A greenfield steel plant owned and operated by Siam Yamato Steel Co. Ltd. has been put on-line in the Rayong region in Thailand. The steelmaking process is based on the melting of steel scrap in an electric arc furnace (EAF) rated at 96 MVA and supplied by SMS Siemag, followed by refining in a ladle furnace (LF) rated at 22 MVA.

The steel plant is fed from a 115 kV power grid. The fault level varies between 1,970 MVA and 3,000 MVA, depending on grid conditions. Considering the substantial size, particularly of the EAF, unless proper measures were taken, strong incandescent lamp flicker could have been expected as a result of the operation of the EAF. This would have been particularly pronounced at minimum fault level.

With a STATCOM® operated on the 22 kV EAF bus, efficient flicker mitigation was attained, and the grid code of the feeding grid is fulfilled for all operating conditions.

In fact, the flicker level at the 115 kV point of common connection (PCC) is influenced by two more steel plants situated in the same region and operated from the same grid. Consequently, the flicker measured is an aggregated value arising from the operation of all three plants.

EAF: Grid Impact

The electric melting process inside an EAF is erratic in its nature, resulting from time to time in an “electrical short” within the furnace’s electric circuit. As a consequence, the consumption of reactive power strongly fluctuates in a stochastic manner. The fluctuation of reactive power flowing through the circuit reactances results in voltage fluctuations, which are most clearly visualized in the flickering light of incandescent lamps serviced by the common grid. 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. Flicker is a very annoying sensation and easily becomes a source of complaints to the grid company.

Flicker is expressed by means of the flicker severity level $P_{st}$, which directly expresses the degree of irritation. The most critical part of the voltage fluctuation spectrum falls around 8 Hz, which is where the human eye is at its most sensitive to light fluctuations. The amount of flicker that arises as a consequence of EAF operation depends on the size of the EAF and the short-circuit power of the grid at the PCC. With an EAF having a short-circuit rating of $S_{SCEAF}$ and a grid having a short-circuit power of $S_{SC}$, a flicker expectation figure can be derived from the following equation.¹ The constant $K_{st}$ (“severity factor”) can assume a variety of values, depending on the EAF setup and operating conditions.

$$P_{st} = K_{st} \frac{S_{SCEAF}}{S_{SC}}$$

(Eq. 1)

¹ Also known as SVC Light®.

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The situation is aggravated by the appearance of interharmonics in the furnace current, interacting in a nonlinear way to produce additional flicker components.

In the given case, the minimum value of $S_{SC}$, corresponding to the most onerous case, amounts to 1,970 MVA at the 115 kV PCC.

With $S_{EAF} = 96$ MVA, $S_{SCEAF}$ can be estimated to some 160 MVA. (The impact of the ladle furnace is insignificant in the context.) Furthermore, with a specified value of $K_{st}=56$, a $P_{st}$ value (uncompensated) around 4.5 can be expected. With the SVC Light in operation, flicker is reduced by a factor > 4.5. By minimizing the flow of reactive current through the PCC, voltage fluctuations, and thus flicker, are minimized.

On top of flicker, an EAF is also a strong source of harmonics and gives rise to voltage and current imbalance between phases.

**Benefits of the Installation**

The flicker reduction capability of a traditional static var compensator (SVC), based on thyristor switching technology, would have been insufficient for the purpose and a STATCOM, a device more potent for the purpose, was decided on instead.

With the STATCOM in operation, a flicker reduction factor $> 5$ is achieved. Furthermore, due to the active filtering capability of the STATCOM, efficient harmonic suppression has been achieved.

The installation of the STATCOM at the steel plant feeder has brought benefits not only to the steel plant, but also to the grid owner:
- Acceptably low flicker level at the PCC.
- Acceptably low amounts of harmonic distortion.
- Negative-phase sequence voltage compensation as part of the flicker compensation.
- A high and constant power factor at the feeding point of the plant, with no back-feed of reactive power into the grid.
- Keeping grid reinforcements at a minimum.

**Main System Design**

The SVC Light is based on a voltage source converter (VSC), built up of insulated gate bipolar transistors (IGBTs). A single converter is utilized, thereby avoiding all paralleling of devices. The converter is directly connected to the 22 kV EAF bus, without any need for a stepdown transformer or other complex magnetic interfaces. As the DC link, DC capacitors are utilized. The SVC Light control scheme is based on pulse-width modulation (PWM), thereby ensuring minimum need for harmonic filtering.

Figure 1 shows a simplified single-line diagram of the SVC Light together with the furnaces and the power transformer.

The SVC is rated at ± 60 Mvar. In addition, the SVC Light comprises a second harmonic filter rated at 30 Mvar, a third harmonic filter (28.5 Mvar) and a ripple filter (1.5 Mvar). The 22 kV bus is connected to the 115 kV grid by a 130/150 MVA power transformer.

The VSC, together with the harmonic filters, gives the SVC Light a total operating range from zero to 120 Mvar capacitive reactive power.

The footprint of an SVC Light is small compared to traditional SVCs based on thyristor technology, mostly due to the symmetrical reactive power range of the VSC, which makes it possible to reduce the harmonic filter sizes.

**Voltage Source Converter** — The VSC is based on IGBTs, which enable high-frequency current switching. The IGBTs therefore give possibilities to control the current much faster than conventional thyristor-based compensators. The IGBT valves are configured as a three-level neutral point clamped (NPC) converter, which is illustrated in Figure 2.

Each phase of the converter has six valves: four IGBT valves with anti-parallel diodes, and two diode valves. All three phases are connected to a common bank of DC capacitors. With this valve configuration, the voltage on the output terminal toward the reactors can achieve three levels: +DC, zero or −DC. The valve current is smoothed by the phase reactors, connecting the IGBT valves to the compensator bus.

The switching of the IGBT valves is controlled by the valve control unit (VCU), which is part of the SVC Light control system. As the required valve current is determined by the control system, the VCU enables the correct switching of the valves. The VCU communicates with each IGBT using optical fibers, one fiber for...
sending switching orders to the IGBT and another fiber for receiving data concerning the IGBT voltages during the switching sequence. The gate unit (GU) located next to each IGBT in the valve receives the switching order and controls the voltage of the IGBT gate. The energy needed for turning on and off the IGBT is sourced by the voltage that rises across each level every time the IGBT turns off. The information sent back to the VCU makes it possible for the operator to observe the status of all IGBTs in the converter.

Valve Stacks — The IGBTs and diodes are of StakPak® type, made to be clamped in a stack of series-connected IGBTs. The collector and the emitter of the IGBT are the top and bottom, respectively, meaning that the current flows vertically in the IGBT stack. An IGBT consists of up to six submodules, where the number of submodules determines the current capability of the component. StakPak IGBTs with different current ratings are shown in Figure 3.

A number of IGBTs are connected in series to handle the high voltage of the converter, typically ±21 kV DC. The short-circuit failure mode of an IGBT is one of the most critical parameters. The StakPak IGBT will fail as short circuit, which enables continued operation without tripping the converter, with the only outcome being
that the other components in the valve will be subject to somewhat higher voltage. Redundancy is thus included in the valve as series-connected IGBTs in each valve.

Each IGBT or diode is mounted between water-cooled heat sinks, giving sufficient cooling to the high-power transistor. All valves are suspended from the ceiling, which ensures that the converter can withstand the seismic requirements of the area.

A view from the valve hall is displayed in Figure 4. The IGBT and diode stacks are seen in the background of the picture, and the DC capacitors are in the foreground.

Valve Cooling System — All IGBTs and diodes are connected to high-voltage potentials, where the heat sinks are used as conductors between the components. This mechanical setup, where the heat sinks are in direct contact with energized parts of the valve, requires that the cooling media is of nonconducting type.

De-ionized water is used as cooling media in a closed-loop cooling system. The water is flowing through all heat sinks and cooled by a heat exchanger connected to the raw water system of the steel production plant. A small part of the water flow is continuously filtered and de-ionized to ensure the low conductivity of the water.

Mechanical Layout
The IGBT valve, together with its DC busbar, DC capacitors and cooling system, as well as the SVC Light control cubicles, were all built into a pre-fabricated building, factory assembled and supplied to the site as one complete unit (Figure 5). The coupling reactor and harmonic filters were erected on-site. The equipment is located indoors, with ample openings in the sidewalls for natural circulation of air.

Due to the factory assembly of major parts of the SVC Light, considerable amounts of time and labor were saved on-site.

Control System
The SVC Light is controlled by a redundant MACH 2 control system. MACH 2 is a very advanced microprocessor-based control system used for SVC, SVC Light, series capacitors and high-voltage direct current (HVDC) systems in a vast number of installations throughout the world. The MACH 2 system has integrated transient fault recorders (TFRs), an event database and possibilities for remote control of the SVC Light. The MACH 2 system I/O interface is used for analog data acquisition of the bus voltages and branch currents in the system, as well as digital inputs and outputs for control of circuit breakers and disconnectors.

The human machine interface (HMI) contains an industrial computer used as an operator work station (OWS) and sequence-of-event recorder (Figure 6).
Flicker Compensation — The main purpose of the SVC Light control system is to reduce the flicker generated by the arc furnace and the ladle furnace. The flicker compensation is an open-loop control, where the SVC Light current order is determined based on the measured furnace currents. A regulator block diagram is shown in Figure 7.

It is mainly the arc furnace that generates flicker, requiring accurate measurements of the individual phase currents. A current measuring device is used both in the electric arc furnace feeder as well as in the converter valve phase currents. Regular current transformers are used for the ladle furnace and harmonic filter currents, where the frequency response is less critical.

Besides the flicker control, SVC Light comprises negative-phase sequence control that compensates for unbalance between the phases. The flicker and negative-phase sequence control are time-critical applications located in a separate digital signal processor (DSP) in the MACH 2 system. The measured load currents, $I_{\text{Load}}$, in the arc furnace and the ladle furnace are used as input to the flicker and negative sequence control function. The VSC current, $I_{\text{VSC}}$, required to compensate the load currents is calculated by the flicker and negative-phase sequence control functions.

The DC voltages, $U_{\text{dc}}$, of the converter valve are continuously measured and regulated by the DC voltage
unbalance control, to ensure that the DC voltages are symmetrical regardless of the asymmetry that can occur in the load currents. The DC voltage control operates continuously to maintain stable and symmetrical DC voltages, in addition to the flicker and negative-phase sequence control. The output from both the DC voltage control and the flicker control is used for determining the current required by the VSC converter. Based on the measured converter currents, $I_{VSC}$, the current control function can limit the current order to protect the IGBTs from overcurrent or overheating.

The VSC converter uses a switching frequency optimum pulse width modulation (SFOPWM) switching pattern, whose switching times are determined based on the current order input. The switching times are synchronized with the bus voltage through a phase locked loop (PLL). Finally, the SFOPWM switching times are converted to firing pulses in an optical interface, the valve control unit, in the MACH 2.

**Active Filtering** — Besides the flicker compensation algorithms, SVC Light also enables active filtering of harmonics in the load current. The ability to reduce the harmonics by active filtering depends on the energy stored in the DC capacitors, which is limited by the voltage and the capacitor bank size.

For this particular application, the converter is optimized for damping of harmonics between the second and the ninth harmonic. The upper plot of Figure 8 shows the harmonic current spectrum of the
EAF. The current spectrum corresponds to the output of the measuring instrument defined by the IEC Standard [IEC 61000-4-7], as well as the continuous spectrum (Ck), are displayed.

**SVC Light Performance**

With a fault level of only 1,970 MVA, flicker compensation requirements can be a challenge. Based on an uncompensated flicker value $P_{st} (95\%) \leq 4.5$, the performance requirements were stated as follows:

- **Flicker:**
  - Maximum compensated $P_{st} (95\%): \leq 1.0$
  - Maximum compensated $P_{lt} (95\%): \leq 0.8$
- **Total Harmonic Distortion (THD):** $\leq 1.5\%$
- **Power Factor:** $\geq 0.95$

**Field Measurements** — The flicker level at the PCC is measured with SYS in operation, and with SYS off-line. Figure 10 shows the active power of the EAF (upper plot) and the measured short-time flicker level $P_{st}$ (red line) and long-time $P_{lt}$ (blue line). The figure shows that operation of SYS has very limited influence on the flicker level at the PCC, i.e., the SVC Light operates in a very disturbed power system.

The resulting flicker caused by independent sources can be estimated by summing up the cubic contribution

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**Figure 11**

- (a) Active and reactive power of the EAF; reactive power of the SVC Light and at the PCC (a);
- (b) estimate of EAF short-circuit power as seen from the 22 kV bus (b);
- (c) flicker, uncompensated and compensated (c);
- (d) and negative-phase sequence current from the EAF and at the PCC (d).
of each individual source. Due to the very high level of background flicker, the method presented in the IEC Standard cannot be directly used, as it would lead to a large error. Also, operation of the EAF without compensation was not possible, due to the strong flicker it would have caused.

Under such conditions, an indirect method to evaluate the flicker contribution from SYS at the PCC based on current is used instead.

The SYS EAF characteristic operating conditions and SVC Light performance can be analyzed using Figure 11. The top plot of Figure 11 displays the EAF power and reactive power of the SVC Light during a typical melting down process. The second plot in the figure is an estimation of the short-circuit power of the EAF as seen from the 22 kV bus. At the beginning of the melting process, the short-circuit power of the EAF reaches about 2 p.u. or 190 MVA, a value above the design value. The high short-circuit power of the EAF results in high flicker level generated by the EAF. The uncompensated flicker level generated by the EAF is displayed on the third plot and reaches 7.8. For this extreme EAF operating condition, the SVC Light reduces the flicker level down to 1.35, resulting in a flicker reduction by a factor of 5.7. In order to reach such significant flicker reduction, the SVC Light reduces the negative-phase sequence current of the EAF, which reaches 20% of the EAF nominal rating, to a level below 2%. After the EAF starting at a high short-circuit level, the EAF resumes normal operating conditions, i.e., at a short-circuit level of about 160 MVA (1.65 p.u.), resulting in an uncompensated flicker level of 6.7. For normal operating conditions, the flicker level is reduced to 1.1. The reduced flicker level target of 1.0 is not reached, as the uncompensated flicker produced by the EAF is above the pre-condition value specified in the contract (uncompensated $P_{st} (95\%) \leq 4.5$).

The total harmonic distortion (THD) and telephone interference factor (TIF) are shown in Figure 12b and 12c, respectively. Figure 12a indicates the SYS EAF power. The SYS contribution to the THD and TIF, thanks to the SVC Light, is unnoticeable.

Power Factor — The power factor of the EAF only is in the range of 0.75–0.8. With the fast flicker and reactive power compensation provided by SVC Light, the power factor at the 115 kV bus is controlled to $\cos \varphi = 1.00$ during the entire measuring period. Figure 13 shows the large variation in power factor of the EAF, with an average of $\cos \varphi = 0.77$, as well as the compensated power factor.

The results of the field measurements can be summarized as follows:

- Flicker reduction factor, $P_{st}$ 5.2
- Flicker reduction factor, $P_{lt}$ 5.3
- THD at the 115 kV PCC 1.0%
- Power factor at the 115 kV PCC 0.99

Summary

A STATCOM rated at 22 kV, 0–120 Mvar (capacitive) has been commissioned in a greenfield steel plant in Thailand. The purpose of the STATCOM (also known
as SVC Light® is to mitigate flicker emanating from the operation of an electric arc furnace (EAF) in the plant rated at 96 MVA. The flicker is due to erratic voltage fluctuations caused by the consumption of reactive power of the EAF.

The STATCOM is based on insulated gate bipolar transistor (IGBT) technology.

The steel plant is fed from a 115 kV grid. The fault level varies between 1,970 MVA and 3,000 MVA, depending on grid conditions. Considering the substantial size of the EAF, without flicker mitigation measures taken by means of the STATCOM, strong incandescent lamp flicker could have been expected as a result of the operation of the EAF.

Due to a very high level of background flicker, the standard IEC method for flicker evaluation could not be used, as it would have led to a large error. Also, operation of the EAF without compensation was not possible, due to the strong flicker it would have caused. Consequently, an indirect method of flicker evaluation based on current measurements was used.

The resulting flicker reduction factor at the 115 kV point of common connection is better than 5.

Besides flicker mitigation, the STATCOM also performs active filtering of harmonics emanating from the EAF.

Also, requirements on harmonic limitation and power factor correction in the feeding grid have been fulfilled.

References


2. IEC 61000-4-7, Electromagnetic compatibility (EMC) — Part 4-7: Testing and measurement techniques — General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.

3. IEC 61000-3-7, Electromagnetic compatibility (EMC) — Part 3-7: Limits — Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems.


Did you find this article to be of significant relevance to the advancement of steel technology? If so, please consider nominating it for the AIST Hunt-Kelly Outstanding Paper Award at AIST.org/huntkelly.

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