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DIFFERENTIAL MAGNETOMETER METHOD (DMM) FOR THE MEASUREMENT OF GEOMAGNETICALLY INDUCED CURRENTS (GIC) IN A POWER LINE: TECHNICAL ASPECTS

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Geomagnetically induced currents (GIC) are quasi-DC currents which can occur in a power grid as a result of fluctuations in the Earth's magnetic field associated with geomagnetic storms. The differential magnetometer method (DMM) is used as an indirect method for GIC flowing in power lines. A number of technical aspects need to be considered before carrying out the DMM measurements. The technical aspects presented in this paper are (1) the required magnetometer characteristics, (2) the magnetometer calibration process and (3) the alignment of the magnetometer under the power line to enhance the accuracy of the measurements.

Keywords: geomagnetically induced currents, differential magnetometer measurements

1 INTRODUCTION

Geomagnetically induced currents (GIC) are known to initiate abnormal operations on grounded technological systems such as power transmission systems as well as gas pipe lines [1]. The proximity of high latitude regions to the ionospheric disturbances due to the auroral electrojet makes these regions more vulnerable to GIC. However, GIC monitoring in mid- and low- latitude countries such as, China [2], Brazil [3] and South Africa [4] have indicated that the power systems in these regions are exposed to high GIC magnitudes which can have a significant impact on the operation of the systems during geomagnetic storms.

The effects of the GIC on power systems include among others the saturation of the transformers which under worst case conditions may lead to a blackout in the power network resulting from relay tripping and transformer failure [5, 6].

2 GIC MEASUREMENTS IN A POWER TRANSMISSION NETWORK

The GIC flows into the power transmission network through the transformers' neutral-to-ground conductor connection. The GIC then divides equally among the three phases of the transmission network. A number of GIC monitoring system use Hall-effect sensors installed on the neutral-to-ground connection of the transformer to measure GIC [5].

As discussed by Viljanen et al. [7] and Matandirotya et al. [8], GIC can be measured using the differential magnetometer method. With the use of low cost magnetic sensors, this method provides an efficient way of deducing the GIC in an electric power transmission line. The GIC is inferred from the difference of magnetic field measured at two different points, as illustrated in Fig.1. The first measurement point (P1) is located directly under the power line and is subjected to magnetic field caused by both the GIC and the natural fluctuations in the geomagnetic field. The second measurement point (P2) is placed away from any electric power transmission line and is used as reference which records only the geomagnetic field. The difference between the two measurements theoretically gives a magnetic field only due to the GIC.

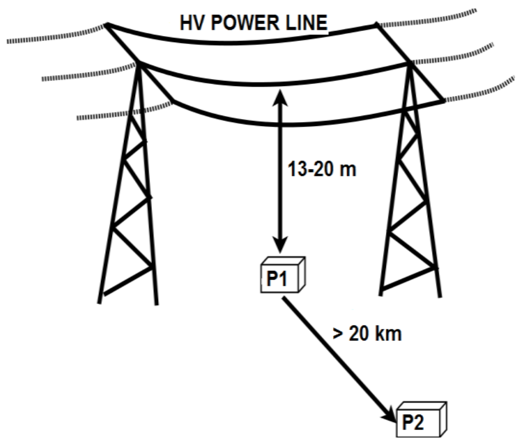

Fig. 1. Magnetometer setup for differential magnetometer method

Currently a pilot project is being run for measuring GIC in part of the Southern African network. The aim of this project is to identify and adapt a low cost magnetic sensor that can be used for GIC measurement in the power lines. The focus of this paper is to discuss the technical aspects that were considered during the preparation and installation of the measurement system. These are magnetometer characteristics, magnetometer calibration process and alignment of the magnetometer under the power line.

The proposed differential magnetometer method (DMM) measurement system consists of a LEMI-011

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magnetometer (http://www.lemisensors.com/?q=LEMI-011), a HOBO data logger (http://www.onsetcomp.com), an in-house designed voltage regulator and a 12V/8Ah battery. Fig. 2 shows the components of the measurement system.

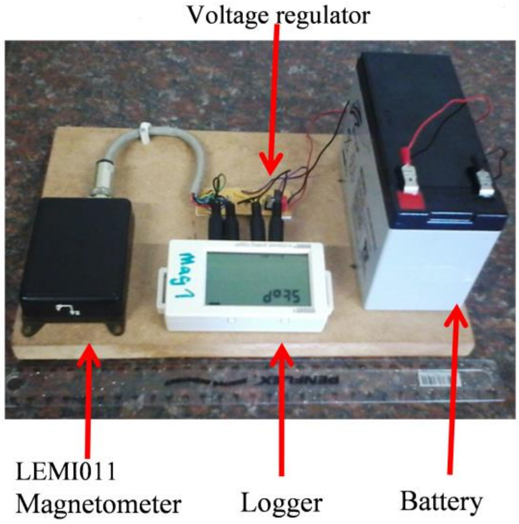

Fig. 2. The components of the DMM measurement system

3 TECHNICAL ASPECTS

3.1 Magnetometer characteristics

The LEMI-011 fluxgate magnetometer was selected for this pilot project. Fluxgate magnetometers are preferred for low frequency measurements due to their stability and robustness [9]. The magnetometer operates over a bandwidth 0-20 Hz. The technical specifications of the LEMI-011 are available at:
http://www.lemisensors.com/?q=LEMI-011.

The following characteristics were considered for the selection of this magnetometer:

a) Three-axis vs absolute measurement

A three-axis magnetometer is preferred when measuring GIC using DMM. This allows the extraction of the horizontal magnetic field component perpendicular to the power line.

b) Bandwidth

The bandwidth of the magnetometer must be well below 50 Hz. Since GIC have a frequency band of 0-10 mHz, it is best to use a magnetometer with a low pass filter and cutoff frequency such that the magnetic field due to the 50 Hz current (normally distributed) is sufficiently suppressed.

c) Temperature Sensitivity

A magnetometer with a low sensitivity for temperature variation over a wide operational temperature range is recommended. Since the magnetometers are buried underground, temperature fluctuations may vary with season.

d) Dynamic range

A wide measurement range is necessary as to allow the magnetometer to record high levels of dynamic magnetic field fluctuation without reaching saturation. Thus, magnetometers with range >± 50 000 nT are recommended.

3.2 Magnetometer Calibration

Every measuring instrument needs to be calibrated to determine the accuracy and the reliability of its output. The system used to calibrate the magnetometers is a Helmholtz coil system [10]. During the calibration process, three tests are performed which are the linearity, Thin-Shell and noise tests. As discussed by Matandirotya *et al* [11], these tests give the user an idea of (a) how the magnetometer reading deviates from the actual magnetic field, (b) the level of orthogonal misalignment and (c) the noise level of the magnetometer.

For the DMM, it is important that calibration of the sensor is done before and after system assembly. Since the packaging of the measurement system is such that the battery, logger and the voltage regulator are in close proximity with the sensor, the level of magnetic interference needs to be determined. Table 1 shows typical characteristics of the magnetometer before and after integration. Fig. 3 shows typical deviation from linearity in terms of the difference between the applied field and the measured field.

Table 1. Typical calibration table

SERIAL NUMBER: N070	Before integration	After integration
	X	
Sensitivity (nT/mV)	27.48	27.53
Offset (nT)	1276.50	1524.20
	Y	
Sensitivity (nT/mV)	27.48	27.44
Offset(nT)	1029.67	3427.4
	Z	
Sensitivity (nT/mV)	27.50	27.52
Offset(nT)	1188.18	1300.90

The final magnetometer measurements are calculated using equation (1),

$$\begin{bmatrix} FieldX \\ FieldY \\ FieldZ \end{bmatrix} = \begin{bmatrix} C_{xx} C_{xy} C_{xz} \\ C_{yx} C_{yy} C_{yz} \\ C_{zx} C_{zy} C_{zz} \end{bmatrix} \times \begin{bmatrix} OutputX \\ OutputY \\ OutputZ \end{bmatrix} - \begin{bmatrix} OffsetX \\ OffsetY \\ OffsetZ \end{bmatrix} \quad (1)$$

where *Field* (*X,Y,Z*) are the measured fields for the three magnetometer channels in nT, C_{xx}, C_{yy}, C_{zz} are the sensor gain mean values for the x, y and z axes, respectively, in nT/mV, *Output*(*X,Y,Z*) are corresponding voltage readings for each channel in mV and *Offset*(*X,Y,Z*) are the electronic offsets for each channel in nT. The off-diagonal elements of the calibration matrix are the mean values as determined from the Thin-shell test which correct for the orthogonal misalignment [11].

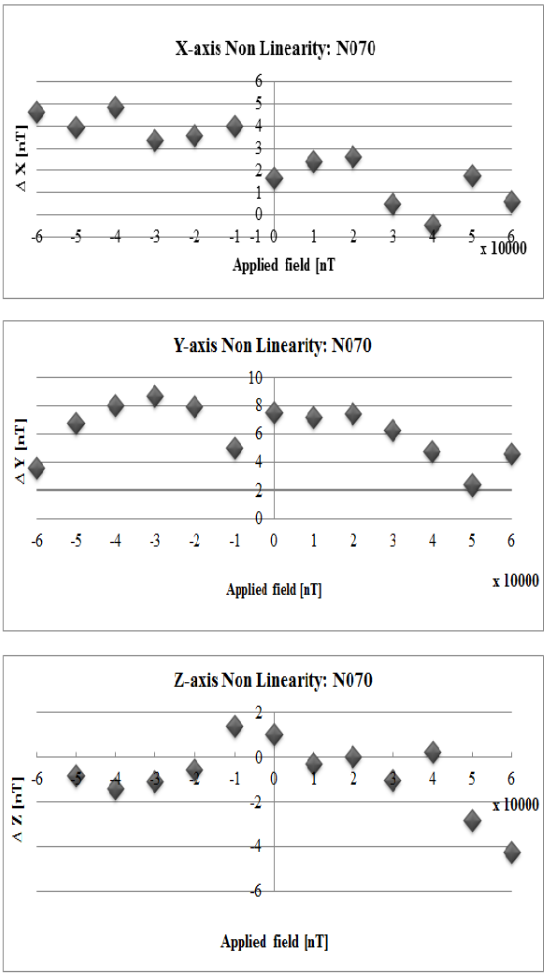

Fig. 3. Deviation from linearity of one of the two magnetometers after system integration

3.3 Magnetometer alignment under the power line

It is important that there is a proper alignment of magnetometer axes and the power lines when executing the DMM. The magnetic field component essential for the estimation of the GIC is the component perpendicular to the line. Since the magnetometers are placed under ground, it is difficult to orientate the magnetometers in such a way that one axis is perpendicular to the line.

Magnetic North is used as the initial reference and the measured field from the Magnetic North is transformed to the power line direction. Alignment of the x-axis with Magnetic North can be achieved by rotating the magnetometer to an angle where the y-axis reading is zero. The field components in the magnetic coordinate system can be transformed to the Geographic coordinate system by using the known declination angle. For example if we consider Fig.4, to transform the magnetic field from *xy* coordinate (geomagnetic) system to *x'y'* coordinate (geographic) we use the declination angle β in the transformation equations as follows

$$B_{x'} = F\cos(\alpha+\beta) = F\cos\alpha\cos\beta - F\sin\alpha\sin\beta \quad (2)$$

$$B_{x'} = B_x\cos\beta - B_x\sin\beta \quad (3)$$

$$B_{y'} = F\sin(\alpha+\beta) = F\sin\alpha\cos\beta + F\cos\alpha\sin\beta \quad (4)$$

$$B_{y'} = B_x\cos\beta + B_x\sin\beta \quad (5)$$

This can be written as

$$\begin{bmatrix} B_{x'} \\ B_{y'} \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} B_x \\ B_y \end{bmatrix} \quad (6)$$

where $\begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}$ is the rotation matrix.

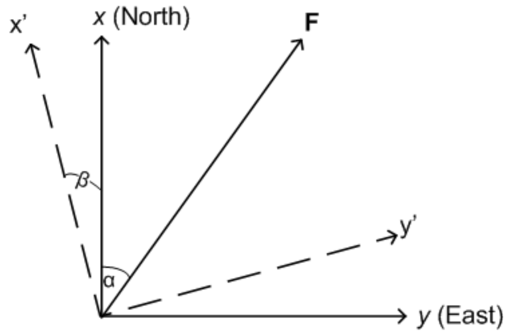

Fig. 4. An example to illustrate the transformation from one coordinate system to the other

Consider a situation where the power line is at an angle θ from the Geographic North. Let the horizontal components of the magnetic field (**B)** in the geographic coordinate system be B_x, B_y. Then the horizontal components of **B** in the power line coordinate system $B_{x''}$, $B_{y''}$ will be achieved through the following transformation

$$\begin{bmatrix} B_{x''} \\ B_{y''} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} B_x \\ B_y \end{bmatrix} = \begin{bmatrix} \cos(\beta+\theta) & \sin(\beta+\theta) \\ \sin(\beta+\theta) & \cos(\beta+\theta) \end{bmatrix} \begin{bmatrix} B_{x'} \\ B_{y'} \end{bmatrix} \quad (7)$$

4 CONCLUDING REMARKS

In order to get accurate estimates of the GIC in a power line by means of the DMM, it is essential to consider all the aspects presented in this paper. Though selected magnetometers may differ, we believe that the tests and processes discussed are applicable and will go a long way in improving the quality of the measured field as well as the accuracy of the estimated or modelled GIC.

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