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Optical sensing in high voltage transmission lines using power over fiber and free space optics

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ABSTRACT

In this work we propose the use of power over fiber (PoF) and free space optics (FSO) techniques to powering and receive signals from an electrical current sensor placed at high voltage potential using a pair of optical collimators. The technique evaluation was performed in a laboratorial prototype using 62.5/125 μm multimode fiber to study the sensitivity of the optical alignment and the influence of the collimation process in the sensing system wavelengths: data communication (1310 nm) and powering (830 nm). The collimators were installed in a rigid electric insulator in order to maintain the stability of transmission.

1. Introduction

In electrical systems, the measurement of current, voltage and temperature in high voltage overhead transmission lines is very important and it requires special monitoring devices, which have to be completely isolated from the ground potential. Many optical techniques have been developed to perform this measurement using, for example, Faraday effect or magnetostrictive effect [1] for current, Pockels effect [2] for voltage, fiber Bragg grating (FBG) [3] for temperature and a light-emitting diode (LED) for leakage current detection on insulator strings [4].

Other way to measure these parameters in high voltage transmission lines is by using PoF (power over fiber) technique [5]. PoF consists in transporting optical energy to powering up electric or electronic devices remotely. PoF offers several advantages when it is used on high voltage environments, such as spark-free, lightning-proof, immunity to electromagnetic pulses, robust in harsh environments, such as, extreme temperatures, moisture, etc. Besides these advantages, the employment of a PoF scheme can replace the energy supplied by metallic cable and batteries located at remote sites, improving the reliability and the security of the system. One of the main benefits of the utilization of PoF technique in substations is the elimination of the need to run conductive copper wire into a high ground rise (GPR) zone. GPR can cause severe interference problems in electronic equipment and systems [6]. Considering that, the sensor using PoF has a complete galvanic isolation to the ground potential and it is practically immune to the GPR effects. The PoF technique has already utilized to monitor current and temperature in high voltage [7–9].

An issue that arises when optical sensors have to be installed in the high voltage potential is how to guarantee that the optical cable stay on electrically passive for many years in operating. Although the optical fibers cables are non-conductive, they cannot be used at the high voltage potential using their regular coating materials because the optical cable would very quickly give rise to catastrophic tracking and erosion [10]. The fiber optic cable can conduct superficial leakage currents since it is exposed to environmental pollutants such as dust, smoke, saline atmosphere, etc [9]. In other words, it is necessary to use a special electric insulator to connect the optical fiber cable from the ground potential to the high voltage potential. The optical fibers have to pass through a hollow core insulator with an appropriated creeping distance. This solution is expensive and demands change of the ordinary insulator used in high voltage transmission lines.

We proposed in this work a new method to connect the optical fiber cable from the ground potential to the high voltage potential. In this approach, we used free space optics (FSO) to transmit and receive the optical signals from optical fiber placed in ground potential to the other one placed in the high voltage potential by using a pair of optical collimators. The collimators kit used in FSO avoids the changing of an ordinary isolator to one with embed-

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ded fiber optic. This technique has already tested [11] using FBG in order to measure temperature in the high voltage transmission lines and the results are promising. In [11] it was demonstrated that the collimators alignment is very sensible to the angular tilt, but lateral misalignment originated from thermal effects can also affect the collimators alignment. These effects were also theoretically calculated in [12].

In this work, we use the techniques FSO and PoF to demonstrate this new concept, transmitting optical supply power to a remote unit placed in a simulated the high voltage potential and receiving data signals from it in the ground potential. In this demonstration, we used an ordinary Hall effect current sensor in the remote unit but any other electrical or electronic sensor could be used instead. Also we used a rigid insulator in order to avoid angular tilt effects and to maintain the stability of the transmission.

The technique evaluation was performed in a laboratorial prototype using 62.5/125 μm multimode fiber for the study of the sensitivity to optical alignment and the intrinsic loss of the collimators for the signal (1310 nm) and the powering (830 nm) wavelengths. Environmental tests were also conducted in order to demonstrate the performance of this technique in a real situation of application.

2. Description of the proposed PoF–FSO system

Fig. 1(a) shows the PoF/FSO system and its components for current sensing. Basically the system is constituted by the PoF control unit, a multimode 62.5/125 μm optical fiber that connects the PoF control unit to the collimator A (model F260APC-1550 from Thorlabs) installed on the base of an ordinary composite electrical insulator (simulated ground potential), a second collimator (B) installed at the top of the same electrical insulator (high voltage potential simulated), the PoF remote unit also installed at the top of the electrical insulator and the electronic current sensor. The insulator is a commercial rigid fiber glass/silicone structure (line post) made for use in 138 kV transmission lines. Fig. 1(b) shows details of the collimator B housing.

According we commented previously the collimators alignment is more sensible to the angular tilt, but using a rigid insulator only lateral misalignment originated from thermal effects can affect the collimators alignment. Indeed, the mechanical kit used to support the collimators pairs is deformed under effect of the external temperature. To mitigate this effect the material of the mechanical kit is stainless steel. This material was chosen to ensure a low thermal expansion and at the same time a good resistance against environmental effects.

Fig. 2(a) shows in more details the elements of the PoF link: the PoF control unit containing a high power laser diode (HPLD – model 2486-L4) operating at 830 nm and an optical receiver, a PoF remote unit containing a GaAs photovoltaic converters (PV – model PPC-6E from JDSU), a rechargeable power supply (RPS), a microcontroller circuit, a 1310 nm Fabry Perot semiconductor laser (FPLD) and the Hall effect current sensor that is connected to the microcontroller circuit. The PoF link is bidirectional by using multimode 830/1310 nm muxes connected to each end of the fiber link (FO).

Although it is possible that the system works in a continuous operation (i.e. operation of the system without charging/discharging cycles), the loss of optical power caused by the FSO collimation process requires that the system operate in a non-continuous operation, such as described in [13]. The Fig. 2(b) presents the diagram of the PoF remote unit containing the RPS. A continuous optical power supply at the wavelength of 830 nm coming from the PoF control unit is injected in two commercial GaAs based photovoltaic converters (PV_1 and PV_2). We used a 50% splitter to divide this power in two parts. In order to make possible the operation of the sensor we introduced in the sensor circuit a super capacitor (C) (or an equivalent association of them) put it in parallel to the PVs. According to Fig. 2(b) a voltage comparator integrated circuit (LT6703-3) is used to turn on a voltage regulator integrated circuit (LT1764) when a specific voltage is reached in the capacitor. This specific voltage is defined by the voltage divider formed by the resistors R_1 and R_2. When this voltage is reached, the comparator circuit enables the output of the regulator circuit, which supply the microcontroller circuit, and the laser driver circuit. The laser transmits the current sensor data in RS232 format using a low threshold 1310 nm Fabry–Perot laser. In the next section, we described the test results of this system.

3. Test results and discussion

The setup shown in Fig. 1(a) was built in order to determine the main parameters that influence the performance of the system. We used a commercial 1–1000 A analog Hall effect current prier as a current sensor. This sensor was connected to an input of the micro-

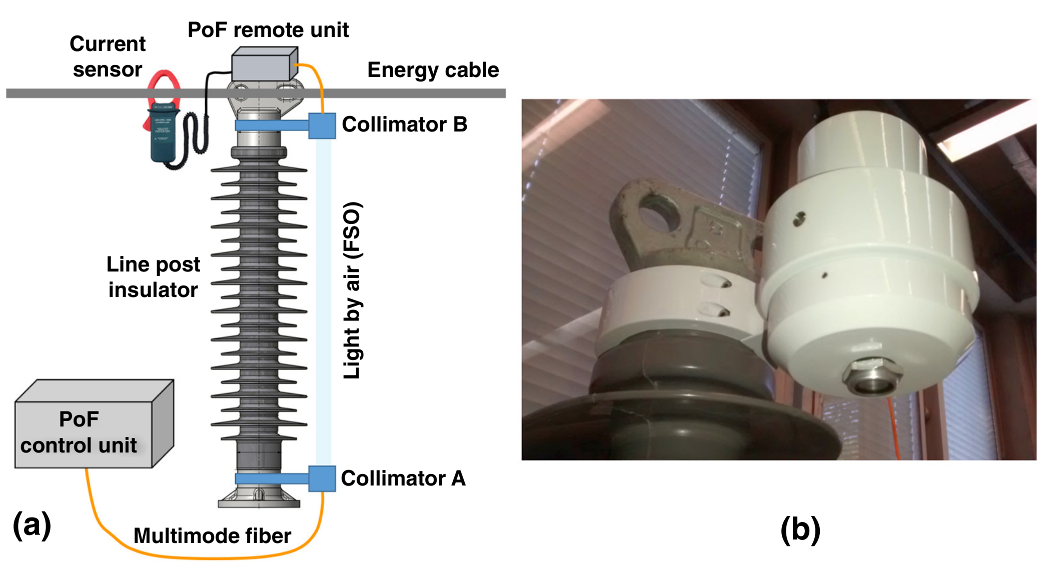

Fig. 1. The proposed POF–FSO system: (a) simplified view and (b) details of the collimator B housing.

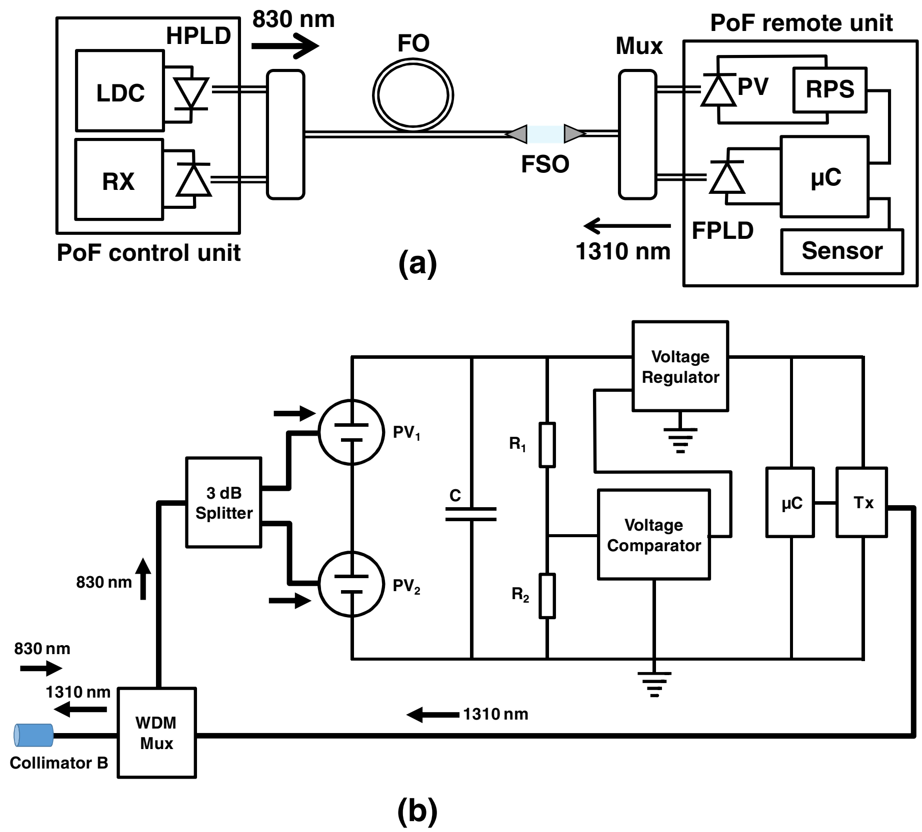

Fig. 2. (a) PoF system schematics including the optical link between control and (b) diagram of PoF remote unit containing the RPS.

controller circuit. The choice of capacitor, the load current and the supply optical power in the remote unit determine the period of the charging/discharging cycle. In [13] is described a more complete study about this cycle. In the present work, the capacitance C is 0.33 F and the load current is 8.6 mA. Fig. 3 shows the voltage and current measurements in the charging/discharging cycle for 240 mW of supply power received in the remote unit. As we can see when the programmable voltage across the capacitor (V_{in}) is reached (6.3 V in this case), the regulator voltage output is enabled supplying a stable output (V_{out}) of 3.3 V to the microcontroller circuit, until Vin reaches a voltage of 3.3 V, when the regulator output is automatically disabled. According to Fig. 3 the charging time is 134 s, the discharging time is 44 s, and the period is 178 s. Therefore, about every 2 min the remote unit sent a data frame of the measured current. In order to verify the cycle dependence with the 830 nm supply power, the HPLD current was changed. The maximum power of the HPLD is 1.41 W. The intrinsic loss of the optical link (for the collimation setup in null lateral misalignment) is 3.9 dB at 830 nm. Fig. 4 shows the charging/discharging time and the period versus the 830 nm power received in the remote unit. As we can observe, increasing the supply power reduces the charging time and increases the load time. When the supply power reaches to 0.5 W, the system behavior is similar to the continuous operation without loading. The cycle period has no significant variation for the supply power range from 0.1 to 0.4 W. For supply power levels less than 0.1 W the charging time and the period increase significantly, reducing in this way the load time. Based on this experiments it is possible to estimate in 0.1 W the minimum

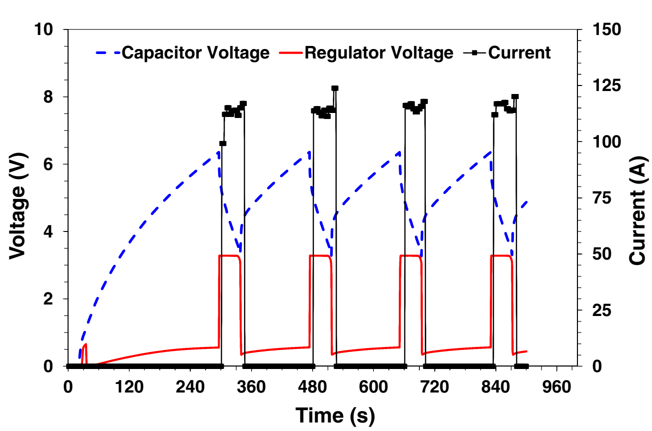

Fig. 3. Voltage and current measurements in the charging/discharging cycle.

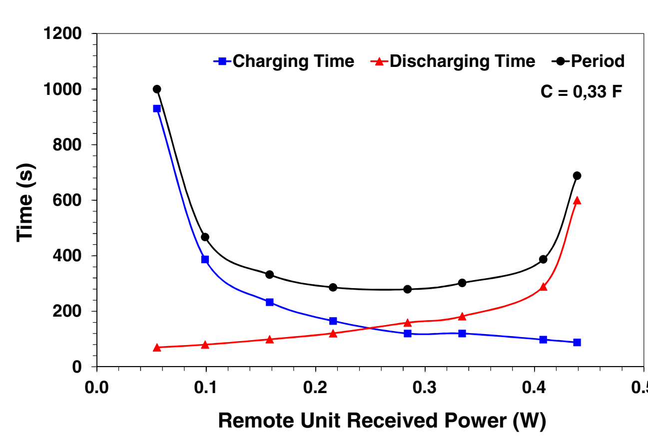

Fig. 4. Charging/discharging time and the period versus the 830 nm power received in the remote unit.

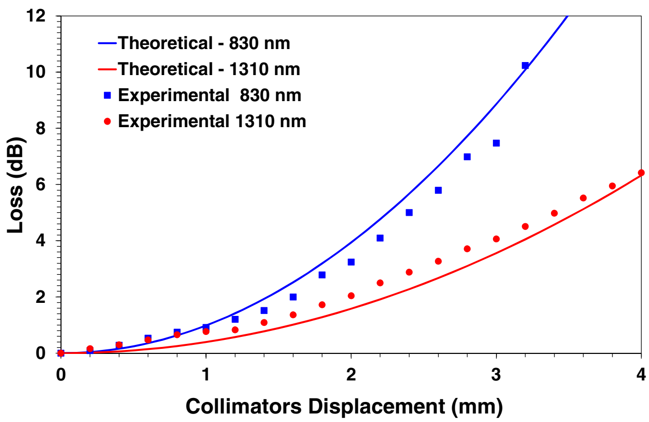

Fig. 5. Misalignment loss for 830 and 1310 nm.

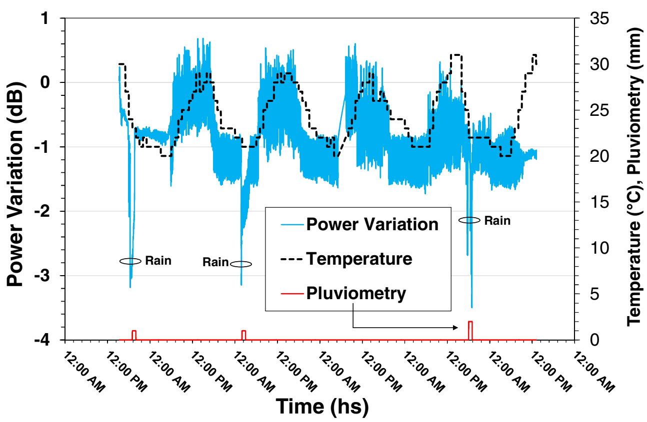

Fig. 6. Temporal variation of the 830 nm optical power in the remote unit measured for 5 days in the external environment.

required supply power in the remote unit need to the system works properly.

Next, we tested the collimation setup in order to observe the sensibility of the FSO system to lateral misalignment using a special optical bench described in [11]. Fig. 5 shows the loss of the collimation setup at 830 and 1310 nm versus the lateral misalignment, as well as theoretical curves derived from [12] where influence of misalignments was studied for graded index lenses. The theoretical misalignment loss expression from [12] is given by:

$$L(x) = \frac{20}{\ln(10)} \frac{2n^2\pi^2w^2}{\lambda^2z^2 + 4n^2\pi^2w^4} x^2 \tag{1}$$

In this expression L is lateral loss in dB, n is the index of refraction of the glass set to 1.5, λ is the wavelength, z is longitudinal separation, equal to 1.5 m and x is the lateral displacement. The spot size w was the fit parameter. The mean best fit achieved was $w = 0.0629286$ mm. Here we used a simplification, assuming equal collimators and let the output spot size, w, be the only fit parameter, as in (1). Considering that, the system can work well since the remote unit receives power ranging from 0.1 to 0.4 W (6 dB variation). We can estimate from Fig. 5 that the collimation setup could misalign around 2.7 mm from its best-aligned position. This range is comfortable for the present collimation setup. In Fig. 5, we can observe that the misalignment loss for 1310 nm is less critical than 830 nm.

Next the setup shown in Fig. 1(a) was put in outdoor environment in order to verify its performance in a real situation of application. Fig. 6 shows the temporal variation of the 830 nm optical power in the remote unit measured for 5 days in the external environment. As we can observe the maximum power variation due to the thermal effects is around 1.5 dB. The most important effect in the power variation is due to the rain. In this case, the power variation reaches to 3.5 dB. Is it possible that for high intensity rainfall the system can lose the transmitted signal and supply power.

4. Conclusion

In this work we have demonstrated the use of power over fiber and free-space-optics transmitting optical supply power to a remote unit placed in a simulated the high voltage potential and receiving data signals from it in the ground potential. The results demonstrated that the system works well within a 6 dB range of power variation. Tests conducted in external environment indicated that the system is enough robust to operate in typical climate conditions, but high intensity rainfall can temporarily disrupt the optical transmission.

It is important to mention that this technology can be used in other optical sensing applications in dangerous areas where the transitions in an optical sensing link should be done by air, such as, nuclear plants, refineries, etc.

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