ENERGY AND ENVIRONMENTAL SAVINGS IN STEEL MAKING BY MEANS OF SVC LIGHT

Rolf Grünbaum, Tomas Gustafsson
ABB Power Systems AB
AC Systems Division
SE-721 64 Vasteras
Sweden
Phone: +46 21 32 40 00
rolf.grunbaum, tomas.b.gustafsson@se.abb.com

Thomas Johansson
ABB Power T&D Company Inc.
Raleigh, NC 27606
USA
Phone: +1 (919) 856 2379
thomas.johansson@us.abb.com

Ulf Olsson
Uddeholm Tooling
SE-683 85 Hagfors
Sweden
Phone: +46 563 179 24
ulf.olsson@uddeholm.se

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INTRODUCTION

Electric Arc Furnaces (EAF) are growing in importance in steel making as scrap based metallurgy is gaining momentum all over the world. EAFs, as loads on the network, are characterized by high and strongly erratic consumption of reactive power, strong harmonic generation, as well as unsymmetrical loading of its three phases. As a result, unless properly remedied, more or less heavily disturbed currents and voltages will gain their way into the feeding grid, and once there, spread over the grid to other, neighbouring facilities.

As a particularly annoying effect of EAF operation, flickering of incandescent lamps can arise, to detriment of the human environment far away from the source of the sensation. Harmonics and unsymmetry between phases can lead to added losses in the grid, as well as malfunction and overheating of other plant connected to the grid.

For a number of years, Static Var Compensation (SVC) has been utilized in conjunction with the operation of EAFs for improving of power quality. Productivity increases in the EAF process have come as a benefit in many cases, as well.

With steadily increasing furnace ratings, safekeeping of power quality in feeding grids has become an issue of growing importance.

At the same time, deregulation of the electricity supply industry is forcing an accelerated quest for rationalization of power grid structures and cuts in operating and maintenance costs of the same. This is leading to a simplification of power transmission infrastructure in a number of cases, chiefly making old 220 kV structures superfluous, and, therefore, subject to scrapping. This, in fact, is seen happening in several countries in Europe at present.

As a consequence, some steel plants which were previously fed from 220 kV grids will be uprated to 400 kV, while others will now have to take their power from the next lower level, i.e. 90-145 kV regional power systems. At this level, short circuit power, as a rule, is considerably lower. This, of course, will have a detrimental impact on power quality in the grids feeding the plants, and disturbances of various kinds will be felt to a higher degree in other parts of the grids.

This is taking place at the same time as power quality is coming into focus at a scale hitherto unseen from an environmental as well as contractual point of view. On one side, penalizing of power subscribers for violations of power quality requirements will, to an increasing degree, become common as part of contractual negotiations, as will “rewarding” of the subscriber for upkeeping of power quality by means of reduced tariffs. On the other hand, the ability to guarantee a certain degree of power quality to customers from the side of the power supplier will enable the supplier to attract customers, as well as to offer “premium” (=higher) rates for “premium” (=better) power quality.

With the advent of continuously controllable semiconductors for high power applications, Voltage Source Converters (VSC) far into the tens of MVA range have become a reality. The SVC Light concept brings together VSC technology with IGBTs (Insulated Gate Bipolar Transistors), to enable power quality improvement, and in particular flicker mitigation to a degree hitherto unseen, as well as productivity increases in steel production.

EAF: GRID IMPACT

As a load on the network, an EAF is characterized by the following items:

Strong and erratic consumption of reactive power;
Strong generation of harmonics, odd, even, as well as interharmonics;
unsymmetrical loading of the phases.

Reactive power consumption

The load diagram of an EAF can be seen in Fig. 1. From it, it is evident that the variation of reactive power around the operating point, ΔQ, is far greater than the active power variation, ΔP. This heavy and varying consumption of reactive power gives rise to a corresponding depression as well as fluctuation of the bus voltage. Voltage fluctuations inside a band of frequencies to which the human eye is particularly sensitive, typically 0,1 Hz to 25 Hz, gives rise to flicker.

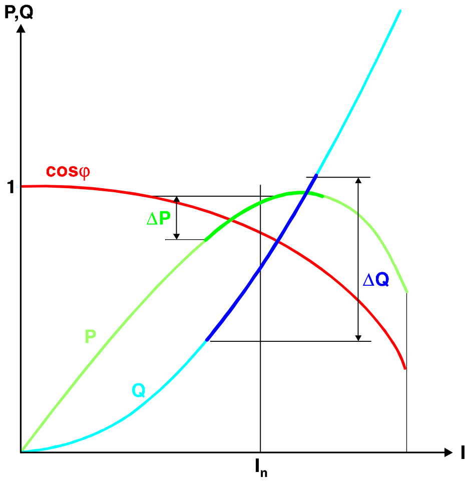

Fig. 1: Load characteristics of an EAF.

Flicker

Flicker is expressed by means of the Flicker Severity Level P_{st} which directly expresses the degree of irritation with $P_{st} = 1$ meaning the limit of disturbance. The flicker threshold curve according to IEC (Fig. 2) shows maximum permitted voltage fluctuations as a function of frequency inside the flicker spectrum for the borderline case of $P_{st} = 1$. The most critical part of the spectrum falls around 8 Hz, which is where the human eye is at its most sensitive to light fluctuations.

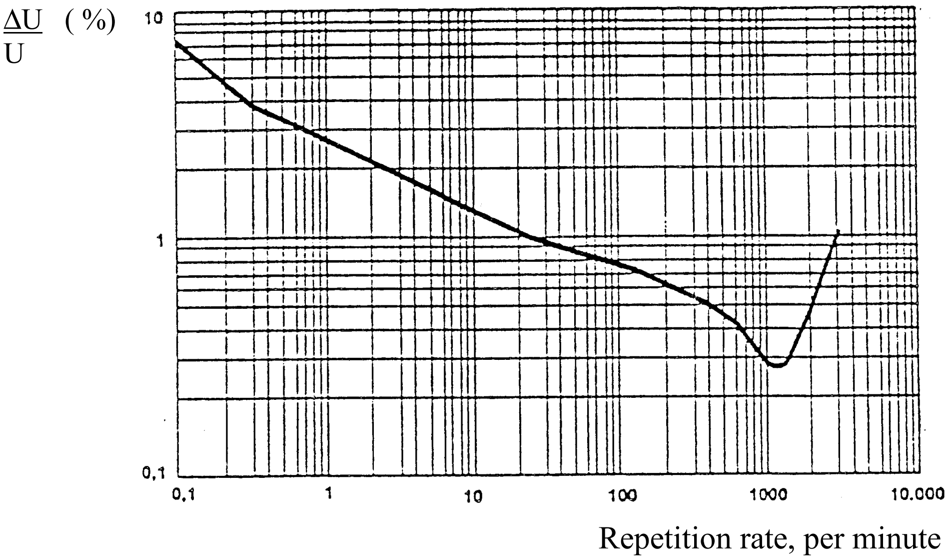

Fig. 2: Flicker threshold curve.

The basic standard to be used for flicker measurement is IEC 1000-4-15. The measuring device (flickermeter) gives results on each successive 10 minutes interval (P_{st} values), as well as on 2 hours intervals (P_{lt}). According to the UIE works, a P_{st} limit may be occasionally exceeded, provided that the corresponding part of the observation period is sufficiently small (typically no more than 1%). The corresponding P_{st}(99%) can then be used as a correct value [1].

A qualitative idea of the amount of flicker that can be expected from an EAF with some certain relationship between load size and fault level of grid can be obtained from a simple expression:

$$P_{st}(99\%) \approx K_{st} x \frac{S_{SCEAF}}{S_{SCN}} \qquad (1)$$

$P_{st}(99\%)$:	Short term flicker severity at the point of common connection not exceeded during 99% of the measurement period;
K_{st}:	Flicker severity coefficient of the furnace;
S_{SCEAF}:	Short circuit power of the EAF;
S_{SCN}:	Fault level at the point of common connection.

K_{st}, the flicker severity coefficient of the furnace, is dependant of the conditions of operation of the furnace, and usually varies between 50 and 75 in the case of an AC EAF. $K_{st} = 50$ would correspond to a hot furnace, fed with a mixture of scrap and some other constituents such as sponge iron or hot metal. $K_{st} = 75$ would correspond to the severest case, which is cold start-up of the EAF with 100% scrap.

S_{SCEAF}, the short circuit power of the EAF, is calculated with all reactances in the circuit up to the point of common connection taken into consideration. It is usually a factor √2 to 2 bigger than the rated power of the EAF transformer.

Bus voltage

By dynamic compensating of the reactive power absorbed by the EAF, the bus voltage will not only become rid of fluctuations, but it will also see an increase in its RMS value. This is highly useful, as it permits more active power into the furnace, and hence, a more efficient melting process. This can be capitalized on, either by obtaining of more molten steel per unit time in the process, or, if desired, the same amount of steel in a shorter time.

As valuable by-products, the specific electrode consumption will be lower, as will also the specific energy consumption of the EAF process. All in all, steel can be manufactured at higher productivity and with lower specific costs.

Power factor

Since the reactive power consumption of the EAF is compensated for, the power factor of the plant is improved. This brings with it a decrease of electricity billing.

Harmonics

The strongly nonlinear characteristic of the arc furnace as a load on the network gives rise to a comprehensive spectrum of harmonics. The picture is aggravated by mechanical resonances in the furnace set-up, which are transmitted into the arc through electrodes and vessel. They subsequently appear in the arc current, contributing to the harmonic spectrum of the EAF.

The overall picture is a harmonic spectrum containing odd as well as even components, plus interharmonics. The latter will also interact to produce flicker components, particular in the case of interharmonics below $2f_o$, where f_o is the fundamental frequency (50 Hz or 60 Hz).

Phase unbalance

The electrodes of an AC EAF are controlled phasewise and the arcs running between electrodes and scrap may differ from each other in current and voltage at each given instant. Arcs will be struck and extinguished in an erratic way, particularly during meltdown as scrap moves and caves in inside the vessel. The result will be unsymmetrical loading between phases, with, in the extreme case, even zero current in one or more phases for part of the time.

The load unsymmetry, unless properly remedied, will propagate into the feeding grid and show up as negative-phase sequence components in the grid voltage. Such components will add to system losses and may cause damage to rotating machinery elsewhere in the grid.

An assessment of the amount of unbalance to be expected in conjunction with an EAF can be made by means of the following expression:

$$V_- / V_+ \approx S_L / S_{SCN} \qquad (2)$$

V_-: Negative-phase sequence voltage at the point of common connection
V_+: Positive-phase sequence voltage at the point of common connection
S_L: Single-phase load demand
S_{SCN}: Fault level of the grid at the point of common connection.

Voltage unbalances higher than 1-2% are usually not permitted in power grids, a level which is easily exceeded with the installing of a fair-sized EAF in a not too strong grid. This means that dynamic load balancing needs to be taken into consideration in the majority of cases as part of power quality assessment in conjunction with EAF installations.

SOLUTIONS FOR ENHANCING OF POWER QUALITY

To minimize the detrimental impact on electrical and human environment from the running of EAF, dynamic compensation has been a solution utilized for a long time. By means of SVC in a traditional sense, i.e. thyristor-controlled shunt compensation of reactive power, power quality has been improved at the point of common coupling as well as in the steel plant itself, which has contributed in an important way to human environment. At the same time, productivity improvement and also cutting of energy losses in the steel process have been attained in a number of cases, as well.

This concept can now be further developed by introducing solutions with increased dynamic response as well as more compact design. This is enabled by the appearance of Voltage Source Converters (VSC) of sufficient voltage and current ratings to make the technology suitable for reactive power compensation in conjunction with electric arc furnaces.

Added value in improving of power quality comes especially within two areas: flicker mitigation, and active filtering of harmonics.

Voltage Source Converter

A VSC of three-level configuration is built up as in Fig. 3. One side of the VSC is connected to a capacitor bank, which acts as a DC voltage source. The converter produces a variable AC voltage at its output by connecting the positive pole, the neutral, or the negative pole of the capacitor bank directly to any of the converter outputs.

By utilizing Pulse Width Modulation (PWM), an AC voltage of nearly sinusoidal shape can be produced without any need for harmonic filtering. This contributes to the compactness of the design, as well as robustness from a harmonic interaction point of view.

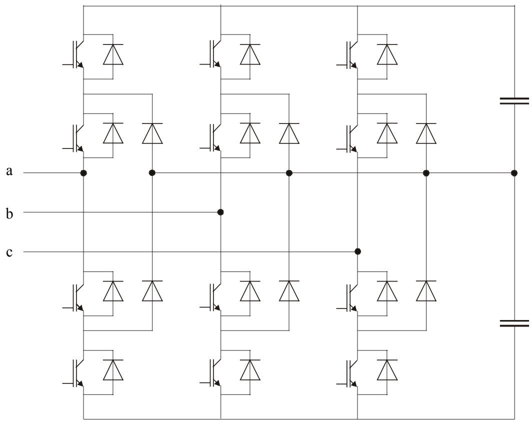

Fig. 3: 3-level VSC configuration.

In the system, the VSC is connected to the EAF bus via a small reactor. With the VSC voltage and the bus voltage denoted V_1 and V_2 respectively, it can be shown that the output of the VSC can be expressed as follows:

$$P = \frac{V_1 V_2}{X} \sin\delta \qquad (3)$$

$$Q = \frac{V_1 V_2}{X} \cos\delta - \frac{V_2^2}{X} \qquad (4)$$

P: Active power of the VSC
Q: Reactive power of the VSC
V_1: VSC voltage
V_2: Bus voltage
δ: Phase difference between the voltages
X: Reactance of the coupling reactor.

From equations (3) and (4) it can be seen that by choosing zero phaseshift between the bus voltage and the VSC voltage ($\delta = 0$), the VSC will act as a purely reactive element. (In reality, a small phase shift is allowed, in order to make up for the VSC losses.)

It is further seen that if $V_1 > V_2$, the VSC will act as a generator of reactive power, i.e. it will have a capacitive character. If $V_1 < V_2$, the VSC will act as an absorber of reactive power, i.e. it will have an inductive character.

SVC Light

SVC Light is a VSC based dynamic compensator, pulse width modulated and utilizing IGBTs as switching device. The switching frequency exceeds 1600 Hz, making SVC Light suitable also as an active filter of EAF harmonics.

By series connection of IGBTs, ratings of tens of Mvar up to more than 100 Mvar are achieved for SVC Light without any need for parallelling of devices. This makes it suitable for compensation of the very largest EAFs, and enables at the same time a robust and compact design.

Presspack IGBTs are used in SVC Light. Presspack IGBTs are packaged in housings almost like conventional high power thyristors (Fig. 4). Inside, IGBT chips and antiparallel diode chips are connected in parallel, with pressure contacts normally providing the electrical contact to the outside.

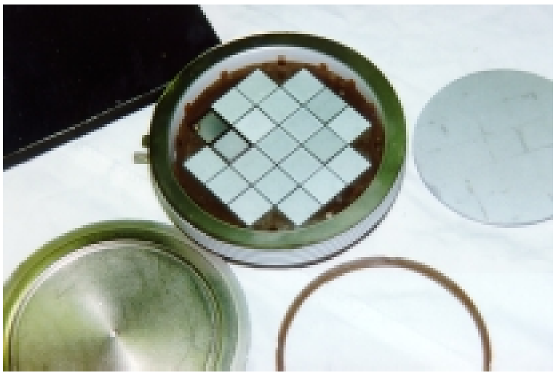

Fig. 4: Presspack IGBTs.

SVC Light uses a three-level VSC configuration. In it, there are four IGBT valves and two diode valves in each phase leg. The valves are built up by stacked devices (with interposing coolers) and an external pressure applied to each stack (Fig. 5). The DC side of the converter is floating, i.e. insulated to ground. The DC capacitor is divided into two capacitor banks in series. Each valve has to withstand the blocking voltage corresponding to the voltage across one of the capacitor banks.

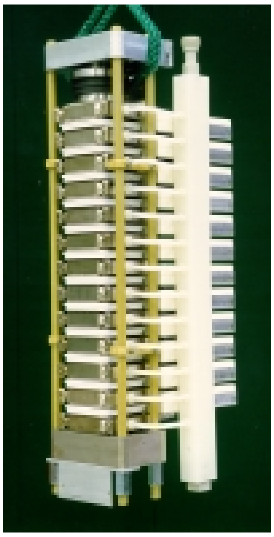

Fig. 5: IGBT stack.

Water cooling is utilized in the IGBT valves, giving a compact converter design and high current handling capacity (Fig. 6). IGBTs capable of handling close to 2000 A_{RMS} are a reality today.

Fig. 6: SVC Light valve assembly.

DC capacitors-The DC capacitors are of a compact, high voltage dry type design, particularly suitable for the application (Fig. 7). By use of metallized film, insulated by means of polymers instead of impregnated materials, the capacitor gets a dry design, making it environmentally very friendly. In manufacturing, it requires neither impregnating fluids nor the use of paint solubles. It has high energy density, which together with its cylindrical shape enables very compact build-up of capacitor banks utilized in SVC Light.

Fig. 7: Dry type, high voltage DC capacitors.

SVC Light control-To mitigate flicker efficiently, the utilized SVC Light control algoritm calculates setpoints for the current to be produced by the SVC Light. In this process, the EAF current as well as the bus voltage are used. It has been found that fluctuations of three different components of the EAF current cause flicker: the reactive current, the active current, and the derivative of the active current [2].

To fast control the SVC Light instantaneous current, a concept with voltage-time area across the coupling reactor is used. This means that by controlling the time a certain voltage is applied across the reactor, the desired current through the reactor can be obtained. Thus, for a reactor with the inductance L, the following is valid:

$$u_L = L\frac{di}{dt} \rightarrow i = \frac{1}{L}\int u_L dt \tag{5}$$

The reactor voltage, u_L, consists of the difference between the bus voltage and the voltage produced by the SVC Light. Now, what can be controlled to influence the current i is the voltage produced by the VSC. By employing PWM, the desired current is obtained fast by applying the proper VSC voltage (Fig. 8).

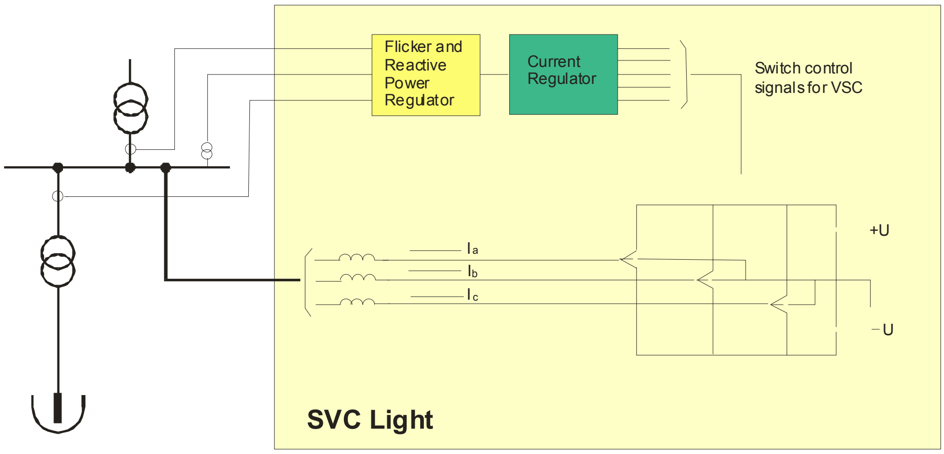

Fig. 8: SVC Light control principle.

A RECENT CASE OF APPLICATION

An SVC Light rated at 0-44 Mvar has been in operation for some time at Uddeholm Tooling in Sweden for the purpose of improvement of power quality in the surrounding grid [3]. The mill is equipped with an EAF rated at 31,5 / 37,8 MVA as well as a ladle furnace rated at 6 / 7,7 MVA. The point of common connection is at 132 kV, with a fault level which in the most unfavourable case does not exceed 1000 MVA.

Applying these figures to equation (1), it is obvious that without any specific measures taken, there would be considerable amounts of flicker emanating from the mill. This was not considered as any serious impediment at the time when the mill was started, but today, requirements on human environment has made the situation different. Consequently, the SVC Light was installed.

The installation comprises a 22 MVA VSC connected to the 10,5 kV EAF bus via air core phase reactors, one in each phase. Furthermore, an 8 Mvar harmonic filter is included, which together with a 14 Mvar filter already existing in the plant provides offsetting of the dynamic range of the VSC from -/+ 22 Mvar to the required 0-44 Mvar (Fig. 9).

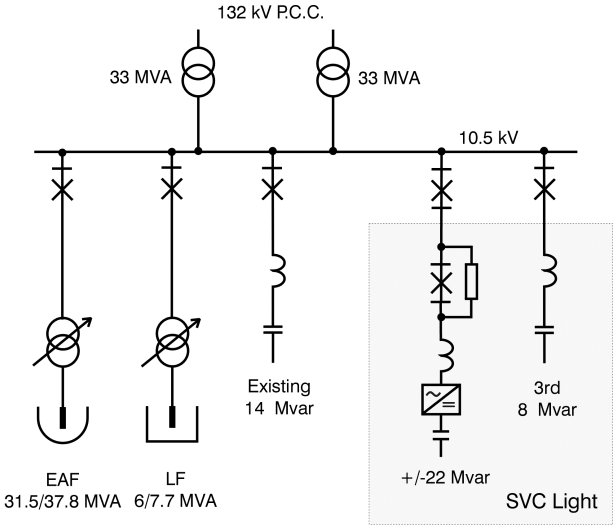

Fig. 9: Single-line diagram of EAF feeding network and compensation.

Flicker mitigation

Preliminary field measurements of flicker mitigation at the point of common coupling have been reported previously [3]. Some initial shortcomings in the measuring set-up have been rectified since, and additional measurements have been performed, with much improved result. The graph below shows the outcome of these measurements (Fig. 10).

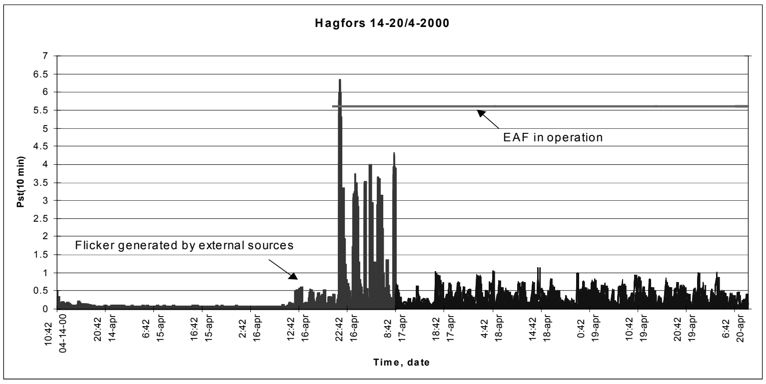

Fig. 10: Flicker generation without and with SVC Light.

A statistical evaluation utilizing the same method as reported in [3] gives as result a flicker severity factor without SVC Light equal to $P_{stA}(95\%) = 3{,}73$, and a flicker severity factor with SVC Light in operation equal to $P_{stB}(95\%) = 0{,}64$. Hence, a flicker mitigation factor with the SVC Light is reached:

$$R_{SVCLight} = \frac{P_{stA}}{P_{stB}} = 5{,}8 \tag{6}$$

Active filtering

The fast response of SVC Light enables its use as an active filter. Fig. 11 shows harmonic recordings at the plant, without SVC Light as well as with SVC Light in operation. What is seen is filtering of the harmonic spectrum of the EAF all the way up to the 14th harmonic, which is the highest harmonic of any significance appearing from the EAF.

The SVC Light itself has practically no harmonic generation below the 33rd harmonic.

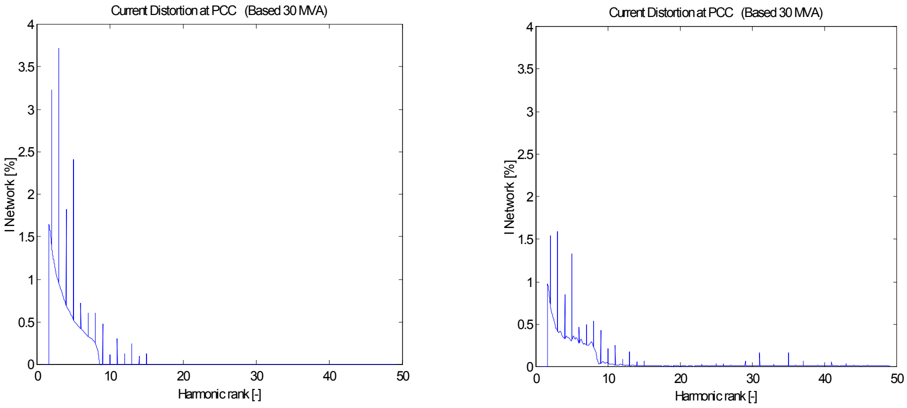

Fig. 11: Active filtering of EAF harmonics.

Furnace power increase

Fig. 12 shows measurements of the active power consumption at the plant without and with dynamic compensation. Through dynamic compensation, the voltage at the furnace busbar is stabilised. The stabilised voltage increases the available furnace input power.

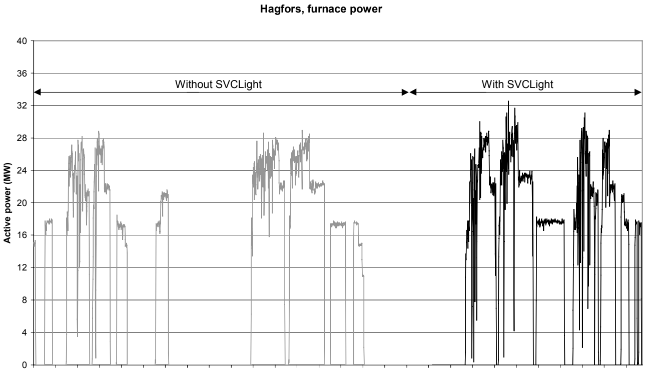

Fig. 12: Active power consumption without and with dynamic compensation.

The active power with SVC Light in operation shows a mean increase by several MW over a melt cycle. This increase is attained at a bus voltage of 10,5 kV. An even higher rise in active power into the furnace would be possible, but at a corresponding overvoltage at the 10 kV bus, which might be undesirable from the point of view of other equipment connected to the bus.

The increase of active power into the EAF enables a somewhat faster melt, and thereby a certain saving in specific energy consumption in the process derivable to lower specific radiation losses from the furnace. This saving will accumulate over the year, to the benefit of the plant operator.

Plant layout

All SVC Light equipment except the phase reactors and the 8 Mvar harmonic filter is housed indoors in a small prefabricated building. The phase reactors and filter have been erected in a small, fenced outdoor yard. All in all, this gives a very compact layout of the installation, Fig. 13.

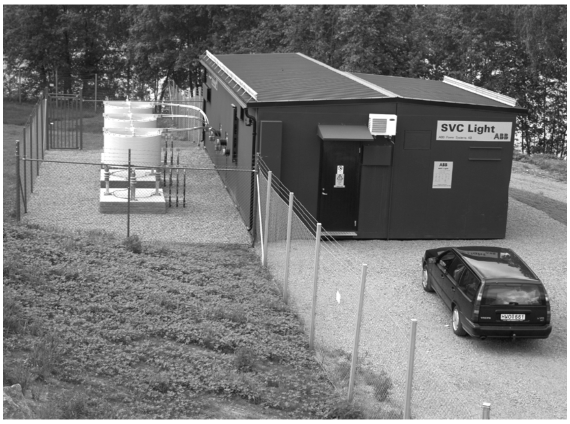

Fig. 13: The Uddeholm Tooling SVC Light.

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