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Lightning protection of a smart grid sensor

Celio Fonseca Barbosa*, Flávio Eduardo Nallin

Centro de Pesquisa e Desenvolvimento em Telecomunicações – CPqD, Campinas, Brazil

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ABSTRACT

This paper presents the protection procedures implemented in a power line sensor in order to make it compatible with the electromagnetic environment, especially with the stresses imposed by lightning flashes. The paper includes the sensor description and simulation results of lightning surges coupled to the device through its external interfaces. It is shown that the protection of the radio-frequency circuitry requires the installation of a high-pass filter at the antenna port and that the protection of the voltage-measuring circuit can be accomplished by using a voltage divider combined with a low-pass filter. By its turn, the protection of the current-measuring circuit is achieved by the installation of surge protective components.

1. Introduction

The implementation of several smart grid functionalities requires the knowledge of relevant information of the power grid, such as voltages and currents along the network, as well as the status of switching equipment [1]. However, the electronic equipment installed in the power grid is subjected to a harsh environment, which includes temperature variations, rain, vibration, and interfering electromagnetic fields. Lightning flashes produce electromagnetic fields that can cause not only interference, but also damage to electronic equipment. These fields can be calculated by the formulations available in the literature (e.g., [2–7]), some of which are used in this paper in order to define the lightning protection techniques implemented in a sensor developed for smart grid applications. A preliminary approach was presented in [8], which is complemented in this paper by improving the antenna model, including the shielding provided by the sensor chassis, and considering the induction from the lightning magnetic field. The first section of the paper describes the sensor itself, and the following sections describe the protection measures implemented in its external interfaces.

2. Sensor description

2.1. General overview

The sensor considered is intended to assess voltages and currents in an aerial distribution line conductor. In order to do so, it has electric and magnetic field transducers which provide signals proportional to the line voltage and current, respectively. The sensor sends this information through a radio link to a concentrator unit installed nearby, i.e., in a range of a few hundred meters. The concentrator processes the information received from a number of sensors, includes a time-stamp from its GPS (Global Positioning System) receiver, and sends a message to the utility's operational control center. This information can be used for different applications. In this particular case, it is used by a dedicated software in order to detect and locate faults along the power grid, including those that are characterized by high impedance. This paper is dedicated to the lightning protection of the sensor, as it has sensitive electromagnetic field interfaces and it is also placed in close proximity to the power conductor.

The sensor chassis is an aluminum box having 80 mm × 125 mm × 57 mm and 3 mm wall thickness, as shown in Fig. 1. It has an L shaped support that is inserted below the base of the insulator normally used in power distribution lines. The sensor installation is straightforward, as it requires only to unscrew partially the insulator holder nut, to insert the sensor, and to screw the nut back. This operation can be carried out with energized lines, if needed. Fig. 2 shows a set of three sensors installed in a three-phase power distribution line (13.8 kV), so that the voltages and currents of the three phases can be measured. The

* Corresponding author at: Rua Aristides Lobo, 242, Campinas, SP 13.083-060, Brazil. Tel.: +55 19 3705 6258; fax: +55 19 3705 6120.
E-mail addresses: grcelio@cpqd.com.br, grcelio.barbosa@gmail.com (C.F. Barbosa).

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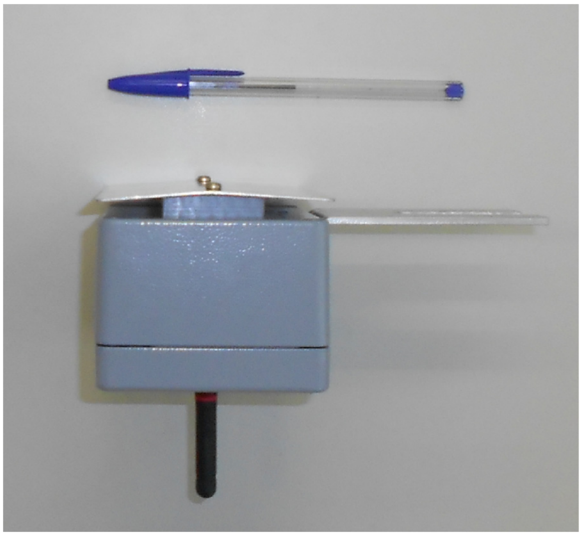

Fig. 1. Close view of a sensor.

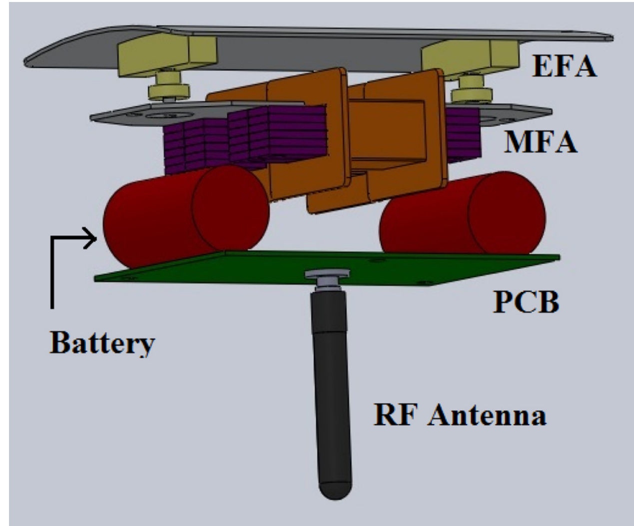

Fig. 3. Sensor schematic view.

concentrator (not shown in the figure) is located in a neighboring pole 50 m away.

2.2. Voltage transducer

Fig. 3 shows a schematic view of the sensor, without its chassis. The roof-like structure is an electric field antenna (EFA), which provides a voltage signal to the sensor printed circuit board (PCB). The PCB is the rectangular structure at the bottom of Fig. 3. The sensor is installed at the base of the insulator, so that the EFA is at the level of the cross-arm (see Fig. 2). In this case, there is a capacitance between the line conductor and the EFA. A capacitor is connected between the EFA and the ground reference, making a capacitive voltage divider that provides a low-voltage signal that is rectified, conditioned, and supplied to the analog-to-digital (AD) converter of the microprocessor.

2.3. Current transducer

In Fig. 3, the structure just below the EFA is a pair of reels that hold two coils, which make the magnetic field antenna (MFA). These coils are excited by the magnetic field produced by the current in the power line conductor and provide a signal that is rectified, conditioned, and supplied to the AD converter.

Fig. 2. A set of three sensors installed in a power line structure.

The sensor is powered by two 1.2 V, 2 Ah, Ni MH batteries (the cylinders just above the PCB), which provides about 5 years of operation without recharging. This is possible due to the sensor very low power consumption in the stand-by mode, which is only 96 μW. In order to extend the sensor autonomy, a special circuit was designed to harvest some energy from the line magnetic field and charge the batteries.

3. Protection of the RF circuitry

The sensor's radio-frequency (RF) circuit is based on a radio transceiver that operates in the 433 MHz band, which proved to be very reliable in the preliminary tests. However, this transceiver presents a high impedance at low frequency to the antenna connection, which makes it prone to be damaged by lightning electromagnetic fields. Indeed, a previous experience with a radio transceiver with similar characteristics produced many failures in the field.

As the RF antenna is vertically polarized, the vertical electric field is the relevant field component for the assessment of the sensor protection. The inducing vertical electric field was calculated using an expression originally developed by Rusck [2] and modified by Barbosa and Paulino [4]:

$$E_{step} = \frac{Z_E I_0}{2\pi v_R}\{\lambda[(vt)^2 + \lambda r_0^2]^{-1/2} - r_0^{-1}\}, \tag{1}$$

where I_0 is the current amplitude, $Z_E = 377\,\Omega$ is the free-space impedance, v is the return stroke velocity, r_0 is the distance from the stroke, v_R is the relative return stroke velocity, t is time, and $\lambda = (1 - {v_R}^2)$ is the square of Lorentz contraction factor. Eq. (1) was developed considering a step channel base current, transmission line (TL) return stroke model, and perfectly conducting earth. It is worth to mention that, according to Rubinstein [3], finitely conducting earth has little influence on the vertical electric field at close range.

Considering that the lightning flash strikes at $r_0 = 50$ m from the sensor, the return stroke velocity is $v = 150$ m/μs (i.e., $v_R = 0.5$), and the channel base current has a unity amplitude ($I_0 = 1$ kA), the vertical electric field E_{step} (t) for a unit step current excitation is obtained from (1). The electric field produced by an arbitrary