Measurement of the geomagnetically induced currents (GIC) by the solar activity

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Abstract: The aim of this study is to measure the currents geomagnetically induced by the solar activity in the high-voltage powerlines of the electric grid, in order to evaluate when its influence can be a risk to these lines and the electrical supply. The procedure is based on the measurements of magnetic field near the lines. The data was collected in Masdenverge (Tarragona). In this work I have developed a Python program to process these data and obtain an estimation of the GIC in the line. The preliminary results show the validity of this method.

I. INTRODUCTION

The Earth's magnetic field is composed by two contributions, the internal and the external fields. The first one is created by the remaining magnetization of some materials and the outer core, due to the fact that this layer is composed by conductive material in movement; this event is called the dynamo's effect. The external field is created by the solar activity. Its most important characteristic is the variations of this field that occur in a short time scale. These variations are caused by the solar storms that happen when the solar wind reaches the magnetosphere and ionosphere, colliding with the atoms of this Earth's atmospheric layer, and ionizing them. The electromagnetic theory states that a variable magnetic field induces an electric field, therefore, variations of the external geomagnetic field can induce electric currents that can be linked to the electric powerline network. In such a case, the GIC appear in the powerlines.

The measures of the GICs in different parts of the world [1] have allowed us to know that GIC are of low frequency (<1 Hz). Thus, GICs are considered to have a quasi-DC current behaviour. The transformers are the elements of the electric powerline network grounded, thus they become the way where GICs can flow to the powerlines.

Although the measures and the observation of increases of current can easily be done using an ammeter, the parameters of the electric grid are very tight and elements like ammeters change this configuration, therefore, the powerline companies prefer other people to not put instrumentation in the lines, because the parameters of the electric grid are very tight and elements like ammeters change this configuration. Then, it is better to do indirect measures. Therefore, the purpose is to work in a way to indirectly determinate the magnitude of the GICs so as to prevent its non-desired effects to the electric grid.

II. MEASURE'S METHOD

The proposed method of measure of the GICs is based on magnetic field measurements near the powerlines. The Ampere's law allows to know the relationship between the magnetic field created by a conductor and its current's intensity:

$$\oint_{\Gamma} \vec{B}\,\overrightarrow{dl} = \mu_o I_{in} \qquad (1)$$

The law is in integral form, where B is the magnetic field, μ_o is the vacuum's magnetic permeability, I_{in} is the intensity flowing through the conductor and the integral and the integral is along a closed circuit Γ that passes through the point of measure of B. The expression (1) is only valid when the medium is not magnetic and thus its magnetic permeability can be considered as the vacuum's permeability. The air, which is the medium that surrounds the powerlines, can be considered as vacuum in our study due to its low density. If the objective is to measure a value of the magnetic field, a detector will register different contributions: in the first place, the geomagnetic field of the zone. In the second place, the current flowing through the powerlines generates a magnetic field that becomes a contribution in the measurement. And finally, there is an induced current in the ground that generates magnetic field too. As it can be seen in reference [2], this last contribution said can be simulated, considering a homogeneous ground, by a virtual powerline under the ground that is farthest than the powerlines. Because of that, this contribution has less order of magnitude. Then, considering the powerlines of the electric grid as a very long and thin conductor, the expression of the magnetic field created by currents can be reduced to:

$$B \approx \frac{\mu_o I_{in}}{2\pi h} \qquad (2)$$

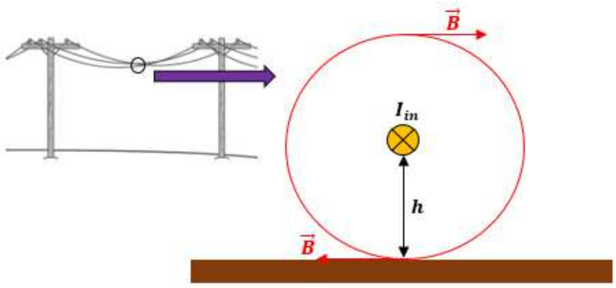

FIG. 1: Scheme of the powerlines.

Where h is the distance between the conductor and the point of measure of B. In the case that the measure is done under the line, h is the height of the powerlines. In order to obtain the contribution of GICs, the proposal is to measure the magnetic field in two different points: the first one under the

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powerlines and the other one far enough from the powerlines so that the contribution of a possible GIC is virtually zero.

Then, the difference between a quiet day and an active day has to be known. From geomagnetism's point of view, a quiet day is a day when the solar activity is low and consequently its influence is negligible (no existence of GICs). On the other hand, in an active day the solar activity is enough important to consider its magnetic influence, thus can appear GICs.

With the measures of magnetic field from both points in a quiet day it can be obtained a transfer function that relates the magnetic field under the powerlines and the magnetic field of the point far from these lines. This is called the Interstation Transfer Function [3]. Considering the conductivity of the ground constant, M can be considered non depending on time. Besides, M is a relationship for the horizontal components x and y, thus the vertical component of the magnetic field is not considered:

$$\vec{B} = \vec{\vec{M}}\vec{B}_o \qquad \begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{pmatrix} M_{xx} & M_{xy} \\ M_{yx} & M_{yy} \end{pmatrix}\begin{pmatrix} B_{xo} \\ B_{yo} \end{pmatrix} \tag{3}$$

Where $\vec{\vec{M}}$ is the interstation transfer function, which is a complex tensor, and $\vec{B}$ and $\vec{B}_o$ are the magnetic fields measured under and far from the lines respectively.

Now, repeating these measures in an active day, the magnetic fields will be $\vec{B}'$ and $\vec{B}_o{}'$. Although in this case the contribution of GICs will exist, $\vec{B}'$ can be separated in two contributions: in the first place, the GICs contribution, and in the second place, the other ones:

$$\vec{B}' = \vec{B}_{GIC} + \vec{B}_{non\ GIC} \tag{4}$$

The $\vec{B}_{non\ GIC}$ would be the field under the lines in the case that the day was quiet, thus it is equivalent to the $\vec{\vec{M}}$ tensor with the field measured far from the lines. Therefore, the equation (4) can be rewritten as the following one:

$$\vec{B}_{GIC} = \vec{B}' - \vec{\vec{M}}\vec{B}_o{}' \tag{5}$$

As the result, knowing the magnetic fields under and far from the lines the contribution of the GICs in an active day can be determined using a transfer function calculated for a quiet day.

The next step is to consider the appropriate coordinate system where the powerlines are in the x direction (system O''). The conversion for a system with powerlines that have an azimuth α is the following one:

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} \tag{6}$$

The x corresponds to the North-South direction and y to the East-West direction. In O'' the expected result for the magnetic field created by the lines is a x'' component equal to zero and thus the y'' component is equal to the total magnetic field. This y'' component is the one who has to be used in Ampere's law to calculate the intensity of GICs:

$$B_{GIC_{y''}} = (-\sin\alpha \quad \cos\alpha)\vec{B}_{GIC} \tag{7}$$

Where $\vec{B}_{GIC}$ is the exposed in the equation (5). The final step is to calculate the intensity using the Ampere's law for a long line (2):

$$I_{GIC} = \frac{2\pi h}{\mu_o} B_{GIC_{y''}} \tag{8}$$

Where h is the height of the powerlines. Therefore, the problem of measuring GICs intensity consists of knowing the physical parameters (height and azimuth), measuring the magnetic field in the two points of measure and determining the interstation transfer function M. The estimation of this function is based on the procedures used in the Magnetotellurics method.

The Magnetotellurics method (MT) is a geophysical technique using natural sources. The measured magnitudes are the magnetic and electric fields and it is used to determine the ground's parameter of conductivity. Indeed, this fields are a superposition of the incident electromagnetic waves with the secondary generated fields induced in the ground. In spite of the habitual use, in the study only the values of the magnetic fields are used. Therefore, the instrumentation consists of the use of magnetometers. A magnetometer is an instrument that measures the magnetic field thanks to its appropriate calibration. In the case of this study the magnetometers were three components fluxgate ones that measures the three components of the magnetic field.

FIG. 2: One of the three fluxgates.

With the purpose of obtaining the values of magnetic field in the two points of interest, we measured B in a high-voltage (400 kV) powerline lines located in Masdenverge, Tarragona. Due to the calm of the place the measures were not influenced by other possible magnetic sources which are not interest of study. In order to obtain the values for the point far from lines, the data from station at Horta de St. Joan (station EBR of intermagnet) owned by Observatori de l'Ebre was used.

III. SIGNAL PROCESSING

The GICs intensity seems that could be obtained directly from equation (8). However, the steps of calculation explained before have to be done in the frequencies domain: Thinking in terms of the signal's processing theory, we have the output signal y(t) of the system and the input signal x(t). The relationship between both is the called transfer function h(t): the convolution product between the transfer function and the input signal is the output signal:

$$y(t) = h(t) * x(t) \tag{9}$$

Applying the Fourier transform to the convolution product it becomes the arithmetic product as the Convolution's Theorem says. Therefore, the equation (9) can be rewritten as the equation (10):

$$Y(f) = H(f) \cdot X(f) \tag{10}$$

$$(F[y(t)] = F[h(t) * x(t)] = F[h(t)] \cdot F[x(t)])$$

Where F is the Fourier's transform operator. Now, figuring the field B (under the lines) as an output signal and the field Bo (from the Observatori de l'Ebre) as an input signal, it is easy to see that it is required to work in the Fourier space in order to obtain the magnetic field B from the natural product of a transfer function with the field Bo.

A. How to obtain the transfer function M

The Interstation Transfer Function was already given. It was calculated using estimations and more information about this can be obtained in the study of the reference [3].

With this information the coefficients M_{xx}, M_{xy}, M_{yx} and M_{yy} can be obtained. Its values were interpolated to have the same frequencies of the measured magnetic fields.

B. From time space to frequencies space: The Short Time Fourier Transform (STFT)

Once the M is obtained and prepared to the calculation, the next step is to pass the magnetic fields data to the frequency space. The most known method is the conventional Fourier transform. This method takes a signal and decomposes it in a superposition of periodic signals, giving, as the result, the spectrum decomposition: a distribution of frequencies with its respective amplitudes. However, in this work we have considered the Short Time Fourier Transform (STFT), which provides information about the changes of the spectrum of the signal in time (what it is called a spectrogram).

The measures of this experiment are a sampling of values at a given sampling frequency. Before applying the Fourier transform, the signal must be prepared: in the first place, if the signal has a trend it has to be eliminated, because the Fourier transforms are thought for a detrended signal. In the second place, a window function (from the beginning to the end of the signal) has to be applied in order to prevent discontinuities. Once it is done, the Fourier transform can be done and then all the calculations.
With Fourier transforms time series are converted to the frequency-time representation applying the STFT, and the result corresponds to a two-dimensional array along time and frequency.

C. Calculation of the GICs signal

Once the transfer function M and the magnetic fields $\overrightarrow{B'}$ and $\vec{B}_o{}'$ are prepared, the equations (5), (7) and (8) can be done in order to obtain the I_{GIC} in the frequency domain. The final step that it has to be done is to do the inverse STFT, so as to get the signal of $I_{GIC}(t)$ in the time domain.

IV. RESULTS

The measures of the experiment were recorded the 25, 26 and 27 of August 2018, one under a powerlines in Masdenverge, Tarragona (FIG. 3) and the values from Bo were obtained from the Observatori de l'Ebre's database (www.observatoriebre.cat) (FIG. 4). The data of both fields corresponds to and have a sampling frequency of 1 Hz. The parameters of the experiment were the following ones: the height of the line is 20.5 meters, and its azimuth is 48 degrees.

The signal processing was done using the developed program in Python. The program imports the values of magnetic fields and the transfer function M, transforms the values to the frequency domain (Fourier transforms), does the relationship operations and an inverse transformation of the values, and applies the expressions (5)-(8) to get the I_{GIC}.

In the following figures FIG.3 and FIG.4, the obtained magnetic fields B and B_o are plotted. The horizontal axis corresponds to the time series and the vertical axis to the variations of the magnetic field. These variations are respect zero because the data series are detrended.

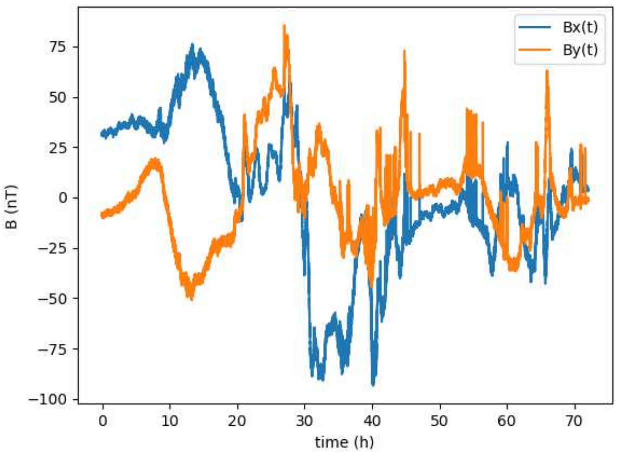

FIG. 3: Data series for the magnetic field under the lines.

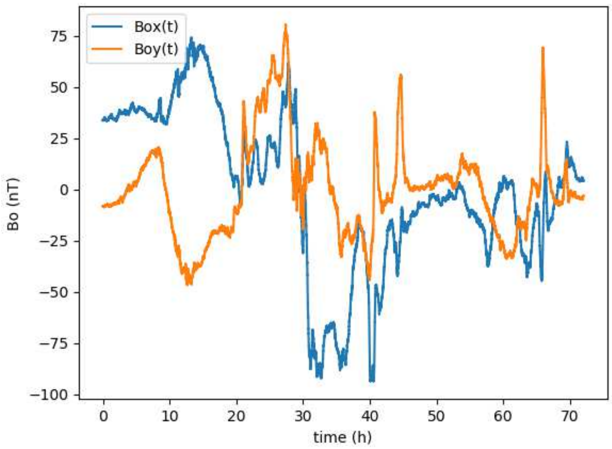

FIG. 4: Data series for the magnetic field from Observatori de l'Ebre.

Hereunder, it is shown the spectrogram of the signal measured under the lines, corresponding to the days 25, 26 and 27 of August 2018. The number of data points corresponding to each STFT segment is 8192 and it has applied a rectangle window with an overlap of the 50% of the window.

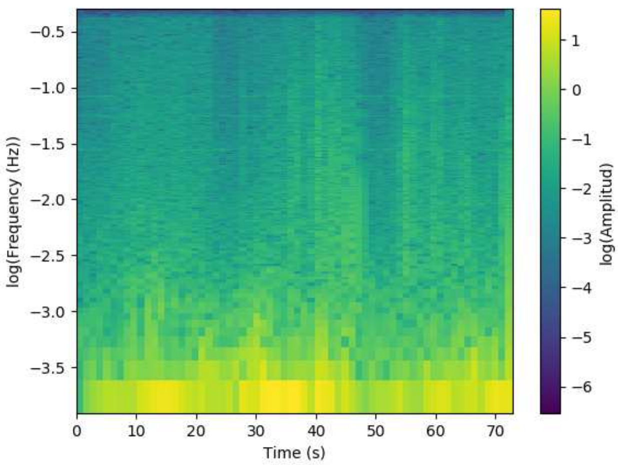

FIG. 5: Spectrogram of the measured signal under the lines.

The horizontal axis corresponds to the times (hours) and the vertical axis to the frequencies (in a logarithmic scale). The pixel of each point (x,y) is more brighter or less depending on the amplitude (and thus the magnitude) of the signal at the corresponding frequency and time. Spectrograms are the way to observe when the solar activity is more intense: the changes of the magnetic field implies the observation of higher frequencies in the signal. In this case, the frequency corresponding to the AC current of the electric grid is not observed because it is a higher frequency than the sampling frequency, and then the changes cannot be seen. Observing FIG. 5 it is possible to see, for example, solar activity near the hour 12 (half day of the 25/08/2018).

At last, after doing all the steps of calculation, the obtained signal for the GICs is the following one:

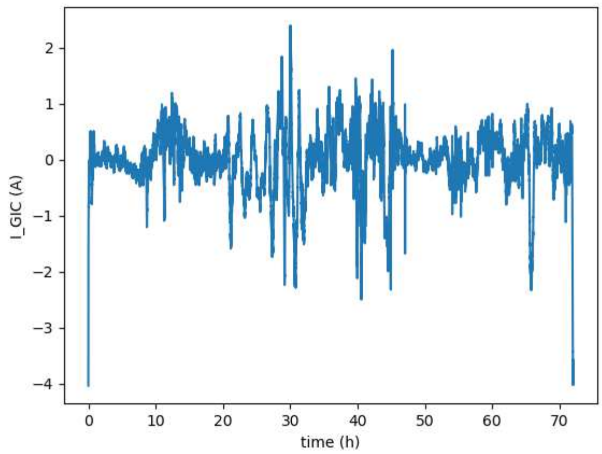

FIG. 6: Signal of the GICs intensity.

The horizontal axis corresponds to the times and the vertical axis to the GICs intensity, in amperes. It can be seen that the signal is not near zero. Indeed, there are some peaks with a magnitude of one ampere. Besides, comparing to the spectrogram shown in FIG.5, the points with peaks of frequency corresponds, in FIG.6, to the peaks of intensity.

Finally, these values can be compared to the common current in the line. The frequency of the common electric grid signal is 50 Hz. In order to obtain it in the spectrum of the signal, the sampling frequency must be at least two times bigger than the 50 Hz, because the maximum frequency that can be obtained with Fourier transforms is the Nyquist frequency that equals to the half of the sampling frequency. For example, with a sampling frequency of 500 Hz, the 50 Hz of the electric grid can be obtained. Then, applying equation (2), the results for common current in the lines are the following one:

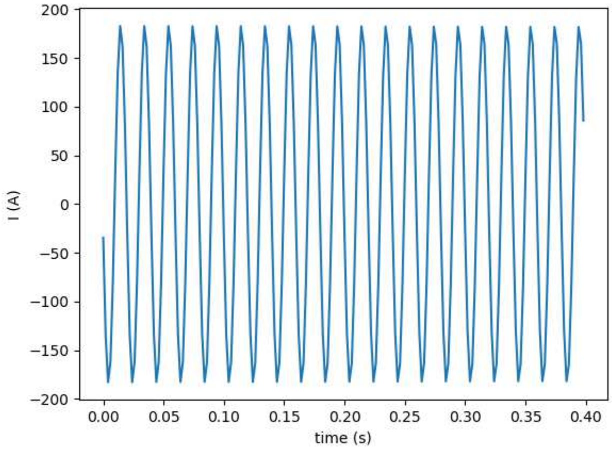

FIG. 7: Signal corresponding to the 50 Hz of the electric grid.

It can be seen that the maximum amplitude is 183 A, two orders of magnitude higher than the amplitude of the measured GICs.

V. DISCUSSION OF RESULTS

It can be seen that the order of magnitude of GICs is around 1 ampere, which is two orders of magnitude smaller in compare to the habitual intensity of the lines. The reason is that the sun is in a minimum of its activity, so the measures of induced currents are not expected to be high. However, they must not be forgotten because it is known that in cases of maximum of solar activity this currents can reach high intensities, like what happened in Quebec in 1989 [4], where the increase of the intensity produced an important blackout.

VI. CONCLUSIONS

In this work it has presented a method and a program to estimate the GICs in a powerline. Although some approximations had to be done and the Interstation Transfer Function has an associated error, the objective of knowing the order of magnitude of GICs has been completed: the program made takes the experimental values from a file, plots the data series, makes the direct and inverse Fourier transforms, shows a spectrogram of the signal and obtains the intensity values. Therefore, it works for studies of any active period of time in which it is wanted to know the magnitude of the GICs.

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