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GSM Based of Unclad Fibre Temperature Sensor for Electrical Transmission Cable Monitoring System

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ABSTRACT

This paper presents a temperature monitoring system for an electrical transmission cable utilizing a global mobile service (GSM)-based unclad fibre sensor. The developed system consists of GSM module, Arduino controller, unclad plastic optical fibre (POF) sensor, light emitting diode (LED) and photodetector. The unclad POF sensor was chosen due to its immunity towards electromagnetic interference as well as its high sensitivity performance. In this work, the transmission cable hazardous temperature is set at 70°C, which is the maximum operating temperature value provided by the National Electrical Code (NEC) NFPA 70. For system characterization, temperature of the cable was varied from 30°C to 70°C. Photodetector output voltage for this temperature variation were recorded at 660 nm and 770 nm operating wavelength. The recorded data shows that the sensor sensitivity performances at 660 nm wavelength are found superior than 770 nm wavelength, which are 0.9710mV/°C and 0.9699mV/°C respectively. As for the GSM communication system, the system was characterized based on accuracy of the information send via GSM text message and its delay. The developed system offers economical and practical monitoring system to be adopted for transmission cable temperature monitoring in remote area.

Keywords:

Electrical transmission cable; Plastic optical fibre (POF); Unclad fibre sensor; Temperature monitoring; Light emitting diode (LED)

1. Introduction

Electrical transmission cables play an important role in transporting electrical energy from electrical generator substation to distribution units. During the operation of power cables, abnormal heat potentially happens and leads to cable burns in extreme cases. There are several incidents have been reported previously caused by overheating of the transmission cable [1,2]. In one of the reported cases, corrosion on the transmission contact elements resulted in the deterioration of contact resistance, thus increasing heat on the electrical parts [2]. Therefore, temperature monitoring of transmission cables is a concern since it can lead to system failure [3-6]. The rise of temperature in this cable can be caused by the cable ageing process as well as environmental effects

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such as rain, wind, lightning, and sunlight [7-9]. Besides, in some cases, overloading of energy transmitted through the power transmission lines can lead to temperature rising [8]. Overloading can significantly increase transmission cable temperature due to the increased current flow exceeding the designed capacity of the cable. Electrical transmission cable temperature monitoring can be realized using many temperature sensors based on magnetic, inductive, piezoelectric, capacitive and optics [10]. Out of these sensor types, the optical temperature sensor offers an advantage in immunity towards electromagnetic interference, making it more accurate to work in the electrical transmission system [11-14].

In literature, most intensity-based optical temperature sensors have been realized using silica and plastic optical fibre (POF). However, temperature sensors fabricated using silica type of fibre are more fragile than POF, requiring careful machinability and handling [6,7,15]. In contrast, sensors fabricated using POF are less fragile, easier to handle, and viable for mass production [7,8,15]. In transmission cable temperature monitoring, the range of temperature that can be detected and the sensor sensitivity are two important characteristics to be considered. More recently, POF sensor sensitivity has been improved by manipulating the thermo-optic coefficient of different materials on the sensor head structure [16-18]. In 2013, a macro-bend temperature sensor fabricated using POF was demonstrated to work in the range from 27°C to 50°C with a sensitivity of $1.92x10^{-3}$ C^{-1} at 660 nm wavelength [19]. Then, the reflective type composed of two Fabry Perot cavities with a sensitivity of 6.85nm/°C for a temperature range from 10°C to 40°C at 595nm wavelength is reported in [20]. Nonetheless, the maximum temperature for both sensors in Moraleda *et al.,* and Zheng *et al.,* [19,20] is below the hazardous temperature set by the National Electrical Code (NEC) NFPA 70, which is at 75°C. In another development, a stress-optical effect was proposed on a U-bent POF sensor, and it demonstrated a comparable sensor sensitivity of 1.04×10^{-3} C^{-1} and 0.994 linearities for a temperature range from 25°C to 100°C at 650nm wavelength [21]. Recently, an unclad POF with a balloon-like bent structure further improved the sensitivity up to 22.2x10-3 $°C^{-1}$ in the range from 40°C to 80°C [15]. The reported performances show the visibility of integrating the unclad POF type of sensor with a communication system for transmission cable temperature monitoring.

For this study, an unclad POF sensor was fabricated, characterized and integrated with a GSM communication system for cable temperature monitoring application. Although high-end communication technology such as artificial neural networks (ANN) [7] and wireless sensor networks [8] have been employed for transmission cable monitoring, these technologies are limited to an area with stable internet connectivity. The following section will describe the methodology for the unclad POF temperature sensor with the GSM communication system integration utilizing the Arduino controller as its data processor.

2. Development of a GSM-Based Unclad POF Sensor

The temperature monitoring system consists of an unclad POF sensor integrated with a data processing unit, a display unit and a GSM transmitting unit. The temperature sensor is designed and developed using POF technology since it has high immunity towards electromagnetic interference. Therefore, it can be attached to a transmission cable for direct temperature measurement. This sensor location can provide better sensitivity of sensing. The sensor location is illustrated in Figure 1. In this work, the POF core is made of polymethylmethacrylate (PMMA) material that is suitable for visible light propagation and easier to handle compared to the other types of fibre [22].

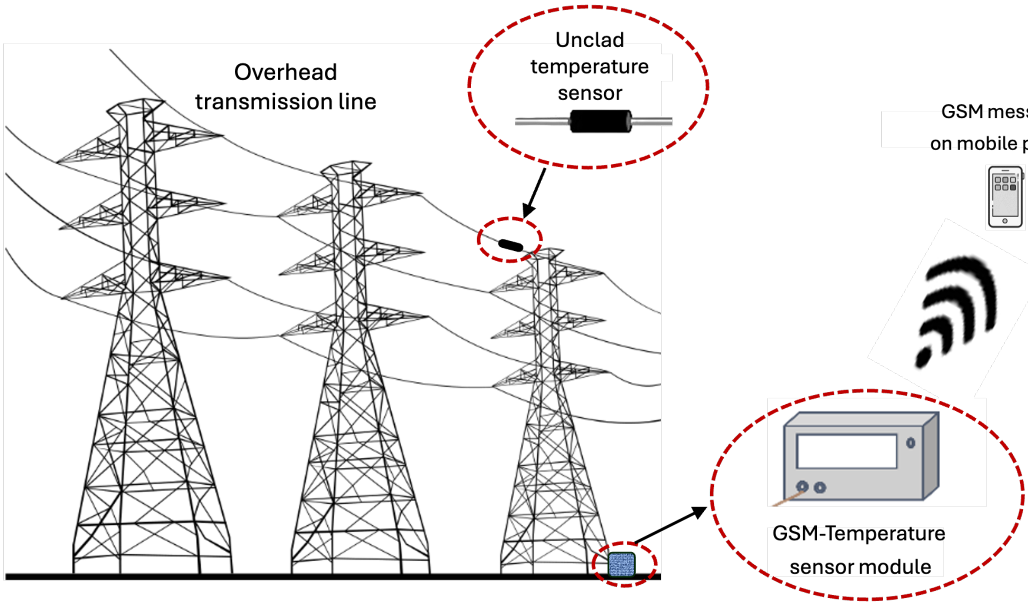


Fig. 1. Location of the sensor on the electrical transmission line (overhead cable)

Removal of a part of POF cladding produces an unclad region as visualised in Figure 2. This unclad section is the sensor head of the system, which will be located next to the transmission cable to sense the temperature changes.

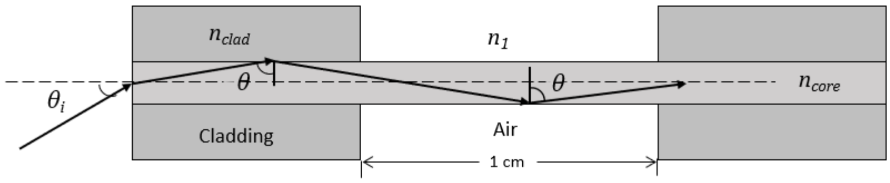


Fig. 2. Cross-section view of the unclad POF sensor

To get a better understanding of how the surrounding temperature influences the light propagation in the unclad POF, optical light propagation loss is studied based on the derived unclad POF mathematical model [23]. The derivation is based on 3 types of refractive index in unclad POF that influence the propagation loss as visualized in Figure 2, which are core refractive index, n_{core}, cladding refractive index, n_{clad} and surrounding refractive index, n_s. In general, attenuation in the POF, α is related to the length of POF, *L*, as well as the input and output power as stated in Eq. (1). Besides, α also can be defined as a multiplication of the number of ray reflections per POF unit length, *N* with the Fresnel transmission coefficient of light at a loss-less core's interface, *T* as stated in Eq. (2).

$$\alpha = -\frac{1}{L} ln \frac{\text{Pout}}{\text{Pin}} \tag{1}$$

$$\alpha = NT \tag{2}$$

For a POF with core radius, *r* and critical angle of θ_c, the *N* and *T* at wavelength λ for a reflected ray at angle θ can be written as in Eq. (3) and Eq. (4) [23].

$$N = \frac{\cot(\theta)}{2r} \tag{3}$$

$$T = \frac{\alpha' \lambda n_2 \cos\theta}{\pi n_{core}^2 - n_2^2 (sin^2\theta - sin^2\theta_c)^{1/2}} \tag{4}$$

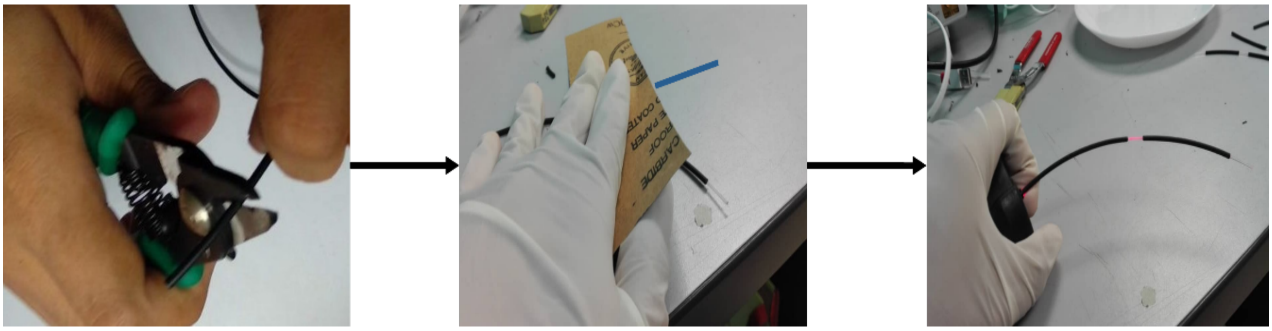
Where α' is a bulk absorption coefficient and $n_2 = n_{clad}$ for the cladding region and $n_2 = n_s$ for the unclad region, producing effective attenuation coefficient, α_{eff} for the unclad POF sensor [23]. Solving Eq. (3) and Eq. (4) by ignoring the higher-order terms, and then substituting them into Eq. (1), the P_{out} can be written as in Eq. (5) [23].

$$P_{out} = P_{in}\,[1 - 0.2304\alpha_{eff} L] \tag{5}$$

Assuming the surrounding environment of the transmission cable has a constant value of pressure and humidity, the transmission cable refractive index n_s will decrease with an increase in the cable temperature. Thus, influencing the P_{out}.

2.1 Unclad POF Sensor Fabrication

The unclad POF used in this experiment was fabricated from PMMA type of fibre with a refractive index of the core and cladding is 1.492 and 1.417, respectively. Fabrication of the sensor starts by determining the length of the unclad region. From the previous research [15], the 1cm length of the unclad region has a low loss performance with good linearity. Therefore, in this work, 1cm of fibre clad will be removed to form an unclad POF sensor head. To unclad the fibre, first, the POF jacket is stripped off using a fibre stripper as shown in Figure 3(a). Then, the exposed POF was submerged with acetone for 10 seconds to etch the POF cladding layer. The etched POF needs to be rinsed with distilled water immediately to stop the etch process. Next, a superfine grit sandpaper shown in Figure 3(b) is used for polishing the unclad region to improve the sensor surface uniformity. To check the outcome of the process, the uniformity of the sensor head was inspected using a fibre fault locator. A uniform unclad surface will produce a uniform light intensity on the region as shown in Figure 3(c).



(a) (b) (c)

Fig. 3. Unclad POF fabrication process (a) stripping, (b)polishing and (c) testing

2.2 Integration of a GSM Communication Module with an Unclad POF Sensor

The fabricated unclad POF sensor will be integrated with other components to form a complete monitoring system. In this work, the system consists of four main modules which are an unclad POF sensor, data processor, GSM transmitter, GSM receiver and LCD unit as shown in Figure 4. The detected transmission cable temperature will be updated in the Arduino UNO processor module for data analysis. The output data and a notification message will be transmitted to the central station using a GSM transmitter module in the text message format.

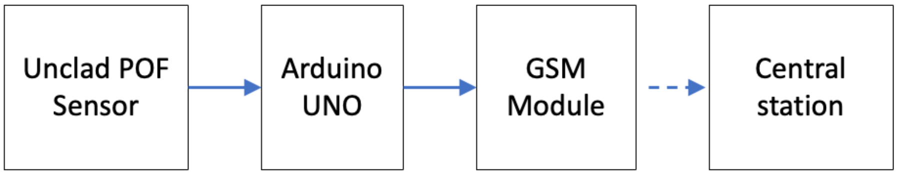


Fig. 4. Monitoring system block diagram

The developed Arduino UNO algorithm used to sense and monitor the cable temperature is described in this section. The 'analogRead' function in the Arduino IDE is used to read temperature data from the unclad POF output voltage. The voltage-to-temperature conversion process is carried out by substituting mathematical relations between these parameters as shown in Figure 5. Then, the Arduino UNO controller will measure the hazardous level by comparing the detected temperature with the threshold temperature. In this work, the threshold temperature is set at 70°C, which is 5°C lower than the hazardous transmission cable temperature. This setting allows early notification to be sent to the central station for further action to be taken.

```
Value = analogRead(sensorPin);
voltage = (Value*5.0) / 1024.0);
temperature= ((1629.5-voltage)/0.9641);
```

Fig. 5. Temperature sensor data reading algorithm

3. Characterization of the GSM-Based Unclad POF Sensor

The experimental setup used to characterize the monitoring system is shown in Figure 6. The unclad POF sensor is located in a dry heat oven, which is used to heat the transmission cable starting from 30°C to 70°C. The maximum temperature is set to 70°C, which is 5°C less than the hazardous temperature stated in the National Electrical Code (NEC) NFPA 70. The transmission cable temperature will be detected by the developed monitoring system and sent to the central monitoring station via the GSM transmitter. In this characterization process, the transmitted data was displayed and recorded on the Arduino serial monitor for observation and data analysis. The characterization process is divided into two parts; sensor and GSM data transmission.

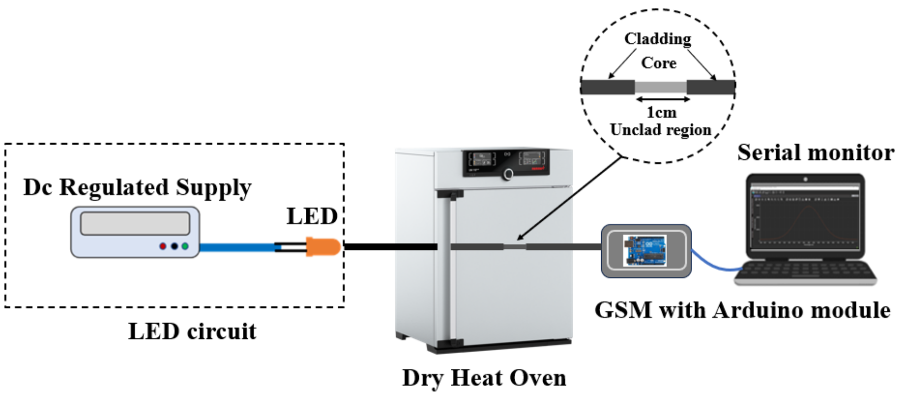


Fig. 6. Experimental setup

The sensor is characterized by its linearity and sensitivity performance. Figure 7 shows the output voltage of the unclad POF sensor at different temperature values. It can be seen that both 660nm and 770nm wavelengths exhibit a linear relationship between these two parameters, with a coefficient of determination R^2 value of 0.9710 and 0.9699 respectively. As for sensor sensitivity performance, the performance can be calculated using the following formulation [15].

$$Sensitivity = \frac{V_2 - V_1}{T_2 - T_1} \text{ mV/°C} \quad (6)$$

In this work, the calculated sensitivity for the system operating at 660nm wavelength is -0.9641 mV/ °C. The sensitivity of the system operating at 770nm wavelength is lower than 660nm wavelength, which is -0.6679 mV/°C. The results show that the sensor operating at 660nm wavelength has better linearity and sensitivity values. This finding is aligned with previously reported work demonstrated in Sulaiman *et al.,* and Kadar *et al.,* [15,24]. Thus, the monitoring system will be developed using this operating wavelength for the system characterization.

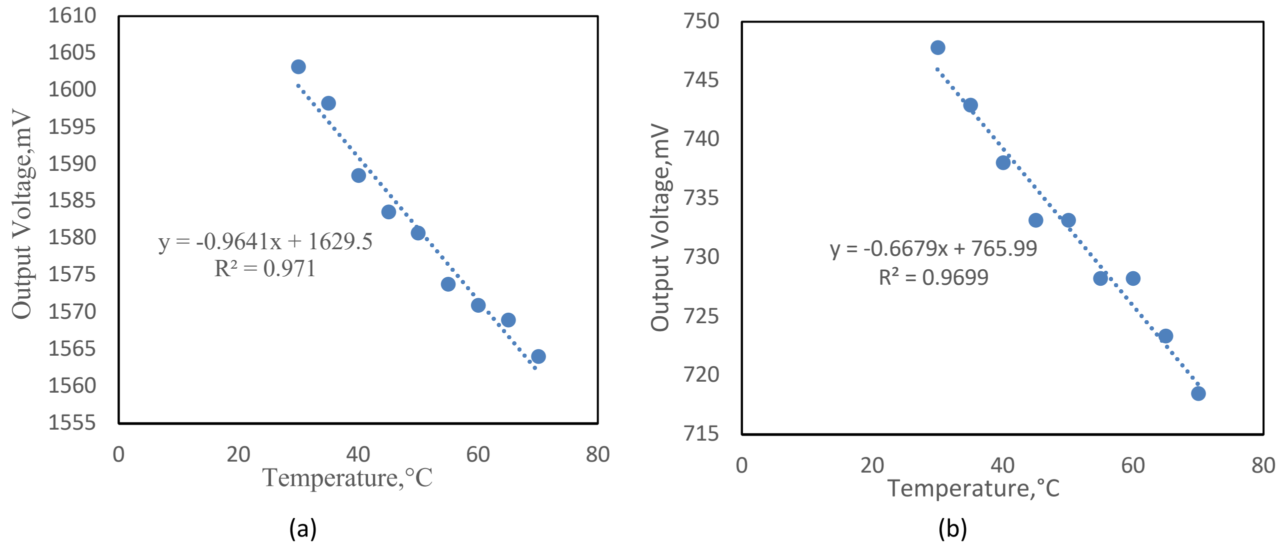


Fig. 7. Output voltage as a function of temperature operating at wavelength (a) 660nm (b) 770nm

As for the GSM data transmission, the system is characterized by its data delay performance. In this work, the GSM transmitter and receiver are located in the same communication station. The time taken to receive the notification data is measured from the data display in the serial monitor and the data displayed in the central station display. In this experiment, the average delay is about 3 seconds. This performance is subject to the quality of service provided by the GSM operator. The measured delay is comparable with the work reported in Kadar *et al.,*; Rinaldi, Kristiyana and Handajadi; Murti *et al.,* [24-26]. The delay in GSM networks can vary based on several factors such as the mobile operator, network congestion, and the type of service being utilized. Figure 8 shows the notification message that appears on the central station display.

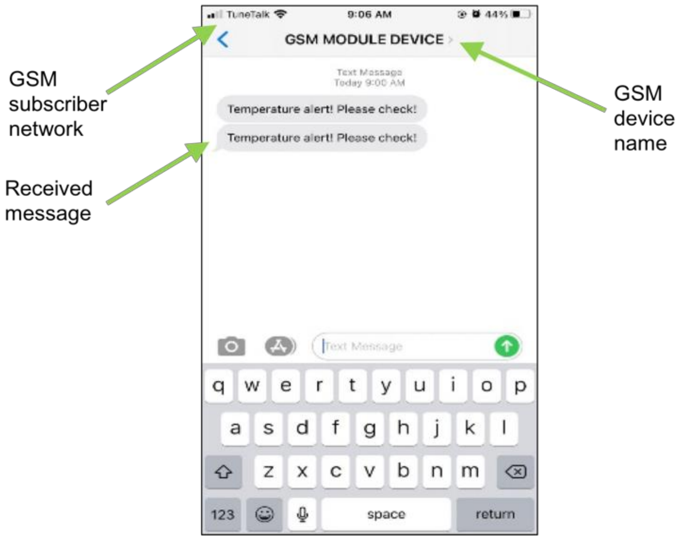


Fig. 8. Notification message received in the central station

4. Conclusions

In conclusion, the GSM-based monitoring system is experimentally demonstrated in this work utilizing an unclad POF temperature sensor. Based on the experimental results, it is evident that the system has good linear relations which is 0.9710 for 660nm wavelength. Moreover, this operating wavelength exhibits a comparable sensitivity performance of -0.9641 mV/ °C. The usage of the unclad POF sensor offers high immunity towards electromagnetic interference caused by the high voltage transmission. Thus, improving the accuracy performance of the monitoring system. In this work, the GSM system delay performance is measured to be 3s. Although GSM is an old communication technology, this technology is still needed for applications that require short data transmission with security in a remote location.

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