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SVC LIGHT: EVALUATION OF FIRST INSTALLATION AT HAGFORS, SWEDEN

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INTRODUCTION

With the advent of continuously controllable semiconductors for high power, voltage source converters (VSC) far into the tens of MVA range have become feasible. This opens up new options for power quality control in areas such as mitigation of voltage flicker from electric arc furnaces ranging from a couple of tens of MVA up to more than 100 MVA. The paper describes the VSC based SVC Light concept and comments on its abilities for power quality enhancement by decreasing or eliminating of phenomena such as voltage flicker, harmonic distortion and phase unbalance.

A current SVC Light installation for flicker mitigation at a steel mill in Sweden is highlighted.

POWER QUALITY: A MATTER IN FOCUS

Modern society relies heavily upon electricity. With deregulation, electricity has become a commodity as well as a means for competition. Power quality, as a consequence, is coming into focus to an extent hitherto unseen. Flickering lamps and TV sets are no longer accepted, nor are deratings of industrial processes due to lacking power quality.

For a grid owner and for a supplier of electricity, an electric arc furnace (EAF) user is a subscriber to power, i.e. a customer, but in the worst case also a polluter of the grid. Out of the EAF may well come an abundance of distortion such as voltage fluctuations, harmonics and phase unsymmetry.

Disturbances emanating from any particular load will travel far, and, unless properly remedied, will spread over the grid to neighbouring facilities. Fortunately, there are means to deal with the situation. One obvious way is to reinforce the power grid by building of new lines, installing new and bigger transformers, or moving the point of common coupling to a higher voltage level.

Such measures, however, are expensive and time-consuming, if they are at all permitted. A straightforward and cost-effective way of power quality improvement in such cases as well as similar is to install equipment especially developed for the purpose in immediate vicinity of the source(s) of disturbance.

As an additional, very useful benefit, improved process economy will often be attained as well, and as a matter of fact enable the said investment to turn out a profitable measure.

Voltage flicker

An electric arc furnace is a heavy consumer not only of active power, but also of reactive power. Also, the physical process inside the furnace (electric melting) is erratic in its nature, with one or several electrodes striking electric arcs between furnace and scrap. As a consequence, the consumption especially of reactive power becomes strongly fluctuating in a stochastic way (Figure 1).

The voltage drop caused by reactive power flowing through circuit reactances in the electrodes, electrode arms and furnace transformer therefore

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becomes fluctuating in an erratic way, as well. This is called voltage flicker and is visualized most clearly in the flickering light of incandescent lamps fed from the polluted grid.

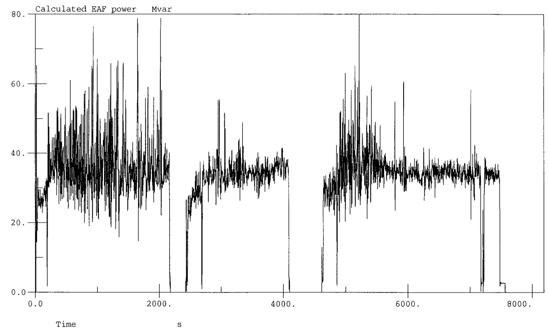

Figure 1: Reactive power consumption of EAF.

Spectral analysis confirms that lamp flicker caused by EAF action is severe around frequencies for which the human eye is particularly sensitive, i.e. below 20 cycles. And for certain, flicker is a very annoying sensation and becomes easily a source of complaint.

SVC LIGHT

To parry the rapidly fluctuating consumption of reactive power of the furnaces, an equally rapid compensating device is required. This is brought about with state of the art power electronics based on IGBT (Insulated gate bipolar transistor) technology. With the advent of such continuously controllable semiconductor devices capable of high power handling, VSC (Voltage Source Converters) with highly dynamic properties have become feasible far into the tens of MVA range.

The function of the VSC in this context is a fully controllable voltage source matching the bus voltage in phase and frequency, and with an amplitude which can be continuously and rapidly controlled, so as to be used as the tool for reactive power control (Figure 2).

The output of the VSC is connected to the AC system by means of a small reactor. By control of the VSC voltage (U_2) in relation to the bus voltage (U_1), the VSC will appear as a generator or absorber of reactive power, depending on the relationship between the voltages. To this controlled reactive power branch, an offsetting capacitor bank is added in parallel, enabling the overall control range of the SVC Light to be capacitive.

The reactive power supplied to the network can be controlled very fast. This is done only by changing the switching pattern in the converter slightly. The response time is limited mainly by the switching frequency and the size of the reactor.

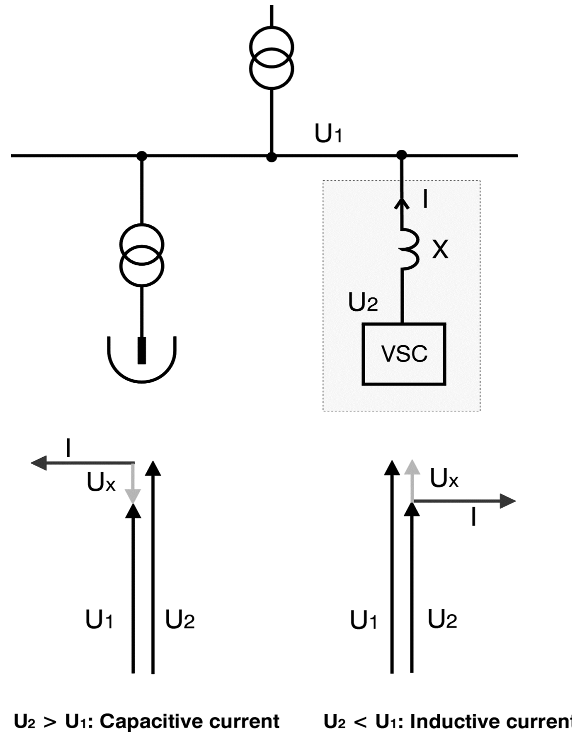

Figure 2: VSC: a controllable voltage source.

The controllability of IGBTs also facilitates series connection of devices with safeguarded voltage sharing across each IGBT. This enables SVC Light to be directly connected to voltages in the tens of kilovolts range. Thanks to this, it becomes unnecessary to parallel converters in order to achieve the power ratings needed for arc furnace compensation (typically tens of MVA).

UDDEHOLM TOOLING SVC LIGHT

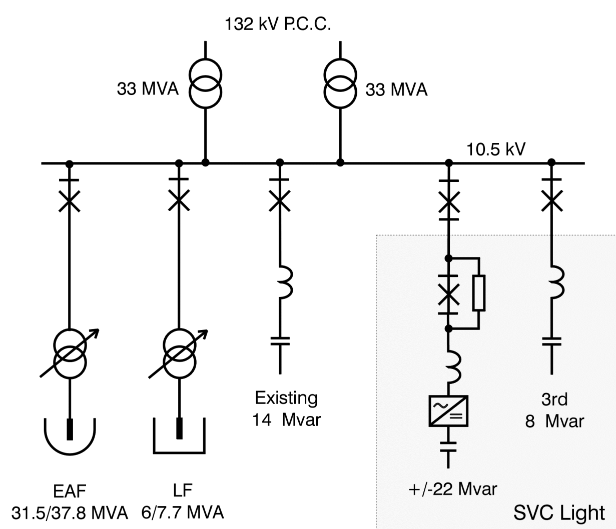

Figure 3: Single-line diagram of EAF feeding network and compensation.

Uddeholm Tooling at Hagfors in mid Sweden is a steel producer with its metallurgical process based on scrap melting in an electric arc furnace (EAF) and subsequent refining by means of a ladle furnace (LF). The EAF is rated 31,5 MVA with a 20% temporary overload capability, whereas the LF is rated 6 MVA plus a 30% overload capability. Both furnaces are fed from a 132 kV grid via an intermediate voltage of 10,5 kV (Figure 3).

The feeding grid is relatively weak, with a fault level at the P.C.C. of about 1000 MVA. It is obvious that this is quite unsufficient to enable operation of the two furnaces while upkeeping reasonable power quality in the grid.

The SVC Light (Figure 3) is rated at 0 - 44 Mvar of reactive power generation, continuously variable. This dynamic range is attained by means of a VSC rated at 22 MVA in parallel with two harmonic filters, one rated at 14 Mvar existing in the plant initially and one installed as part of the SVC Light undertaking, rated at 8 Mvar. Via its phase reactors, the VSC is connected directly to the furnace bus voltage of 10,5 kV. During the energisation of the VSC, the DC capacitors are charged via the charging resistors. While the DC capacitors are charged, the by-pass switch is closed.

VOLTAGE SOURCE CONVERTERS

The input of the Voltage Source Converter is connected to a capacitor, which is acting as a DC voltage source. At the output, the converter is creating a variable AC voltage. This is done by connecting the positive pole, neutral or the negative pole of the capacitor directly to any of the converter outputs. In converters that utilise Pulse Width Modulation (PWM), the input DC voltage is normally kept constant. Output voltages such as a sinusoidal AC voltage can be created. The amplitude, the frequency and the phase of the AC voltage can be controlled by changing the switching pattern.

In SVC Light, the VSC uses a switching frequency greater than 1 kHz. The AC voltage across the reactor at full reactive power is only a small fraction of the AC voltage, typically 15 %. This makes SVC Light close to an ideal tool for fast reactive power compensation.

IGBT

For SVC Light the IGBT has been chosen as the most appropriate power device. IGBT allows connecting in series, thanks to low delay times for turn-on and turn-off. It has low switching losses and can thus be used at high switching frequencies. Nowadays, devices are available with both high power handling capability and high reliability, making them suitable for high power converters.

As only a very small power is needed to control the IGBT, the power needed for gate control can be taken from the main circuit. This is highly advantageous in high voltage converters, where series connecting of many devices is used.

Series connecting of IGBTs

At series connection of IGBTs, a proper voltage division is important. Simultaneous turn-on and turn-off of the series connected devices are essential. In SVC Light, the turn-off and turn-on signals are distributed to the individual IGBTs through a high bandwidth fiber optic system. All IGBT positions are also equipped with a special type of gate unit, which turns the IGBTs on and off with a short delay time and at a controlled dV/dt. After turn-off of a IGBT valve or a diode valve, a small voltage difference will be seen between different IGBT positions. Control of this difference in voltage is done by proper design of the resistive and capacitive voltage dividers.

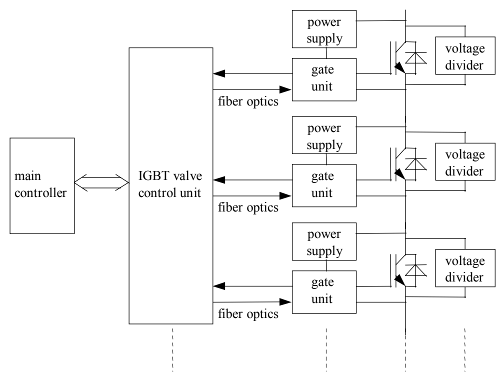

Figure 4: The IGBT valve, with a number of series-connected IGBTs switched simultaneously

In addition to this, every IGBT position is equipped with an over-voltage monitoring system. This system makes it possible to detect if any IGBT position behaves in an unnormal way already during the delivery test. If this would happen, such devices will be exchanged.

Converter valve

The converter topology for SVC Light is a three level configuration. In a three-level converter the output of each phase can be connected to either the positive pole, the midpoint or the negative pole of the capacitor. The DC side of the converter is floating, or in other words, insulated relative to ground. Using PWM, the converter will create a very smooth phase current, with low harmonic content. The three-level topology also gives low switching losses. This means high converter efficiency and high current capability.

The three-level converter used is a so called Neutral Point Clamped (NPC) configuration. This configuration includes four IGBT valves and two diode valves in every phase leg. The DC capacitor is divided into two series connected branches. The different valves are built by stacking the devices on top of each other (between coolers) and by applying an external pressure to the stack.

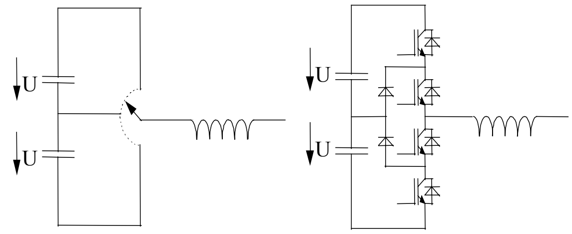

Figure 5a: The principle of a 3-level converter
Figure 5b: Neutral Point Clamped converter (one phase)

The IGBT valves are water cooled, using deionized water. Water cooling gives a compact converter design and high current capability. Compact design also enables the loop inductance between the IGBT valves and the DC capacitors to be kept low, which is beneficial from a loss point of view. In the Hagfors installation the valves are designed to handle approximately 1300 Arms phase current continuously and at transient conditions 1700 Arms.

As a subsequent development stage, SVC Light for direct connection to up to 36 kV AC is appearing.

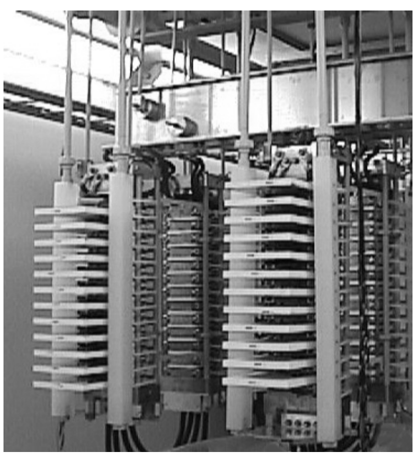

Figure 6: Photograph of IGBT stacks.

Control and protection system

The control and protection system of SVC Light is based on industrial standard PC hardware (operating system Windows NT) to facilitate an open system easily integrated into existing systems at the steel works and externally accessed directly if desired.

The strategy of building the control and protection system based on open interfaces assures that future improvements in the fast developing field of electronics can be used. The system consists basically of three units, the Main Computer, the I/O rack, and the VCU (Valve Control Unit), Figure 7. Communication between the units is performed via industrial standard type busses.

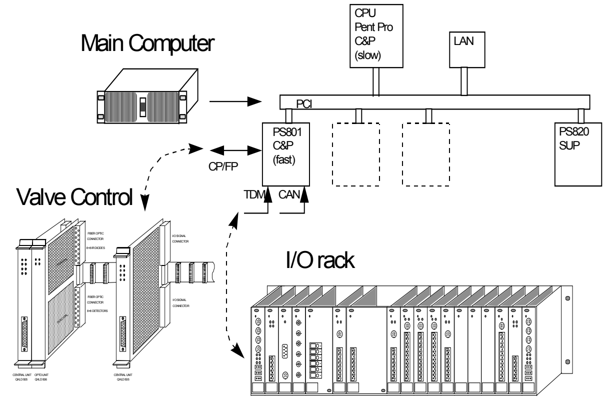

Figure 7: Control system for SVC Light.

The system is operated from an OWS (Operator Work Station), which can be a standard PC. The MMI (Man Machine Interface) is the world´s most used graphic control package for Windows NT - InTouch. InTouch is a flexible software, in which customer adopted MMI can easily be designed.

MITIGATION OF HARMONIC, TRANSIENT AND NEGATIVE PHASE SEQUENCE DISTORTION

The possibility for the SVC Light to “follow” the stochastically varying furnace current gives great opportunity to reduce voltage flicker. However, with its quick response, also other disturbances can be reduced. Figure 8 shows the initial operation of the SVC Light when parallelled to the EAF in Hagfors steel works. Signals show the SVC Light ability to track the rapid changing of the furnace current.

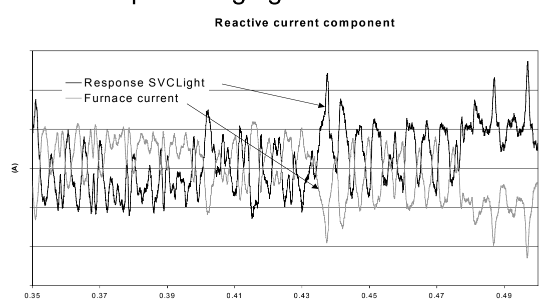

Figure 8: Tracking of rapid changes of the EAF current.

Harmonic filtering

The SVC Light concept offers active filtering where, depending on the application, harmonics up to the 11:th order are damped. With active filtering, the risk of parallel resonances between network components is minimized.

Fast transient damping

With a switching frequency higher than 1 kHz, even fast transients can be damped. In some installations switching transients from a furnace transformer could for example lead to unexpected problems. With the SVC Light technology, the furnace operation with all switching transients will be compensated. The recording below shows the inrush current of the furnace transformer in Hagfors and the SVC Light output current response.

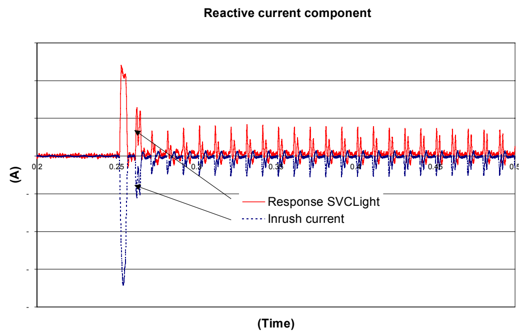

Figure 9: Inrush current of EAF transformer and SVC Light output current response.

Load balancing

For several reasons it is desirable that the load is shared equally by the three phases of the AC system. Too much unbalance may have disturbing or even damaging effects on generators or other rotating machines. With SVC Light, the system from the network will be balanced in all three phases.

POWER FACTOR CORRECTION: ECONOMIC BENEFITS

Since SVC Light is a reactive power compensator, it can also be used to benefit for power factor correction in the steel plant. Its dynamic response ensures that the power factor can be kept high and constant under strongly varying conditions of reactive power demand of the plant. This yields valuable benefits for the owner of the plant, not only in the way of minimized billing for reactive power, but also by decreased active system power losses.

Also, the minimizing of reactive power flow through the plant brings about a very important stabilization of the EAF bus voltage at a high level, which means that more active power can be taken out of the furnace than otherwise. This can be capitalized on by means of increased furnace productivity as well as lower specific production costs (electrode consumption, etc.). A concrete increase of active power output of the EAF has in fact been demonstrated in the Hagfors case, as shown below.

PRELIMINARY FLICKER MEASUREMENTS

Field measurements have been performed in order to evaluate the performance of the SVC Light at Hagfors site. So far, the measurements have mostly been focusing on flicker.

Investigations at site show that the installed auxiliary current transformer in the EAF circuit has too small a power rating, leading to saturation during bore down of the melt. This problem will be corrected, however at this stage no flicker measurements with a correct CT are available.

The recordings and evaluation below show flicker mitigation of 3.4 times. Mitigation is expected to increase to around 4.5 to 5.0 times when new auxiliary transformers have been installed.

The flicker measurements have been performed according to the UIE/IEC method. The method is well known in Europe, Canada, South America and South Africa and is also getting more common in the United States. The bar chart (Figure 10) shows flicker generation from the EAF with and without SVC Light. The chart also shows when the furnace is in operation.

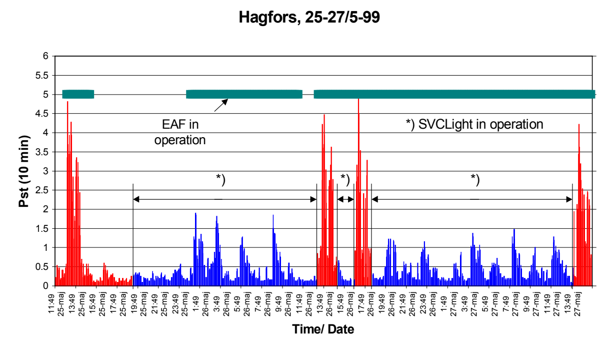

Figure 10:Flicker generation with/without SVC Light.

Statistical evaluation

In order to evaluate flicker generation with and without SVC Light a statistical evaluation has been performed. The figures below show histograms for the following three cases:

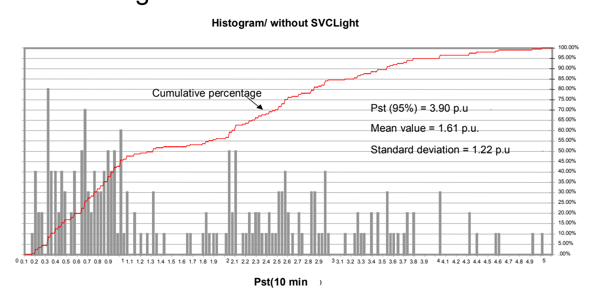

Figure 11a: Furnace in operation, without SVC Light. Pst(95%) = 3.90 p.u.

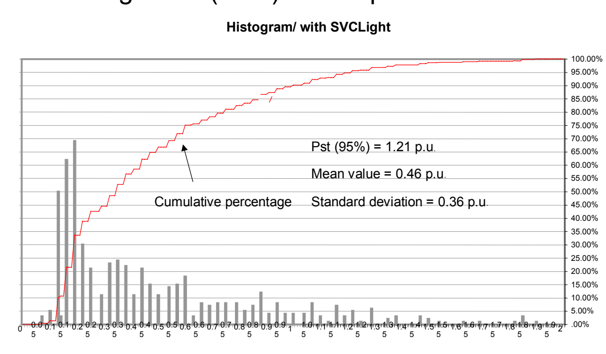

Figure 11b: Furnace in operation, with SVC Light. Pst(95%) = 1.21 p.u.

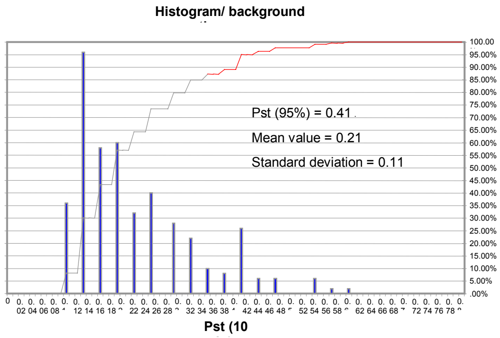

Figure 11c: Background flicker generation.
. Pst(95%) = 0.41 p.u

The practice recommended by UIE (International Union For Electroheat) for evaluation of flicker severity from multiple sources is per the formula:

$$P_{ST} = \left[\sum_i \left(P_{STi} \right)^m \right]^{1/m} \qquad (1)$$

where m is the summation coefficient. The summation coefficient considers the risk of coincident furnace operation. The factor is recommended to vary from 1 to 4. m=4 is used when furnaces run specifically in order to avoid coincident melts. m=1 is used when there is a very high occurrence of coincident voltage changes.

The background flicker is generated by many sources, and will therefore appear more or less constant over the day. To deduct the background flicker, an “m” factor of 1 should be used. However to perform the evaluation in a very conservative way, a factor of two is used.

From (1), in the case of flicker generated by the EAF only and without background flicker, we get with no SVC Light in operation:

$$P_{STA} = \left[\left(P_{ST1}^2 - P_{ST3}^2 \right) \right]^{1/2} = 3.88 \text{ p.u.} \qquad (2)$$

The residual flicker value with the SVC Light and EAF in operation and without background flicker is:

$$P_{STB} = \left[\left(P_{ST2}^2 - P_{ST3}^2 \right) \right]^{1/2} = 1.14 \text{ p.u.} \qquad (3)$$

The flicker mitigation by the SVC Light is:

$$R_{SVCLight} = \frac{P_{STA}}{P_{STB}} = 3.4 \text{ p.u.} \qquad (4)$$

Increased furnace power

An EAF requires a stable voltage supply for optimum performance. SVC Light instantaneously compensates the random reactive power variations, and hence the voltage variations, of the EAF. Reactive power compensation by an SVC Light helps to obtain the following production benefits:

A higher and stabilised voltage level at the furnace busbar, giving:
- Shorter melt down times
- Reduced energy losses
- Reduced electrode consumption.

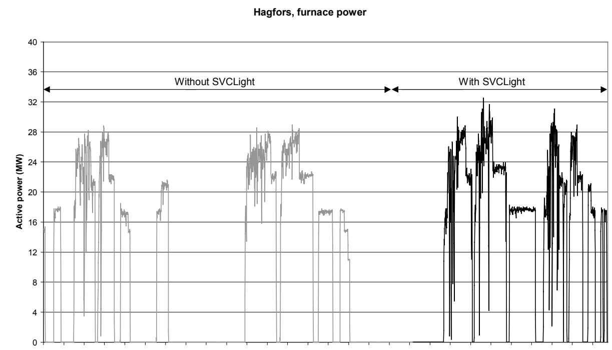

Figure12: Active power consumption at Hagfors without and with dynamic compensation.

Figure 12 shows measurements of the active power consumption in Hagfors 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.

SUMMARY

.Voltage source converters far into the tens of MVA range based on IGBT technology are now a reality. An important as well as sophisticated application for this new technology is mitigation of severe voltage flicker from electric arc furnaces.

An SVC Light, a full scale installation for flicker mitigation based on IGBT equipped VSC equipment has been implemented in a steel mill in Sweden. As an additional valuable benefit, the available melting power of the electric arc furnace has been increased.

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