Low-cost, self-referenced all-fibre polarimetric current sensor for the monitoring of current in the railway catenary

Massimo L. Filograno[*a], Pedro Corredera[b], Laura Monteagudo Lerma[a], Óscar Esteban [a], Miguel Gonzaléz-Herráez[a]
[a]Departamento de Electrónica, UAH, Alcalá de Henares, Spain;
[b]Istituto de Física Aplicada, CSIC, Madrid, Spain

ABSTRACT

In this paper a low-cost all-fiber current sensor is described that fulfills the requirements of robustness, sensitivity, accuracy and cost required for the monitoring of catenary current in changeover sections of the high-speed railway network. Its optical configuration is simplified through the use of few devices with extremely simplified alignment. This allows high sensitivity for low current values and a resolution below the ampere level. The sensing head is packed in a compact box withstanding temperature and position variations without affecting the sensitivity of the set-up. The electronics incorporates self-referencing that makes it robust to small misalignments and power variations in the optical source. Field tests will be reported in the conference.

Keywords: optical fibre, current sensor, polarimetric sensor, Faraday effect

1. INTRODUCTION

The railway traffic in European networks is rapidly increasing during the last years, and is foreseen an increase of three times the present freight and passengers levels by 2020 [1]. Considering this growth, a number of R+D initiatives have been taken in order to optimize the railway infrastructures maintenance and availability. These initiatives are specially important considering the important deployment of high-speed railway lines all over Europe.

A key issue in high-speed railway lines is the protection of the catenaries in changeover sections. Changeover sections are non-fed sections of the catenary that are placed between sections fed with different phases. These sections are located at intervals of several tens of kilometers and they introduce discontinuities in the current collection done by the train. Since the train passes at high-speed between the two sections, impairments due to electric arc formation may lead to significant damage of the infrastructure [2]. To avoid this situation, it is essential to ensure the correct operation of the train before and after the changeover section: the train must switch-off the current collection before arriving and switch-on again when the changeover section is passed. The non-fed section is essentially passed by inertia.

Whenever the train does not switch-off the current collection before arriving, electric arcs may form and destroy the railway catenary. To avoid these situations, it would be necessary to activate adequate protection systems. These should imply monitoring the current in the catenary before the changeover section. Whenever a train passes without switching off the current collection, adequate signaling should be provided and the switching process should be done by the infrastructure itself. Thus, an exhaustive control of the electrical phase distribution in the changeover section must be performed. Efficient and robust electrical current sensors are therefore essential for their inclusion in the measurement and security systems of the railway networks. Essentially, the sensors developed for this application have to be very sensitive to low currents (to ensure detection of all the unwanted events) and only moderately precise for high currents.

Several approaches have been used to perform electrical current measurements in the railway catenary. Sensors based on Hall effect have been mostly used so far, but they do not provide good isolation at 25 KV and beyond (or they become extremely expensive). Modern high-speed railways run on these voltage levels, and thus optical current transformers are much more interesting for this application. Schemes for optical current transformers can be polarimetric [3] or

[*] massimo.filograno@depeca.uah.es; phone +34 91 885 6908

interferometric [4,5], and there are also sensors based on magnetostrictive or piezoelectric transducers with Bragg gratings written in optical fibres [6,7].

In this work, we propose a polarimetric current sensor based on the Faraday magneto-optic effect for the development of a cost-effective all-fibre current sensor for this application. Our setup is specially adapted to the requirements of this application, namely: AC current measurements with high sensitivity, dynamic range up to 500 A, moderate accuracy over the full range, low cost and robustness to environmental and mechanical changes. The setup is electronically self-referenced to account for small misalignments in the polarization and power variations in the optical source.

2. SENSOR SETUP

Our current sensor makes use of the Faraday effect. The Faraday effect is a magneto-optic effect by which a linearly polarized light passing through a suitable material rotates an angle (θ) in proportion to the magnetic field parallel to the optical axis. This Faraday rotation angle is therefore proportional to the magnitude of the magnetic field (H) and the propagation inside the optically active material. The proportionality constant is the well known Verdet constant (V). Thus, the Faraday rotation can be easily calculated by the equation (1)

$$\theta = V \times H \times L \tag{1}$$

In our case, the magnetic field is caused by a linear conductor and the material through which light is propagated is a mere single-mode optical fibre coiled around the conductor. In this case, the rotation angle is given by equation (2)

$$\theta = \mu_0 N V I_c \tag{2}$$

Thus, even though conventional fibres present a low Verdet constant, we can compensate this small sensitivity to some extent with the increase of the number of turns around the conductor. In the case of our sensor, we have used 1000 turns around the conductor. Furthermore, we have used a reflective configuration, which duplicates the effective length of the material under magnetic field effect, and makes easier the installation of the sensor for field measurements (single cable, simplified alignment). This ensures a very high sensitivity in the setup, which is one of the requirements for this application.

The sensor arrangement is shown in figure 1, where the interrogation unit and the sensor head can be seen. The interrogation unit contains the light source, which is a super luminescent diode (SLD) providing an almost linearly polarized beam. This beam is launched through an optical fibre isolator to a 3dB coupler. After the coupler, a polarization controller (PC) allows to maximize the optical power which will be launched to the optical fibre through an in-fibre polarizer (FP). The resulting interrogation unit is quite compact. It is meant to be installed in a control station relatively far from the sensing head, and once the system is adjusted, no further maintenance should be done.

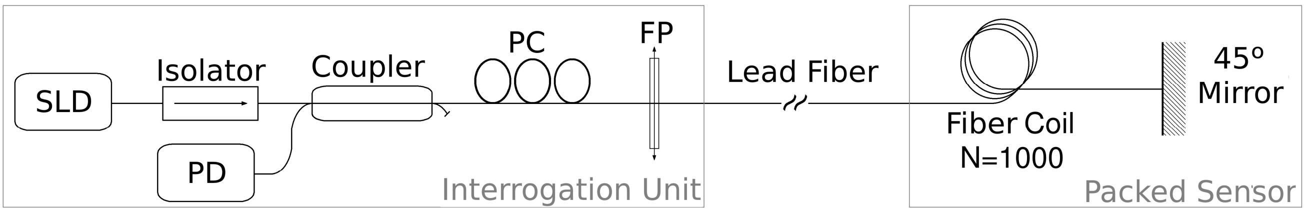

Figure 1. Scheme of the implemented polarimetric current sensor. Note that the packed sensor is a monolithic, low-weight block that can be easily installed in the catenary.

The sensor head is composed by two main elements: a fibre coil with N = 1000 loops which is to be placed around the current flow line, and a modified Faraday mirror. The key point of the setup is this modified Faraday mirror. Essentially, this device is a conventional low-cost and widely available Faraday mirror with two strong permanent magnets positioned close-by. This allows a wide tuning of the angle of rotation introduced by the mirror, and therefore the working point in the transfer function of the sensor sketched in fig 3. When no modification of the original Faraday rotation (90º) is selected (point A of the transfer function in Figure 2), the sensitivity to low currents is zero. Thus, this is an undesired working point. By modifying the position of the magnets one can tune the working point to introduce an additional rotation of $\pi/4$ rad (point Q in the transfer function), so that the final output can be written as

$$I_{out} = I_0 \cos^2\left(2\,\mu_0\, I_c\, V\, N + \pi/4\right) \tag{3}$$

where I_0 is the input optical power, μ_0 is the vacuum magnetic permeability, I_c is the current intensity, V is the Verdet constant for the optical fibre at the used wavelength (1550nm) and N is the number of loops (1000 in our case). This is the point of maximum sensitivity. The alignment of the magnets is extremely simple: we introduce an AC current and we maximize the AC signal in the PD. With an additional DC current we can verify that we are in the mid-range between two points of minimum sensitivity. Once the alignment is done, the magnets are glued and no further movement of the magnets is done.

In our setup, we can get a relatively good linearity in the range 0-500 A with a resolution well below the ampere level. For a maximun current value of 500A, the rotation angle due to the magneto-optic effect keeps under 22º, which is still in the approximately linear response region. Thus, the setup is considered linear over the whole range with a constant sensitivity. Nonlinearities below 24% should be expected in the maximum current value. Considering the purpose of the sensor we deliberately prefer a better sensitivity to small currents although losing accuracy. Generally in order of the purpose is possible to tune the number or coils.

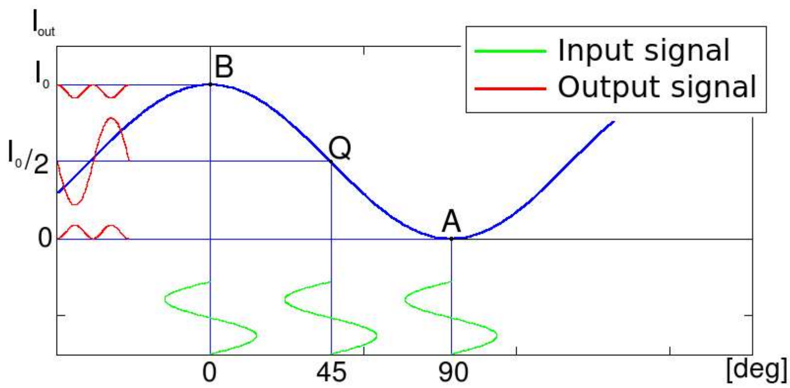

Figure 2. Plot of the optical power received by the PD as a function of the rotation angle introduced in the Modified Faraday Mirror.

The complete system, including the electronic signal processing, has been designed to work with AC currents of 50 Hz. This allows to use electronic filters in detection to improve the signal to noise ratio. Modulation and demodulation of the optical power is also achieved to improve the signal to noise ratio by means of synchronous demodulation. The fact that the signal is AC also allows introducing a simple electronic self-referencing technique: an Automatic Gain Control. Thus, any small variation in the optical power of the source or the polarization controller alignment does not affect the setup since the gain is adapted so as to keep the mean value constant (both the mean value and the amplitude of the AC component depend on I_0).

3. EXPERIMENTAL RESULTS

The sensor was tested in the lab with 50 Hz AC current in the range of 0-700 [A]. The measured output remains stable for fixed values of current, regardless of movements, temperature variations (in the 15-25ºC range) and movements of the polarization controller of the SLD. During the first part of the tests we found stability, a good S/N ratio and a useful immunity to changes of polarization and power in the SLD when the ACG-circuit is active. The analog transfer function of the circuit is shown in Fig. 3. We can see a good sensitivity at low currents (≅10 mV/A at the output of the circuit) and a slight sensitivity loss for higher currents. Typical train currents are always below 400 A.

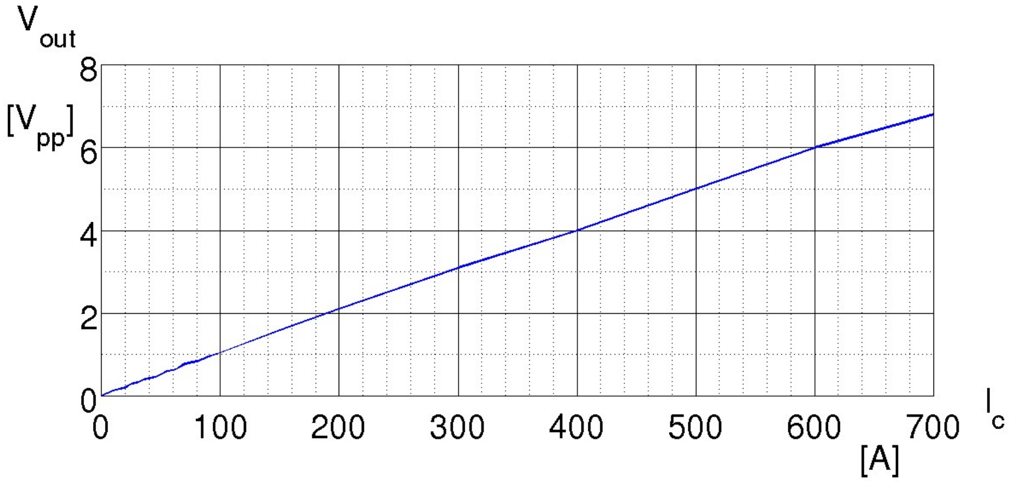

Figure 3. The output voltage of the complete sensor setup as a function of the RMS current fed through it. The current and its RMS value are provided by the LET-400-RDC current generator manufactured by EuroSMC.

In Fig. 4 we see a photo of the installation for a preliminary test in the catenary feeder. The system is presently being validated in working conditions. This means that temperature variations over a wide range of ambient temperatures will be tested and validated soon. From previous results, we expect errors up to 10% in the range of temperature variations tested. Even with this amount of error, the detection of current consumption by the train before the changeover section remains reliable.

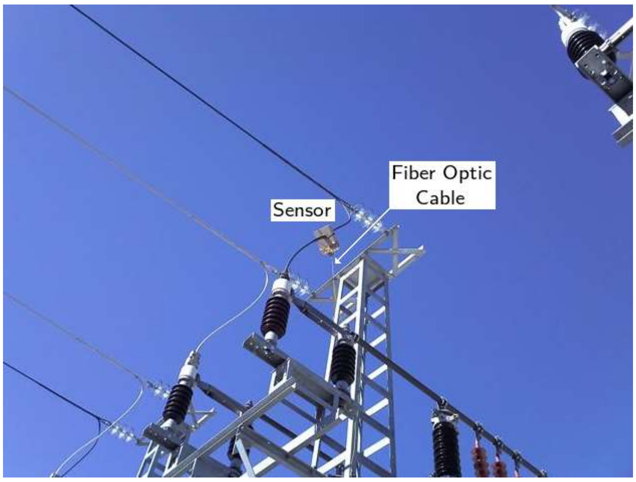

Figure 4. The site where the sensor is mounted for a first test is a feeder supply cable of the catenary of a high speed railway infrastructure.

4. CONCLUSIONS

We have described a low-cost all-fiber current sensor that fulfills the requirements of robustness, sensitivity, accuracy and cost required for the monitoring of catenary current in changeover sections of the high-speed railway network. Its optical configuration is simplified through the use of few devices with extremely simplified alignment. This allows high sensitivity for low current values and a resolution below the ampere level. The accuracy is comparably low but sufficient for the application. A complete set of field tests will be reported in the conference.

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