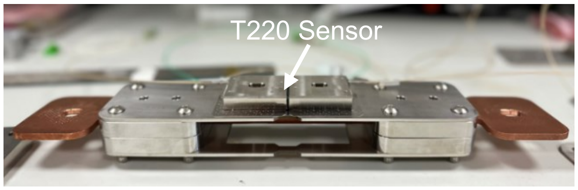

Fig. 1. Optical sag sensor attached to the HDC rod.

To ensure symmetry and to prevent bending of the sensor structure, identical mounting plate was placed on the opposite side of the rod as can be seen in Fig. 1 [18]. The distance between the mounting plates and the rod surface was 5 mm.

III. SENSOR CHARACTERIZATION

A. Experimental Setup

A 10 kN Testometric tensioning machine (model M350-10CT) equipped in a dedicated temperature chamber was used to perform force characterization of the sag sensor at temperatures between 20 ˚C and 180 ˚C. The sag sensor installed on the HDC rod was placed between the machine grips, as shown in Fig. 2.

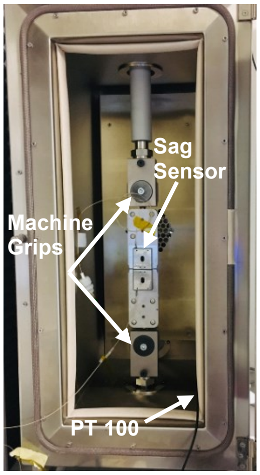

Fig. 2. Sag sensor installed in the tensioning machine.

The force measurements were logged using a load cell and the machine's software. During the tests, the applied force was ramped up from 0 kN to 3 kN in 500 N steps over 1 minute between the force levels and held for 2 minutes at each force level. The force was then ramped down in the same fashion, at every 500 N steps. The force was cycled 3 times at each temperature level. The temperature in the chamber was controlled by the machine controller. For temperature monitoring, a 4-channel PT-104 temperature logger (Pico

Technology) was used with a PT100 platinum resistance thermocouple (PRT) having -50 ˚C to +250 ˚C temperature range and an accuracy of ±0.03%. The temperature of machine was increased in 20 ˚C steps between the considered range at a rate of 1.2 ˚C/minute resolution and left for 2.5 hours at each level to obtain stable temperature before force cycling took place. During characterization, the optical sensor was interrogated at 1 kHz and the FBGs' wavelengths were logged by an FBG interrogator.

In addition to the above-mentioned experiments, the sensor was characterized between -20 ˚C and 20 ˚C in an environmental chamber (Thermotron 2800) at no force applied. While performing experiments, to obtain stable temperature in the machine there was a waiting time of 2 h, before ramping up again for other temperature value at the rate of 5 ˚C/h. The temperature and FBG wavelength readings were acquired as previously.

The results of the sensor force and temperature characterization are presented below.

B. Results

Examples of the applied force (i.e., 0 kN to 3 kN) and strain FBG wavelength waveforms logged at 20 °C for 3 continuous cycles are shown in Fig. 3. As mentioned in experimental setup section the hold time of force at each step is 2 minutes while ramping up and down, in 500 N steps. Force on the sensor was applied for 3 cycles continuously to facilitate the comparison of profile during characterization of the sensor.

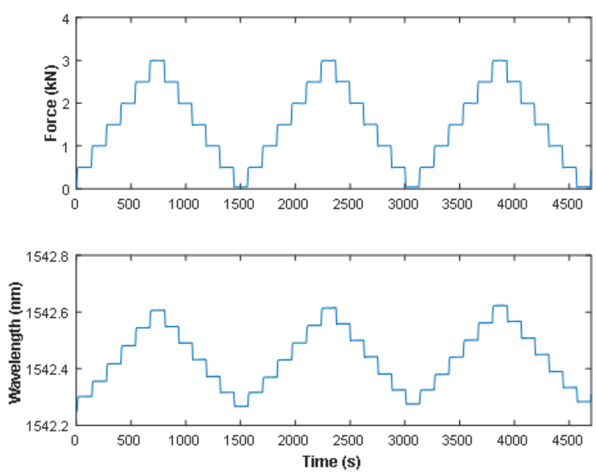

Fig. 3. Force and strain FBG wavelength waveforms during cycling at a temperature of 20 °C.

To plot the sag sensor characteristics, the force and wavelength data were averaged from 3 cycles. The average is taken from the hold time flat area for both force and wavelength, as shown in Fig. 3.

The response of the sag sensor to the force applied at temperatures between 20 °C and 180 °C, is shown in Fig. 4. There has been a linear change in sag sensor response at the considered temperature steps.

An example of the sensor response to force at a constant temperature of 20 °C is shown in Fig. 5. The average values from 3 cycles has been taken for force going up and going down. The sensor sensitivity to force is approximately 0.116 nm/kN ±2 pm/kN when the force was ramped up or down.

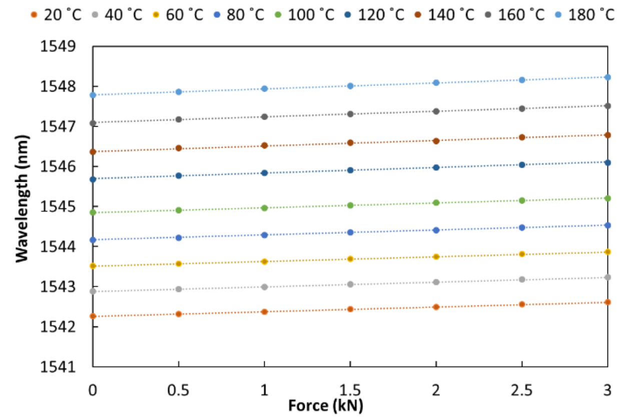

Fig. 4. Sag sensor response to force at temperature 20 ˚C to 180 ˚C.

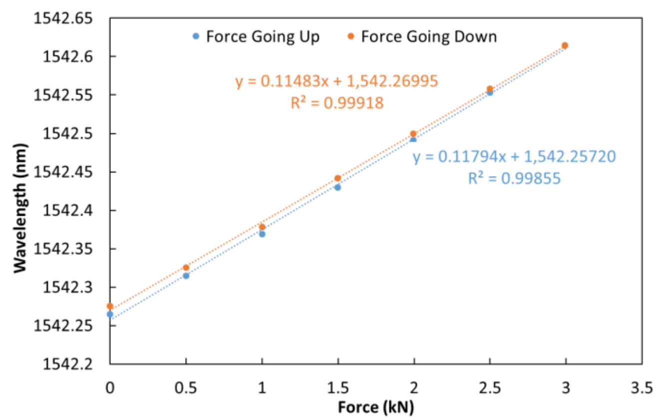

Fig. 5. Sag sensor response to force at a temperature of 20 ˚C.

The temperature sensitivities of approximately 30 pm/°C for the strain and temperature FBG sensors to temperature within the -20 °C to 180 °C range can be observed in Fig. 6.

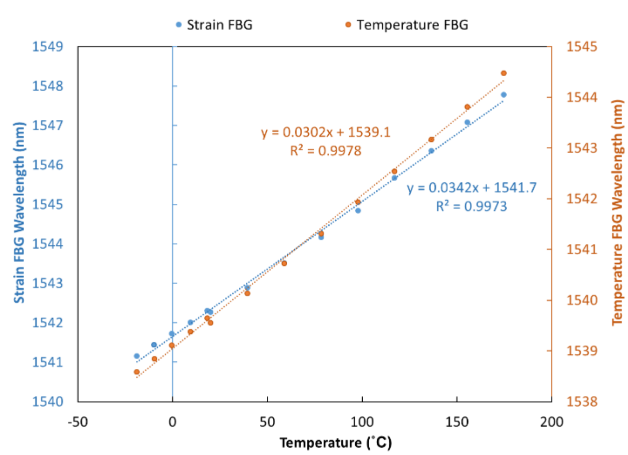

Fig. 6. Sag sensor response to temperatures between -20 ˚C and 180˚C.

The change in the sag sensor sensitivity to force is approximately 25% within the considered temperature range, as shown in Fig. 7.

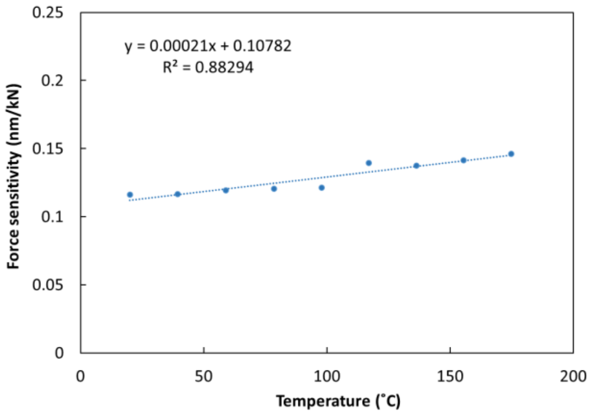

Fig. 7. Change in the sag sensor sensitivity to force within the considered temperature range.

The change in the sag sensor sensitivity to temperature is 2% within the considered force range, as shown in Fig. 8.

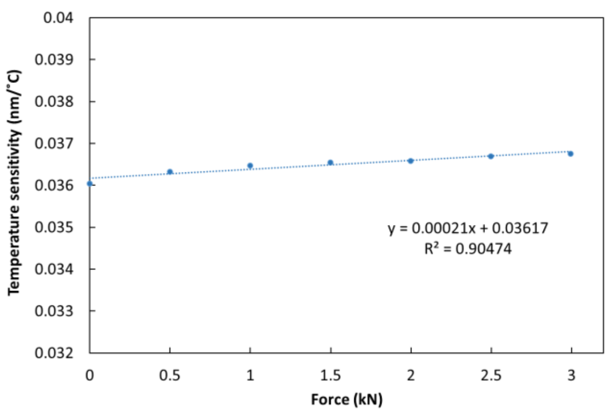

Fig. 8. Change in the sag sensor sensitivity to temperature for the considered force range.

The experimental results show little change in the sag and temperature sensor sensitivity, which ensures that sensors will be effective to use in the real application. The sensor characterization results show that the device should be suitable for monitoring mechanical parameters of HTLS lines.

IV. CONCLUSION

In this paper, the extended characterization of an optical sag sensor for HTLS overhead lines has been presented. The sensor was subjected to force up to 3 kN and temperatures between -20 ˚C and 180 ˚C in the laboratory conditions. The sensitivities of the sag sensor to force and to temperature estimated from the experiments were around 0.116 nm/kN and 30 pm/˚C, respectively. The change of force sensitivity was 25% within the considered temperature range and the temperature sensitivity changed by 2% within the considered force range. Based on the sensor characterization presented in the paper, it was concluded that the device should be effective for monitoring mechanical parameters of HTLS lines. Future work will focus on the investigation of sensor capabilities to monitor fatigue of the conductor.

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REFERENCES

[1] "Statistical Review of World Energy to pass to new home at the Energy Institute," Feb. 2023.

[2] IEA (2022), "World Energy Investment 2022, IEA," Paris, 2022.

[3] K. Kopsidas, S. A. Rahman, M. A. AlAqil, and S. Rolfo, "Advancing OHL Rating Calculations: Modeling Mixed-Convective Cooling and Conductor Geometry," *IEEE Transactions on Power Delivery*, vol. 38, no. 1, pp. 610–619, Feb. 2023, doi: 10.1109/TPWRD.2022.3197325.

[4] E. Fernandez, I. Albizu, M. T. Bedialauneta, A. J. Mazon, and P. T. Leite, "Review of dynamic line rating systems for wind power integration," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 80–92, Jan. 2016, doi: 10.1016/j.rser.2015.07.149.

[5] Elsewedy Cables, "High Temperature Low Sag conductors," Elsewedy Cables."

[6] ZMS Cable Trans More, "HTLS Conductor Cables," *https://kvcable.com/products/htls-conductor-cable/*.

[7] Sterlite Technologies, "HTLS conductor technology."

[8] F. V. B. de Nazare and M. M. Werneck, "Hybrid Optoelectronic Sensor for Current and Temperature Monitoring in Overhead Transmission Lines," *IEEE Sens J*, vol. 12, no. 5, pp. 1193–1194, May 2012, doi: 10.1109/JSEN.2011.2163709.

[9] E. Cloet and J.-L. Lilien, "Uprating Transmission Lines through the use of an innovative real-time monitoring system," in *2011 IEEE PES 12th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance (ESMO)*, IEEE, May 2011, pp. 1–6. doi: 10.1109/TDCLLM.2011.6042218.

[10] H. Wang, S. Han, L.-J. Lv, and L.-J. Jin, "Transmission line sag measurement based on single aerial image," in *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, IEEE, Nov. 2017, pp. 1–5. doi: 10.1109/M2VIP.2017.8211435.

[11] X. Sun *et al.*, "Novel Application of Magnetoresistive Sensors for High-Voltage Transmission-Line Monitoring," *IEEE Trans Magn*, vol. 47, no. 10, pp. 2608–2611, Oct. 2011, doi: 10.1109/TMAG.2011.2158085.

[12] T. S. Hsu *et al.*, "An IoT-based Sag Monitoring System for Overhead Transmission Lines," in *2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia)*, IEEE, Mar. 2019, pp. 515–519. doi: 10.1109/GTDAsia.2019.8715975.

[13] M. Wydra, P. Kisala, D. Harasim, and P. Kacejko, "Overhead Transmission Line Sag Estimation Using a Simple Optomechanical System with Chirped Fiber Bragg Gratings. Part 1: Preliminary Measurements," *Sensors*, vol. 18, no. 1, p. 309, Jan. 2018, doi: 10.3390/s18010309.

[14] K. Skorupski *et al.*, "Overhead Transmission Line Sag Estimation Using the Simple Opto-Mechanical System with Fiber Bragg Gratings—Part 2: Interrogation System," *Sensors*, vol. 20, no. 9, p. 2652, May 2020, doi: 10.3390/s20092652.

[15] J. Nelson *et al.*, "Development and testing of optically-interrogated current sensors," in *2016 IEEE International Workshop on Applied Measurements for Power Systems (AMPS)*, IEEE, Sep. 2016, pp. 1–5. doi: 10.1109/AMPS.2016.7602871.

[16] G. Fusiek, J. Nelson, P. Niewczas, J. Havunen, E.-P. Suomalainen, and J. Hallstrom, "Optical voltage sensor for MV networks," in *2017 IEEE SENSORS*, IEEE, Oct. 2017, pp. 1–3. doi: 10.1109/ICSENS.2017.8234104.

[17] G. Fusiek and P. Niewczas, "Design of an optical sensor with varied sensitivities for overhead line sag, temperature and vibration monitoring," in *2022 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, IEEE, May 2022, pp. 1–6. doi: 10.1109/I2MTC48687.2022.9806489.

[18] G. Fusiek, H. Singh, and P. Niewczas, "Temperature and force characterization of an optical sag sensor for overhead line monitoring," in *2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Malaysia, May 2023.

[19] Technica SA, "T220 FBG Surface Strain Sensor," *https://technicasa.com/t220-surface-strain-sensor/*.