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Harmonics and Flicker in an Iron and Steel Industry with AC arc furnaces

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Abstract. An AC arc furnace is an unbalanced, non-linear and time-varying load, which can cause many power quality problems to the electric network inside the plant and in its electrical vicinity. Although different studies addressing harmonics and flicker analyses on arc furnaces can be found in the bibliography, it is very difficult obtain an exact model that considers all the parameters that influence the process, and therefore it is necessary to obtain actual measurements under different conditions. This paper presents measurement results for harmonic distortion, flicker and unbalance obtained over three different measurement campaigns on an iron and steel industry (SNL), as well as the pertinent conclusions. Measurement campaigns were performed on an AC arc furnace of 83 MW (170 TM) with a 120 MVA transformer connected by a 'dirty' 220 kV line (55 km) to the Substation of Carregado, where other feeders supply industrial and domestic consumers. Finally, the dynamic behaviour of an SVC will be analysed and compared to that of a STATCOM by means of simulation studies.

Key words.

Flicker, harmonics, power quality, arc furnaces.

1. Introduction

Electric arc furnaces are currently one of the main steel production methods. Anything from ordinary steels to special alloyed steels with other metals can be obtained with this method, usually using steel scrap as the starting material.

The melting and tuning arc furnaces are the elements with the highest consumption of electrical energy in the steelworks, and also those which are most 'polluting', causing waveform distortion. Siderurgia Nacional de Produtos Longos (SNL) is a steel producing company with a factory located in Seixal (near Lisbon), with a 120 TM furnace connected to a 120 MVA transformer. The factory is fed at 220 kV through a dedicated 55 km line connecting to the Substation of Carregado.

Although the electric circuit of the furnace is relatively simple, its operation is quite complex. This is due to the presence of the arc, which has a nonlinear behaviour causing the voltage and current waves to be non-sinusoidal.

The instantaneous value of the arc voltage in an arc furnace depends mainly on the height of the arc, that is, the length of the arc established between the graphite electrode and the scrap. This height changes constantly and very quickly, and these changes are casual and totally unpredictable and cannot be avoided by the electrode regulation system.

Arcs also change position at all moments, that is, they change the points on which they are established in the fusion material, thus changing the angle formed by the three electrodes [1].

Harmonics, inter-harmonics, voltage flicker and unbalance are the power quality problems introduced to the power system as a result of the nonlinear and stochastic behaviour of the arc furnace's operation. The nonlinear voltage-current characteristic of the arc can cause harmonic currents which when circulating through the electric network produce harmonic voltages, possibly affecting other users.

The importance of AC electric arc furnaces in flicker generation is high. Due to their random electric behaviour and the intermittent operating cycle (tap-to tap), the influence in power quality is always negative. If the steel-making factory is electrically close to a medium size town and connected to a HV electrical grid, it will be important to consider the various factors influencing the situation and magnitude of the different power supplies to this interconnected grid.

The furnace shell is isolated, and it is represented by a star connection of the three arcs, so if the three arcs were equal the load would be balanced, and the zero-sequence component of the current wave would be null. In reality, unbalance operation is the normal situation in the meltdown process and this produces zero sequence harmonics in the arc current. However, due to the characteristic intertwine of the three-phase system, these harmonic components are quite lower than those to be found in the current wave of a single-phase arc.

Different studies on arc furnace harmonics analysis can be found in the bibliography; for example, [1] presents an arc model to carry out an harmonic analysis of an AC three-phase arc furnace with a single-phase circuit. This model is based on V-I characteristic of the arc and takes into account the effect of the arcs' unbalance on the zero sequence harmonics.

In arc furnaces, in addition to the elements that allow us to conduct electrical energy to the arc, there are other elements that are necessary to improve the performance of the furnace, increasing its performance and decreasing its disruptive action on the grid. These devices are dynamic compensation systems and include the Static Var Compensator (SVC) and the STATCOM. This factory has an SVC supplied by Alstom.

In its simplest form, the SVC consists of a TCR (*Thyristor-Controlled Reactor*) in parallel with a bank of capacitors. From an operational point of view, the SVC behaves like a shunt-connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the internal network of the factory. It is used extensively to provide fast reactive power and voltage regulation support. The firing angle control of the thyristors enables the SVC to provide almost instantaneous response.

2. Measures

2.1. Harmonics measurements

The basic measurement of the voltage harmonics and interharmonics shall be carried out in accordance to the EN 61000-4-7 standard, with the measuring equipment following a given scheme specified in the standard. Most instrument models nowadays use the Discrete Fourier Transform, usually implementing an algorithm called Fast Fourier Transform.

Since arc melting is a stationary stochastic process, it is very difficult to obtain an accurate model for an arc furnace as an electrical load. The factors that affect arc furnace operation are the melting materials, the position of the electrodes, the electrode arm control scheme, and the system's voltage and impedance. For all these reasons, it is very important to carry out measurement campaigns.

The short-circuit capacity (Scc) at the Substation of Carregado is 4400 MVA, while the Scc at the point of connection of the internal network is 1370 MVA. Since all power quality measurements carried out must be referred to the interconnection point at the substation, the ratio 1370/4400 will be taken into account on an approximate basis; This means that any measures taken at the plant have an impact on interconnection of less than one third (31 %).

This approach is, at the very least, approximate because it means considering that the transmission of disturbances is only affected by the relationship of short circuit capacities, which is a gross simplification of the reality.

A much more appropriate approach would be to take measurements at both sites simultaneously, with two equal measuring devices programmed to start recording data at the same time. However, the additional cost of this solution led to its rejection by the company.

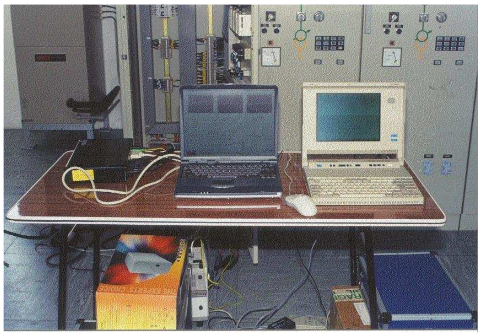

Figure 1. Measure equipment installed at the factory

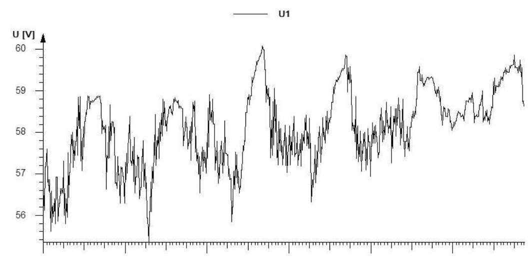

Figure 2. Voltage of Phase 1 versus time

The voltage data are affected by the transformation ratio of measurement voltage transformer, 220kV/100V.

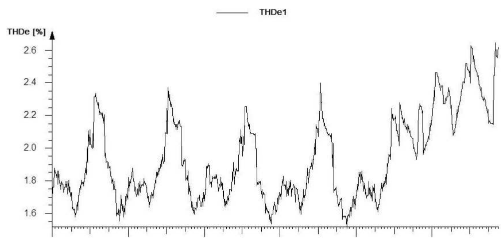

Figure 3. Total Harmonic Distortion of Voltage (Phase 1) versus time

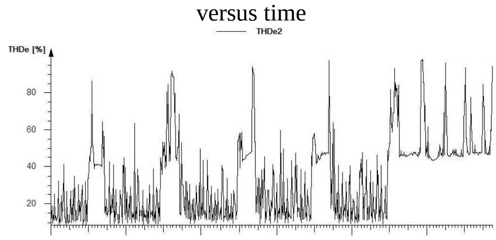

Figure 4. Total Harmonic Distortion of Current (Phase 1) versus time

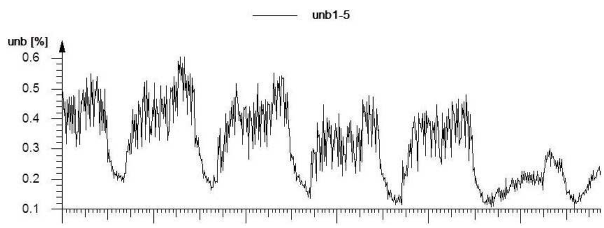

Figure 5. Voltage unbalance versus time

The voltage unbalances, Figure 5, with a maximum value of 0,53%, are within the specified limits.

Table 1. Summary of the minimum/maximum phase-neutral voltages measured at the Measurement Point of the SNL factory.

PHASE-NEUTRAL VOLTAGE		
	Minimum	**Maximum**
Phase 1-N	118072 V (ΔU= -7,03%)	130416 V (ΔU= 2,69%)
Phase 2-N	116410 V (ΔU= -8,34%)	129988 V (ΔU= 2,35%)
Phase 3-N	118119 V (ΔU= -6,99%)	130558 V (ΔU= 2,8%)

In Table 1 we can see the maximum and minimum values of the phase-neutral voltages of each of the three phases during a seven-day measurement campaign.

Table 2 shows that the SVC system has little impact on voltage THD, but that there is a significant increase in the current THD when the SVC is connected. This is a consequence of the electronic devices that form the structure of the SVC.

Table 2. Summary of the minimum/maximum voltage THD and the minimum/maximum current THD at the Measurement Point of the SNL factory with and without the SVC system installed and the arc furnace consuming about 30 MW.

WITHOUT SVC		
Minimum/maximum voltage THD		
	Minimum	Maximum
Phase 1	1,39 %	2,73 %
Phase 2	1,19 %	2,77 %
Phase 3	1,29 %	2,78 %
Minimum/maximum current THD		
Phase 1	4,64 %	98,59 %
Phase 2	4,47 %	65,41 %
Phase 3	4,63 %	91,75 %
WITH SVC		
Minimum/maximum voltage THD		
	Minimum	Maximum
Phase 1	1,52 %	2,65 %
Phase 2	1,35 %	2,70 %
Phase 3	1,42 %	2,71 %
Minimum/maximum current THD		
Phase 1	8,38 %	97,98 %
Phase 2	6,87 %	74,97 %
Phase 3	8,45 %	89,42 %

The minimum standards for class A voltage harmonics measurement is defined in standard EN 61000-4-7. Measurements must be taken at least up to the 50^{th} order harmonic.

Along the three seven-day measurements, with the arc furnace consuming around 30 MW, the maximum value of the voltage THD at the measurement point of the factory was 2,78% (about 0,86% at the Substation of Carregado) and the 95^{th} percentile of each of the significant harmonics are within the limits set by standard EN50160. The highest voltage harmonic value obtained was 2,96%, for the 5^{th} harmonic. The corresponding value at the Carregado substation will be of about 0,92%.

The highest harmonic value for even harmonics was 0,369% for the 2^{nd} harmonic (about 0,12% at the Substation) which is a very low value. In any case we must take into account that the arc furnace is working under its nominal power (at about 37%).

The harmonic distortion of the current depends on harmonic impedance Z(n) (inner impedance of the factory for each harmonic) and also on the impedance of the SVC, power absorbed by the load connected to it, amount and type of the materials, etc. This current harmonic distortion is very high and different for each phase. The maximum current THD value measured at the measurement point was 98,59%, corresponding to an estimate 30,56 % at the Substation.

Regarding even harmonics, the highest individual harmonic value is 0,369 % (2^{nd} harmonic) at the point of measurement, with an estimated of 0,12 % at the substation, which is comfortably far from the 0,5% set limit; therefore, even at full power it is unlikely that the 0,5% limit will be exceeded.

2.2. Flicker measurements

We consider of great importance to evaluate the levels of flicker at the factory without and with the SVC installed, and also the impact on the Substation of Carregado, where the electric distribution company, EDP, sets a limit for flicker which is not exactly the maximum of 1 established by the EN 50160 standard.

The International Standard IEC 61000-4-15:2010 (first version February 2003) provides functional and design specifications for a flickermeter. Therefore, flicker measurements are carried out in accordance with the above-mentioned standard.

The flickermeter used for flicker measurements was that developed by the UIE (*International Union of the Electromechanics*) which, despite a number of drawbacks (including memory limitation, maximum number of P_{st} values recorded, and some programming issues), is recognised as a reliable and flexible instrument.

Figures 6 to 8 represent P_{st} flicker measured over three consecutive days in phase 1. Flicker measurements on phases 2 and 3 are similar to those of phase 1. The periods when the arc furnace is working are clearly visible, coinciding with higher flicker levels. When the furnace is not working, flicker levels are very low.

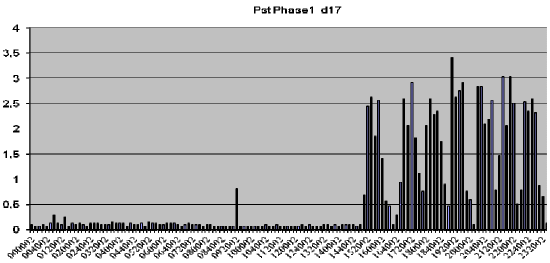

Figure 6. P_{st} flicker of Phase 1 versus time with SVC in day 17

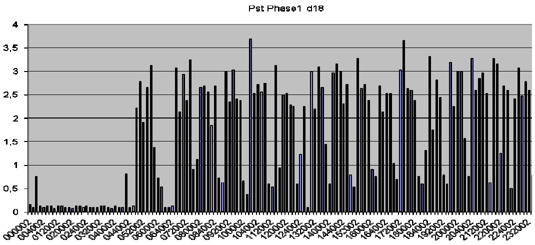

Figure 7. P_{st} flicker of Phase 1 versus time with SVC in day 18

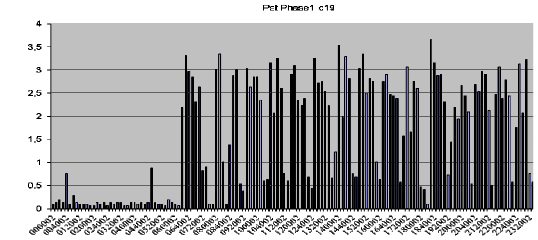

Figure 8. P_{st} flicker of Phase 1 versus time with SVC in day 19

Table 3 compares flicker levels, revealing that the inclusion of the SVC system reduces the levels of flicker significantly [2].

The long-term flicker, P_{lt}, can be obtained by 12 values of short-term flicker, P_{st} [3], according to equation (1).

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{sti}^{3}}{12}} \quad (1)$$

The levels of short-term flicker for 95% percentile of the measured values ($P_{st95\%}$) in the Substation of Carregado are just within the limits set by the EN 50160 Standard for P_{lt}. The maximum value of the $P_{st95\%}$ flicker obtained at the factory measurement point with the SVC installed was 3,313, corresponding to 1,031 at the Substation. This value was measured on day 19, in phase 2, with an absorbed power of 30690 kW [2]. The maximum value of the $P_{st95\%}$ flicker obtained at the factory measurement point without SVC was 6,375, in phase 2, day 12, corresponding to around 1,985 in the Substation of Carregado; that will surely cause P_{lt} to raise over the limit set by the EN 50160 Standard, and also over of the limit of 1,1 established by the Portuguese regulation agency to allow the connection of the factory to the grid.

Table 3. Summary of the maximum $P_{st95\%}$ flicker per day, at the Measurement Point of the SNL factory and at the Substation (estimated) without and with an SVC system (arc furnace power of about 30 MW)

SNL FLICKER MEASUREMENTS WITHOUT SVC					
Maximum $P_{st95\%}$ flicker per day at the measurement point					
DATE	d9	d10	d11	d12	d13
Phase 1	0,125	6,031	6,313	6,031	5,938
Phase 2	0,156	5,750	6,313	**6,375**	5,781
Phase 3	0,125	5,688	5,625	5,688	5,188
Maximum $P_{st95\%}$ flicker per day at Carregado Substation					
DATE	d9	d10	d11	d12	d13
Phase 1	0,039	1,878	1,965	1,878	1,849
Phase 2	0,049	1,775	1,965	**1,985**	1,800
Phase 3	0,039	1,771	1,751	1,771	1,615
SNL FLICKER MEASUREMENTS WITH SVC					
Maximum $P_{st95\%}$ flicker per day at the measurement point					
DATE	d16	d17	d18	d19	d20
Phase 1	0,156	2,906	3,281	3,313	3,280
Phase 2	0,156	2,844	3,281	**3,313**	3,219
Phase 3	0,188	2,750	3,031	3,156	3,094
Maximum $P_{st95\%}$ flicker per day at the Carregado Substation					
DATE	d16	d17	d18	d19	d20
Phase 1	0,049	0,905	1,022	1,031	1,021
Phase 2	0,049	0,885	1,022	**1,031**	1,002
Phase 3	0,058	0,856	0,944	0,983	0,963

Time-domain simulation analysis of the arc furnaces with a three-phase circuit are quite costly due to computational time, and those which are performed on a single-phase circuit are not quite exact concerning harmonic content, mainly on the magnitude of zero sequence components.

3. Using a STATCOM instead of an SVC

When SNL planned to install a device to reduce the flicker that would be generated by the facility when the arc furnace was operating, the authors' advice was the installation of a STATCOM, based on a series of reasons that are indicated below.

The STATCOM can be defined as an "electronic generator" of dynamic reactive power, which is designed to provide a smooth and continuous voltage regulation, control the reactive power generation, compensate voltage fluctuations (including those causing flicker), control the power factor and damp the oscillation power [3].

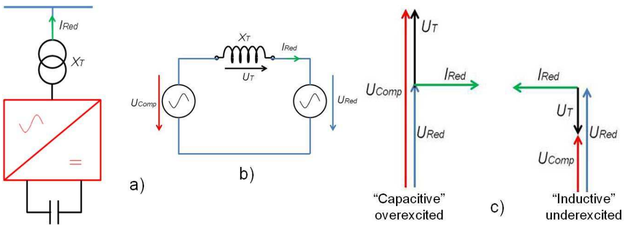

Figure 9. Schematic representation of a STATCOM connected to the network, its equivalent circuit and vector diagrams.
a) Basic scheme for connecting a STATCOM to the power grid.
b) Simplified one phase diagram of a STATCOM.
c) Vector diagrams representing the capacitive and inductive performance of a STATCOM.

A STATCOM is basically a VSC (*Voltage Source Converter*) connected through an inductance to the network. Figure 9 a) shows an example of a STATCOM connected to a network. Figure 9 b) shows a simplified diagram of a STATCOM. The coil represents the reactance of a transformer. The reactive power can be varied by modifying the voltage amplitude of the SVC.

The vector diagram in Figure 9 c) helps to understand the principle of operation of STATCOM. For this, a 1:1 ratio transformer is assumed. Also, a constant network voltage is assumed, whereby the U_{Red} voltage remains at a constant value. If the U_{Comp} vector value is higher than the network voltage vector, the vector representing the voltage drop in the X_T reactance is in the same direction as the voltage compensating vector. Then the compensation current I_{red} circulates in the positive direction, established by convention in Figure 9 b) and vector diagram on the right in Figure 9 c). In this situation, the STATCOM acts as a capacitor. If the voltage vector value of the U_{Comp} compensator is less than the U_{Red} network voltage vector, the vector representing the voltage drop in the X_T reactance shall have a direction opposite to that of the voltage compensating vector. Then the current of the I_{red} compensator will circulate in the opposite direction (negative) as can be seen in the vector diagram on the right of Figure 9 c). In this situation, the STATCOM acts as an inductance. In all cases the vector representing the I_{red} network current shall be 90º displaced in relation to the U_{Red} network voltage. In the latter situation, the STATCOM's power is purely reactive.

STATCOM has response speeds below one cycle (transition ratio between total capacity and total inductance below 20 ms) and it has a favourable behaviour during system disturbances. Other advantages of the equipment are its compact and modular construction that allows easy installation and relocation, as well as adequate flexibility in the possible future adaptation if the requirements of the installation change, and the generation of reactive current independently of the network voltage.

When the STATCOM is connected to the system via a transformer, it can inherently have enough reactance to enable a satisfactory operation of STATCOM. In some practical applications where significant harmonic disturbances occur, like the case of factory SLN, it may be necessary to include, within the converter scheme, a harmonic filter or a capacitor bank. In such case, the use of reactors (apart from the coupling transformer) may also be necessary to limit the flow of harmonic currents from the converter to the capacitor bank.

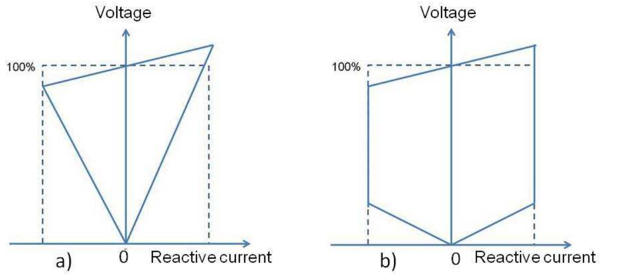

Figure 10. Reactive current as a function of voltage
a) of an SVC b) of a STATCOM

Figure 10 a) shows the variation of the reactive current as a function of the voltage of the widely used and well-known reactive power compensator, the SVC (*Static Var Compensator*). The SVC combines TSCs (*Thyristor Switched Capacitors*) with TCRs (*Thyristor Controlled Reactors*). Due to this, it is possible to apply a gentle variation of reactive power within the range of the total installed reactive power.

Figure 10 b) represents the reactive current as a function of the voltage of a STATCOM. The behaviour is similar to that of an SVC, that is to say it allows a smooth variation of the reactive current within the operating range with a high dynamic behaviour. Compared to the SVC, its advantages are that the current injection is independent of the voltage of the system, with faster control and reduced space needs.

Starting from an electrical system similar to that of the SNL factory, with its transformers and the line of interconnection with the Substation of Carregado, different types of disturbances such as short circuits, sags, interruptions and voltage fluctuations were simulated using MATLAB/Simulink, in scenarios without any FACTS installed as well as in situations where an SVC is installed, or a STATCOM at a given point in the system. Simulations also helped to determine which of the two FACTS devices has a better dynamic behaviour.

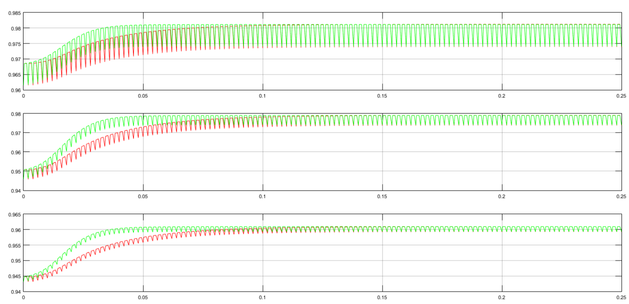

Figure 11. Comparison of the voltage response of the SVC (red curve) and STATCOM (green curve) in the system to flicker

In Figure 11 it can be seen that STATCOM has a faster response than the SVC, which seems quite logical if one takes into account that STATCOM has virtually no delay associated with the switching of the thyristors of an SVC (about 4 ms), since STATCOM uses IGBTs, which provide a much faster switching.

From the operator's point of view, a solution for compensating reactive power without mechanically switched components is preferred, which means either using the SVC or the STATCOM, depending on each particular case.

Despite having been shown that the dynamic behaviour of STATCOM was far better than that of the SVC, the company decided to install an SVC, basically due to the cost of the initial investment.

4. Conclusions

In normal conditions but working at about 30 MW below the nominal power (83 MW) and with an SVC we can conclude briefly that:

The total harmonic distortion in voltage is also found in the working conditions in which the measurements have been made, below the established limits (<1,5%). The maximum value at the measuring point is 3,18% which, doing the approximate correlation established by the short circuit capacity ratio, corresponds to 0,99% at the Substation of Carregado, for an average furnace power of about 30 MW.

It should be noted that, similar to what is feared to happen with the flicker, levels of harmonics would be modified to the extent that the power of the furnace is modified, possibly exceed 1,5% for a power of 83 MW; this will always depend, of course, on the behaviour of the SVC at this level.

Harmonic voltage distortion rates for individual harmonics are below the established value (individual harmonic voltage of odd order < 1,0%). The maximum distortion rate, 2,96% at the measuring point, was obtained for the 5^{th} harmonic. The impact on the Substation of Carregado would be 0,92%, value close to the maximum (1%) established; therefore, with the furnace working at nominal power there is a good chance that the value of 1% will be exceeded.

As seen before, the harmonic distortion of the current is dependent on the impedance to each harmonic, which in turn varies, at each moment, with the quantity and type of scrap. This harmonic distortion in current results, as can be seen in the graphs, much higher than the established levels, with distorting rates of the individual harmonics also high. (Total minimum current distortion >6%). The maximum current distortion reaches values that at first glance seem unbelievable.

The unbalance, with a maximum value of 0,53%, is within the specified limits, the same can be said of cosφ, although with certain oscillations that make that during the times when the furnace does not work the cosφ turns out to be very low.

The levels of flicker, both P_{lt} and $P_{st95\%}$ are, for the power to which they were determined, below the maximum levels ($P_{st95\%}$<1,1) established by EDP in the Carregado Substation.

It should be noted that, by contract, the power of the arc furnace for which the measurements were made was approximately 37 per cent of the rated power required; therefore, it is to be feared that $P_{st95\%}$ Flicker daily values exceeding 1,1 (at the Substation of Carregado) will occur when the furnace operates at its nominal power (83 MW) always depending, of course, on the behaviour of the SVC at nominal power, behaviour which is unknown.

After the numerous analyses carried out, it can be concluded that basically both devices are able to do the same function. However, from the results of the simulations, it has been found that at lower voltages than those of the normal range of voltage regulation, the STATCOM can generate more reactive energy than the SVC. This is due to the fact that the maximum capacitive power generated by an SVC is proportional to the square of the system voltage (constant susceptibility), while the maximum capacitive power generated by a STATCOM decreases linearly with the voltage (constant current). This ability to provide more reactive capacitive power during a disturbance is an important advantage of STATCOM over the SVC.

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