POWER QUALITY MEASUREMENTS IN A STEEL INDUSTRY WITH ELECTRIC ARC FURNACES.

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Abstract**—**Many loads connected to electric power systems can cause power quality problems at all voltage levels and for very different power ratings due to their unbalanced and non-linear behavior characteristics.

This paper describes the aspects of power quality at the point of common coupling (PCC) where an arc furnace for steel melting with alternating current is connected. By measurements of Flicker, harmonics content in voltage and current, active and reactive power and power factor, the preservation of the reference levels for the supply voltage and emission limits for the furnace as a customer are evaluated.

The evaluation of power quality of contemporary International and Argentinian standards is given.

The different phases in the operation of the arc furnace are described in detail and illustrated with measurements.

Index Terms**—** Arc Furnaces. Flicker. Harmonics. Power Quality. STATCOM. SVC.

I. INTRODUCTION

In order to ensure the electromagnetic compatibility in distribution networks, the perturbation levels in different points of them must be confined to certain limits [1] and [2], process that involves a permanent control of emissions due to every disturbing load connected to the network.

Electric arc furnaces loads can result in serious electrical disturbances on a power system. Low level amplitude modulation of the supply voltage of less than 0.5% can cause annoying Flicker in lamps and invoke public complaints when the frequencies lie in the range of 3-10 Hz.

An electric arc furnace of 75 MW for steel melting was connected at 132 kV voltage level in the Transmission System of Buenos Aires (Argentina). A second electric arc furnace of the same power rating will be connected in the future. The IITREE has made measurements of some power quality indicators to check the reference levels at the Point of Common Coupling (PCC) and the emission levels of the arc furnace as a disturbing load. The quantities measured are voltage and current harmonics, Flicker, power factor and active and reactive power.

According to the electrical parameter data, a single phase electric circuit of the arc furnace was obtained. The measurements made during the several phases in the operation of the arc furnace support the validity of the model.

Technical solutions for the Flicker problem are presented.

II. DESCRIPTION OF THE POWER SYSTEM AND PCC

The one-line diagram of the power system and the steelwork is shown in Fig. 1.

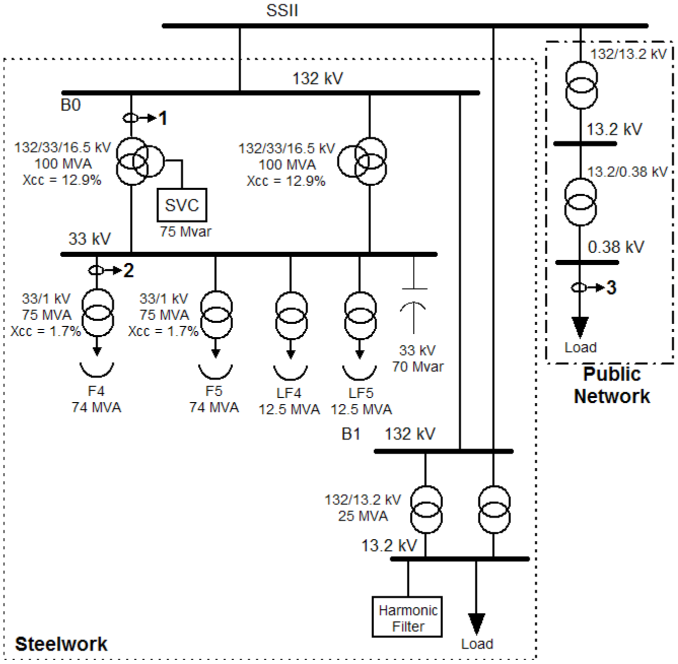

Fig. 1: Electrical system configuration.

As it is shown in Fig. 1, the steelwork is supplied directly from public transmission network at 132 kV. Power quality measurements were made at 132 kV (point 1) and in the measuring transformers on the primary side of the arc furnace transformer (point 2). Flicker measurements at low voltage levels of public network (point 3) were also performed.

III. CHARACTERISTICS OF ELECTRIC ARC FURNACES

An electric arc furnace consists of a refractory lined shell which holds the charge, usually scrap metal. Three large electrodes, usually of graphite, are held in special clamps on a swing support structure which can be swung aside for charging, and which allows each electrode to be raised or lowered according to the output of the control system.

After the furnace is charged with scrap, operation begins by lowering the electrodes to strike electric arcs between the electrodes and the scrap. The heat generated by the three electric arcs provides the energy required to melt the scrap.

There are several phases in the operation of the arc furnace, each presenting a different impact on the power system in terms of Flicker, namely the:

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- Boring period.
- Melting period.
- Refining period.

Fig. 2 shows the measured active and reactive power consumption during the first part of the heat cycle. From this figure it is possible to distinguish the strong active and reactive power variations in the first minutes of the process.

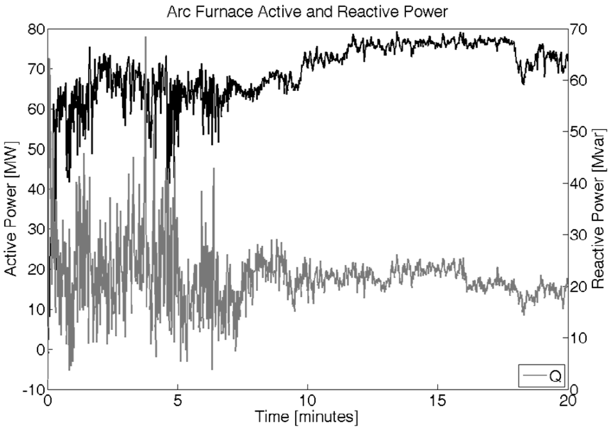

Fig. 2: Arc furnace active and reactive power .

In terms of Flicker impact on the power system, the most critical stages are the boring and melting periods, which occur every time a new basket with scrap metal is added. These periods are characterized by strong stochastic variations in the reactive power absorbed by the arc furnace.

The one-line diagram of the arc furnace electrical installation is shown in Fig 3.

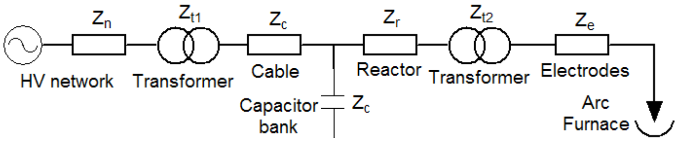

Fig. 3: One-line electric diagram of the arc furnace.

The arc can be represented as a variable resistance in a single phase equivalent circuit of the furnace and its supply system, as it is shown in Fig. 4 [3].

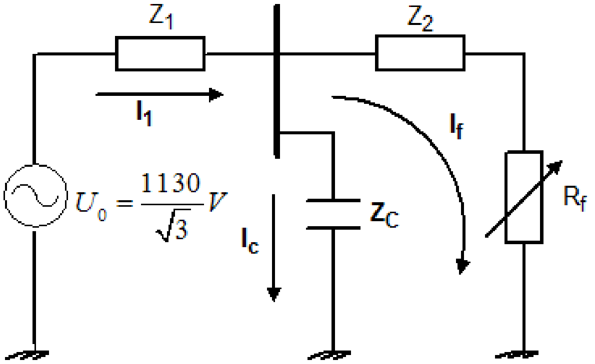

Fig. 4: One-line circuit of arc furnace and its supply system.

Although this model is a simplification of the real furnace and implies balanced arc furnace operation, it gives accurate account of furnace operation in terms of averaged quantities, as it will be demonstrated by measurements. The control of the circuit of Fig. 4 is by means of vertical movement of the graphite electrodes, which controls the arc length and therefore its voltage, and by varying the transformer taps, which modifies U_0. The electrical parameter data of the arc furnace feeding system are shown in Table I.

Table I. Electrical installation parameters.

Electrical Parameter	**Manufacturer/Owner Information**
HV network	$S_{cc} = 2800$ MVA, $X/R = 9$
Step down transformer	132/33/16.5 kV, 100/100/130 MVA $Z_{cc} = 12.93\%$, $X/R = 36$
MV cable	$X_c = 0.112\ \Omega$, $R_c = 0.032\ \Omega$
Capacitor Bank	$U_n = 33$ kV, $Q_n = 70$ Mvar
Series Reactor	$X_r = 3.1\ \Omega$, $X_r/R_r = 195$
Furnace Transformer	33/(0.46 to 1.13) kV, 75 MVA $Z_{cc} = 1.7\ \%$, $X/R = 5.8$
Electrodes and Flexible leads	$X_e = 2.4\ m\Omega$, $R_e = 0.34\ m\Omega$

The electrical parameters of the equivalent circuit, referred to the secondary side of the arc furnace transformer are detailed in Table II.

Table II. Parameters obtained with the equivalent circuit.

Parameter	**Equations and values**
U_0	$1130/\sqrt{3}V$
Z_1	$X_1 = X_n + X_{t1} + X_c = 1.409\ m\Omega$ $R_1 = R_n + R_{t1} + R_c = 0.109\ m\Omega$
X_c	$18.24\ m\Omega$
Z_2	$X_2 = X_r + X_{t2} + X_e = 6.428\ m\Omega$ $R_2 = R_r + R_{t2} + R_e = 0.427\ m\Omega$
Total Current	$\lvert I_1 \rvert = \frac{U_0}{\lvert Z \rvert}$
Electrode Current	$\lvert I_f \rvert = \frac{U_0 \cdot \lvert X_c \rvert}{\lvert Z \rvert \cdot \sqrt{(R_2+R_f)^2 + (X_2+X_c)^2}}$
Capacitor Current	$\lvert I_c \rvert = \frac{U_0 \cdot \sqrt{(R_2+R_f)^2 + (X_2)^2}}{\lvert Z \rvert \cdot \sqrt{(R_2+R_f)^2 + (X_2+X_c)^2}}$
EAF Active Power	$P_f = 3 \cdot R_f \cdot \lvert I_f \rvert^2$ [MW]
EAF Reactive Power	$Q_f = 3 \cdot X_2 \cdot \lvert I_f \rvert^2$ [Mvar]
EAF Apparent Power	$S = \sqrt{P_f^{\,2} + Q_f^{\,2}}$ [MVA]
Losses in equivalent resistance	$P_{losses} = 3 \cdot R_2 \cdot \lvert I_f \rvert^2$ [MW]
Shunt capacitor Reactive power	$Q_c = 3 \cdot X_c \cdot \lvert I_c \rvert^2$ [Mvar]
Short circuit power in EAF transformer	$S_{sc} = 3 \cdot \frac{U_0^{\,2}}{\lvert Z_1 \rvert} = 905\ MVA$
EAF short circuit power	$S_{scf} = 3 \cdot \frac{U_0^{\,2}}{\lvert Z_1 + Z_2 \rvert} = 165\ MVA$

It is possible now to estimate the general load variations of the electric arc furnace by using the equivalent circuit shown in Fig. 4. The results are shown in Fig. 5.

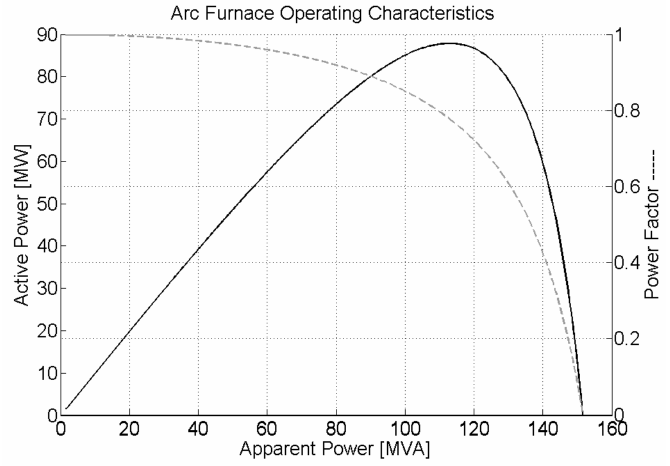

Fig. 5: Furnace operating characteristics.

If the impedances Z_1 and Z_2 were unknown, they could be estimated by the short circuit test [4] and [5]. In this test the electrodes are immersed in the liquid scrap, and the load becomes a 3-phase short circuit, which is equivalent to $R_f = 0$ in Fig. 4. Measuring line-to-ground voltages and currents in the primary of the furnace transformer during the short circuit (U_{cc} and I_{cc}), the impedances could be estimated as:

$$Z_1 = \frac{|U_0 - U_{cc}|}{I_{cc}} \text{ and } Z_2 = \frac{U_{cc}}{I_{cc}} \qquad (1)$$

To analyze the different phases in the operation of the electric arc furnace, measurements of phase voltages and currents were made. The utilized instrument was a HIOKI 8855 waveform-recorder, with 12 bits resolution and 8 isolated channels. The sampling frequency adopted was 2 ksamples/s.

Boring period

This period is characterized by strong variations of both active and reactive power caused by stochastic variations in the arc length due to the irregular surface of the scrap metal. The measurement results are shown in Fig. 6 and Fig. 7.

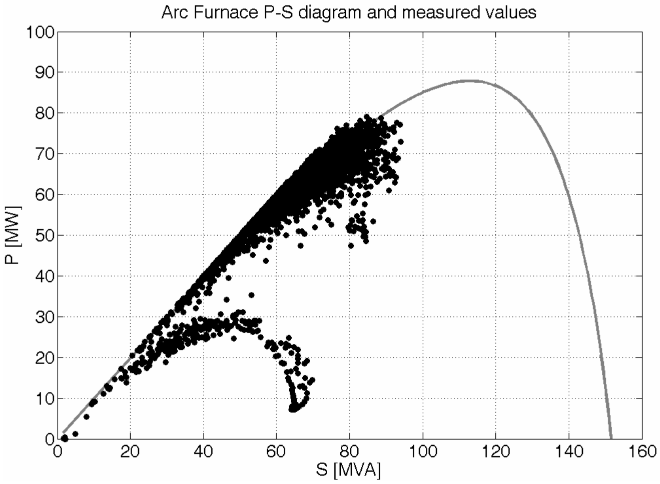

Fig. 6: Calculated P-S characteristic and measured points during the Boring period.

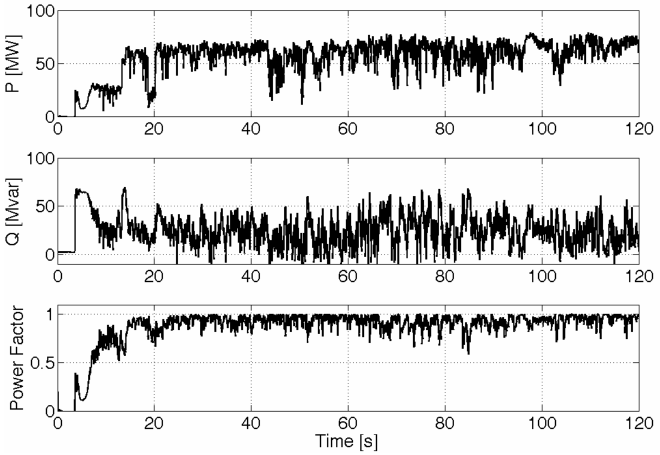

Fig. 7: Measured power factor and active and reactive power during the Boring period.

Melting period

The results obtained from measurements taken in this period are shown in Fig. 8 and Fig. 9.

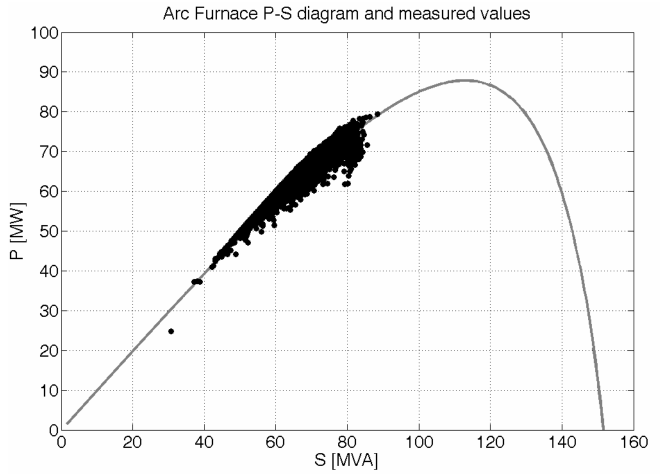

Fig. 8: Calculated P-S characteristic and measured points during Melting period.

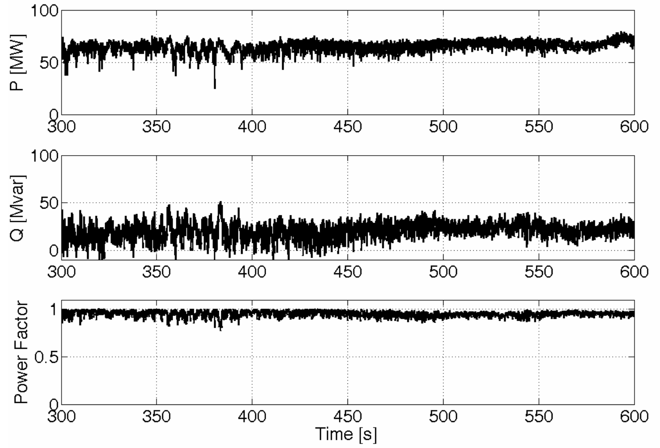

Fig. 9: Measured power factor and active and reactive power during Melting period.

Refining period

The results obtained from measurements taken in this period are shown in Fig. 10 and Fig. 11.

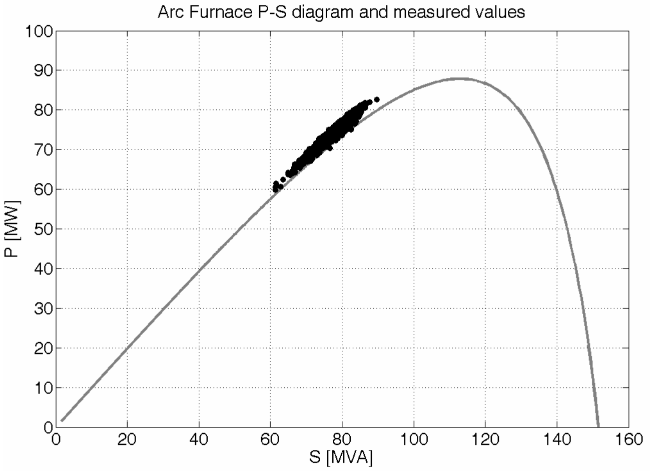

Fig. 10: Calculated P-S characteristic and measured points during Refining period.

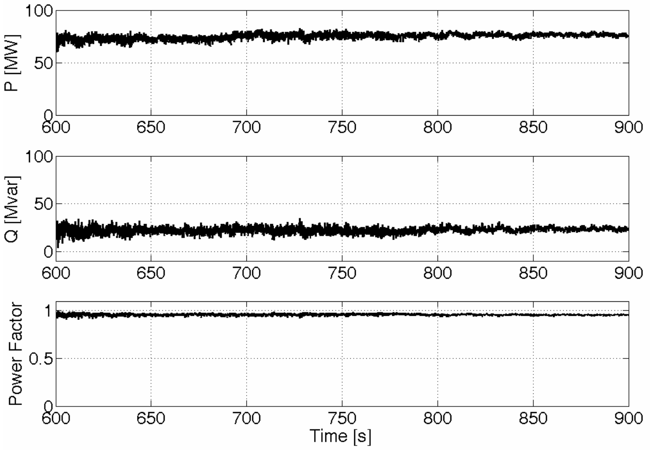

Fig. 11: Measured power factor and active and reactive power during Refining period.

It is interesting to note the similarity between the measured points and the calculated characteristics of the electric arc furnace obtained from electrical data.

IV. STANDARDS AND RECOMMENDATIONS

Repetitive voltage fluctuations in power systems need to be controlled within reasonable low levels in order to reduce to an acceptable level their impact on domestic and commercial customers. The main reason for such control actions is the effect of the arc furnace operation on the light output of incandescent electric lighting i.e., Flicker, that can cause irritation for the eye and therefore to human beings.

According to Argentinian regulations it is the responsibility of utilities and/or power system operators to ensure the electromagnetic compatibility (EMC) of the whole system and the equipment connected to it. In this respect compatibility levels have to be considered as reference values for the coordination of emission and immunity of equipment connected to the power network. The compatibility levels have to be considered on statistical basis, generally adopting the principle that the levels chosen will not be exceeded in both time and space with a 95% probability.

A summary of Flicker compatibility levels and planning levels for LV, MV and HV networks [6] is given in Table III.

Table III: Summary of IEC Flicker standards.

Standard		**IEC 61000-3-7 [7]**	**IEC 61000-2-12 [8]**
Purpose		Defines planning levels for controlling emissions	Defines compatibility levels for MV networks
Objectives at MV	P_{st}	0.9	1
	P_{lt}	0.7	0.8
Objectives at HV-EHV	P_{st}	0.8*	Not applicable
	P_{lt}	0.6*	Not applicable

Remarks: *Assuming an attenuation factor of 1 between HV-EHV to MV-LV.

For assessment purposes, the minimum period of observation should be one week, and the $P_{st99\%}$ and $P_{lt99\%}$ values resulting from the measurements should be compared with the allowed relevant 99% or 95% emission limits. The following relationships are considered:

$$P_{st99\%} = 1.25\, P_{st95\%}$$
$$P_{lt95\%} = 0.84\, P_{st95\%}$$

V. FLICKER MEASUREMENTS

To evaluate the Flicker levels of the steelwork, the IITREE performed some Flicker measurements with the IEC 61000-4-15 [9] normalized flickermeter Boconsult B9-DSP. Fig. 12 shows the normalized one-week P_{st} measurements in 132 kV busbar B0 and Fig. 13 shows the statistical results.

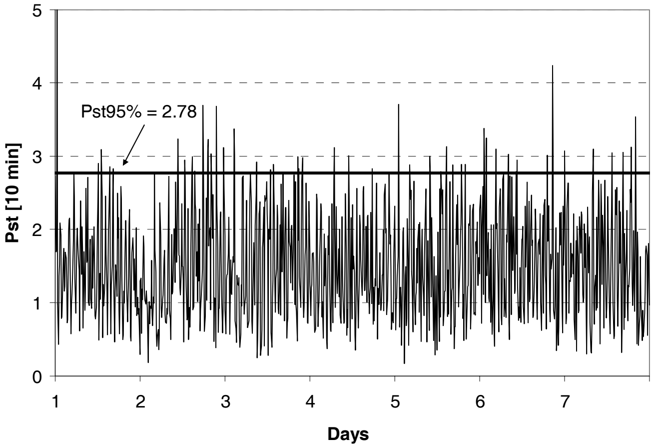

Fig. 12: Normalized P_{st} measurement at 132 kV.

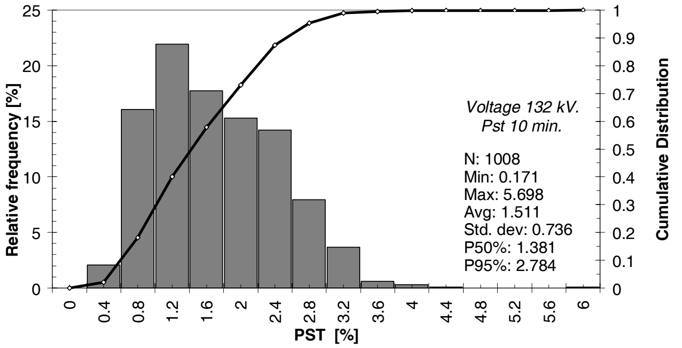

Fig. 13: Statistical results of P_{st} measurement at 132 kV.

Simultaneous 1-minute Flicker measurements were performed at 132 kV and 33 kV busbars and in residential customers (220 V). These measurements were carried out to quantify the Flicker propagation factor. The results are shown in Fig. 14, Fig. 15, Fig. 16, Fig. 17 and Fig. 18.

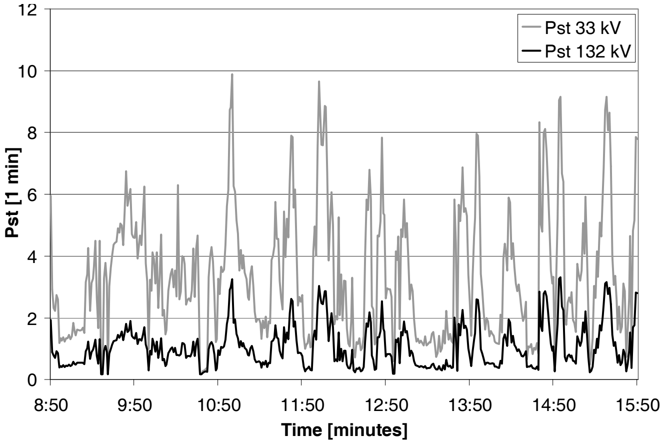

Fig. 14: P_{st} measurements at 132 kV and 33 kV.

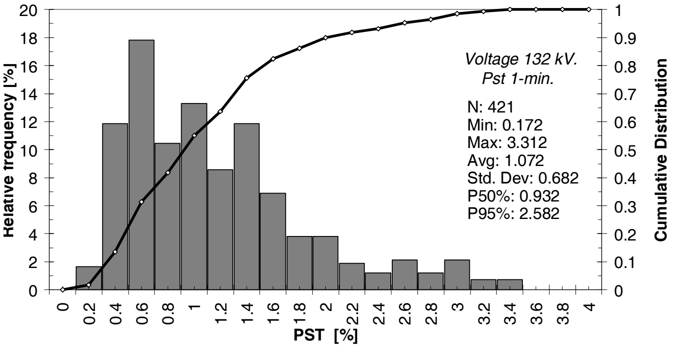

Fig. 15: Statistical results of P_{st} measurement at 132 kV.

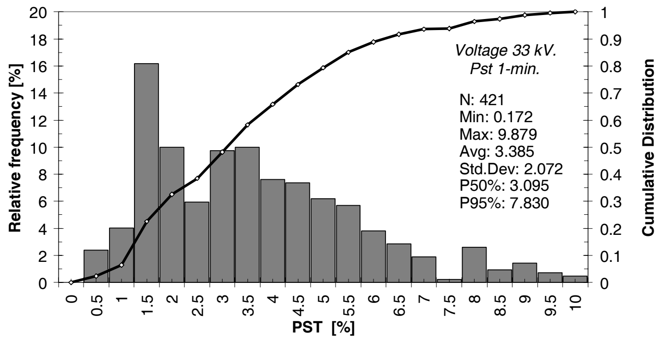

Fig. 16: Statistical results of P_{st} measurement at 33 kV.

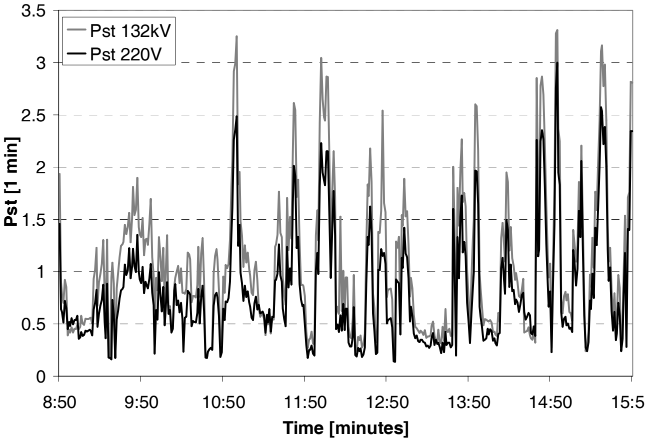

Fig. 17: P_{st} measurements at 132 kV and 220 V.

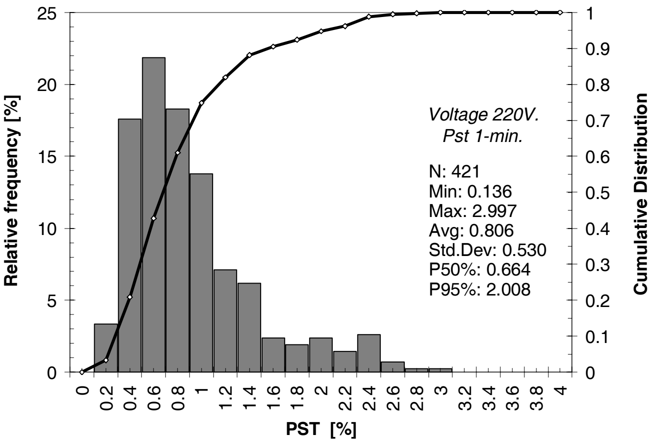

Fig. 18: Statistical results of P_{st} measurement at 33 kV.

Table IV shows a summary of the P_{st} measurement at different voltage levels.

Table IV: P_{st} measurement summary.

	MV network (33 kV)	**HV network (132 kV)**	**LV network (220 V)**
S_{cc} (MVA)	905	2800	-------
Flicker level ($P_{st95\%}$)	7.83	2.58	2.01

Verification of measured Pst95% values and determination of Flicker transfer coefficients

The CENELEC EN 50160 European Standard specifies the main characteristics of the voltage at the customers supply terminals in public low and medium voltage distribution systems under normal operating conditions. According to that Standard, the arc furnace Flicker in the 33 kV busbar could be estimated by:

$$P_{st95\%} \approx 40......70 \frac{S_{scf}}{S_{sc}} \tag{2}$$

For the arc furnace analyzed:

$$P_{st95\%} \approx 40......70 \frac{165}{905} = 7.29......12.76 \tag{3}$$

The measured value of $P_{st95\%} = 7.83$ is in this possible range.

In a radial system, the relationship between Flicker in two nodes of the network and the corresponding short circuit power at those nodes could be estimated by:

$$P_{st132kV} = P_{st33kV} \cdot \frac{S_{cc33kV}}{S_{cc132kV}} = 2.53 \tag{4}$$

This value is similar to the one obtained by measurements in the 132 kV busbar. The downstream to upstream Flicker transfer coefficient is:

$$T_{MV/HV} = \frac{P_{st95\%}(33kV)}{P_{st95\%}(132kV)} = \frac{7.83}{2.58} = 3.04 \tag{5}$$

$$T_{MV/HV} = \frac{S_{cc}(132kV)}{S_{cc}(33kV)} = \frac{2800}{905} = 3.09 \tag{6}$$

The upstream to downstream Flicker transfer also can be established using the Flicker measurements.

$$T_{LV/HV} = \frac{P_{st95\%}(220V)}{P_{st95\%}(132kV)} = \frac{2.01}{2.58} = 0.78 \tag{7}$$

Knowing the Flicker transfer coefficient plays an important role when allocating the Flicker emission limit to a proposed load. For example, the global Flicker emission allowance G_{PstMV} at a MV busbar connected to an upstream HV busbar is given by [7].

$$G_{PstMV} = \sqrt[3]{L^3_{PstMV} - T^3_{PstHM} \cdot L^3_{PstHV}} \qquad (8)$$

Where L_{PstMV} is the Flicker planning level at the MV busbar, T_{PstHM} is the Flicker transfer coefficient between HV and the MV system, and L_{PstHV} is the Flicker planning level at the HV busbar. Using indicative planning levels of [7] ($L_{PstMV} = 0.8$ and $L_{PstHV} = 0.9$) and considering the measured Flicker transfer coefficient of $T_{PstHM} = 0.78$, the global short-term Flicker emission is $G_{PstMV} = 0.55$.

Flicker situation of the steelwork according to the Argentinian Standards

The emission limit for Flicker according to the Argentinian Standard Res. 99/97 [1] of ENRE is dependent of the short circuit power of the system at PCC and the power of the consumer, as can be seen in Table V.

Table V: Individual Emission Limits [1].

MV and HV (1 < U ≤ 220 kV) $K2 = S_L/S_{sc}$	Individual Emission Limits (PST)
$K_2 \leq 0,005$	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

The steelwork apparent power could be determined according to the maximum demand power and power factor limit described in Res. 99/97.

$$S_L = \frac{120x10^6}{0.85} = 140MVA \qquad (9)$$

It is possible now to estimate the ratio between the steelwork apparent power and the short circuit level at the steelwork substation.

$$K_2 = \frac{S_L}{S_{sc}} = \frac{140x10^6}{2800x10^6} = 0.05 \qquad (10)$$

With this K factor it is possible to obtain by Res. 99/97 the maximum Flicker that could be emitted by the steelwork.

$$P_{st\max} \leq 0.79$$

According to this value it is possible to estimate the Flicker compensation ratio:

$$FI = \frac{P_{streal}}{P_{st\lim it}} = \frac{2.78}{0.79} = 3.5 \qquad (11)$$

Flicker compensation by the SVC

The theoretical Flicker improvement ratio of the SVC is:

$$FI = 1 + 0.75 \cdot \frac{Q_{SCV}}{S_{rAF}} \approx 1.6 \qquad (12)$$

With: $Q_{svc} = 75$ Mvar and $S_{rAF} = 0.6*S_{scf} = 100$ MVA

The measured SVC Flicker compensation ratio was:

$$FI = \frac{P_{st33kV}}{P_{st132kV}} \cdot \frac{1}{\left(1 + \frac{S_{sc132kV}}{S_{sc33kV}}\right)} \approx 1.1 \qquad (13)$$

The lower measured Flicker compensation ratio is due to the fact that the SVC is placed in the tertiary winding (16.5 kV) of the step down transformer, and to the slow speed of response of the SVC control system.

Flicker estimation with two arc furnaces in service

The Flicker emission level in the future operating condition of two identical arc furnaces can be estimated by:

$$P_{st95\%2f} = \sqrt[3]{\sum_{j=1}^{2}\left(P_{st95\%j}\right)^3} = 3.25 \qquad (14)$$

The Flicker levels in the different voltages levels will change in a proportional relation.

VI. FLICKER COMPENSATION

Minimum short circuit power to avoid compensation

In order to meet with Res. 99/97, the maximum $P_{stLimit} = 0.79$ must be considered. For the present case:

$$P_{st1} = 2.78 \quad \text{and} \quad S_{cc1} = 2800 \text{ MVA}$$

Then it yields:

$$S_{cc2} > 9850 \text{ MVA}$$

If the short circuit power at the steelwork busbar is 9850 MVA or more, there is no need for Flicker compensation. This could be implemented by connecting the steelwork to the immediately high voltage level (500 kV). In this particular case, this solution is technically and economically impossible.

STATCOM compensator rating

The fast response of the Static Compensator (STATCOM) makes it an efficient solution to compensate the reactive power variations, and therefore to limit Flicker at MV levels [10]. From observations of practical installations the approximate equation to estimate the rating of a STATCOM is [11]:

$$Q_{STATCOM} = 0.54 * \sqrt{(FI)} * S_{rAF} = 100 \textbf{ Mvar} \qquad (15)$$

In practice, this would mean a compensator installation consisting of a ± 50 Mvar STATCOM and a 50 Mvar filter.

The existing SVC together with a STATCOM will provide the following benefits:

- The STATCOM as a voltage source will provide a more balanced set of three phase voltages to the arc furnace and due to its higher speed of response will act as an active filter to reduce harmonics generated by the EAF and SVC.
- In addition, the STATCOM will effectively damp parallel resonance with the power system especially at harmonic frequencies. In some cases, it may eliminate the need for the installation of second and third harmonic filters.
- The presence of the STATCOM will increase the operational efficiency and speed of response of the SVC enabling the hybrid compensator to perform in a superior manner to a compensator consisting of only an SVC.

VII. HARMONIC MEASUREMENTS

To characterize the behavior of the electric arc furnace as a perturbing load, some particular analyses of measured currents were carried out. The Flicker emitted by the arc furnace is related to the spectral components of the current envelope. The normalized spectral components of current in the different operating conditions are shown in Fig. 19.

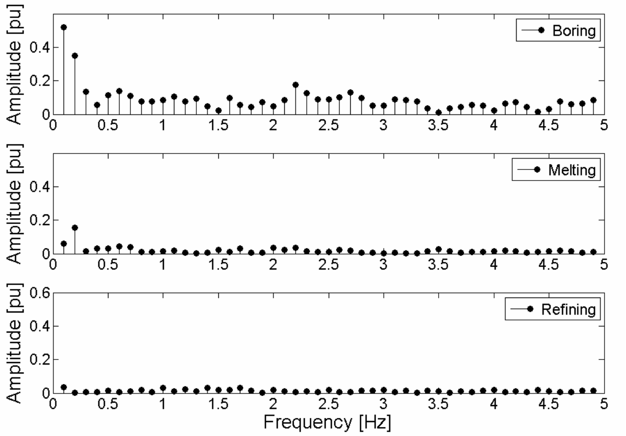

Fig. 19: Spectral components of current envelope.

The arc furnace produces interharmonics of low frequency and high amplitude during the Boring period which cannot be eliminated by passive filters. These interharmonics are responsible for the high Flicker levels measured during this period. Fig 20 and Fig 21 show the 1-minute current harmonic measurements in the primary side of the furnace transformer.

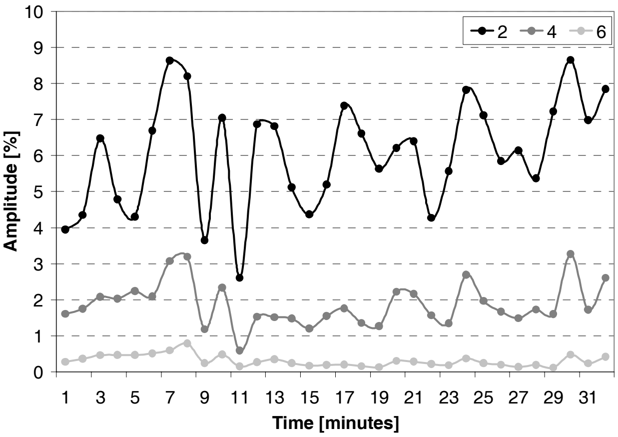

Fig. 20: Even current harmonics measured.

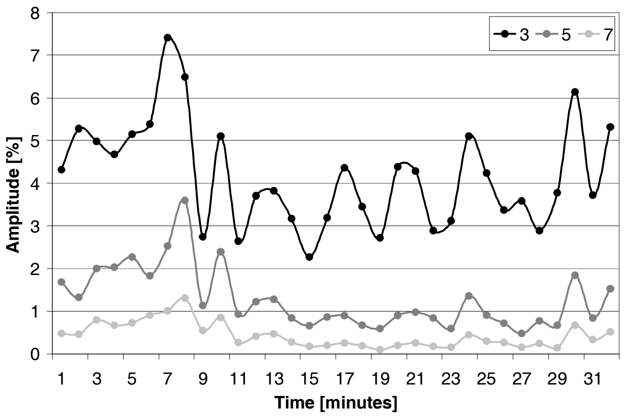

Fig. 21: Odd current harmonics measured.

Table VI summarizes the results of harmonic content of arc furnace current described in IEEE 519 Standard [12], and the results obtained from measurements.

Table VI: Harmonic content of arc furnace current.

Furnace Condition		Harmonic current [%] of fundamental				
		I_2	I_3	I_4	I_5	I_7
Initial melting (active arc)	Theoretical	7.7	5.8	2.5	4.2	3.1
	Measured	8	7	2.8	3.8	1.4
Refining (stable arc)	Theoretical	-	2.0	-	2.1	-
	Measured	4	2.2	1.2	1	0.5

The Argentinian Standard is ENRE's Res. 184/00 [2]. Reference levels to be met are those which should be guaranteed at each supply point. Transgression probability should not be above 5 % a week. The adopted values for harmonics depend on the voltage level [13]. The results obtained for one-week measurements of voltage and current harmonic levels are shown in Fig 22, and Fig 23.

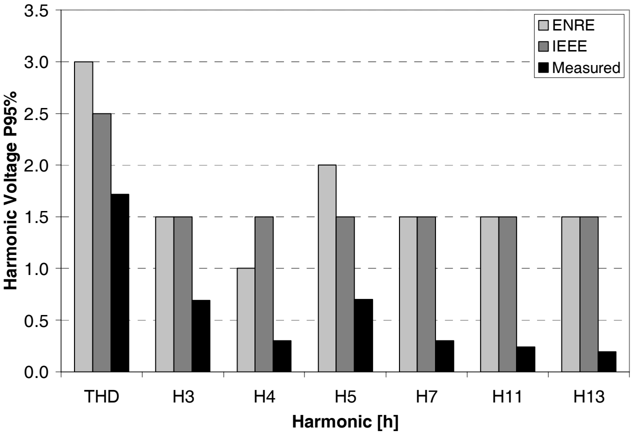

Fig. 22: Voltage harmonics reference levels and measured.

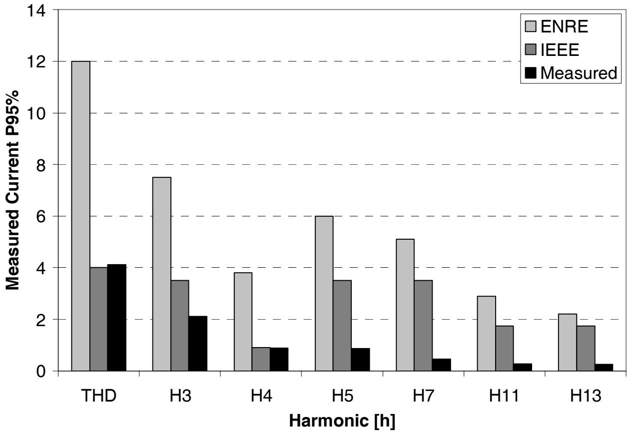

Fig. 23: Emission limits and current harmonics measured.

According to Res. 99/97 [1], to evaluate the emission limits, the harmonics currents should be referred to the current obtained from the maximum load demand of 120 MW and an indicated power factor of 0.85. According to IEEE 519 [12] the current distortion limits for general distribution systems are based on the size of the load compared to the size of the power system to which the load is connected.

The ratio I_{sc}/I_L is the ratio of the short circuit current available at the PCC, to the maximum fundamental load current. The even harmonics are limited to 25% of the odd harmonic limits. In the present case the ratio $I_{sc}/I_L = 20$.

The results obtained for one-week measurements of voltage and current harmonic levels are summarized in Table VII and Table VIII.

Table VII: Reference levels for voltage harmonics according to ENRE and IEEE and measured voltage harmonics.

	THD	H3	H4	H5	H7	H11	H13
ENRE Limits	3	1.5	1	2	1.5	1.5	1.5
IEEE Limits	2.5	1.5	1.5	1.5	1.5	1.5	1.5
Measured $P_{95\%}$	1.72	0.69	0.30	0.70	0.30	0.24	0.19

Table VIII: Emission limits for current harmonics according to ENRE and IEEE and measured current harmonics.

	THD	H3	H4	H5	H7	H11	H13
ENRE Limits	12	7.5	3.8	6	5.1	2.9	2.2
IEEE I_{sc}/I_L	4	3.5	0.9	3.5	3.5	1.75	1.75
Measured $P_{95\%}$	4.12	2.11	0.88	0.86	0.46	0.27	0.25

In IEEE 519 Standard it is not indicated if the emission limits must be applied to the medium, the $P_{95\%}$ or to the maximum measured current harmonics. If we choose the $P_{95\%}$ value, the current THD is above the IEEE limit.

VIII. CONCLUSIONS

In the first section of this paper a detailed analysis of the several phases of operation of an arc furnace is included.

Reported measurements also describe power factor, active and reactive power variations, and current harmonic content, in the different phases of operation of the arc furnace. The current harmonic content measured during initial melting and refining is similar to the theoretical values described in [12].

The Flicker level measured in the steelwork is high and exceeds the reference level at PCC. Flicker compensation ratio needed for the determination of compensator rating is calculated.

The current harmonic levels measured during initial melting period are high, but in the normalized one-week measurement only the THD is above the IEEE emission limits.

The main characteristics and rating of a STATCOM device, which can represent a future solution to the Flicker emission problem, is given. The STATCOM due to its fast dynamic response is able to reduce the Flicker significantly better than a SVC of comparable rating. The STATCOM offers additional advantages in terms of much smaller harmonic generation and smaller physical size and footprint.

IX. REFERENCES

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X. BIOGRAPHIES

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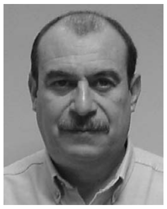

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