STATCOM, a Prerequisite for a Melt Shop Expansion - Performance Experiences

Rolf Grünbaum, *Member, IEEE,* Tomas Gustafsson, Jean-Philippe Hasler,
Tomas Larsson, *Member, IEEE,* Matti Lahtinen, *Member, IEEE*

***Abstract*—A new Electric Arc Furnace, EAF, for stainless steel was to be installed in northern Finland. Due to the large power of the new EAF, above existing furnaces, and the relatively weak grid, concerns were raised. The concerns were mainly focusing on flicker, annoying illumination fluctuations caused by voltage fluctuations. However, also power quality properties as for instance unbalance were considered. Requirements were set up by the transmission utility, Fingrid, on flicker improvement in the installation as a condition to proceed. To cope with this, a compensator had to be installed. A STATCOM was found to be the optimal technology to meet the requirements. The STATCOM finally built was based on the ABB SVC Light® concept.**

The paper gives an introduction to the EAF installation and its compensation. Results from initial flicker simulations and from verifying performance measurements in the form of flicker improvement ratio and reduction in negative phase sequence currents are also given.

***Index Terms*—Arc furnace, Flicker mitigation, Insulated gate bipolar transistors, Metals industry, Pulse width modulated power converters, Reactive power control, Static VAR compensators**

I. NOMENCLATURE

EAF	Electic Arc Furnace
EMTDC	ElectroMagnetics Transient program
FACTS	Flexible AC Transmission Systems
IGBT	Insulated Gate Bipolar Transistor
PCC	Point of Common Coupling
Pst	Flicker level, short time
PWM	Pulse Width Modulation
SVC	Static Var Compensator
VSC	Voltage Source Converter

II. INTRODUCTION

A new melt shop with a 140 MVA, +20% short time overload, Electric Arc Furnace, EAF, for stainless steel has been installed in northern Finland. The EAF is taking its power from a feeding grid with a PCC at 400 kV. Due to a modest short circuit level at the PCC, unless properly remedied, the EAFs would become a formidable source of disturbances, which would spread through the grid to other consumers of electric power. The EAF is also a heavy consumer of reactive power.

The EAF is a generator of several kinds of disturbances, which, unless remedied, add up to more or less strong deterioration of power quality. Large and stochastic variations in reactive power consumption give rise to large and rapid grid voltage fluctuations, which show up as illumination flicker, a particularly annoying sensation for people exposed to it.

Furthermore, the EAF is an unsymmetrical load on the three-phase feeding grid, giving rise to current and voltage unbalance in the grid. Normally, only very limited levels of unsymmetry can be allowed without deteriorating the power quality for other consumers connected to the same grid.

Last but not least, the EAF is a generator of harmonics, odd and even, as well as interharmonics. To summarize this, the above are reasons why compensation of an EAF is required.

III. REQUIREMENTS ON POWER QUALITY

The European Union has firm regulations on power quality issues such as flicker: acceptance levels, methods for measurement, and flicker meters [1]. As a consequence, the Finnish Transmission System Operator and grid owner, Fingrid, is placing exact requirements on subscribers to power connected to its grid system, in order that proper power quality in the grid be safeguarded at all times. This fact, in the present case of AvestaPolarit Stainless Oy, induced a need for measures to neutralize the grid polluting effects from the EAF. In this situation, there were two options:

1. Upgrade the feeding grid to meet the requirements for a higher fault level than before to accommodate the new EAF load
2. Install a device dedicated to the mitigation of the grid disturbances emanating from the EAF.

The need for large transmission capacity in itself requires a new dedicated line to the steel factory. This line has been built at the 400 kV level and has moved the PCC from the former 110 kV level to the 400 kV level. When the new EAF was to be connected in parallel to existing units, the flicker level was expected to exceed acceptable values even at the 400 kV level. The flicker at the 400 kV level is not critical, but nearby transformers will transmit flicker downstream to 110 kV,

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R. Grünbaum is with ABB Utilities, dept RUM, 721 64 Västerås, Sweden (e-mail: rolf.grunbaum@se.abb.com).

T. Gustafsson is with ABB Utilities, dept RUP, 721 64 Västerås, Sweden (e-mail: tomas.b.gustafsson@se.abb.com).

J.-P. Hasler is with ABB Utilities, dept RH, 721 64 Västerås, Sweden (e-mail: jean-philipe.hasler@se.abb.com)

T. Larsson is with ABB Utilities, dept RTA, 721 64 Västerås, Sweden (e-mail: tomas.x.larsson@se.abb.com)

M. Lahtinen is with Fingrid Oyj, Helsinki, Finland (e-mail: matti.lahtinen@fingrid.fi)

where problems may arise.

As an extra benefit with a compensator, increased power in the EAF would be achieved, enabling an improvement of process economy for the plant. This was an important factor because the fault level at 110 kV is relatively low, and a large voltage depression would occur without a compensator. The STATCOM type of compensator was preferred, as it would facilitate a higher and steadier voltage. It would also give shorter melting times yielding a more economical melting and an increase of production capacity.

IV. FACTS: SVC LIGHT®

FACTS is an acronym for Flexible AC Transmission Systems. It comprises a family of devices, controllable through state of the art computerized control systems in conjunction with high-power electronics.

Typically, FACTS solutions are mostly justified where the application requires one or more of the following characteristics:

- Rapid response;
- Frequent variations of output;
- Output smoothly adjustable.

One particular member of the FACTS family is the SVC Light [2], [3], which was selected as a compensator in the present case. The SVC Light is a STATCOM based on a three-level VSC, Voltage Source Converter, design, utilizing IGBTs as switching element and a control concept based on PWM. The IGBT is a reliable component for this power range and has a large potential for the future. It is therefore judged to be the component best suited for this kind of application.

The main objective for the installation of the SVC Light was to rapidly and accurately compensate for the reactive power taken from the AC grid by the electric arc furnace during all the melting phases. Additionally the fast control system of SVC Light would improve the power quality and reduce the flicker levels generated.

The SVC Light at AvestaPolarit Stainless Oy is rated at 33 kV, 0 to 164 Mvar capacitive reactive power, continuously dynamically variable over the entire range, see Fig. 1.

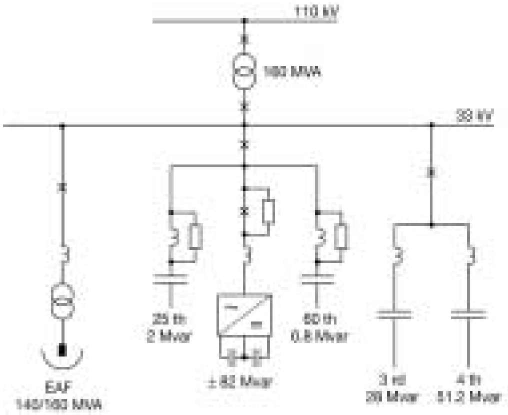

Fig. 1. Single line diagram of the EAF and the SVC Light.

In Fig. 1, the EAF is shown to the left. Then two high-pass filters for reduction of harmonics follow together with the VSC and its switchgear. A resistor is temporarily inserted in series with the VSC during start-up. The resistor is used to limit the inrush current during the start sequence. Finally two filters to provide bulk power to bias capacitive reactive power are found. The harmonic filters are designed to fulfill the specified voltage and current distortion at PCC. To fulfill these requirements the tuning and damping of the harmonic filters have been selected.

The total filter rating is equal to the VSC rating providing an operation range from zero to twice the VSC rating. Fig. 2 shows a photo of the installation.

Fig. 2 The AvestaPolarit SVC Light installation.

V. GRID OWNER'S BENEFIT

The installing of the SVC Light at AvestaPolarit Stainless Oy´s feeder has brought benefits not only to the steel plant, but also to the grid owner:

- Acceptably low flicker level at the Point of Common Coupling.
- Acceptably low amounts of harmonic distortion.
- Adequate load balancing between phases of the 110 kV grid.
- A high and constant power factor at the feeding point of the plant, with low and constant reactive power consumption from the grid.
- Keeping grid reinforcements at a minimum.

Hence, this is a win-win situation where the steel works as well as the utility can gain from the SVC Light installation.

VI. THE VOLTAGE SOURCE CONVERTER AND ITS CONTROL

In the VSC, the valves are built-up by stacked devices with interposing coolers, see Fig. 3. One side of the VSC is connected to a capacitor bank, which acts as a DC voltage source.

By utilizing PWM, an AC current of nearly sinusoidal shape is produced, requiring only very limited harmonic filtering.

Fig. 3. SVC Light IGBT valve assembly.

Physical compactness, technical simplicity, as well as commercial viability have resulted in a concept totally free from paralleling of units, i.e. the total MVA rating is accommodated within one single VSC. Keeping the considerable rating in mind, +/- 82 Mvar, it enables a hitherto unseen degree of economy in the utilization of the IGBT valve concept.

To rapidly control the SVC Light instantaneous current, the 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:

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

The reactor voltage, u_L, consists of the difference between the bus voltage and the voltage produced by the SVC Light. According to the above expression, what can be controlled to influence the current, *i*, is the voltage produced by the VSC. By employing PWM, the desired current is obtained by rapidly applying the proper VSC voltage.

Fig. 4 gives an overview of the SVC Light control principle. The EAF current is measured together with the AC bus voltage. VSC current set points are calculated mainly based on the instantaneous EAF reactive current component. Also, to provide an efficient mitigation of flicker, portions of the active current component are used [4]. Furthermore, the reactive power of the total process comprising the EAF and the SVC Light is controlled to minimize the reactive power consumption from the grid.

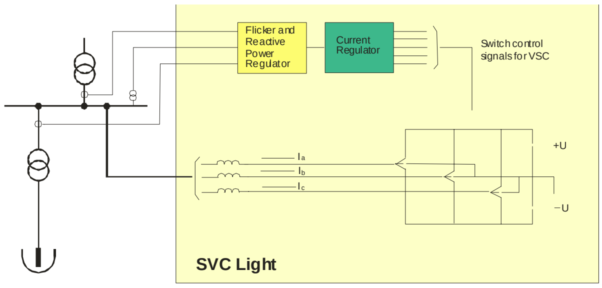

Fig. 4. SVC Light control principle.

VII. FLICKER MITIGATION PRE-STUDY

A flicker mitigation study was performed at the design stage, evaluating the flicker improvement ratio that could be expected with the SVC Light in operation. The phase currents of an existing smaller but similar AvestaPolarit Stainless Oy EAF for stainless steel were utilized. Recorded currents were scaled to the size of the new EAF and studied using the EMTDC simulation program package. To perform the study, a detailed model was used with the power system as well as the EAF with the SVC Light.

The complete SVC Light system was represented in the EMTDC model. The model included all main circuit components such as the IGBT converter with its DC capacitors, the phase reactors and the harmonic filters. The model also included a complete representation of the control system and the valve firing system.

The EAF was represented as a current source, reproducing the current waveform recorded on the old AvestaPolarit Stainless Oy EAF. The data used in the simulation had a length of 10 minutes, starting at the beginning of a meltdown process, the most troublesome part of the melt from a flicker point-of-view.

To evaluate the flicker level, the voltage fluctuations were computed at the 33 kV bus. The flicker level Pst was then estimated according to IEC [1].

A model of the flicker meter was included in the digital model. The voltage measured at the PCC was passed through different filters to obtain the flicker level according to the desired criteria. The output of the flicker meter was based on the instantaneous flicker value of the IEC meter (output 3).

Using the model and the input data, the flicker level at the 33 kV bus was estimated both with and without the SVC Light in operation. Fig. 5 first shows the flicker without the SVC

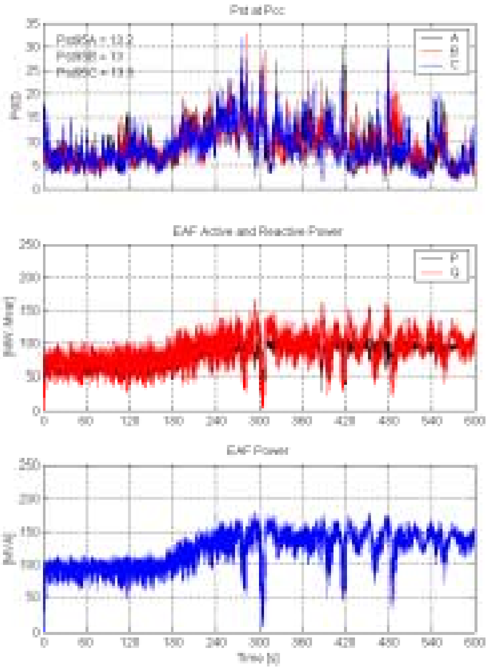

Fig. 5. Flicker level at the 33 kV bus and EAF power without the SVC Light.

Light. In Fig. 6, the corresponding flicker levels at the PCC are shown with the SVC Light in service.

Based on the figures, it can be noted that the active, useful, power of the EAF increases when the SVC Light compensates the reactive power consumed by the EAF. This is beneficial for the steel process with shorter melting times, as well as for the power supplier with less reactive power flow.

The design studies indicated a flicker improvement ratio of approximately 13/3.1=4.2. This was sufficient for the project to commence.

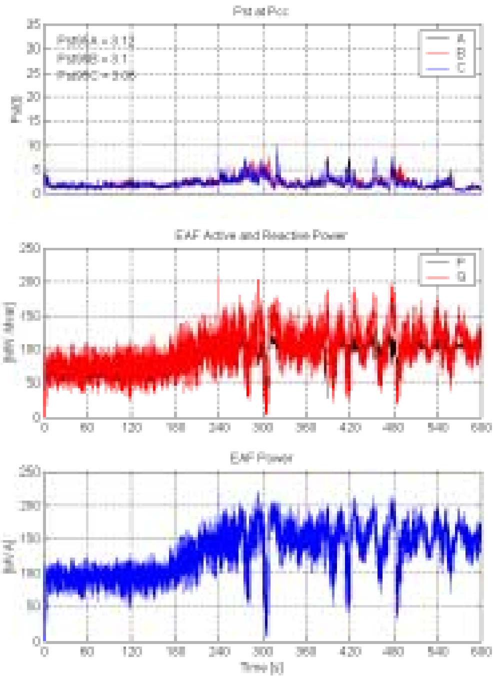

Fig. 6. Flicker level at the 33 kV bus and EAF power with the SVC Light.

VIII. FIELD MEASUREMENTS

A. Evaluation method

Field measurements have been performed to validate the flicker improvement performance. The object was to find the specified flicker improvement ratio defined by the following method [5], [6] recommended by Fingrid.

The phase currents of arc furnace and compensator should be digitally recorded simultaneously during a typical melting period. The fluctuating voltages and corresponding instantaneous flicker levels should then be calculated using the impedance of the grid. The grid model was tuned to give optimal correlation between flicker caused by the measured 33 kV voltages and flicker caused by the calculated voltages, which were based on the measured currents. Using only the arc furnace currents the reference Pst_0 is found. This corresponds to what could be expected without any compensation. Then, the reduced flicker level Pst_1 is calculated using the total current of the arc furnace and the compensator. This corresponds to the real operation case. The improvement ratio Pst_0/Pst_1 is finally calculated over the whole melting period and then evaluated.

B. Measurement set-up

Measurements in a dynamic process with high sampling frequency require special attention when selecting the equipment. A sophisticated measurement computer with high bandwidth and synchronous sampling was found suitable for the task. For the measurements, totally four three-phase signals are of interest:

1. The 33 kV bus voltages
2. The EAF currents
3. The VSC currents
4. The filter currents

The raw data were sampled with a frequency of 5200 Hz for off-line analysis. For verification purposes, two different standard flicker meters were connected simultaneously with the measurement computer. In the following plots, data from these flicker meters are shown together with the results from the specified method. A good correlation between the signals will verify the evaluation method and the correctness of the used model.

The normal configuration of the industrial power system is that the EAF has common connection with other equipment at the 110 kV level. To this level, also other disturbing loads like FeCr furnaces are connected. To minimize the background disturbances and get a more clean case, the industrial power system was reorganized in a way that the first common connection point during the measurements was at the 400 kV level. All the measurements shown in the paper were made with this configuration. The EAF had the same operation cycle and the same type of scrap during the full measurement period.

C. Measurement analysis

First, the off-line flicker meter was verified against the standard flicker meter output. In this process, tuning of the grid model is one part. The results are shown in Fig. 7.

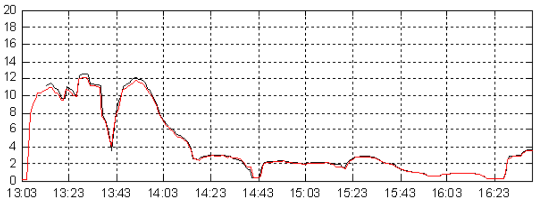

Fig. 7. Verification of the off-line flicker meter.

The deviations between the Pst value calculated from measured bus voltage and the Pst values obtained from the flicker meter are ignorable. The error is generally about 2-4 % except during large Pst changes. Note that the Pst-meters are not synchronized, which explains the large errors at large Pst value changes.

This test validates the quality of the input data and the accuracy of the flicker meter implemented in the digital model.

In Fig. 8, subplot 1 shows the EAF active and reactive power, the two top curves. The bottom curve shows the reactive power taken from the grid. Subplot 2 shows a comparison between actual measured 33 kV voltage and the corresponding calculated voltage. The ignorable error is a verification of the grid impedance model. Subplot 3 shows four different Pst curves calculated during sliding 10 minute intervals. The top curve with the highest Pst levels shows the case with only EAF current and no compensation. The three bottom curves only have small deviations and show flicker curves based on the measured voltage, on the calculated voltage and on data from the standard Pst meter.

The flicker level from the simulation using EAF, VSC and filter currents gives the same flicker level as the external flicker meter and the flicker level using the measured voltage. Subplot 4, finally, shows the flicker improvement ratio calculated as the ratio between Pst values with only EAF currents and Pst values with the SVC Light in operation.

The flicker improvement at the beginning of the melt-down process is ignored because it contains the time window when the EAF was not in operation and non-applicable flicker values.

Operation of the EAF with full power requires stable voltage and an efficient compensator. Operating the EAF without compensation is also possible, however, at a reduced power. During the measurement campaign measurements at reduced EAF power were performed both without and with the SVC Light in operation. Fig. 9 shows the results of the data processing. The plots are of the same type as in Fig. 8.

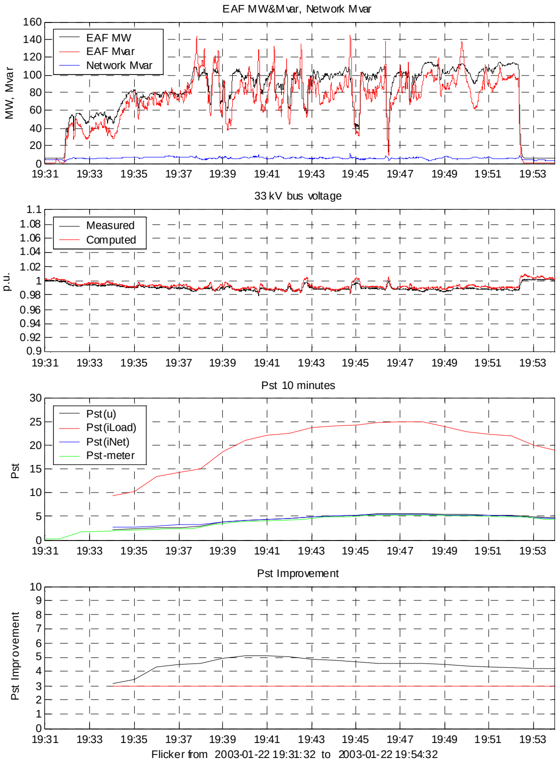

Fig. 8. Flicker with full EAF power and with SVC Light in operation.
subplot 1: EAF power and grid reactive power.
subplot 2: Voltage profile; measured (black) and simulated (red).
subplot 3: Sliding Pst 10-minute values from measured voltage (black),
from simulation with EAF current only (red),
simulated with EAF+VSC+Filter currents (blue) and
from external flicker meter (green).
subplot 4: Simulated flicker improvement ratio.

Two melts with the same EAF transformer tap changer patterns are shown. At approximately 14:40, the SVC Light was put on line. Subplot 2 showing the 33 kV bus RMS voltage clearly indicates the difference. The large voltage peaks during the melting without the SVC Light are due to load rejection. The voltage is then controlled with the 110/33 kV transformer tap changer and finally reaches the set point. The voltage set point was chosen below unity to reduce the voltage amplitudes after load rejection.

D. *Flicker improvement ratio*

The flicker improvement ratio is calculated during a time window were the EAF is in operation. When the EAF is out of operation the flicker improvement will be unity in case of no background flicker and below unity to zero if there is disturbing background flicker existing.

The flicker improvement ratio was calculated using a time window beginning 10 minute after EAF melting start and ending at the end of the same heat. The 10 minute delay corresponds to the 10-minute time window used by the flicker meter to exclude the period the EAF was not in operation.

The method was applied to the data in Fig. 8 with full EAF power. This time window includes two EAF transformer energizations and includes the time window with the highest flicker level recorded during the measurements. The result was

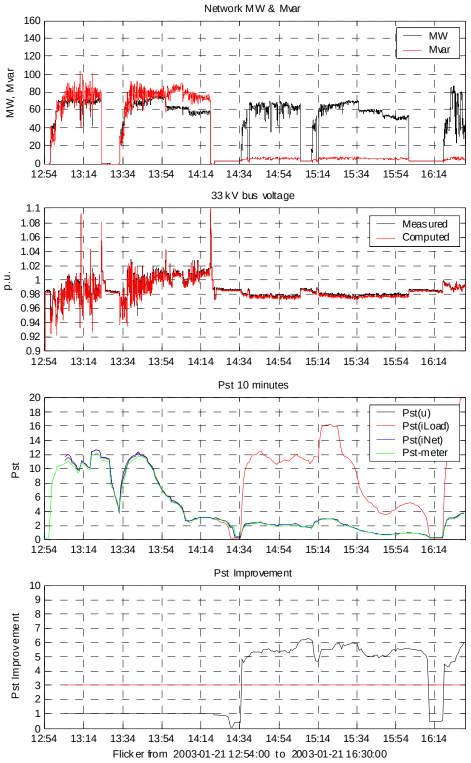

Fig. 9. Flicker without and with the SVC Light, reduced EAF power. Subplots as in Fig. 8.

a flicker improvement ratio of 4.6 times for full EAF power.

On the other hand, the flicker improvement ratio in Fig. 9 with lower power in the EAF is between 5 and 6 times. If higher flicker improvement is desired, it is hence essential to choose an adequate rating of the SVC Light.

E. Reduction of negative phase sequence

Apart from the flicker mitigation performance of the SVC Light, it also contributes to the reduction of negative phase sequence currents in the grid. Fig. 10 shows the positive and negative phase sequences of the grid current without (top) and with (bottom) the SVC Light in operation. The period shown is the same as in Fig. 9.

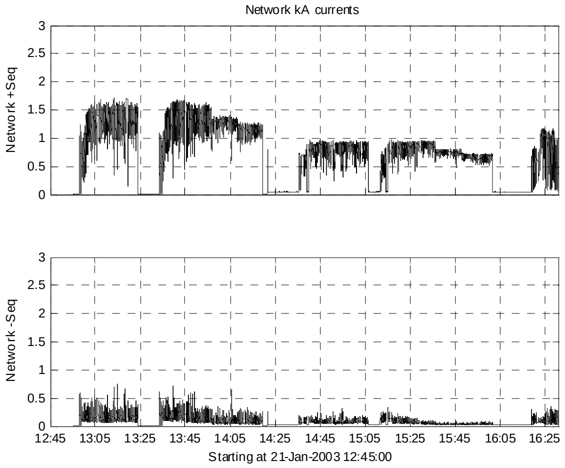

Fig. 10. Positive and negative phase sequence currents without and with the SVC Light in operation.

With the same EAF active power, the grid impact has been considerably reduced with the SVC Light in operation. The positive sequence current corresponding to the reactive power has been removed giving a lower and less turbulent grid current. The reduced negative phase sequence gives lower stress on the equipment.

IX. CONCLUSIONS

An EAF for stainless steel has been installed in northern Finland. Studies performed before the installation indicated a requirement for flicker mitigation. The chosen solution was based on the ABB SVC Light® concept. In the pre-study, a flicker improvement ratio was calculated to 4.2 times. This was later verified in the field. Measurements showed an actual improvement ratio of 4.6 times, which is very close to the expected value. Furthermore, it has been shown that it is possible to reach a flicker improvement ratio between 5 and 6 times if the SVC Light rating can be chosen freely.

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XI. BIOGRAPHIES

Rolf Grünbaum was born in Gothenburg, Sweden, in 1944. He received his M.Sc. degree in Electrical Engineering from Chalmers University of Technology, Gothenburg, Sweden in 1970.

Mr. Grünbaum has been active in ABB and previously Asea for a number of years. He is currently working for ABB where he is Area Responsible for Marketing of FACTS and Reactive Power Compensation Systems.

Tomas Gustafsson was born in Askersund, Sweden, in 1959. He received his B.Sc. degree in Electrical Engineering from Mälardalen University, Västerås, Sweden in 1992.

Mr. Gustafsson currently is working for ABB, where he is responsible for sales of Reactive Power Compensation systems, FACTS in industrial applications.

Tomas Larsson was born in Sävsjö, Sweden, in 1964. He received his M.Sc. and Ph.D. degrees from the Royal Institute of Technology, Stockholm, Sweden, both in Electrical Engineering, in 1991 and 1998 respectively.

Dr. Larsson currently works for ABB and is involved in projects concerning reactive power compensation and flicker mitigation using voltage source converters.

Jean-Philippe Hasler was born in Tramelan, Switzerland, in 1958. He received his M.Sc. degree in Electrical Engineering from the Ecole Polytechnique Federale de Lausanne, Switzerland in 1986.

Mr. Hasler joined ABB in 1986 where he was developing control systems and protection algorithms for multi-terminal HVDC. He joined the FACTS division of ABB in 1993 where he is conducting power system studies.

Matti Lahtinen was born in Helsinki, Finland, in 1945. He received his M.Sc. degree in Electrical Engineering from the Helsinki University of Technology in 1974.

Mr Lahtinen 1974 joined Imatran Voima Oy, IVO, as laboratory engineer and worked in the Laboratory Department. He has been professor in the Technical College of Helsinki responsible of Transmission and Distribution Systems Education. He joined IVO Power System Technology Department in 1990, moved to IVO Transmission Services Ltd in 1992 and to Fingrid Oyj in 1997 and is now Manager of Power Quality.

Mr Lahtinen is a member of IEEE, CIGRE and a member of Study Committee C4 (System Performance).