Perturbation Measurements on HV Overhead Lines using Electric Field Sensors

Pedro Issouribehere, Daniel Esteban, Fernando Issouribehere, *IEEE* Member, Gustavo Barbera, and Hugo Mayer

***Abstract*—** It is widely known that in most countries there are severe Power Quality rules that Utilities as well as customers have to comply with. Therefore, it is necessary to assess carefully the levels of disturbances.

The traditional procedure to determine the origin of such disturbances is to perform field measurements in all the plants containing power electronic equipment, electric arc furnaces, etc., located near the point in which high levels of disturbances have been detected. Nevertheless, in most cases field engineers find it difficult to have access to the plants belonging to Utilities and also to the different industries settled nearby, which are also likely to emit disturbances. In addition, the task of installing the PQ recorder in the electrical cabinets inside the plant demands a considerable time, as well.

With the intention of avoiding all the difficulties that can arise when field engineers are searching for a disturbing load, it was considered a great challenge to design a novel device to make the field work simpler. Such a challenge was based on designing a measuring system capable of recording voltage waveforms with no physical contact with the installations and without the assistance of Utilities personnel. In order to achieve this goal an Electric Field Sensor (EFS) was employed in the design of the measuring system.

This paper deals with the results of testing an electric field measurement system – completely designed by the authors – for monitoring voltage Flicker and harmonics in overhead power systems [1]-[3]. Some results of field measurements performed in plants containing disturbing loads are shown.

***Index Terms*—** Disturbing Load. Electric Field Sensor (EFS). Flicker. Harmonics. Total Harmonic Distortion.

I. INTRODUCTION

The public electricity service in Argentina, which was privatized in the early nineties, is carried out by different Agents and the control is performed by a Regulatory Agency (ENRE). The IITREE of La Plata University provides technical assistance to the Utilities and the Authorities.

Nowadays, after almost twenty years of experience, it is possible to conclude that when it is necessary to find a disturbing source, traditional measurements through voltage transformers in many places could be impractical, time consuming, and expensive.

In this article, an alternative way of measuring voltage perturbations based on sensing the Electric Field is described in detail. Experimental and field measurements results validate the proposed method.

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II. FUNCTIONING PRINCIPLE OF EFS

Unshielded electrical power systems generate electric fields, which can be measured accurately at distances from the conductors that are one order of magnitude larger than typical system dimensions. The field at a particular location and time is a function of the instantaneous voltage on all conductors and depends on the geometry of both the power system and its environment.

The electric current that flows between the plates of a parallel-plate capacitor immersed in an electric field – as shown in Fig. 1 – is given by:

$$i_C(t) = \omega \cdot \varepsilon_0 \cdot A \cdot E \cdot \cos(\omega t) \tag{1}$$

Where:

ε_0: Permittivity of free space = 8,854x10-12 [F/m]
A: Surface area [m^2]
E: Electric field magnitude [V/m]

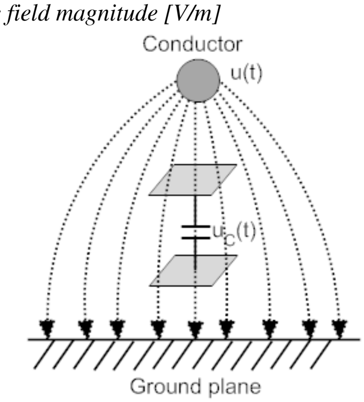

Fig. 1: Measuring electric field between two electrodes.

If an external capacitor C_B is connected between the parallel plates, and if this capacitor is not influenced by the electric field E – as shown in Fig. 1 – the capacitor potential magnitude is given by:

$$\dot{U}_C = -j \cdot \dot{I}_C \cdot X_C = \frac{-j \cdot \dot{I}_C}{\omega \cdot C_B} = -j \cdot (\varepsilon_0 \cdot A / C_B) \cdot E \tag{2}$$

It can be deduced that the potential in the capacitor C_B is proportional to the electric field E through a transduction constant:

$$k_E = (\varepsilon_0 \cdot A / C_B) \text{ [m]} \tag{3}$$

This relationship is independent of frequency, and therefore, if the electric field varies randomly, also the electric potential will follow the same rule. In general:

$$u_C(t) = k_E \cdot e(t) \tag{4}$$

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On the other hand, the electric field e(t) at a point between two electrodes of an electric system, which are subjected to an electric potential difference u(t), as it is shown in Fig 1, and the potential u(t) are linearly related by a constant k_G that depends exclusively on the system geometry:

$$e(t) = K_G \cdot u(t) \tag{5}$$

If the expression (5) is substituted in expression (4) results:

$$u_C(t) = k_E \cdot k_G \cdot u(t) \tag{6}$$

The final conclusion is that if the potential across the capacitor CB is measured, it can be obtained through the constants k_E y k_G the electric potential u(t). If a voltage gain G_V is included between the measured potential $u_m(t)$ and the existing potential in the capacitor $u_C(t)$, it is possible to obtain the final expression:

$$u(t) = \frac{u_m(t)}{G_V \cdot k_E \cdot k_G} \tag{7}$$

Where:

u(t): Potential to be determined [V].
$u_m(t)$: Potential measured with the EFS [V].
G_V : Voltage gain between the output of the electric field sensor and the measurement equipment [V/V].
k_E: EFS transduction constant = $\varepsilon_0 A / C_B$ [m].
k_G: Geometric constant of the physical installation [1/m].

For the case of sensing the waveshape, as it is the case of measuring perturbations referred to the fundamental frequency voltage, it is not necessary to know the constants G_V, k_E, k_G, been sufficient to verify the linearity and the independence of frequency.

III. SIMULATION OF EFS PERFORMANCE IN MEASURING HARMONICS

In order to verify the ability of EFS to measure voltage harmonics and flicker in a three-phase system, some MATLAB simulations were performed. Fig. 2 shows the EFS placed in a generic point near a three-phase system.

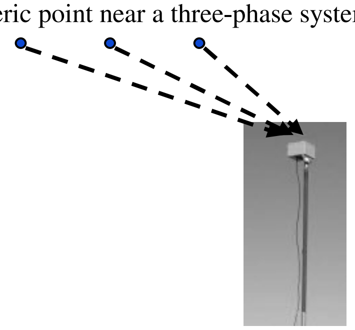

Fig. 2: EFS placed near a three-phase transmission line.

The voltage measured across the EFS sensor is a composition of the three-phase voltages, as is described in (8).

$$\dot{U}_m = k_1\left(\dot{U}_{R1} + \dot{U}_{Rh}\right) + k_2\left(\dot{U}_{S1} + \dot{U}_{Sh}\right) + k_3\left(\dot{U}_{T1} + \dot{U}_{Th}\right) \tag{8}$$

Where:

$\dot{U}_{R1}, \dot{U}_{S1}, \dot{U}_{T1}$ *: Fundamental values of each phase voltage.*

$\dot{U}_{Rh}, \dot{U}_{Sh}, \dot{U}_{Th}$ *: Harmonic values of each phase voltage.*

$\dot{U}_m$ *: Potential measured with the EFS [V].*

k_1, k_2 and k_3: Coupling geometric constants.

Solving equations, the relationship between the measured harmonic voltage and the real harmonic value (both referred to the fundamental value) is described in (9):

$$\left|\frac{\dot{U}_h}{\dot{U}_1}\right|_{measured} = \left|\frac{\dot{U}_h}{\dot{U}_1}\right|_{real} \cdot \frac{k_1 + k_2 e^{-jh120^\circ} + k_3 e^{jh120^\circ}}{\left(k_1 + k_2 e^{-j120^\circ} + k_3 e^{j120^\circ}\right)} \tag{9}$$

As it was mentioned above, the goal of the simulations was to determine what the system measures when it is exposed to a three-phase system. Therefore, a three-phase voltage containing harmonics from the 2^{nd} order to the 6^{th} order was applied to the system. In addition, three different sets of arbitrary values of k_1, k_2 and k_3 were chosen. The amplitude of each harmonic order was fixed so as to achieve a relationship between them that can be considered representative.

The results obtained from simulations are summarized in Table I. It is possible to conclude that the system measures properly positive and negative sequence components but not zero-sequence components. The measured zero-sequence voltages are sensitive to the coupling geometric constants.

Table I. Simulation results.

Harmonic number [h]	Sequence of Harmonic [h]	Amplitude [%]	Measured voltage [%] $k_1 = 1$ $k_2 = 0.66$ $k_3 = 0.33$	Measured voltage [%] $k_1 = 1$ $k_2 = 0.1$ $k_3 = 0.05$
2	-	**1**	1	1
3	0	**2**	6.86	2.48
4	+	**1**	1	1
5	-	**10**	10	10
6	0	**1**	3.43	1.24

IV. EFS HV LAB EXPERIENCES AND CONTRAST

To verify the ability of EFS to measure perturbations, the EFS was installed below a high voltage cable in IITREE-UNLP High Voltage Lab, as shown in Fig. 3.

The cable was fed by a 220V/50 kV transformer, which was excited by an electronic power generator. In this generator, the voltage fluctuation amplitude and frequency can be programmed in such a way that a specific Flicker level can be adjusted. The generated Flicker magnitude was measured with a second IEC recorder, connected in a traditional way. For measuring voltage harmonics, a similar test was performed.

Fig. 3. EFS placed in the High Voltage Lab.

Table II and Table III show the results of flicker and harmonic measurements, respectively:

Table II. Flicker measurement results.

Flicker		Fluctuations [changes per minute]					
		1620			110		2
Pst [pu]	Generated	1.05	1.81	7.99	1.05	1.93	1.03
	Measured with EFS	1.08	1.88	8.35	1.04	1.93	1.03

Table III. Harmonic measurement results.

Harmonics		Order						
		3º	5º	7º	9º	11º	13º	15º
Level [%]	Generated	2.93	2.90	2.89	2.84	2.81	2.77	2.69
	Measured with EFS	2.96	2.93	2.93	2.88	2.86	2.84	2.78

In the case of Flicker, the performed comparison ensures that the measurement system EFS + recording equipment meet the standardized tests to achieve a measuring error not larger than ±5 %, as the one accepted in IEC 61000-4-15 standard.

Regarding harmonics, the performed comparison ensures that the measurement system EFS + recording equipment meet standardized tests for equipment Class I according to IEC 61000-4-7 standard [4]-[6].

V. FIELD MEASUREMENTS PERFORMED WITH EFS

As it was mentioned above, the main purpose of this measuring system is to search for disturbing loads by sensing the electric field below overhead lines. Therefore, in order to assess its performance a number of field tests were carried out.

At first, a measuring campaign was performed in Buenos Aires province transmission network.

Measurements were made in the surroundings of Bragado 132 kV node. This node is fed by a 220 kV transmission line, which is part of the main interconnected grid in 500 kV.

Regarding Flicker, an instrument measuring the Pst in a normalized 10-minute period, was installed in a low voltage level of Bragado distribution network (220 V), and was used as a reference for those measurements performed below the high voltage lines with the EFS. All the measurements performed with EFS were synchronized and correlated with the low voltage Flicker measurements.

With the purpose of making the field work easier, a special frame was designed to attach the EFS to the roof rack of a vehicle. In the interior of the vehicle, a harmonic and flicker recorder and a computer were installed. In Fig. 4 a general view of the whole system is shown.

The appropriate EFS location is determined by moving it bellow the overhead line until obtaining a voltage signal within the dynamic range of the recording equipment.

The measurement period was over one hour, whereas the integration period was fixed at 10 minutes.

Fig. 5 shows the results of simultaneous Flicker measurements in Bragado 220 V (traditional measurement) and in Bragado 132 kV high voltage line with the EFS.

Fig. 4. Electric Field Sensor (EFS) on the roof rack of the vehicle.

In addition to the good correlation observed between both measurements, an upstream to downstream Flicker transfer coefficient within 0.75 to 0.8 could be established for high Flicker values.

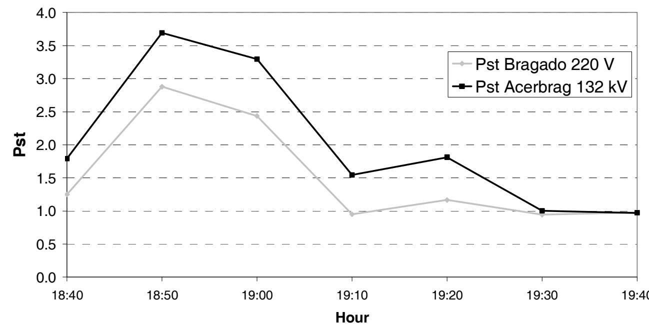

Fig. 5. Simultaneous Flicker measurements in Bragado node. Traditional method in LV network, and EFS method in HV line.

Fig. 6 shows the results of simultaneous Flicker measurements in Bragado 220 V (traditional measurement) and in Chivilcoy and Bragado 132 kV overhead line with the EFS.

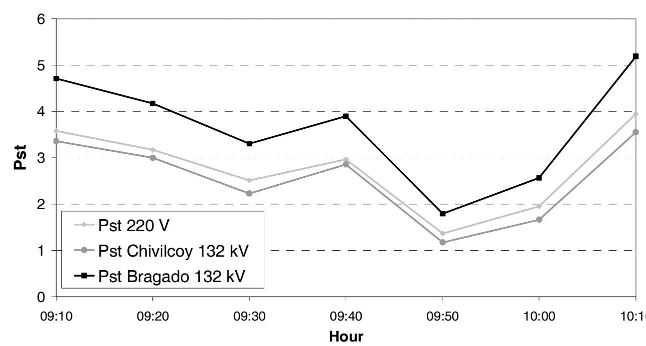

Fig. 6. Simultaneous Flicker measurements. Traditional method in LV network, and EFS method in HV lines.

Considering the higher values, the relation between the Flicker measurements in Bragado 132 kV and Chivilcoy 132 kV is 0.71.

Regarding the main harmonics, the obtained results are shown in Figures 7 to 9.

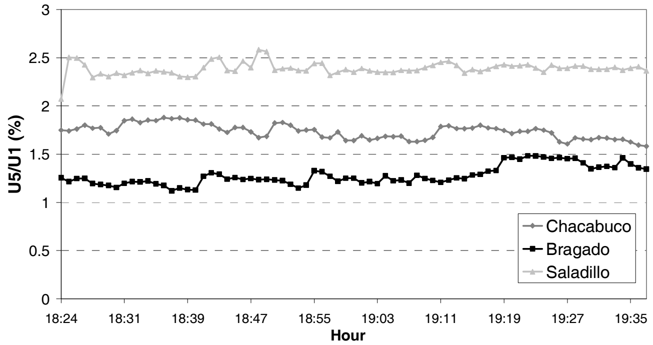

Fig. 7. 5th harmonic profiles in 132 kV transmission lines.

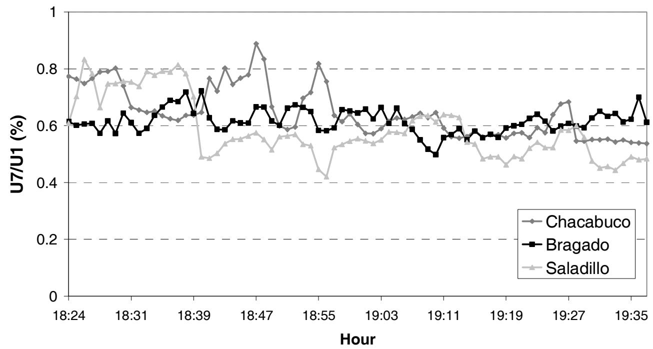

Fig. 8. 7th harmonic profiles in 132 kV transmission lines.

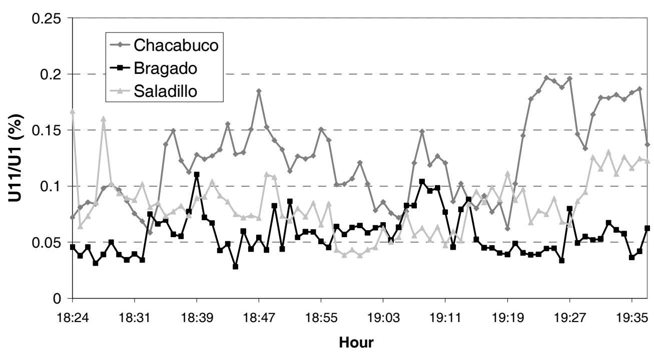

Fig. 9. 11th harmonic profiles in 132 kV transmission lines.

By this simple way, it is possible to measure with appropriate sensitivity the voltage harmonics, and to determine which nodes have a higher probability of meeting the Power Quality limits established in Argentina. As a result, it is possible to conclude that:

- Saladillo 132 kV node exceeded the 5th harmonic limits (2 % in IEC 61000-3-6 [7] and 1.5 % in IEEE 519-1992 [8]).
- Chacabuco and Bragado nodes are within the International and Argentinian limits. However, in the case of Chacabuco node it should be checked longer (i.e. by performing a one-week normalized measurement).

A few months later, another measurement was performed in several 132 kV transmission lines, in the south of Santa Fe province, Argentina.

In that case, voltage harmonics were measured by using two different recorders, i.e. one installed in the substation through the existing Voltage Transformers, whereas the other working together with the EFS. In Figures 10 to 13 the trends of 3rd, 5th, 7th and 11th voltage harmonics are shown. Consequently, only the 3rd one is a zero-sequence component.

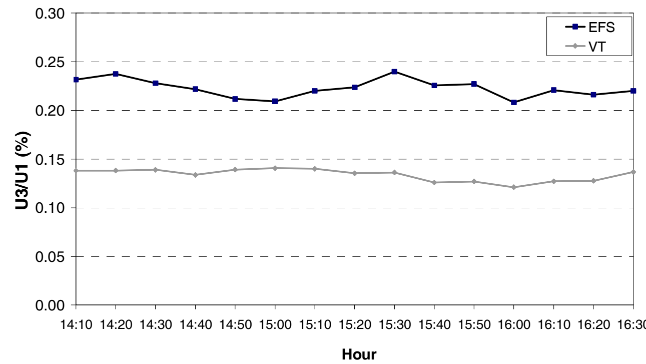

Fig. 10. 3rd harmonic trend.

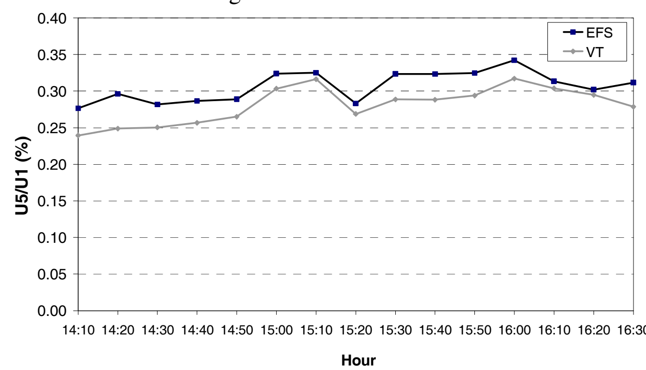

Fig. 11. 5th harmonic trend.

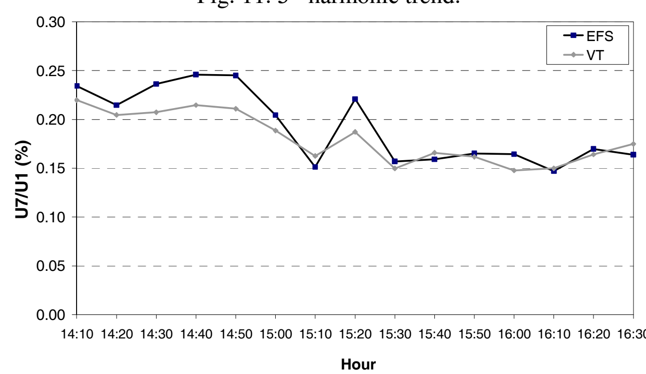

Fig. 12. 7th harmonic trend.

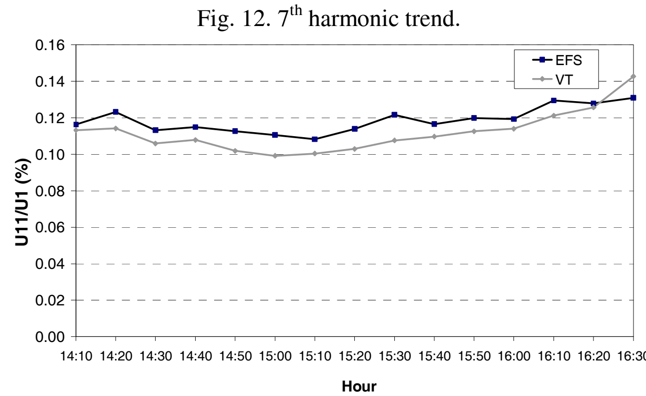

Fig. 13. 11th harmonic trend.

As it is observed in the profiles, for 5th, 7th and 11th harmonics the measurement carried out with the EFS shows a pattern similar to that one performed with the recorder connected to the Voltage Transformer. Nevertheless, as regards 3rd harmonic, the difference noticed between both trends is highly significant.

VI. CONCLUSIONS

The increasing interest in performing Power Quality measurement campaigns on transmission and distribution systems, at present, is in contrast with the following aspects:

• The voltage transformers used to measure voltage perturbations in MV or HV substations are not usually available in-site because they are under utilities commercial jurisdiction. In other circumstances their connection is so expensive that cannot be justified.

• In harmonics measurements, the adequate frequency response of voltage transformers must be proven and it is very common to find that they do not have an appropriate bandwidth (BW).

• Bandwidth requirements can be solved by using capacitive voltage dividers, such the ones used in High Voltage Labs, but they require much more room and, in consequence, it is not always possible to fit them inside a power substation. Sometimes it is also necessary to switch-off the substation or the specific power line - where the disturbances should be measured - in order to connect the measuring equipment. In many cases it is impossible to perform those operations.

The Electric Field Sensor (EFS) designed by IITREE-UNLP can be used to measure voltage disturbances that are referred to the voltage nominal value - such is the case of Harmonics and Flicker. The EFS has the following advantages:

- The measurements based on the EFS represent a practical method to measure harmonics, flicker and other perturbations related to industrial frequency voltage, in compliance with IEC rules.
- By using this device it is possible to measure voltage disturbances in a simple way, without getting into the plants. Therefore, it can be used as a powerful tool to find disturbing loads along overhead transmission/distribution grids by having access to them from public areas.
- It is also a powerful tool to assess the impact of massive power electronics embedded in the integration of renewable sources to the power system. At the moment, in Argentina a large number of wind farms are being completed. By using this technique, a statistical inspection of Power Quality in extended electrical systems will be carried out in 2013.
- Only in those points in which high levels of disturbances were detected, an IEC normalized one-week measurement should be performed [5]. This traditional method involves connecting the PQ recorder to the electrical cabinets inside the plant and measuring not only the harmonics in the voltage, but also those emitted by customers.
- The EFS based measurement method is particularly useful when both cost and physical location drawbacks cannot be addressed.

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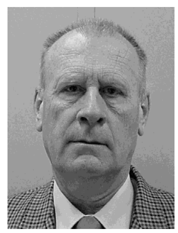
VIII. BIOGRAPHIES



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