SVC Light – a powerful tool for power quality improvement

ABB has developed and introduced a new technology called SVC Light which brings together the VSC (Voltage Source Converter) and IGBT (Insulated Gate Bipolar Transistor) to create a tool offering unique possibilities for power quality improvement in the high power range. The new technology is being installed at a steel plant in Sweden, where it will mitigate flicker caused by the operation of a large electric arc furnace.

The appearance on the market of continuously controllable semiconductor devices capable of handling high powers has made voltage source converters with highly dynamic properties feasible far into the tens of MVA. ABB's newly introduced SVC Light concept, which combines VSC and IGBT (Insulated Gate Bipolar Transistor) technology, offers completely new options for power quality control in areas previously closed to it or which have been only partly manageable, eg the mitigation of voltage flicker caused by heavy industrial loads fed from weak distribution grids.

Power quality

The risk to the utility

During the 1990s the issue of flicker has grown dramatically in importance, especially in countries in which the electrical power market has been deregulated. Power quality has become a strength in the marketplace. Utilities who ignore their customers, whatever their size, risk losing them to competitors. This has set the stage for solutions that, by mitigating flicker, give utilities a competitive edge.

The steelworks' point of view

The short-circuit power of the electricity network and the available power often place restrictions on the maximum production that can be planned for new steelworks. The small, additional investment in SVC Light is quickly paid back by the increase in productivity that it allows. SVC Light not only stabilizes the voltage and ensures sufficient power, but also, by mitigating flicker, eliminates the risk of flicker restrictions dictating the size of the installed electric arc furnace. With SVC Light, neither flicker requirements nor high electrical power demand need to be limiting factors when planning new steel plant projects.

The first SVC Light project, at the Uddeholm Tooling steel plant in Hagfors, Sweden, is running at full speed. Energization is planned at the end of 1998 and the official hand-over to the customer is scheduled for January 1999.

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Disturbances travel far and wide

To the steelmaker using scrap as his basic raw material, the electric arc furnace (EAF) is both an essential and efficient piece of equipment. The grid owner and the electricity supplier, however, see the EAF user not only as a customer, but also, in the worst case, as a contributor of pollution to the grid. The EAF may be the source of massive distortion in the form of voltage fluctuations, harmonics and phase unsymmetry. Also, the grid may have to carry reactive power during operation of the EAF, causing transmission losses and impeding the flow of useful, active power.

The same, or similar, can be said about other kinds of heavy industrial loads (eg, rolling mills, large mine hoists, etc), all of which take their power from distribution grids.

If they are not properly contained, disturbances emanating from any one industrial load will spread via the grid to neighbouring facilities **1**.

Fortunately, there are ways of dealing with the problem of poor or insufficient power quality in grids. One obvious one is to reinforce the power grid by building new lines, installing new and more powerful transformers, or moving the point of common coupling to a higher voltage level. Such measures, however, are expensive and time-consuming, if they are permitted at all.

A simple, straightforward and cost-effective way to improve power quality is to install dedicated equipment in the immediate vicinity of the source(s) of disturbance. SVC Light (SVC stands for Static Var Compensator) was developed especially for this purpose.

As an additional benefit, SVC Light improves the process economics, making the investment more attractive to the owner of the installation(s) causing the disturbance and actually making the investment profitable after a limited period of time.

Voltage flicker

An electric arc furnace is a heavy consumer of not only active but also reactive power. Also, the physical process taking place in the furnace (electric melting) is erratic by nature, involving one or several electrodes striking electric arcs between the furnace and the scrap. Consequently, the consumption of reactive power fluctuates especially strongly **2**.

Because of this, the voltage drop caused by reactive power flowing through circuit reactances in the electrodes, electrode arms and furnace transformer also fluctuates erratically. The result is voltage flicker, evidence of which can be seen most clearly in the flickering light of incandescent lamps fed from the polluted grid.

Spectral analysis confirms that lamp flicker caused by EAF action is severe around frequencies to which the human eye is particularly sensitive, ie below 20 Hz. As it is a very annoying sensation, flicker quickly becomes a cause for complaint.

The International Union of Electroheat (IUE) and the IEC have cooperated in defining a quantity, P_{st}, for expressing flicker severity. According to this definition, P_{st} = 1 means that in a group of people exposed to light flicker, half of them will notice it.

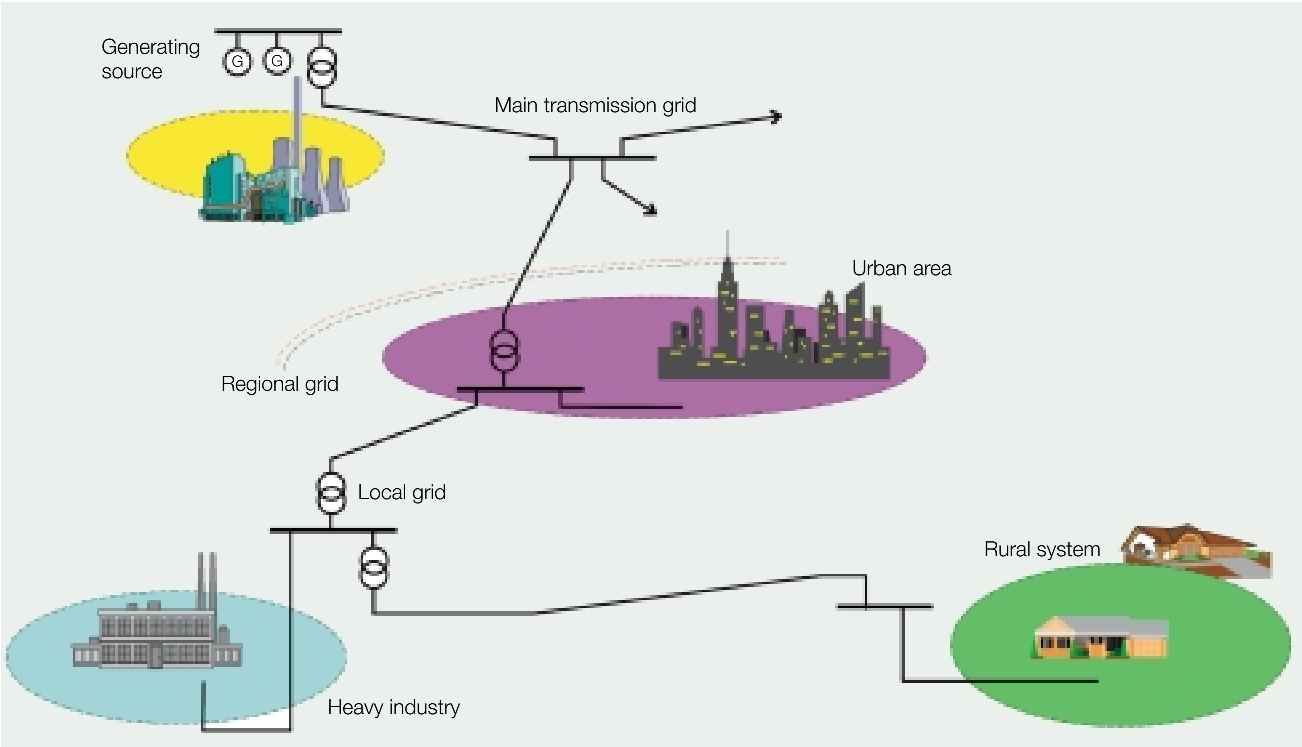
SVC Light

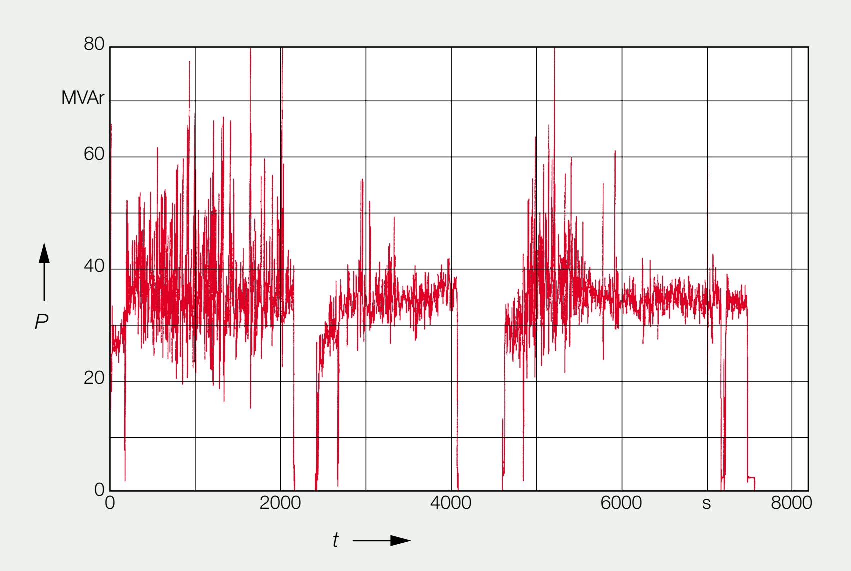
SVC Light is a flicker mitigating device that attacks the root of the problem, ie the erratic flow of reactive power through the supply grid to the furnace. It does this by measuring the reactive power consumption and generating a corresponding amount for injection into the system, thereby reducing the net reactive power flow to an absolute minimum. As an immediate consequence, voltage flicker is also minimized.

Important added benefits are a high and constant power factor, regardless of the load fluctuations over furnace cycles, as well as a high and stable bus rms voltage. These benefits translate into improved furnace productivity as well as lower operating costs due to lower specific electrode and energy consumption and reduced refractory wear.

To balance the rapidly fluctuating consumption of reactive power, an equally rapid compensating device is required.

How disturbances emanating from an industrial load spread via the grid to other facilities **1**





Reactive power consumption of an electric arc furnace (EAF) **2**

P Calculated EAF reactive power

t Time

This is achieved with state-of-the-art power electronics based on IGBT technology. With the advent of continuously controllable semiconductor devices capable of handling high powers, voltage source converters with highly dynamic properties have become feasible far into the tens of MVA.

The function of the VSC in this context is to provide a fully controllable voltage source matching the bus voltage in phase and frequency, with an amplitude which can be continuously and rapidly controlled. A VSC with such characteristics can be used for reactive power control **3**.

By controlling the VSC voltage in relation to the bus voltage the VSC acts as a generator or absorber of reactive power, depending on the relationship between the voltages. A range-offsetting capacitor bank is connected in parallel with this controlled reactive power branch to make the overall control range of SVC Light capacitive.

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

Voltage source converters

The input of the voltage source converter is connected to a capacitor, which acts as a DC voltage source. The converter produces a variable AC voltage at its output by connecting the positive pole or the negative pole of the capacitor directly to any of the converter outputs. In converters that utilize pulse width modulation (PWM) the input DC voltage is normally kept constant. The output voltage can be, for example, a sinusoidal AC voltage, the amplitude, frequency and phase of which can be controlled by changing the switching pattern.

Voltage source converters that utilize PWM are widely used today, even dominating in applications such as speed and torque control of AC motors.

In electrical transmission and distribution applications, voltage source converters featuring PWM have many uses, for example as rectifiers and inverters in HVDC systems, as reactive power compensators, as power conditioners and for connecting different kinds of energy sources or loads to the electric network.

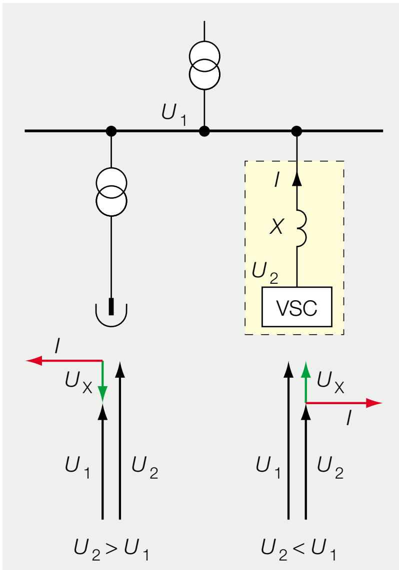
VSC for reactive power compensation

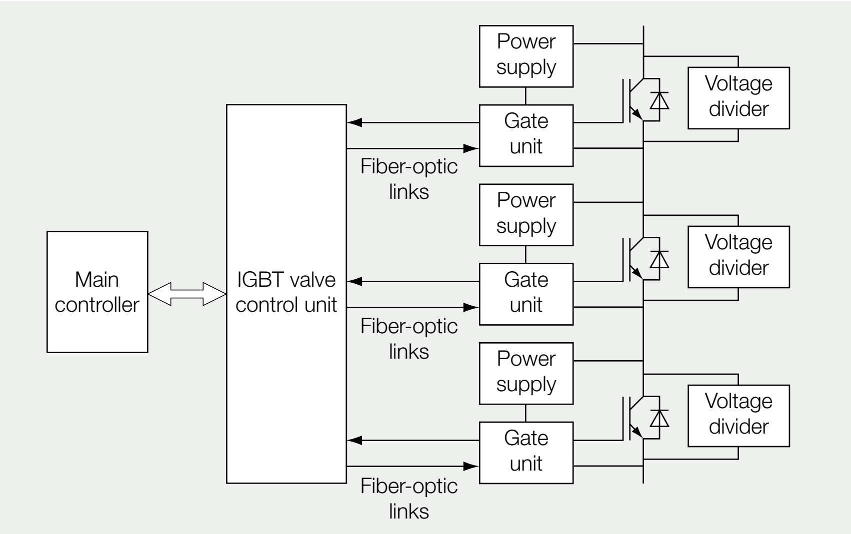
If the output of a VSC is connected to the AC system by means of a small reactor, the VSC can be said to resemble a synchronous generator without any rotating mass. By controlling the output voltage of the VSC in such a way that it has the same phase angle as the line voltage, the converter can either consume or generate reactive power. This is done by

Voltage source converter (VSC) used for reactive power control **3**

$U_2 > U_1$: capacitive current
$U_2 < U_1$: inductive current

I Current
U_1 Bus voltage
U_2 VSC voltage
U_X Reactor voltage
X Reactance





The IGBT valve with simultaneously switched, series-connected IGBTs **4**

controlling the amplitude of the output voltage **3**. If the output voltage is higher than the line voltage, the converter will generate reactive power and act as a shunt capacitor. If the output voltage is lower than the line voltage, the converter will consume reactive power and act as a shunt reactor. The reactive power supplied to the network can be controlled very fast; all that is required is a slight change in the switching pattern in the converter. The response time is limited mainly by the switching frequency and the size of the reactor.

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, being typically 15%. SVC Light therefore comes close to being the ideal tool for fast reactive power compensation.

This raises the question of why voltage source converters are not more widely used today for static compensation. To answer this question it has to be considered that the VSC utilizes turn-off type power devices, such as GTOs (Gate Turn Off Thyristors) or IGBTs, and that to connect the VSC to the 10–36 kV distribution system direct, eg without using an intermediate transformer, a high-voltage converter is needed. This calls for series-connection of the power devices. Also, a high switching frequency is required to keep the harmonics supplied to the network small and ensure fast step response by the compensator. The combination of series-connected turn-off type power devices and a high switching frequency creates several technical challenges. Intensive R&D at ABB Power Systems has brought forth solutions that effectively address these issues.

The IGBT

The most suitable power device for SVC Light was found to be the IGBT because its short turn-on/turn-off delay times make it relatively easy to connect in series. Also, since it features low switching losses it can be used at high switching frequencies. Another advantage is that no d*i*/d*t* limiting reactors or snubber capacitors are needed. Instead, d*i*/d*t* and d*u*/d*t* control can be performed by gate control. Nowadays, several manufacturers offer devices combining high power capability and high reliability – features which make the device also suitable for high-power converters.

The IGBT is a bipolar transistor with an MOS (Metal Oxide Semiconductor) gate to which either a positive or negative voltage is applied for control purposes. Since only a very low power is needed to control the IGBT, the power for gate control can be taken from the main circuit. This is highly advantageous in high-voltage converters, in which many devices are connected in series.

Presspack IGBTs are used in SVC Light. The press-pack IGBT is a new device, developed to meet the very high demands made on reliability and now being used in the new generations of high-speed trains, where the combination of high power and high reliability is very important.

A presspack IGBT is packaged in a housing almost like a conventional high-power thyristor. Inside it, IGBT chips and antiparallel diode chips are connected in parallel, with pressure contacts normally providing the electrical contact to the outside. This type of device features a short-circuit failure mode, which is very favourable in a converter with series-connected devices. Thus, a device that fails will act as a short circuit. Since redundant devices are a standard feature of SVC Light, failure of one device will have no effect on the converter, which can continue operating at full power. The failure is monitored and the device can be replaced at a time which will cause minimum disturbance to the process.

The IGBTs in the Hagfors installation in Sweden are rated at 2.5 kV for a nominal current of 1,800 A. The turn-off capability of the device is 3.6 kA in normal operation. In the event of a short circuit the device itself will limit the current to less than 10 kA. In this case, the short circuit is detected by a protection system and the device can be safely turned off by applying a so-called 'soft turn-off' signal to the gate.

Series connection of IGBTs

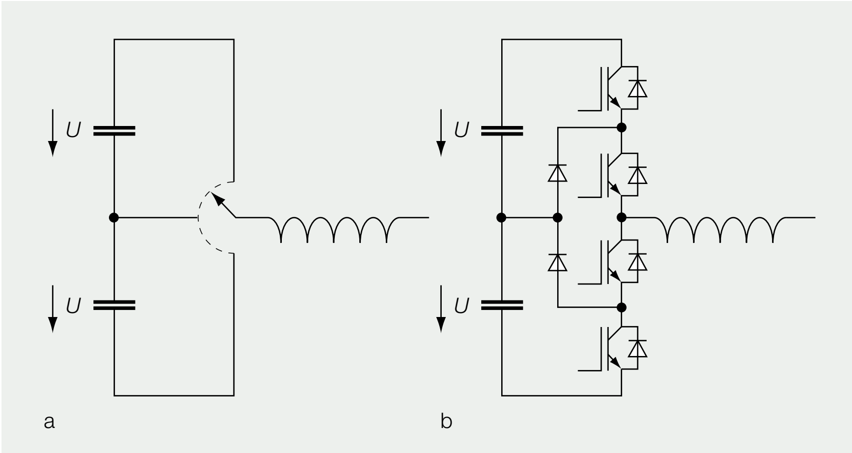
When connecting IGBTs in series it is important for the voltage to be properly divided. Simultaneous turn-on/turn-off of the series-connected devices is essential. In SVC Light, the turn-off and turn-on signals are distributed to the individual IGBTs by a high-bandwidth, fiber-optic system. The IGBTs 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 d*u*/d*t*. Turn-off of an IGBT valve or diode valve is followed by a small voltage difference between the different IGBT positions. This difference is controlled by proper design of the resistive and capacitive voltage dividers **4**.

In addition, every IGBT has its own overvoltage monitoring system for the detection of abnormal IGBT behaviour.

Converter valve

The converter in the Hagfors installation has a three-level configuration. In a three-level converter, the output of each phase can be connected to the positive pole, the midpoint or the negative pole of the capacitor. The DC side of the converter is floating, ie insulated to ground. With PWM and a switching frequency of 1,650 Hz, the converter will produce a very smooth phase current with low harmonic content. The three-level topology also ensures low switching losses for a higher converter efficiency and current-carrying capability.

The three-level converter is used in a so-called Neutral Point Clamped (NPC) configuration **5a**, **5b**. In this configuration there are 4 IGBT valves and 2 diode valves in every phase leg. The DC capacitor in this case is divided into two series-connected capacitors. Every IGBT/diode valve has to withstand the blocking voltage corresponding to the voltage across one of the capacitors.



Principle of the three-level converter (a) and a neutral point clamped (NPC) converter configuration (b) (one phase) **5**

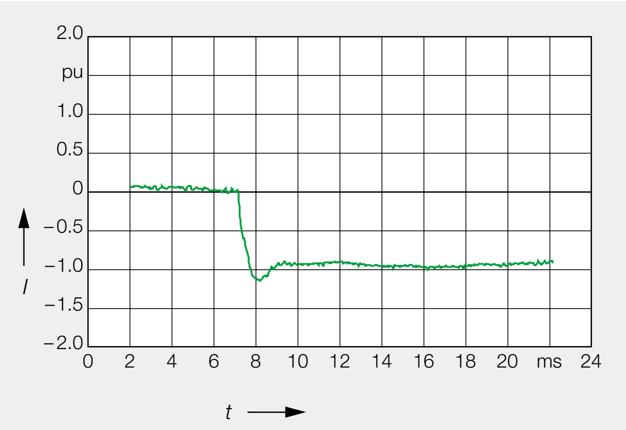
U *Voltage*

The valves are built by stacking the devices (with interposing coolers) and applying an external pressure to the stack **6**.

The IGBT valves are cooled with deionized water. Water-cooling allows a compact converter design and high current-carrying capability. The compact design, besides allowing a smaller footprint, also has the advantage that the loop inductance between the IGBT valves and the DC capacitors can be kept low, which helps to reduce the losses. The valves in the Hagfors installation are designed for continuous phase currents of approximately 1,300 A (rms) and transient values of 1,700 A (rms).

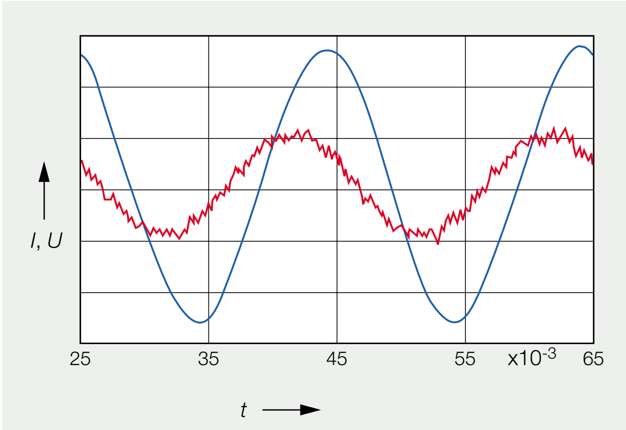
The three-phase converter, DC link capacitors and a small control room were delivered as a single transportable unit to the Hagfors site. A separate unit was used to transport the cooling system and indoor

IGBT stacks **6**



Step response measurement obtained with an analogue model of SVC Light **7**

I *Current*
t *Time*



EAF bus voltage and SVC Light output current waveshapes **8**

Red *SVC Light current*
Blue *Bus voltage*

switchgear. The Hagfors converter is connected to a 10.5 kV AC system.

ABB Power Systems can also deliver SVC Light for direct connection to higher voltages, ie up to 36 kV AC.

Flicker mitigation

ABB Power Systems' broad experience in the field of flicker mitigation has shown that successful flicker damping is highly dependent not only on the switching frequency but also on the time delay between the sampling of the measured values and the next switching instant, and ultimately on the implemented control algorithms.

Computer studies and field measurements of EAF reactive power compensation give a good idea of how flicker compensation can be optimized. To fully utilize the developed control strategies a reactive power compensator is required that can be controlled at least 15 times faster than existing technology (100 Hz). This kind of performance can only be achieved with VSC technology based on IGBTs.

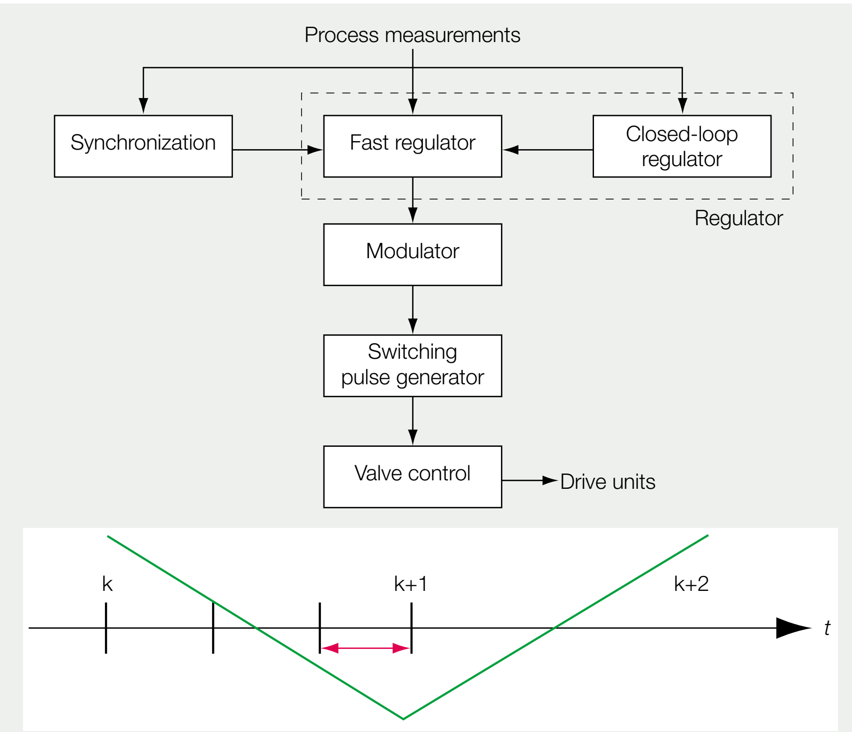
As an example of the attainable performance, **7** shows the step response from zero to maximum output. By introducing IGBTs, step responses within 1 ms can be achieved.

The measurement shown in **7** is from an analogue model of SVC Light. It is part of a larger system that includes a downscaled model of an electrical arc furnace and a TCR (Thyristor Controlled Reactor). This system can be used to perform real-time studies of compensator performance in an industrial system. The model has been very useful during the development

Control procedure for minimum delay between sampling of the measured process parameters and the next switching instant **9**

k *Sample no*
t *Time*

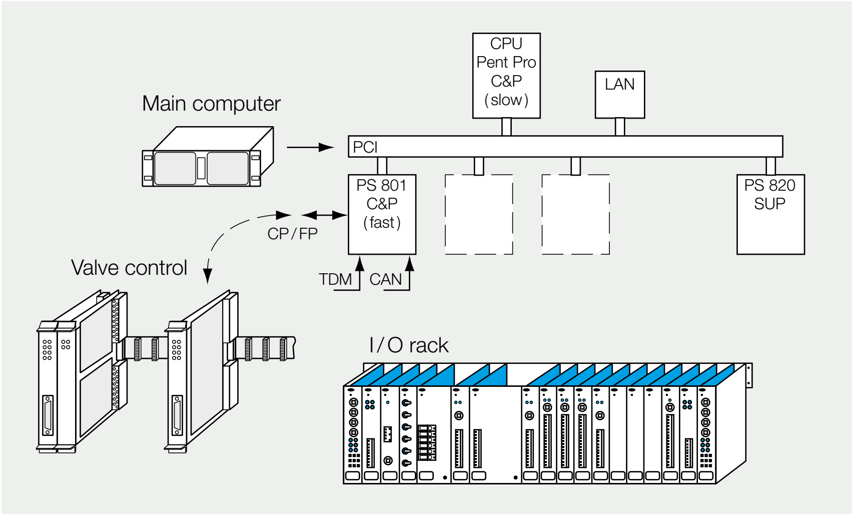
Green *Carrier wave*
Red *Calculation time*



of both software and hardware for flicker compensators.

PWM enables VSC technology to be fully utilized. While the switching frequency has to be chosen high enough for flicker mitigation purposes, consideration also has to be given to losses and harmonic requirements. For the Hagfors installation a pulse number of 33, corresponding to a switching frequency of 1,650 Hz, was chosen. The time between consecutive switching is therefore only 303 µs. In practice, the result is a compensator capable of continuous control of the reactive power. The impact of the valve switching is reduced to negligible kinks in the compensator output current **8**.

Another prerequisite for optimum flicker mitigation is a minimum delay between sampling of the measured process parameters and the next switching instant. One standard control procedure is to synchronize the process parameter measurements with the main circuit switching instants, which in this case would result in a time delay of 303 µs. However, studies have shown that a further reduction would have additional benefits for flicker mitigation. The goal has therefore been to perform the calculations for the flicker algorithm (fast regulator) as



MACH2 control and protection system for SVC Light **10**

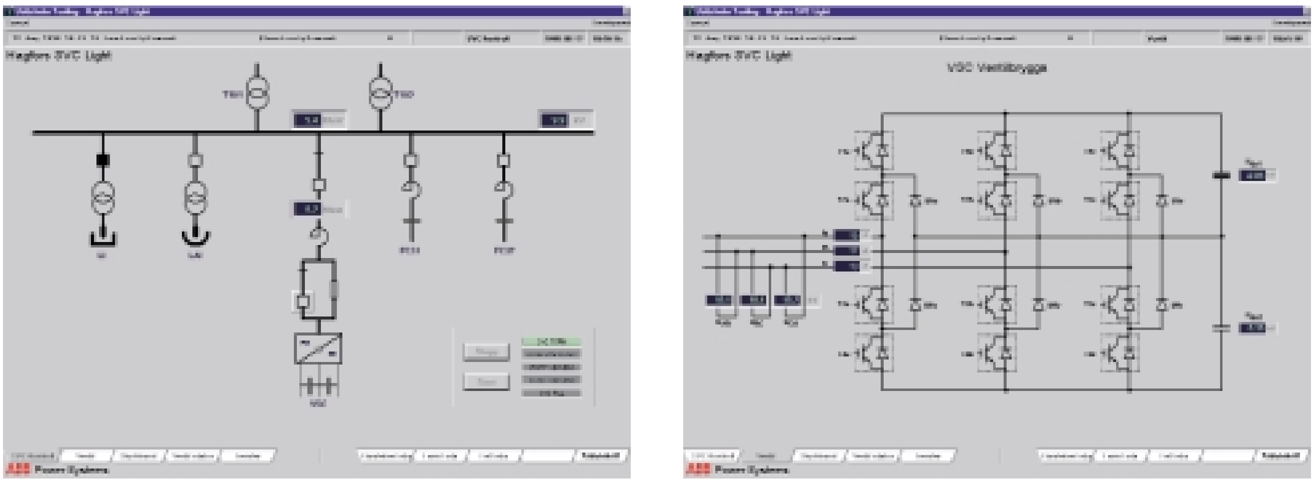
CAN	*Controller area network*
CPU	*Central processing unit*
CP/FP	*Control pulses/firing pulses*
LAN	*Local area network*
PCI	*Peripheral component interconnect bus*
SUP	*Supervision board*
TDM	*Time division multiplexed bus*

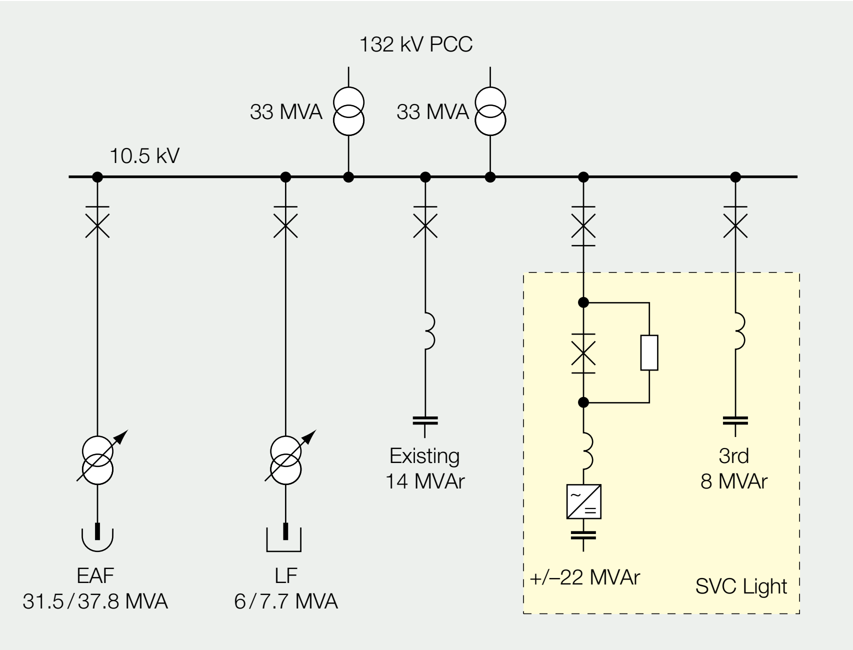
close as possible to the switching operation, ie basing them on values measured as late as possible. **9** shows how the process measurements are carried out as close as possible to the switching operation in order to minimize delay to the actual calculation time.

MACH2 control and protection system

To ensure fast and extensive data processing, ABB Power Systems developed the MACH2 control and protection system. It is based on industrial standard PC hardware (with Windows NT) in order to facilitate an open system which can be easily integrated in existing systems at the

Overview of the Hagfors plant (left) and a VSC valve detail (right) – two of the graphics on display at the operator workstation **11**





Single-line diagram of the Hagfors furnaces and the installed SVC Light configuration **12**

EAF	*Electric arc furnace*
LF	*Ladle furnace*
PCC	*Point of common coupling*

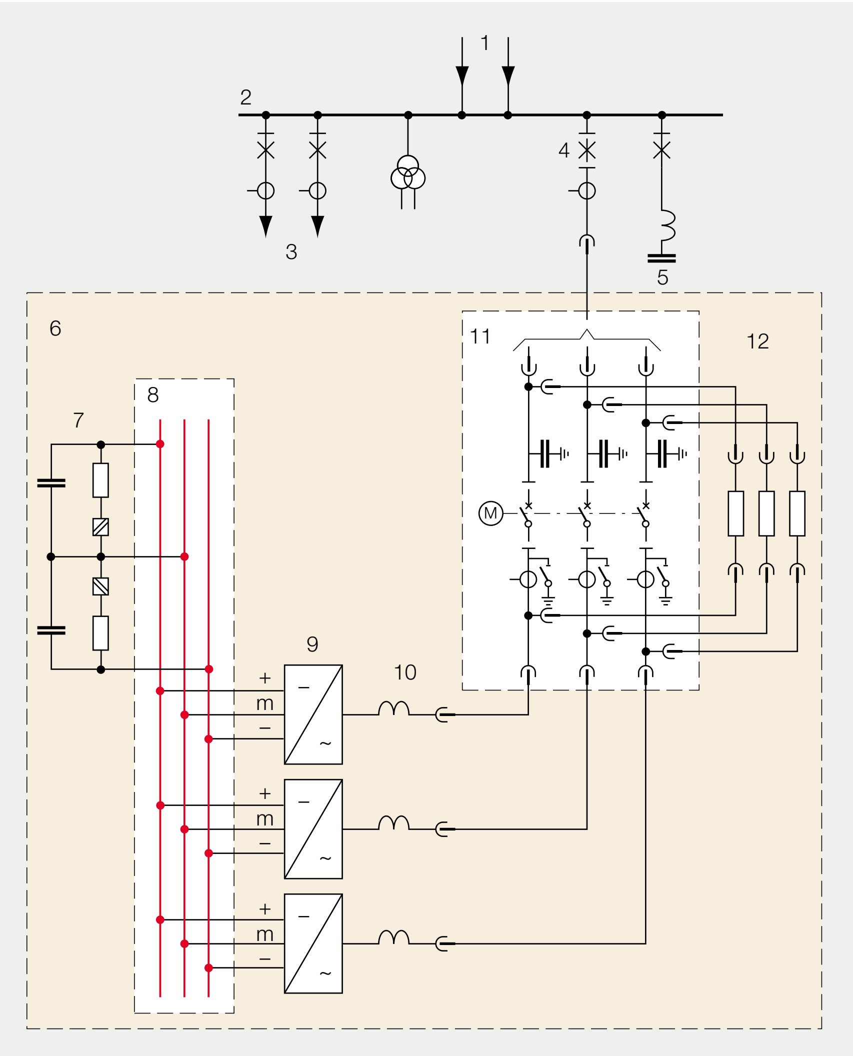
steelworks and externally accessed directly by RAS (Remote Access Services).

The strategy of basing the control and protection system on open interfaces ensures that advantage can also be taken of future improvements in the fast-changing field of electronics. Basically the system consists of three units: the main computer, the I/O rack, and the valve control unit. Communication between the units takes place over standard industrial buses **10**.

Operation of SVC Light

The system is operated from an operator workstation (OWS), which can be a standard PC. The man-machine interface (MMI) is the world's most used graphic control package for Windows NT – InTouch. InTouch software is highly flexible, even offering a full Chinese version, and allows specially customized MMIs to be easily designed **11**.

Start and stop sequences are initiated at the OWS. SVC Light currents and volt-



Main circuit diagram of Hagfors SVC Light **13**

1 *Incoming feeders*
2 *EAF bus*
3 *Load (furnaces)*
4 *Main circuit-breaker*
5 *Harmonic filter*
6 *SVC Light container*
7 *Capacitors*
8 *DC bus*
9 *Valves*
10 *Reactors*
11 *Bypass switch*
12 *Pre-insertion resistors*

m *DC side midpoint*

ages, event and alarm lists, and the statuses of all the equipment are displayed. InTouch uses DDE (Dynamic Data Exchange) to collect data from the control and protection system. This enables data to be collected by any computer on the local area network, which is set up as a DDE server. InTouch also has its own sequence of events recorder, which time-tags DDE variables as defined by the user.

Powerful single-board computer

In addition to the standard equipment, specially designed hardware has been developed by ABB Power Systems to ensure the high performance required. The fast regulator is implemented, together with other functions, on a single-board computer (PS801) containing a cluster of six very powerful digital signal processors (DSPs) from Analog Devices, which together provide a calculation capacity of more than 700 Mflops (million floating point operations per second). The activities of these DSPs are coordinated by an Intel general-purpose processor on the same board. Also on this board is the logic for the control pulse generation, which is implemented in one large FPGA (Field Programmable Gate Array) circuit.

The programs for the processors and DSPs are stored in flash PROMs, which are programmed and erased on the board. Changes to the software can therefore be made without having to remove the boards from their position.

In addition to the supervisory tasks assigned to each part of the system, all of the hardware, software and communications are monitored continuously by a separate supervision board, PS820. This combination of distributed supervision and central supervision board guarantees the high reliability required for high-power applications.

Hagfors SVC Light system **14**

Interface to the process and valve control

An I/O rack with digital and analogue I/Os can also be connected. This processes and summates the collected data and afterwards sends them to the main computer via data buses. Each analogue input board has a DSP, which can be used for data preprocessing (eg, conversion from phase to vector representation and filtering) to minimize the amount of data that has to be communicated to the regulators.

The PS801 board generates control pulses for the IGBT valve, which the valve control unit (VCU) converts into light signals for transmission to the gate units. Besides receiving IGBT control signals from the VCU, the gate units also send status information on the different IGBT

Simulation of SVC Light flicker mitigation in the Hagfors plant **15**

P_{st} *Flicker severity*
t *Time*

Red *Uncompensated*
Blue *With SVC Light*

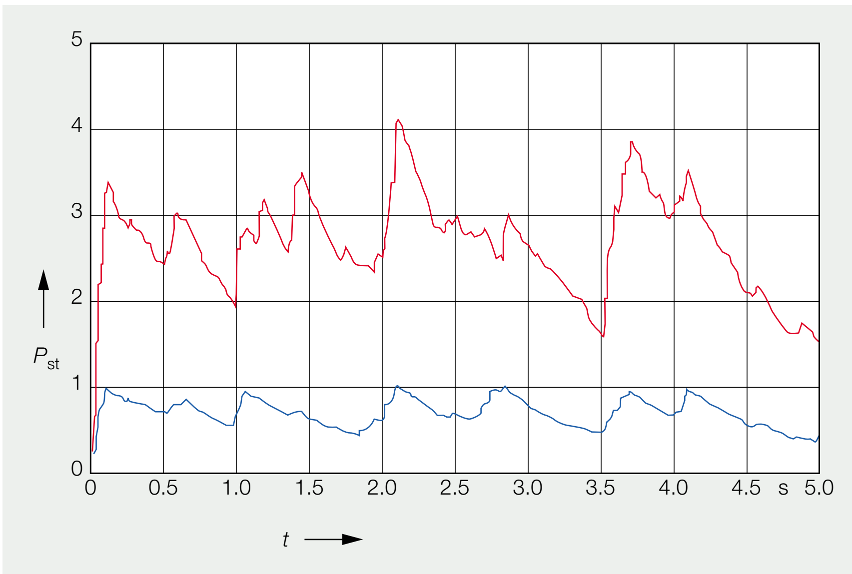


Table 1:
Technical data of the Hagfors SVC Light installation

Furnace bus voltage	10.5 kV
Rated power, EAF	31.5/37.8 MVA
Rated power, LF	6/7.7 MVA
Dynamic range, SVC Light (capacitive)	0–44 MVAr
Targeted flicker level with SVC Light in operation	$P_{st,95} = 1$
Power factor at PCC (compensated)	> 0.95

EAF *Electric arc furnace*
LF *Ladle furnace*

positions to the valve monitoring system. The VCU is also responsible for the fast valve protection.

Communication between the systems is via three different buses:

- PCI (Peripheral Component Interconnect) bus, a standardized high-performance, parallel back-plane bus (32-bit version) with a transfer capability of 133 Mbyte/s.
- CAN (Controller Area Network, ISO 11898) buses, which handle digital orders, eg to breakers, and indications.
- TDM (Time Division Multiplexed) buses, with high-speed synchronous serial channels for the transfer of numerical data between the I/O rack and the main computer.

Uddeholm Tooling – a pioneer

At Uddeholm Tooling at Hagfors in central Sweden, the metallurgical process is based on scrap melting in an electric arc furnace and subsequent refining in a ladle furnace. The arc furnace is rated at 31.5 MVA with a 20% temporary overload capability, whereas the ladle furnace is rated at 6 MVA plus 30% overload. Both furnaces are fed from a 132-kV grid via an intermediate voltage of 10.5 kV [12].

The grid is relatively weak, with a fault level at the point of common coupling (PCC) of about 1,000 MVA. It is obvious that this is too low to allow operation of the two furnaces and at the same time ensure an acceptable power quality for the grid.

A qualitative idea of the amount of flicker that can be expected with this combination of load size and grid fault level can be obtained from a simple expression:

$$P_{st} \approx 75 \frac{S_{SCEAF}}{S_{SCN}}$$

where P_{st} is the flicker severity, S_{SCEAF} the short-circuit power of the electric arc furnace and S_{SCN} the fault level of the grid at the PCC. A measure of the worst-case flicker is obtained by inserting in the formula double the power rating of the EAF, ie 63 MVA, and the lowest value for S_{SCN}. This gives the value of 4.5 for P_{st}, corresponding to severe flicker and calling for measures capable of effective mitigation.

The SVC Light installation [13], [14] has a reactive power rating of 0–44 MVAr. This dynamic range, which is continuously variable, is obtained with a 22-MVA VSC in parallel with two harmonic filters, one rated at 14 MVAr and already existing in the plant, and one, rated at 8 MVAr, installed as part of the SVC Light project. The VSC is connected directly, via its phase reactors, to the furnace bus voltage of 10.5 kV. This is made possible by connecting IGBTs in series in order to attain the required voltage rating of the equipment.

To prevent the DC capacitors from being charged to an inadmissibly high level through the antiparallel diodes of the three-level bridge, inrush current limiting resistors are included in the starting sequence of SVC Light, after which the resistors are bypassed.

Powerful flicker mitigation

The maximum residual flicker level targeted for the 132-kV PCC with SVC Light in operation is $P_{st}(95) = 1$. This level is based on the results of simulations performed for the actual Hagfors installation [15].

An open-loop control system ensures that flicker is reduced with an optimum rate of response. As an additional feature, a second, slower function is included for power factor control. It allows the plant power factor to be kept stable at the pf setting of > 0.95 at all times.

The technical data of the Hagfors SVC Light installation, which requires a floor area less than 200 m^2 in size, are summarized in *Table 1*. The installation is due to become operational at the end of 1998.

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