PERTURBATION MEASUREMENTS ON OVERHEAD NETWORKS USING ELECTRIC FIELD SENSORS

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ABSTRACT

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 aerial power systems [1].
To prove the viability of this technique, an electric field sensor (EFS) was installed in our University High Voltage Laboratory, and in the HV network near a steel mill.
Using the output of the electric field sensor, the voltage perturbations in any of the mentioned scenarios were determined. The deduced voltage perturbations agreed with direct measurements using conventional capacitive and resistive voltage dividers and voltage transformers.
This technique can be used where cost or physical location drawbacks make the use of conventional methods difficult.

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 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.

DESCRIPTION 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:

$$i_C(t) = \omega \cdot \varepsilon_0 \cdot A \cdot E \cdot \cos(\omega t) \qquad (1)$$

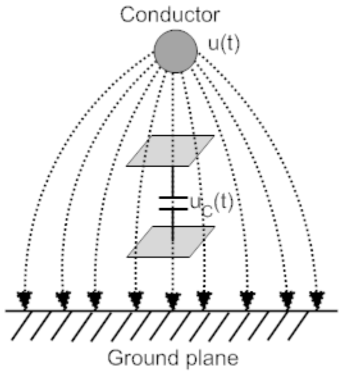

Fig. 1. Measuring electric field between two electrodes.

Where:

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

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:

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

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:

$$u_C(t) = k_E \cdot e(t) \qquad (3)$$

On the other hand, the electric field e(t) at a point between two conductors of an electric system is a consequence of an electric potential difference u(t), as shown in Fig 1.

The final conclusion is that if the potential across the capacitor C_B is measured, the electric potential u(t) can be obtained as:

$$u(t) = \frac{u_m(t)}{G_V \cdot k_E \cdot k_G} \qquad (4)$$

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 measured perturbations referred to the fundamental frequency voltage, it is **not necessary to know the constants G_V, k_E, k_G**, being enough to **verify the linearity and the independence of frequency**.

HV LAB EXPERIENCES AND CONTRAST

To verify the ability of EFS for measuring perturbations, the EFS was installed below a high voltage cable in IITREE-UNLP High Voltage Lab, as shown in Fig. 2.

Fig. 2. EFS placed in the High Voltage Lab, under a cable fed with fundamental frequency voltage and Flicker.

The cable was fed by a 220V/50 kV transformer, which was excited with 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 normalized electronic equipment, connected in a conventional way, as shown in Fig. 3.

Fig. 3. Electronic power generator, Flicker measured through voltage measurement (black equipment over the table) and Flicker measured through EFS (white equipment).

For measuring voltage harmonics, a similar test was performed.

Table I and Table II show the results of Flicker and harmonic measurements, respectively:

Table. I: Flicker measurement results

Flicker		Fluctuations [changes per minute]					
		1620			110		2
Pst [p.u.]	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. II: 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 [2] 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 [3] standard.

EFS FIELD MEASUREMENTS

Flicker measurements

In order to verify the effectiveness of this technique for detecting the presence and for quantifying the amount of Flicker in high voltage networks, a measuring campaign was performed in Buenos Aires province transmission network.

Measurements were made in the surrounding area of Bragado 132 kV node. A one-line-diagram transmission system is depicted in Fig. 4.

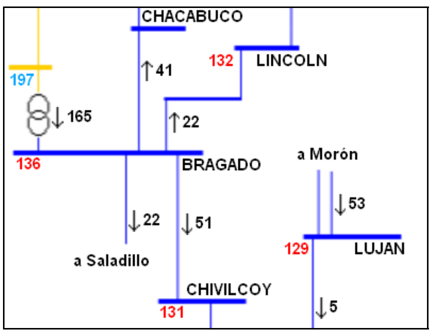

Fig. 4. One-line-diagram of the Argentinean transmission system in the nearest of Bragado.

This node was fed by a 220 kV transmission line, which is part of the main interconnected grid in 500 kV. Bragado node supplies a wide geographical area in the centre of Buenos Aires province in 132 kV.

Recording equipment, measuring Flicker in the traditional way and every 10 minutes, was installed in a low voltage level of Bragado LV (380/220 V) distribution public network, and was used as reference for measurements performed below the high voltage lines with the EFS. All measurements carried out with EFS were synchronized and correlated with the low voltage Flicker measurements

The results of Flicker measurements in the low voltage network of Bragado city are shown in Fig. 5.

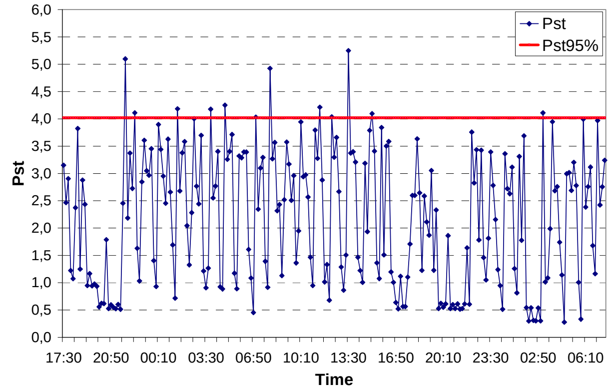

Fig. 5. Flicker measurements in Bragado City.

The Flicker value not exceeded in both time and space with a 95% probability was $P_{st} = 4$. This value was 4 times higher than the acceptable limit, according to international standards and Argentinean regulations [4].

For starting the field measurements, the EFS was placed on top of a pole, approximately 2 meters above ground, to avoid the influence of nearby objects in motion that eventually could change the electric field at a frequency that alters Flicker measurements. Fig. 6 shows the EFS placement on the rear part of a vehicle. Note: Safety distances should be respected. Eventually, the EFS could be placed directly on the roof of the vehicle. These precautions do not apply to harmonics.

Fig. 6. EFS placement nearby an overhead line.

The EFS placement was carried out by moving it around the overhead line to be measured, in order to obtain a voltage signal within the dynamic range of the recording equipment. Fig. 7 shows the results of simultaneous Flicker measurements in Bragado LV (traditional measurement) and in Bragado 132 kV high voltage line with the EFS.

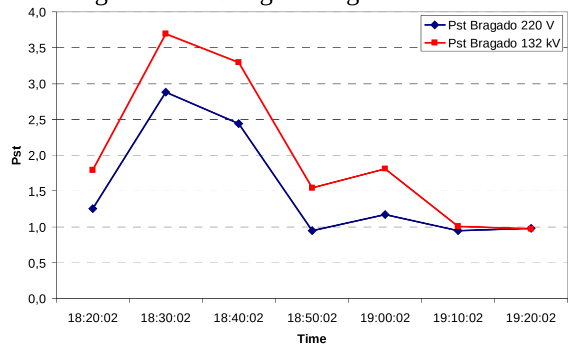

Fig. 7. Simultaneous Flicker measurements in Bragado node in LV network and in HV network with EFS.

As a result of this first measurement, for high Flicker values the upstream to downstream Flicker transfer coefficient within 0.75 to 0.8 could be recognized.

Fig. 8 shows the results of simultaneous Flicker measurements in Bragado LV (traditional measurement) and in Chivilcoy 132 kV overhead line with the EFS. The calculated Flicker level in Bragado 132 kV is also included.

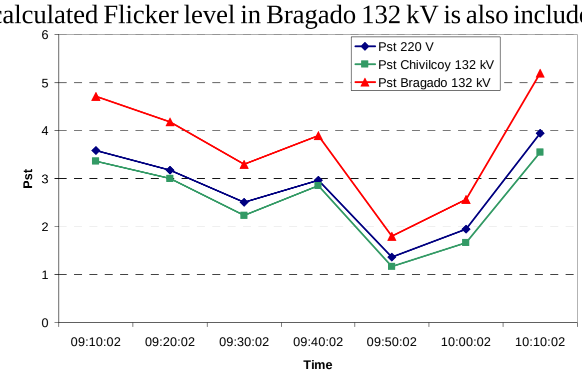

Fig. 8. Simultaneous Flicker measurements in Bragado LV network and Chivilcoy HV network with EFS.

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

To have solid reference values for the Flicker transfer coefficients from different nodes, the high voltage network presented in Fig. 4 was simulated in the Alternative Transient Program (ATP) and all the Flicker transfer coefficients from a Flicker source in Bragado were obtained. The results are shown in Table III.

Table. IIII: Flicker transfer coefficients obtained with ATP.

Node	Pst_n/Pst_1
Bragado 132 kV	1.00
Chivilcoy 132 kV	0.74
Chacabuco 132 kV	1.00
Saladillo 132 kV	0.75
Lincoln 132 kV	0.64

The measured Flicker transfer coefficient in Chivilcoy was 0.71. According to simulations this value was 0.74. According to that degree of agreement it is possible to conclude that Flicker in Chivilcoy node has its origin in Bragado node. Similar results were obtained in other HV nodes.

Harmonic measurements

Harmonic measurements were performed simultaneously with Flicker measurements, with the same EFS and the same recording equipment.
For demonstration purposes, Fig. 9 shows the results obtained from the average of 1 minute voltage harmonic measurements, held for one hour in each site.

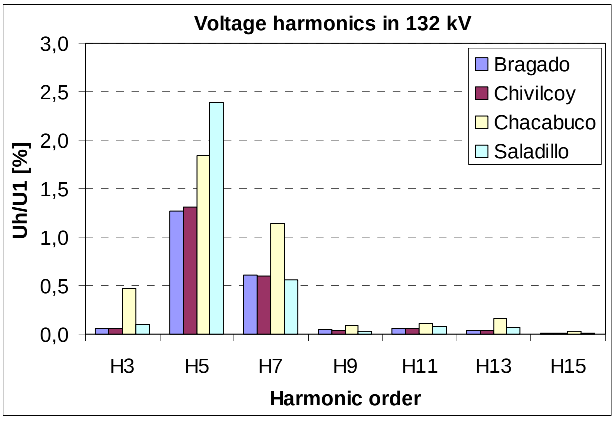

Fig. 9. Voltage harmonics respect to fundamental voltage [%] in 132 kV measured with EFS.

By this simple way, it is possible to measure, with good sensitivity, the voltage harmonics, and to determine which nodes have a high probability of meeting the Power Quality limits applied in Argentina (e.g. Bragado and Chivilcoy) and which nodes will exceed the limits (e.g. Saladillo).

Remarks

As results of EFS field measurements it is possible to conclude the following:

- The Flicker measurements in overhead lines with the EFS are feasible to perform in compliance with required uncertainties, according to International Standards.
- The EFS output is a single measurement and results in a composition of unknown proportions of the three-phase voltages. In so special situations where three-phase values are necessary, conventional measurement must be carried out.
- The following steps could be followed to find the geographic location of the predominant Flicker source:
  1. Perform measurements with an EFS in different nodes of the power system – keeping one conventional Flicker measurement in a reference place –.
  2. Obtain the topology and the electrical data of the power system to be inspected, and determine (by manual calculations or by computer simulations) the effects of a predominant Flicker source in different nodes of the power system.
  3. Correlate both results and determine the geographic location of the predominant Flicker source.
- In the case of voltage harmonic measurements, in which every harmonic has different sequence components (positive, negative and zero), the EFS does not allow for normalized zero sequence voltage harmonic measurements. By this measurement method, the 3rd harmonic value (and its multiples) results in a higher value than the real one. The technique of approaching the EFS to only one phase could be a useful tool to appreciate the real value of those harmonics.

CONCLUSIONS

The increasing interest in performing power quality measurement campaign on distribution systems is at present 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 it is not worth it.
- The adequate frequency response bandwidth (BW) of voltage transformers must be proven and it is common to find they do not meet the requirements, especially in EHV levels.

However, the Electric Field Sensor (EFS) designed by IITREE-UNLP has the following advantages:

- It is a practical and simple normalized way to measure harmonics, Flicker and other voltage perturbations.
- It can be used as a powerful tool for finding disturbing loads along a transmission / distribution network.

The EFS based measurement method has demonstrated to be particularly useful where the cost or physical location drawbacks make the use of conventional methods difficult.

REFERENCES

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[2] IEC 61000-4-15.-*"Flickermeter. Functional and design specification"*.

[3] IEC 61000-4-7 Second Edition. 2002-8.-*"Testing and measurements techniques - General guide on harmonics and inter-harmonics measurements and instrumentation, for power supply systems and equipments connected thereto"*.

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