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Measurements of disturbances produced by power electronic devices on EHV overhead lines using Electric Field Sensors

P.E. ISSOURIBEHERE D.A. ESTEBAN F. ISSOURIBEHERE G.A. BARBERA
IITREE-FI UNLP
Argentina

SUMMARY

It is widely known that more and more power electronic devices are being installed in power systems. The main reasons of this are the increasing number of large variable speed drives connected to medium or high-voltage grids, the installation of devices for voltage control and flicker mitigation such as SVCs, and last but not least the electronic equipment required to integrate renewable energy sources – such as wind farms – to the existing power system.

On the other hand, nowadays, in most countries there are severe Power Quality rules that Utilities as well as customers have to comply with. Therefore, even though power electronic devices are installed in networks in order to improve certain issue, it is also necessary to assess carefully the levels of disturbances – mainly harmonics – that they also emit.

The traditional procedure to determine the origin of such disturbances is to perform field measurements in all the plants containing power electronic equipment, 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 aerial power systems **[1]**. Some results of field measurements performed in plants containing disturbing loads are shown.

KEYWORDS

Disturbing Load – Electric Field Sensor (EFS) – Flicker – Harmonics – Power Quality – Power Electronics

Pedro Issouribehere: pedroi@iitree-unlp.org.ar

1. 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]

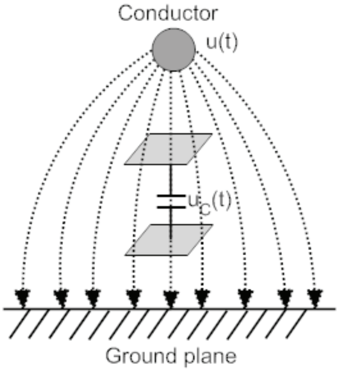


Fig. 1. Measuring electric field between two electrodes.

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:

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

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:

$$u_C(t) = k_E \cdot e(t) \tag{3}$$

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:

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

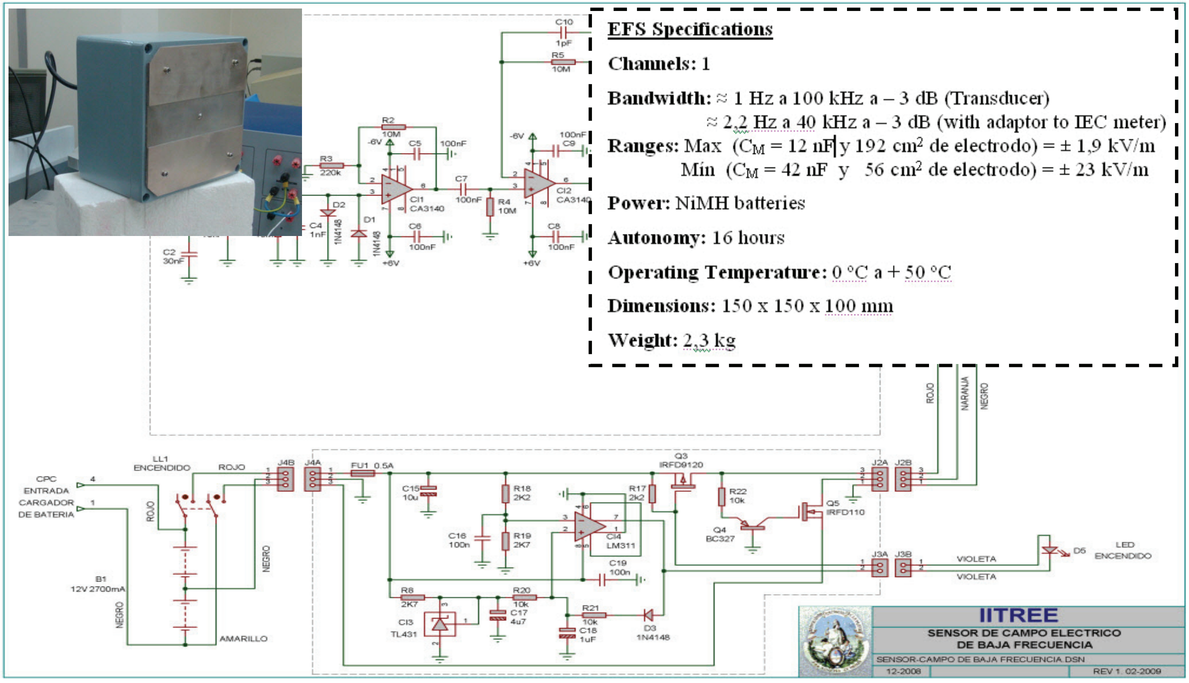
Where:

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**.

2. IMPLEMENTATION AND CONSTRUCTION OF EFS

In Fig. 2, the physical aspect of the EFS is shown, with the electric schematics and some technical specifications including measuring range, bandwidth, autonomy, etc. **[2]**



EFS Specifications

Channels: 1

Bandwidth: ≈ 1 Hz a 100 kHz a – 3 dB (Transducer)
≈ 2,2 Hz a 40 kHz a – 3 dB (with adaptor to IEC meter)

Ranges: Max (C_M = 12 nF y 192 cm² de electrodo) = ± 1,9 kV/m
Min (C_M = 42 nF y 56 cm² de electrodo) = ± 23 kV/m

Power: NiMH batteries

Autonomy: 16 hours

Operating Temperature: 0 °C a + 50 °C

Dimensions: 150 x 150 x 100 mm

Weight: 2,3 kg

Fig. 2. Electric Field Sensor (EFS) technical specifications.

3. SIMULATIONS 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. 3 shows the EFS placed in a generic point near a three-phase system.

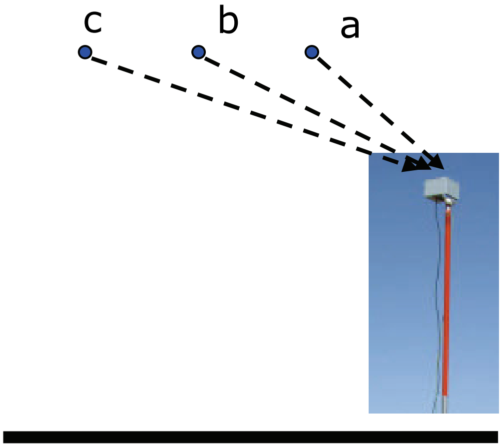


Fig. 3. Electric Field Sensor (EFS) placed near a three-phase transmission line.

The voltage measured across the EFS sensor is a composition of the three-phase voltages, as it is described in (5).

$$\dot{U}_m = k_1\left(\dot{U}_{R1} + \dot{U}_{Rh}\right) + k_2\left(\dot{U}_{S1} + \dot{U}_{Sh}\right) + k_3\left(\dot{U}_{T1} + \dot{U}_{Th}\right) \tag{5}$$

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 (6):

$$\left|\frac{\dot{U}_h}{\dot{U}_1}\right|_{measured} = \left|\frac{\dot{U}_h}{\dot{U}_1}\right|_{real} \cdot \frac{k_1 + k_2 e^{-jh120^\circ} + k_3 e^{jh120^\circ}}{\left(k_1 + k_2 e^{-j120^\circ} + k_3 e^{j120^\circ}\right)} \tag{6}$$

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 2nd order to the 6th 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 as representative of a real case.

The results obtained from simulations are summarised in Table I. From the obtained results is possible to conclude that the system measures properly both positive and negative-sequence components. In contrast, the system is not able to evaluate zero-sequence components since the measured values lie always above the real amplitude of the harmonic (e.g. 3rd and 6th components). What's more, the measured voltages are highly sensitive to the coupling geometric constant values.

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 = 0.25 k_3 = 0.125	Measured voltage [%] k_1 = 1 k_2 = 0.1 k_3 = 0.05
2	-	**1**	1	1	1
3	0	**2**	6.86	3.34	2.48
4	+	**1**	1	1	1
5	-	**10**	10	10	10
6	0	**1**	3.43	1.67	1.24

4. 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. 4.

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 normalised electronic equipment, connected in a conventional way, as shown in Fig. 4. For measuring voltage harmonics, a similar test was performed.

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 [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 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 standardised 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 standardised tests for equipment Class I according to IEC 61000-4-7 standard.

Fig. 4. EFS placed in the High Voltage Lab, under a cable fed with fundamental frequency voltage, harmonics and flicker.

5. MEASUREMENTS PERFORMED TO DETECT DISTURBING LOADS

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.

Several installations containing suspicious loads were chosen to perform the field tests. Among them were:

- An industry that manufactures aluminium products.
- A factory that produces ceramic bricks.
- A small industrial park, in which different types of factories are located.
- A large substation containing a **S**tatic **V**ar **C**ompensator (SVC).
- High voltage network in the surroundings of a steel plant.

At first, the idea was to perform measurements only in EHV lines. Nevertheless, then it was considered appropriate to measure in different voltage levels. As a consequence, it would be possible to assess the sensitivity of the EFS to the different voltage systems.

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 recorder and a computer were installed.

In Fig. 5 two pictures taken during the field tests are displayed. On the left it is shown a general view of the whole system, while on the right the EFS appears in the foreground.

Fig. 5. Electric Field Sensor (EFS) on the roof rack of the vehicle.

In all the cases the length of the measurement was over one hour, whereas the integration period was fixed at one minute.

As it was mentioned above the measuring system is not able to measure the zero-sequence components accurately. Thus, in all the results presented in the next paragraphs such harmonics will not be taken into account.

MEASUREMENT RESULTS

Industry that manufactures aluminium products

This plant is fed in 132 kV. It produces aluminium products such as profiles, bars and tubes Among its machinery it includes rolling mills, which are prone to emit disturbances towards the grid. For this reason, measurements below the lines arriving at the plant were carried out.

The measurement was performed at midday. In Fig. 6a the averaged harmonic content up to the 20th order is depicted. The highest component turned out to be the 5th one, as it is typical in HV power systems. Consequently, in Fig. 6b the 5th harmonic trend throughout the hour is shown.

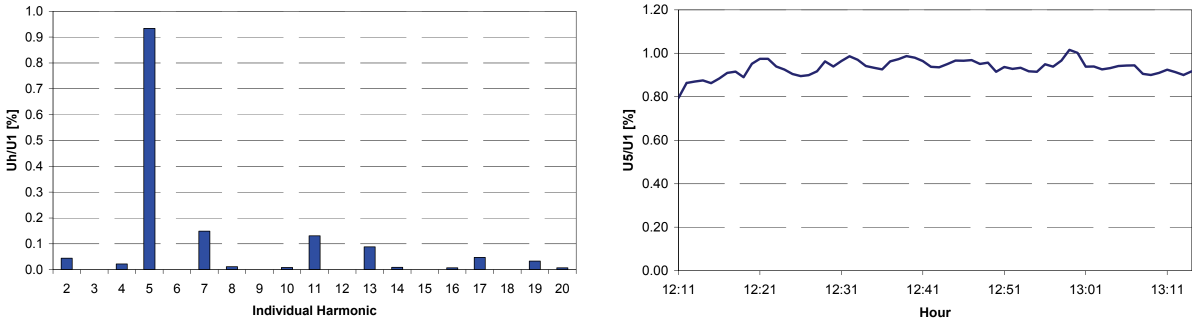


Fig. 6. a) Harmonic Content, b) 5th Harmonic profile. Factory of aluminium products.

During the measurement period the 5th harmonic remained below 1%, which is precisely the half of the reference level in Argentina.

Factory of ceramic bricks

This plant is fed in 13.2 kV. Due to the production process required to manufacture ceramic bricks the plant contains different loads such as conveyor belts and overhead travelling cranes. Such loads are normally controlled by **V**ariables **S**peed **D**rives (VSDs). Therefore, high levels of harmonics are expected in the power system near the plant. In order to assess the impact of the plant on the grid, harmonic measurements were performed by using the EFS.

The measurement began at 02:26 pm and lasted slightly more than one hour. During the measurement period it was noticed that some harmonic levels increased severely after the first thirty minutes, i.e. about 03:06 pm (Fig. 7b). The harmonics that increased their values were 5th, 7th, 11th, 13th, 17th and 19th. All of them are harmonics of orders 6k±1 for integer values of k, which are the orders which are present in six-pulse rectifier currents **[3]**. Therefore, it can be concluded that at 03:06 pm one or several powerful six-pulse rectifiers began working.

The averaged harmonic content is displayed in Fig. 7a. Again, the presence of harmonics of orders 6k±1 is clearly observed.

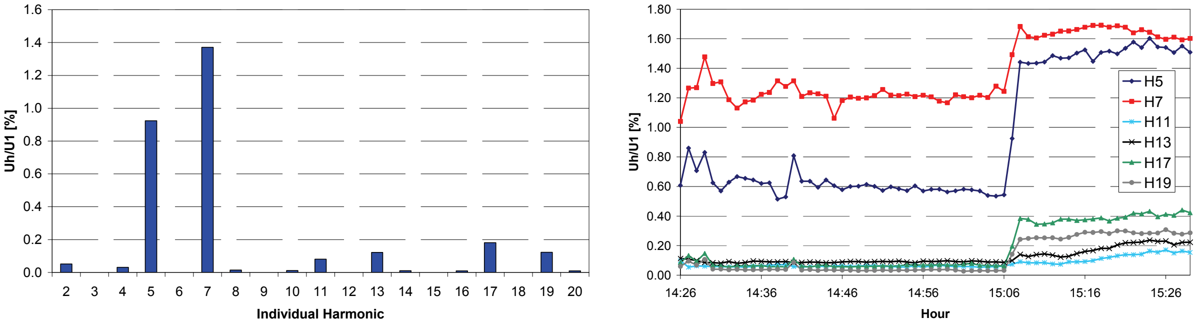


Fig. 7. a) Harmonic Content, b) Harmonic profiles. Factory of ceramic bricks.

Industrial park

On the outskirts of La Plata there is a small industrial park, where several local industries have settled down. Within the park there are about fifteen plants producing electrical cables, prefabricated houses, plastic products and so forth. All the factories are fed in 13.2 kV.

With the purpose of determining whether such loads emit disturbances to the grid, measurements using the EFS were carried out.

In this case, the harmonic that stood out was the 5th component. The 11th and the 13th components came after (Fig. 8a). The profiles of such harmonics appear in Fig. 8b. Particularly, the 5th harmonic showed a slightly downward trend. It may have been due to modifications in the loads belonging to the plants.

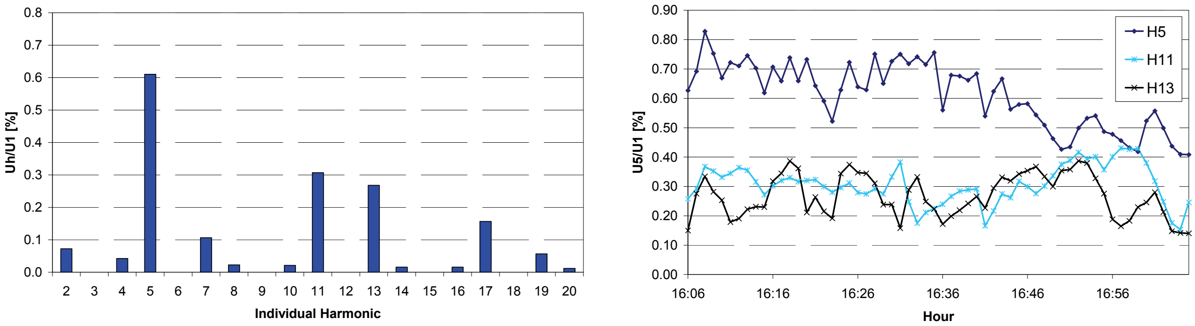


Fig. 8. a) Harmonic Content, b) Harmonic profiles. Industrial park.

Substation containing a SVC

Fifty kilometres to the north of Buenos Aires it is located one of the largest substations belonging to the Argentinian high-voltage system. The station contains three transformers of 800 MVA each.

Different overhead lines of 500 kV and 220 kV arrive and emerge from the station. In addition, there are two identical Static Var Compensators connected to the tertiaries of the transformers 1 and 2. Both units operate in parallel and are controlled by a common regulator. The purpose of the SVCs is to stabilize the voltage in the 500-kV bar in both static and dynamic conditions.

Each SVC contains two 80-MVAr TCRs (**T**hyristor-**C**ontrolled **R**eactor) and two 80-MVAr TSCs (**T**hyristor-**S**witched **C**apacitor). Thus, as a whole, the installed reactive power in terms of capacitors reaches 320 MVAr. The same occurs in terms of reactors.

Due to the inclusion of power electronics in the SVC, generation of harmonics is expected **[4]**. In addition, the amplitude of each harmonic is highly dependent on the thyristor firing angle. Consequently, it was decided to perform measurements below the 220 kV overhead lines that emerge from the station.

The obtained results are displayed in Fig. 9. In a) the harmonic content is shown. Actually, such values resulted lower than expected. The reason of this could be that the grid is powerful enough to absorb the harmonic currents emitted by the non-linear load that both TCRs and TSCs represent.

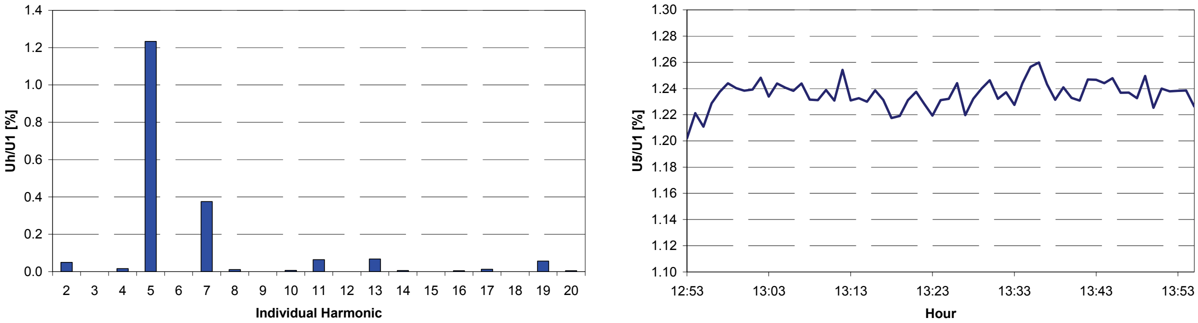


Fig. 9. a) Harmonic Content, b) 5th Harmonic profile. Substation containing a SVC.

In Fig. 9b the 5th harmonic trend is depicted. This harmonic remained steady between 1.2 % and 1.26 %.

High voltage network in the surroundings of a steel plant

A measuring campaign was performed in Buenos Aires province transmission network. Measurements were made in the surrounding area of Bragado 132 kV node, where a large steel plant is placed. In Fig. 10 the profiles of the main harmonics in three nodes are shown.

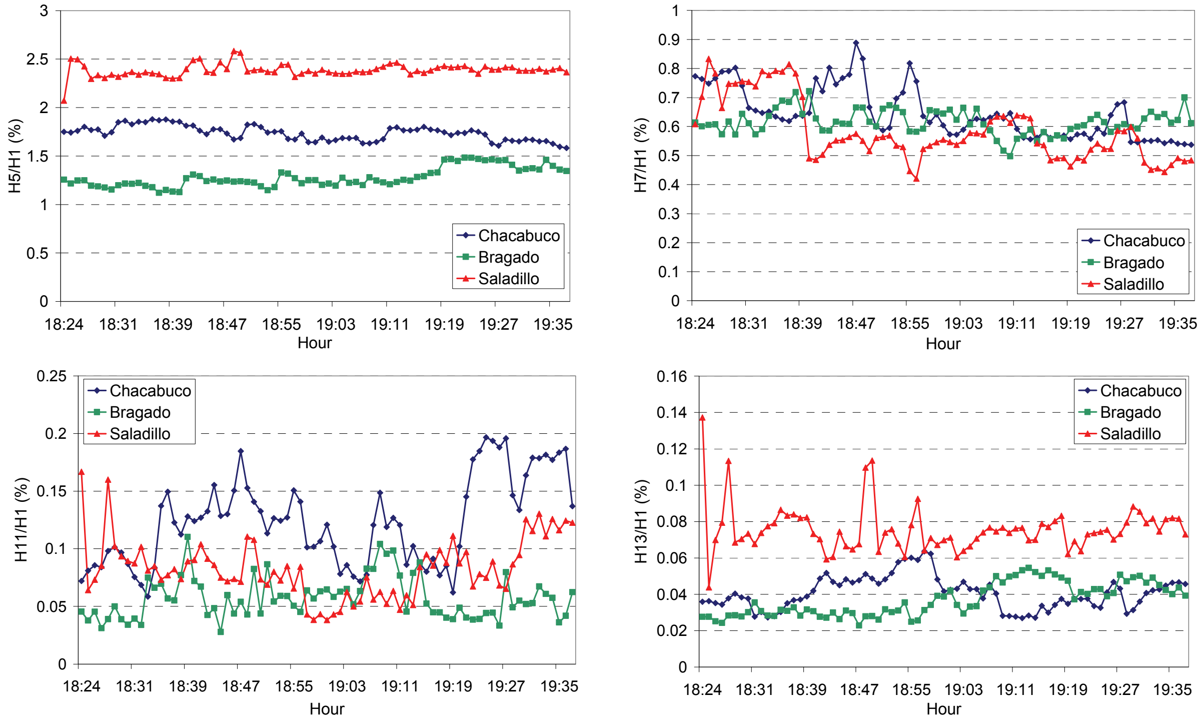


Fig. 10. Harmonic content in 132 kV lines. 5th, 7th, 11th and 13th harmonic profiles.

By this simple way, it is possible to measure with appropriate sensitivity the voltage harmonics, and to determine which nodes have a high 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 both IEC 61000-3-6 and Argentinian Standard Res. ENRE 184/00, and 1.5 % in IEEE 519-1992).
- 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 normalised measurement **[5]**).

6. CONCLUSIONS

- A measuring system based on an Electric Field Sensor (EFS) was designed and constructed.
- A series of field measurements were carried out in order to assess the performance of such a measuring system. In some cases it was possible to detect the presence of disturbing loads connected to the grid. Most of them consisted in equipment containing power electronics.
- 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 2012.
- Only in those points in which high levels of disturbances were detected, an IEC normalised 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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