Compatibility between Disturbance Emission and Argentinian Power Quality Regulations in Iron and Steel Industries

P. E. Issouribehere, J. C. Barbero, G.A. Barbera, and F. Issouribehere, *Member, IEEE*

Abstract— **Measurements and studies developed to mitigate harmonic and flicker emission to public networks are presented in this paper. Two different real cases are analyzed. The first one is a new electric furnace with low power factor, which is added to the load consisting of other existing furnaces. The installation had a reactive compensation bank which, according to measurements and studies, would cause harmonic resonance with weak public networks. As technical solution, a dumped C−type filter was designed, taking advantage of the existing bank, to comply with limits established by ENRE 99/97 and IEEE 519/1992. The other case deals with a 2.5 MW electric arc furnace fed from the public MV network. The carried out measurements harmonics, voltage and current unbalances, active and reactive power, power factor and flicker determined that the high flicker level was the most critical disturbance. In addition, the compensation factors required to comply with reference levels and also to determine the dimension of the suitable static compensator were calculated.**

Index Terms — **Electromagnetic Compatibility. Flicker. Furnaces. Harmonic distortion. Power Quality.**

I. Introduction

Argentinian regulations follow severe international criteria for disturbances emitted from disturbing loads to the network. This is in order to ensure the electromagnetic compatibility between the supplier and customers.

Meeting these regulations frequently requires studying local measures to mitigate the perturbations injected by disturbing loads into the electric distribution system.

Experiences developed in two real cases based on measurements and studies, carried out to mitigate harmonic and flicker emission, are presented in this paper.

The first case corresponds to a new electric furnace of submerged anode and low power factor type, in an Argentinian plant of products for steel making. Such furnace was added to the load represented by other existing furnaces.

The plant is fed from the public MV distribution network at 13.2 kV. The new electrical installation was designed for a 14 MW low power factor furnace.

Pedro E. Issouribehere, Juan C. Barbero, Gustavo A. Barbera and Fernando Issouribehere are with IITREE-LAT, Facultad de Ingeniería, Universidad Nacional de La Plata. (B1900AMF) 48 y 116, La Plata. Argentina. (e-mail:.iitree@iitree-unlp.org.ar).

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The installation had a 14 MVAr modular compensation bank to compensate reactive energy which, according to studies and measurements, would cause some resonance with the network. To take advantage of the existing bank, dumped C-type and third order filters were simulated. Thus, limits established by ENRE 99/97 and IEEE 519/1992 were fulfilled.

The other case deals with a 2.5 MW electric arc furnace for steel melting fed from a 13.2 kV network. Measurements of voltage and current harmonics and unbalances, active and reactive powers, power factor and flicker were carried out. The results determined that flicker was the most critical disturbance. Then, it was calculated the compensation factor required to comply with international and Argentinian reference levels and to determine the suitable static compensator size.

One of the purposes of this paper is to present technical solutions for both cases.

II. Case I: Harmonic Resonance between the Reactive Compensation Bank and the Network

An electric furnace of submerged anode and low power factor type was added to other existing furnaces fed from different supplies. A power factor compensation bank was installed with the new furnace.

Since it was suspected that the connection of the compensation bank would cause some resonance with the network, it was not possible to connect it during the measurements. Therefore, the effect of the capacitors had to be studied by simulations.

A. Measurements

In order to characterize the phenomenon, measurements were carried out for two periods. In each period, the furnace was melting different products.

The recorded data (P_{st}, THD and harmonic currents) yield:

- *Flicker*: P_{st} value not exceeded during 95% of the time (worst phase) was $P_{st95\%} = 1.01$ in the first period and $P_{st95\%} = 0.57$ in the second. The limit established by Argentinian regulation is $P_{st95\%} = 1$.

- Voltage harmonics: THD value not exceeded during 95% of the time (worst phase) was $THD_{95\%} = 0.91\%$ in the first period and $THD_{95\%} = 0.99\%$ in the second. The limit established by Argentinian regulation for MV networks is $THD_{95\%} = 8\%$ [2].
- Current harmonics: Table I summarizes the statistics of harmonic rms values averaged over 10-minute intervals.

TABLE I
HARMONIC RMS VALUES. STATISTICAL SUMMARY.

		Fund	I2	I3	I4	I5	I6	I7
1st Case	I_{AVG}	639.1	2.06	4.64	0.92	3.14	0.43	1.10
	$I_{95\%}$	663.3	5.52	7.78	2.73	4.80	1.49	1.89
2nd Case	I_{AVG}	844.8	1.35	5.05	0.52	5.45	0.37	1.48
	$I_{95\%}$	860.1	1.73	7.23	0.89	6.98	0.65	1.73

Recorded levels of voltage harmonics at 13.2 kV busbar were under the limits established by Argentinian regulations.

In the case of flicker, the P_{st} levels were acceptable.

However, harmonic emission levels require a more detailed study, due to the magnification effect that will be expected if the capacitor bank is included.

B. Determination of network Q factor

That magnification ratio depends on the real Q factor of the network. To determine this factor, the transient current due to the insertion of a (7.2 + 4.8) MVAr modular bank was recorded. This bank belonged to another furnace in service.

The transient corresponded to the insertion of the 4.8 MVAr stage while the 7.2 MVAr stage was already operating. Fig. 1 shows the transient current evolution in phase S. In this figure, the fundamental current was filtered.

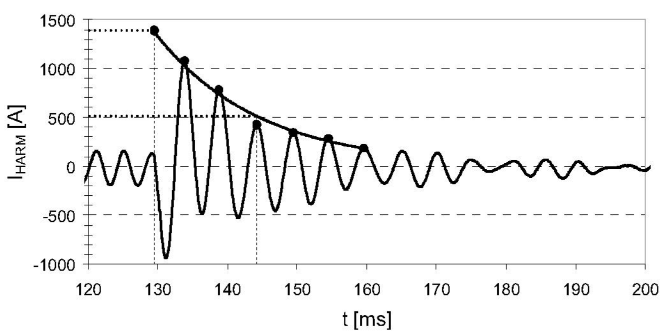

Fig. 1. Transient current (without fundamental) during capacitor bank insertion (Phase S).

A stable level of 5th harmonic before the insertion is seen. The oscillatory transient current, whose pulsation is ω_0, can be expressed as:

$$i(t) = I_{max} \sin(\omega_0 t + \varphi) e^{-t/\tau} \qquad (1)$$

being:

$$\tau = \frac{1}{\xi \omega_0} = Q \frac{T_0}{\pi} \qquad (2)$$

the time in which the oscillation amplitude decreases to $1/e$ of the initial amplitude. If τ is measured in times (N) of the oscillation period ($T_0 = 2\pi / \omega_0$), then:

$$\tau = N \cdot T_0 \qquad (3)$$

In Fig. 1, τ is 14 ms and substituting this value in (3) yields:

$$N \cong 2.7 \qquad (4)$$

Then comparing (2) with (3), Q factor of the network yields:

$$Q = N\pi \cong 2.7\,\pi = 8.5 \qquad (5)$$

This is an important experimental result that will be used in further simulations.

C. Study of the new furnace emission

In order to determine the furnace emission, limits regulated by ENRE [1] and IEEE [3], adapted to furnace nominal conditions (the current corresponding to a 14 MW demand with PF = 0.85), were used as reference in Table II. In this table, it was considered the supply in present conditions (S_{SC}/S_L<20), a foreseen improvement in the same MV supply (20<S_{SC}/S_L<50), and an eventual future feeding from the HV network (S_{SC}/S_L>50).

The furnace emission levels were adopted as the highest $I_{95\%}$ value for each component from Table I. By comparison of these emission levels to those shown in Table II, it was concluded that the installation without the (5 + 5 + 4) MVAr bank would comply with the limits regulated by both ENRE and IEEE, under the three considered possibilities of the public network.

TABLE II
LIMITS OF HARMONIC EMISSION TO THE PUBLIC NETWORK.

Harmonic	ENRE 99/97		IEEE 519/1992					
			Present MV				Future HV	
	Present MV and future HV		S_{SC}/S_L < 20		20<S_{SC}/S_L<50		S_{SC}/S_L > 50	
	%	A	%	A	%	A	%	A
1	100	650	100	650	100	650	100	650
2	10	65	1	6.5	1.75	11.4	1.25	8.1
3	7.5	48.75	4	26	7	45.5	5	32.5
4	2.5	16.25	1	6.5	1.75	11.4	1.25	8.1
5	6	39	4	26	7	45.5	5	32.5
6	1	6.5	1	6.5	1.75	11.4	1.25	8.1
7	5.1	33.15	4	26	7	45.5	5	32.5

Nevertheless, the operation of the plant without the capacitor bank is not the usual operating condition, due to the violation of the power factor limit established by ENRE.

To study the effect of connecting the compensation bank, it was adopted the equivalent circuit of the furnace supplied from the 13.2 kV public network, simplified to this end. This model is depicted in Fig. 2.

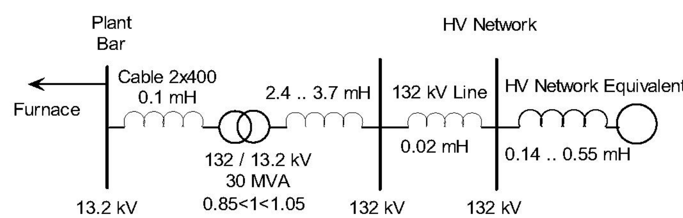

Fig. 2. Equivalent circuit of the furnace electric supplied from public network. Values are referred to 13.2 kV.

In this figure, it is considered the effect of the transformer taps and variations of short circuit power (S_{SC}) upstream the 132 kV busbar. These S_{SC} variations were simulated by different local generation conditions (2700 MVA, 3300 MVA and 4300 MVA).

The compensation capacitors and the network form an RLC circuit that tends to magnify the harmonic currents emitted by the load (Fig. 3). The considered Q factor of the network is the one obtained in the previous section.

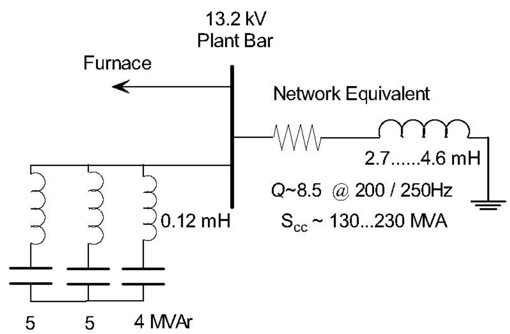

Fig. 3. Simplified circuit used to simulate harmonic emission including the capacitors. Values are referred to 13.2 kV.

Fig. 4 shows the current transfer curves obtained from different bank configurations and short circuit power conditions at the supply point. For each bank stage, the transfer curve varies along with the short circuit power of the network, between the indicated extremes.

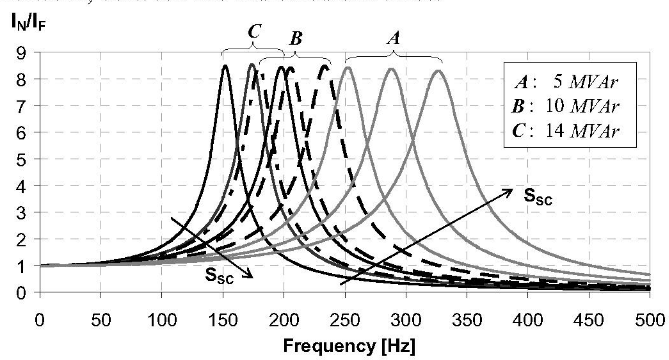

Fig. 4. Ratio between the network current and the furnace current versus frequency.

The worst magnification conditions, which were obtained from the evolving curve, are summarized in Table III. Magnification values obtained for cero-sequence current components were not applicable (capacitor bank with floating neutral). That is why the corresponding coefficients were set to one.

TABLE III
I_N/I_F RATIO. MAXIMUM VALUES EXPECTED WITH CAPACITORS CONNECTED.

Harmonic	1	2	3	4	5	6	7
I_N/I_H	----	1.7	1	8.3	8.3	1	5.1

If the capacitor bank was connected like in the original project, harmonics emitted to the network could be predicted by taking the maximum $I_{95\%}$ from Table I (worst case), and multiplying it by the corresponding magnification factor from Table III. These results are summarized in Table IV. Values higher than limits presented in Table II, were remarked in Table IV. The exceeded limits were also remarked in Table II.

TABLE IV
FURNACE EMISSION LEVEL WITH CAPACITORS CONNECTED (WORST CASE).

Harmonic		1	2	3	4	5	6	7
Magnified Furnace Emission $I_{95\%}$	%	100	1.45	1.2	3.51	9.0	0.23	1.5
	A	650	9.4	7.8	23	58	1.5	10

When the compensation capacitors are connected, the new furnace harmonic emission will exceed the limits regulated by both, ENRE and IEEE for the 4th and 5th components. The 2nd component will slightly exceed IEEE limits.

D. Mitigation procedures

Different mitigation procedures to comply with the regulated limits were studied. The main purposes were:

- To use the installed capacitor bank without modifying the existing installations.
- To minimize required works to implement the mitigating measures.

Studied alternatives used a series dumped filter common to the three banks. The analyzed dumped filters were those known as C-type (Fig. 5a) and third order (Fig. 5b).

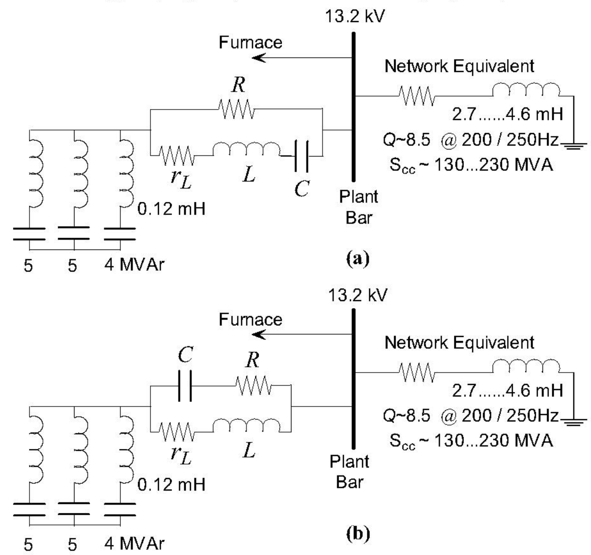

Fig. 5. Analyzed filters. (a) C-type. (b) Third Order.

Cases considered in this study are shown in Table V.

TABLE V
COMPONENT VALUES FOR SIMULATED CASES.

Case	Type	L [mH]	R [Ω]	C [μF]	r_L [Ω]
1	Without Filter	---	---	---	---
2	C	3.18	1.3	3180	0.04
3	3rd Order	3.4	1.1	550	0.04

Fig. 6 illustrates the I_N/I_F vs. frequency relationship for the three studied cases, taking into account the different conditions of S_{SC} and compensation.

For each component, it is convenient to express emission limits in terms of the I_N/I_F ratio by calculating the ratio between the limit of Table II and the worst $I_{95\%}$ value of Table I. The obtained results are summarized in Table VI.

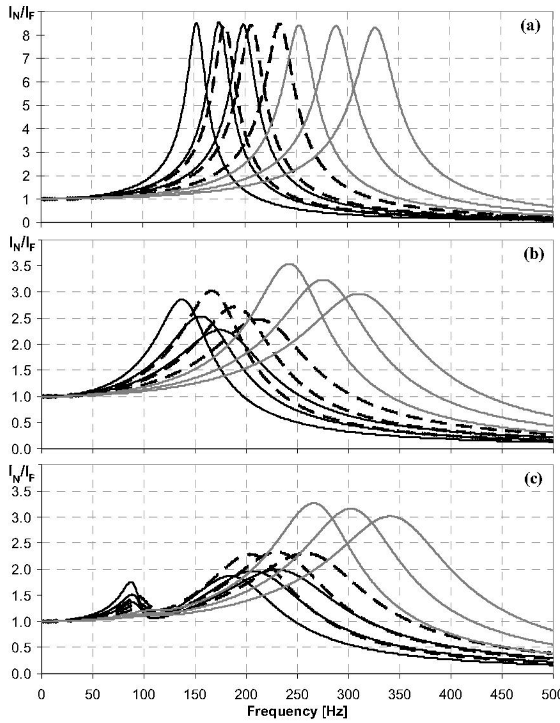

Fig. 6. Ratio between network current and current generated by the furnace as a function of the frequency. (a) Case 1: without filter. (b) Case 2: C-Type filter. (c) Case 3: Third order filter.

TABLE VI
MAXIMUM VALUES OF THE RATIO I_N/I_F FOR THE THREE SIMULATED CASES.

Harmonic	I_N/I_F max			I_N/I_F Maximum Allowed according Standard limits			
	Case (from Table V)			ENRE 99/97	IEEE 519/1992		
					MV		HV
	1	2	3	MV y HV	$\frac{S_{SC}}{S_L} < 20$	$20 < \frac{S_{SC}}{S_L} < 50$	$\frac{S_{SC}}{S_L} > 50$
1	----	----	----	------	------	------	------
2	1.7	1.5	1.4	11.8	1.2	2.1	1.5
3	1	1	1	6.3	3.3	5.8	4.2
4	8.4	2.6	2.3	5.9	2.4	4.2	3.0
5	8.3	3.5	3.1	5.6	3.7	6.5	4.7
6	1	1	1	4.4	4.4	7.6	5.5
7	5.1	2.4	3.0	17.5	13.8	24.1	17.2

For present supply conditions, the IEEE limits for the 2nd component could never be fulfilled and the 4th component could be slightly lower than IEEE limits only in case 3. This is due to the extremely restrictive criteria of the Standard for these components. However, measurements have revealed that even components of emitted current could be appreciably diminished depending on the produced compound. Thus, according to the furnace typical production, it is possible that those limits could actually be fulfilled.

For the other harmonics, any of the studied alternatives are sufficient to maintain their values below regulated limits.

Table VII shows the characteristics of the filter components and their requirements for each analyzed case. These values were obtained by considering that:

- The nominal reactive power of the capacitor bank was 14 MVAr at 13.2 kV.
- Indicated requirements corresponded to a nominal 13.2 kV voltage and this value should be corrected for other operating limits.
- Inductance and reactor losses were adopted taking into account weight and size of the reactors, since an indoor assembly was considered due to environmental pollution.

TABLE VII
FILTER ELEMENTS. CHARACTERISTICS AND REQUIREMENTS FOR EACH CASE.

Case	Reactor to be installed			Resistor to be installed				Capacitor to be installed		Existing Bank
	L	r_L	I_L	$P_{rL\,(3PH)}$	R	I_R	$P_{R\,(3PH)}$	C	U_{CFIL}	ΔU_{BCO}
	mH	Ω	A	kW	Ω	A	kW	µF	V	%
1	--	--	--	--	--	--	--	--		0
2	3.18	0.04	568.0	38.7	1.3	17.6	1.2	3180	569.2	0.1
3	3.4	0.04	784.8	73.9	1.1	142.1	66.6	550	582.0	10.6

E. Comments

The best alternative is the C-Type filter (Case 2) due to the following:

- A suitable filtering is obtained except for even harmonics. This exception is true for all the alternatives.
- The overvoltage in the capacitor bank is the lowest and the normalized overload [4] will not be exceeded for the present harmonic distortion.
- The current in the reactor is the lowest of the several studied alternatives, which means a less voluminous reactor (this element defines the volume of the installation for the complete filter).
- The installation power losses are the lowest.

III. CASE II: FLICKER GENERATED BY AN ARC FURNACE AND MITIGATION

The second case deals with an 8-ton electric arc furnace (EAF) of 2.5 MW for steel melting. This furnace was connected to the Argentinian distribution system.

The electrical one-line diagram of the power system is shown in Fig. 7.

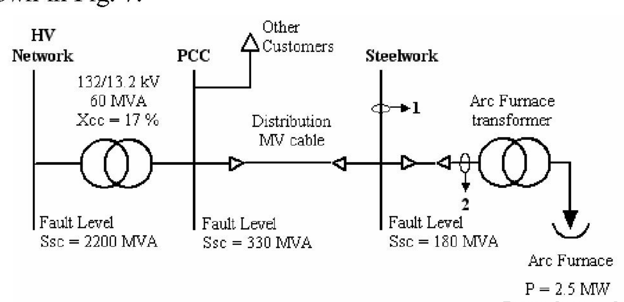

Fig. 7. Electrical system configuration.

As it can be seen, the steel industry is supplied directly from public distribution network at 13.2 kV level.

After the furnace is charged with scrap, operation begins by lowering the electrodes to strike electric arcs between the electrodes and the scrap. Due to the random motion of the electric arc and resulting changes in the arc length, there are random fluctuations in current, which cause voltage fluctuations upstream the furnace in proportion to the system impedance.

The main purpose for controlling voltage fluctuations in power systems is to reduce their effect on domestic and commercial customers, especially on the light output of electrical lighting that causes annoyance to human beings (phenomenon known as flicker).

A. Flicker Measurements

Flicker measurements were carried out by IITREE with an IEC normalized flickermeter. Fig. 8 shows the normalized one-week, 10-minute-interval P_{st} measurements.

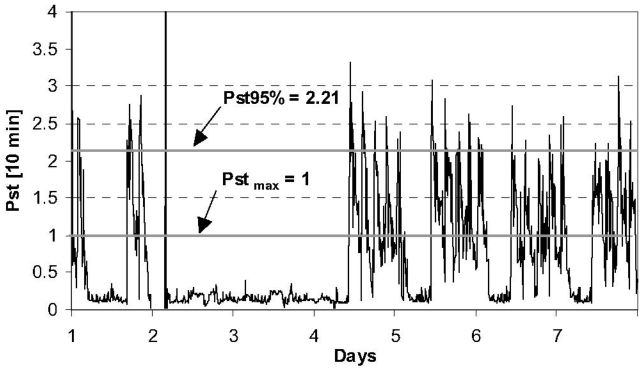

Fig. 8. P_{st} measurements during a week.

Obtained statistical results from the normalized flicker measurement are shown in Table VIII.

TABLE VIII
STATISTICAL RESULTS OF FLICKER MEASUREMENTS.

Total observations of 10 minutes	1008
$P_{st95\%}$	2.21
Observations with P_{st} > 1	288
Percent of measurement with P_{st} > 1	28.6 %

The obtained value of $P_{st95\%} = 2.21$ is above the limits of European and Argentinian Standards.

The flicker emission limit, according to Argentinian Standard [1], depends on both short circuit power of the system at the PCC and the consumer power demand, as it can be seen in Table IX.

TABLE IX
INDIVIDUAL FLICKER EMISSION LIMITS ACCORDING TO [1].

MV and HV customers (1kV < U ≤ 220 kV) $K_2 = S_L/S_{sc}$	**Individual Emission Limits (P_{st})**
$K_2 \leq 0.005$	0.37
$0.005<K_2 \leq 0.01$	0.46
$0.01<K_2 \leq 0.02$	0.58
$0.02<K_2 \leq 0.03$	0.67
$0.03 <K_2 \leq 0.04$	0.74
$0.04 < K_2$	0.79

B. Verification of $P_{st95\%}$ and K_{st} values obtained from measurements

According to [5], the flicker emitted by the EAF could be estimated by:

$$P_{st99\%} = 48......85\frac{S_{scf}}{S_{sc}} \quad (6)$$

If $P_{st99\%}\ \Delta\ 1.25\ P_{st95\%}$ then:

$$P_{st95\%}\ \Delta\ 40......70\frac{S_{scf}}{S_{sc}} \quad (7)$$

For the studied arc furnace:

$$P_{st95\%}\ \Delta\ 40......70\frac{5.6}{180} = 1.3......2.2 \quad (8)$$

The highest value is similar to the measured one.

An empirical prediction formula to estimate flicker level at PCC is recommended for a.c. furnaces [6]:

$$K_{st} = P_{st95\%}\frac{S_{sc}}{S_{scf}} = 70 \quad (9)$$

S_{SCf} = 5.6 MVAis the EAF short circuit power.
S_{SC} = 180 MVA   is the network short circuit power.
K_{st} is a flicker emission coefficient. A value of K_{st} should be considered in the range from 40 to 80.

C. Flicker improvement ratio (FI)

The EAF apparent power could be determined according to the power factor limit described in [1].

$$S_L = \frac{2.5x10^6}{0.85} = 2.95\ \text{MVA} \quad (10)$$

Then, the ratio between EAF apparent power and the short circuit level at the steel industry substation can be estimated.

$$K_2 = \frac{S_L}{S_{sc}} = \frac{2.95x10^6}{180x10^6} = 0.016 \quad (11)$$

With this K_2 value, the maximum flicker that could be emitted by the steel industry can be obtained from Table IX:

$$P_{st\ Limit} \leq 0.58 \quad (12)$$

Thus, the flicker improvement ratio can be obtained:

$$FI = \frac{Pst real}{Pst\ Limit} = \frac{2.2}{0.58} = 3.8 \quad (13)$$

This parameter is essential to determine the flicker compensator size.

D. Flicker propagation

The relationship between flicker and short circuit power in two nodes of the network could be estimated by:

$$Pst2 = Pst1\frac{Ssc1}{Ssc2} \quad (14)$$

Results obtained for the present case are shown in Table X.

TABLE X
FLICKER PROPAGATION

	Steel industry Busbar (13.2 kV)	**PCC (13.2 kV)**	**HV network**
Short circuit Power (MVA)	180	330	2000
Flicker level ($P_{st95\%}$)	2.2	1.2	0.2

E. Minimum short circuit power to avoid compensation

In order to comply with [1], and according to the first line of Table IX, the minimum P_{st} emission limit is:

$P_{stLimit} = 0.37$

From (14), it is possible to calculate the minimum short circuit power at the steel industry busbar to comply with this emission limit. For the present case P_{st} and S_{SC} values are:

$P_{st1} = 2.2$ $\quad S_{SC1} = 180$ MVA

Then, to reach the condition:

$P_{st2} \leq P_{stLimit} = 0.37$

from (14), the S_{SC2} required value yields:

$S_{SC2} \geq 1100$ MVA

If the short circuit power at the steel industry busbar is 1100 MVA or higher, flicker compensation will not be necessary. This technical solution could be implemented by connecting the steel industry to the HV network (132 kV).

F. Compensator Rating

The most effective way to control voltage fluctuations and therefore, to limit flicker is to compensate the reactive power variations of the fluctuating loads at medium/high voltage levels. The fast response of the Static Compensator (STATCOM) makes it an efficient solution for improving power quality in distribution systems.

In order to estimate the rating for an EAF STATCOM, an approximate equation is given in [7] and reproduced here:

$$Q_{STATCOM} = 0.54 \cdot \sqrt{(FI)} \cdot S_{ratedAF}$$

$FI = 3.8$ is the flicker improvement ratio.
$S_{ratedAF} = 0.65 \cdot S_{scf} = 3.7$ MVA is the EAF rating.
$S_{scf} = 5.6$ MVA is the EAF fault level.

The compensator rating is then:

$$Q_{STATCOM} = 0.54 \cdot \sqrt{3.8} \cdot 3.7 \cong 4\,\text{MVAr}$$

IV. CONCLUSIONS

The sequence of procedures followed in this work is that arising from a good engineering practice: measurement, evaluation, model parameter attainment, definition and further implementation of mitigation alternatives.

In the first case, the installation had a reactive compensation bank which, according to measurements and studies, would cause harmonic magnification. Different mitigation measures to comply with the regulated limits were studied. A C-type dumped filter was chosen and then designed. It was a great goal to measure Q factor through switching banks. This case also puts in evidence the different criteria of severity from IEEE and international (IEC) standards.

In the second case, the flicker level measured in the steel industry busbar was high and exceeded the reference level. The first solution deals with the connection of the steel industry to the immediate high voltage level. The second solution deals with the installation of a STATCOM-type compensator, whose basic characteristics have been established. Either choice should be made according to technical and economic factors.

Authors expect that this work can be used as a guide for other cases involving electric furnaces.

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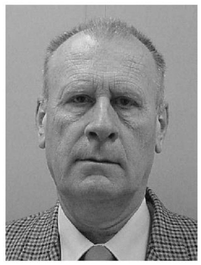
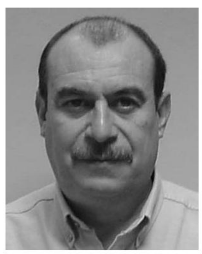


Pedro E. Issouribehere was born in Balcarce, Argentina, on September 19, 1945. He received the Engineer degree from La Plata National University, Buenos Aires, Argentina, in 1971. He has worked as a researcher for IITREE-LAT since 1970, a R&D University Institute. He is a specialist in electronic equipment development for non conventional electrical measurements.
He is in charge of the IITREE-LAT Technical Assistance Area. Currently his research interests are power quality and electromagnetic environmental impact, and their applications in South American electrical markets.
He is a full professor at the Electrical and Electronic Engineering Department, La Plata National University, Argentina.
He is currently the President of CIGRÉ Technical Committee, Argentina.



Juan C. Barbero was born in Capital Federal, Argentina, on December 25, 1955. He received the Engineer degree from La Plata National University (UNLP), Buenos Aires, Argentina on 1983.
He has been with IITREE-LAT since 1987 where currently he is concerned with power quality in power systems, industry installations and distribution systems.
Since 1999 he has been an Associate Professor at the Electrical and Electronic Department, UNLP.

Gustavo A. Barbera was born in La Plata Argentina, on February 20, 1972. He received the Engineer degree from La Plata National University, (UNLP) Buenos Aires, Argentina, in 1996.
He has worked as a researcher for IITREE-LAT of UNLP since 1996. He carries out and processes power quality measurements, especially regarding voltage level and disturbance studies.
He is a professor at the Electrical and Electronic Engineering Department, UNLP.

Fernando Issouribehere was born in La Plata, Argentina, on March 22, 1975. He received the Engineer degree from La Plata National University, Buenos Aires, Argentina, in 1999.
He has worked as a researcher for IITREE-LAT since 2000. His research interests include power systems operation and control, power quality, and power electronics.
He is an assistant professor at the Electrical and Electronic Engineering Department, UNLP.