VOLTAGE SOURCE CONVERTER TRANSMISSION TECHNOLOGIES

- THE RIGHT FIT FOR THE APPLICATION

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Abstract – Voltage Source Converter (VSC) technology has been selected as the basis for several recent projects due to its controllability, compact modular design, ease of system interface and low environmental impact. This paper describes the rationale for selection of VSC technology and the latest technical developments utilized in several recent projects.

Keywords – VSC - HVDC – IGBT - Valves – PWM - FACTS - STATCOM – SVC – Flicker – Power Quality

1. INTRODUCTION

Traditional HVDC and FACTS installations have often provided economic solutions for special transmission applications. HVDC is well-suited for long-distance, bulk-power transmission, long submarine cable crossings, and asynchronous interconnections. Static var compensators (SVC) provide a reserve source of dynamic reactive power thereby raising power transfer limits. HVDC and FACTS technologies permit transmitting more power over fewer transmission lines.

Deregulated generation markets, open access to transmission, formation of RTO's, regional differences in generation costs and increased difficulty in siting new transmission lines, however, have led to a renewed interest in FACTS and HVDC transmission often in non-traditional applications. This is especially true with the lag in transmission investment and the separation in ownership of generation and transmission assets. HVDC and FACTS transmission technologies available today offer the planner increased flexibility in meeting transmission challenges.

HVDC transmission and reactive power compensation with voltage source converter (VSC) technology has certain attributes which can be beneficial to overall system performance. HVDC Light™ and SVC Light™ technology developed by ABB employs voltage source converters (VSC) with series-connected IGBT (insulated gate bipolar transistor) valves controlled with pulse width modulation (PWM). VSC converters used for power transmission (or voltage support combined with an energy storage source) permit continuous and independent control of real and reactive power. Reactive power control is also independent of that at any other terminal. Reactive power control can be used for dynamic voltage regulation to support the interconnecting ac system following contingencies. This capability can increase the overall transfer levels. Forced commutation with VSC even permits black start, i.e., the converter can be used to synthesize a balanced set of three phase voltages much like a synchronous machine.

2. GENERAL SYSTEM CONSIDERATIONS

2.1 Dynamic Reactive Power Compensation – SVC vs. STATCOM

An SVC provides voltage regulation and dynamic reactive power reserve by means of thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC) for var absorption and production respectively. A STATCOM accomplishes the same effect by using a VSC to synthesize a voltage waveform of variable magnitude with respect to the system voltage as shown in Figure 1. Although both FACTS devices require filters which form an integral part of the net capacitive reactive power supply, the filters are usually a larger part of the reactive power supply in an SVC. For very weak system applications, it is advantageous to have smaller filters. Often control of these FACTS devices is coordinated with mechanically-switched capacitor banks (MSC) to bias their dynamic operating range and maintain reactive power reserve margin.

The STATCOM branch offers both reactive power absorption and production capability whereas an SVC requires separate branches for each. The STATCOM, especially when controlled with PWM, allows faster response and thereby improves power quality. This is very useful to mitigate flicker from disturbances caused by electric arc furnaces at steel mills. For normal ac network disturbances where oscillatory modes usually do not exceed 1.5 Hz, however, the additional bandwidth may provide no real system benefit.

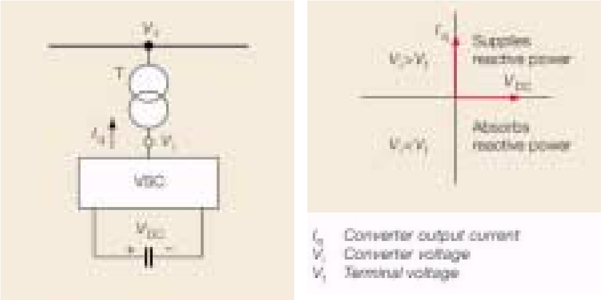


Figure 1. STATCOM

One of the main reasons for installing an SVC or STATCOM in transmission networks is to increase the power transfer capability where limited by post-contingency voltage criteria or undervoltage loss of load probability. Determining the optimum mix of dynamic and switched compensation is a challenge. Control systems are designed to keep the normal operating point within the middle of the SVC or STATCOM dynamic range.

If, after a disturbance, the FACTS device temporarily hits its capacitive limit, reactive power production will be decreased. For an SVC this decrease will be with voltage squared, whereas with a STATCOM it will be with voltage. Most overhead transmission voltage support applications require more dynamic capability on the capacitive side than on the inductive side. It is more economical to do this with TSC branches than with STATCOM branches. Depending on the rating criteria, it can often be more economical to use a larger SVC especially considering the extra dynamic vars supplied at nominal voltage. With parallel shunt banks, the difference in the composite device V-I characteristics becomes less as illustrated in Figure 2.

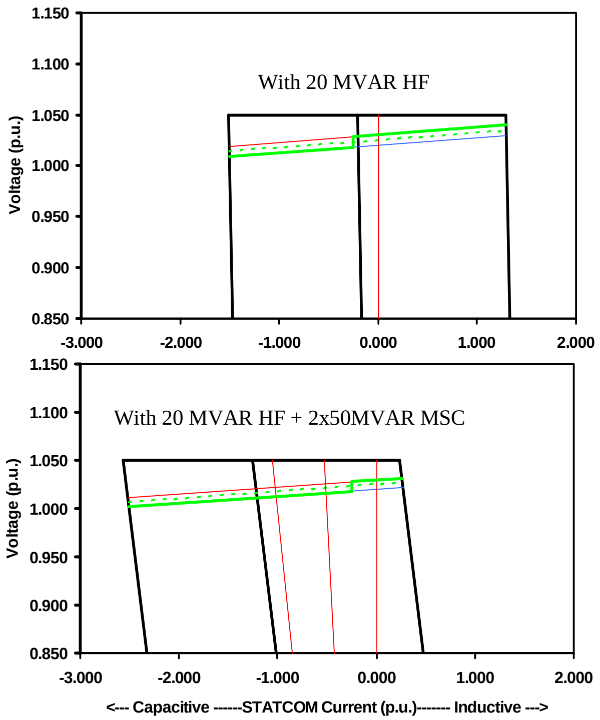


Figure 2. V-I Diagram ±150 MVAR STATCOM

Finding the optimal FACTS solution must be evaluated together with the owner in each unique situation for the respective transmission system. It is usually recommended to base the decision on a thorough system study. Ultimately, it is the owner/user's task to define the system requirements for the FACTS device, and the supplier to determine the optimal solution.

2.2 DC Transmission System – Current Source Converters vs. VSC

Conventional HVDC transmission employs line-commutated, current-source converters requiring a synchronous voltage source in order to operate. The conversion process demands reactive power from filters, shunt banks, or series capacitors which are part of the converter station. Any surplus or deficit in reactive power must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the system or the further away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance.

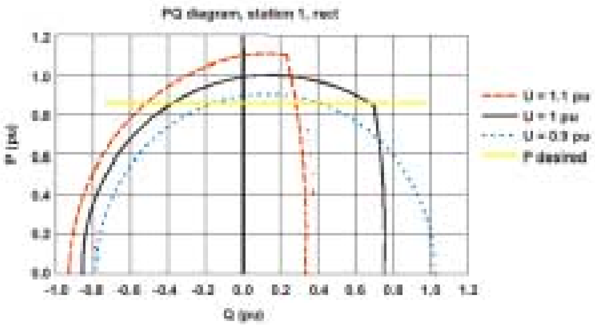


Figure 3. VSC P-Q Characteristic

Proper control of the converter and its associated reactive power compensation allows the ac system voltage to be held within a fairly tight and acceptable range. Unlike a generator or static var compensator, however, a conventional HVDC converter cannot provide much dynamic voltage support to the ac network. HVDC conversion technology using voltage source converters, however, can not only control the power flow but also provide dynamic voltage regulation to the ac system. Figure 3 depicts the P - Q characteristics for a VSC designed for HVDC transmission. The capacitive limit is due to imposing a voltage limitation. If the system voltage is reduced, this limit increases. The reactive power control range available depends on the active power operating point.

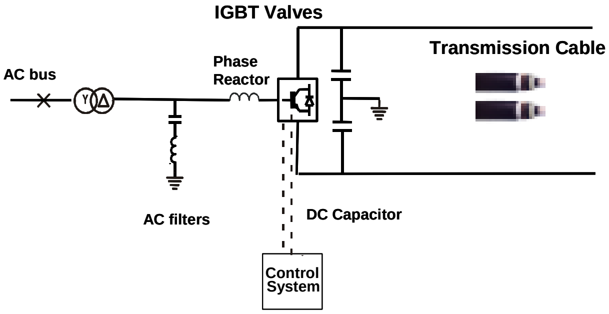


Figure 4. VSC Transmission

The following factors make VSC-based transmission attractive:

- Independent control of reactive and active power
- Reactive control independent of other terminal(s)
- Simpler interface with ac system
- Compact filters
- Provides continuous ac voltage regulation
- No minimum power restriction
- Operation in extremely weak systems
- No commutation failures
- No restriction on multiple infeeds
- No polarity reversal needed to reverse power
- Black-start capability
- Variable frequency
- HVDC Light cable - economic extruded polymer

2.2.1 VSC Converter Design

VSC-based HVDC transmission utilizes several important technological developments:

- High voltage valves with series-connected IGBTs
- Compact, dry, high-voltage dc capacitors
- High capacity control system
- Solid dielectric DC cable

A special gate unit and voltage divider across each IGBT maintain an even voltage distribution across the series connected IGBTs. The gate unit not only maintains proper voltage sharing within the valve during normal switching conditions but also during system disturbances and fault conditions. A reliable short circuit failure mode exists for individual IGBTs within each valve position.

Depending on the converter rating, series-connected IGBT valves are arranged in either a three-phase two-level or three-level bridge. In three-level converters, IGBT valves may also be used in place of diodes for neutral point clamping. Each IGBT position is individually controlled and monitored via fiber optics and equipped with integrated anti-parallel, free-wheeling diodes. Each IGBT has a rated voltage of 2.5 kV with rated currents up to 1500 A. Each VSC station is built up with modular valve housings which are constructed to shield electromagnetic interference (EMI). The valves are cooled with circulating water and water to air heat exchangers. PWM switching frequencies for the VSC typically range between 1-2 kHz depending on the converter topology, system frequency and specific application.

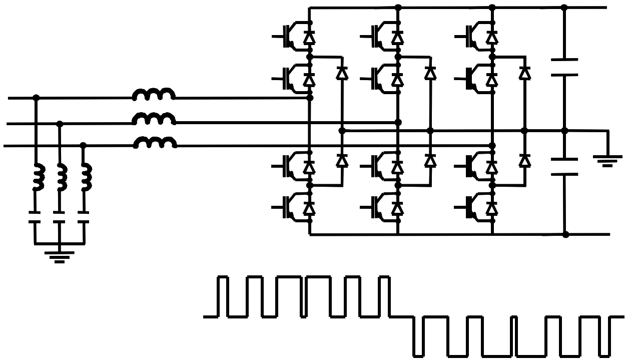


Figure 5. PWM Signal for Three-Level VSC

Each VSC is effectively mid-point grounded and coupled to the AC bus via phase reactors and a power transformer with intermediary shunt AC filters. The AC filters are tuned to multiples of the switching frequency. This arrangement minimizes harmonic content and avoids dc voltage stresses in the transformer which allows use of a standard AC power transformer for matching the AC network voltage to the converter AC voltage necessary to produce the desired DC transmission voltage.

DC capacitors are used across the dc side of the VSC. For transmission applications there may also be DC filters and a zero-sequence blocking reactor. The filters and zero-sequence reactor are used to mitigate interference on any metallic telephone circuits that run adjacent to the DC cables. The total capacitance of the pole to ground DC capacitors vary with the application. DC capacitance is higher for VSC used for flicker mitigation.

2.2.2 VSC Control and Protection

In the VSC-based HVDC transmission schemes described herein, the switching of the IGBT valves follows a pulse-width modulation (PWM) pattern. This switching control allows simultaneous adjustment of the amplitude and phase angle of the converter AC output voltage with constant dc voltage even with a two-level converter. With these two independent control variables, separate active and reactive power control loops can be used for regulation.

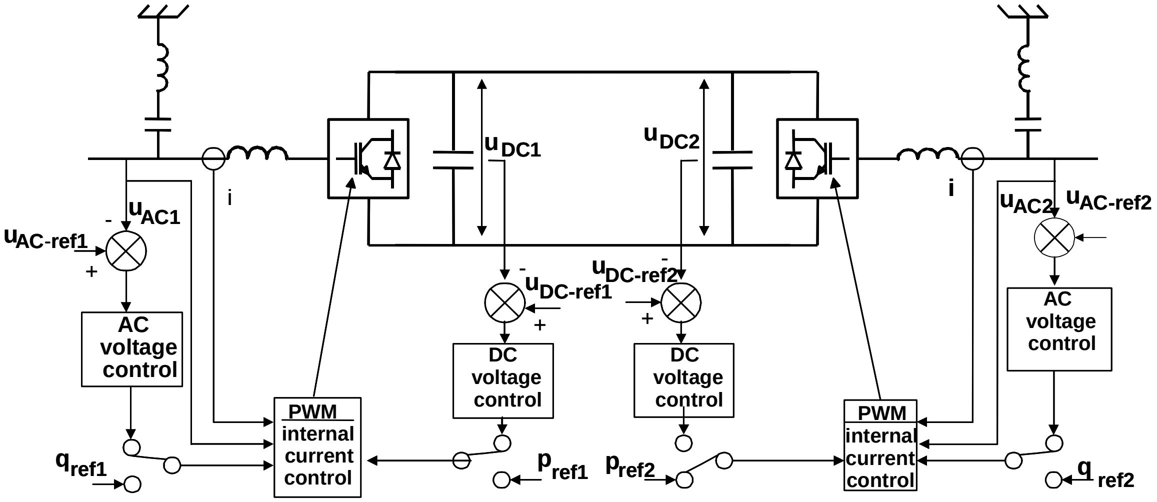
The active power control loop can be set to control either the active power or the DC side voltage. In a DC link, one station will be selected to control the active power while the other must be set to control the DC side voltage. The reactive power control loop can be set to control either the reactive power or the AC side voltage. Either of these two modes can be selected independently at either end of the DC link.

The station control and monitoring system (SCM) consists of two primary parts: 1) human machine interface (HMI) and data storage and 2) control and protection (CP). Communication among the different parts is via LAN (Local Area Network) with optical fibers.

The HMI is via local and remote OWS (Operator Work Stations). The OWS allows the operator on-line access to operational status and settings of control and protection systems and to integrated diagnostic information such as the event list, alarm list, fault list, and disturbance recordings of the control and protection system. Serial connections to existing SCADA-systems are made via established standards and common hardware.

The control and protection system is comprised of state of the art computers, micro-controllers and digital signal processors. Each VSC has two independent CP systems for redundancy to ensure high reliability. Multiple transient fault recording (TFR) functions are integrated into the CP. This allows recording of any signals in the CP at selectable time spans and resolutions limited only by data storage capacity. This feature provides complete information about the dynamic performance of the converter.

Control and protection is implemented with a fully graphical block diagram programming language supported by an extensive library. A graphical debugger tool is available for ease in troubleshooting. For the VSC-based HVDC and SVC systems, the gate units contain a primary valve/bridge protection that acts in only few ns. A back-up protection that operates in less than 3 µs is also provided based on the current flowing in the DC capacitors and phase reactors.



$$\begin{cases} P = \dfrac{U_{ac} \cdot U_v}{X} \cdot \sin(\delta) \\ Q = \dfrac{U_{ac} \cdot (U_{ac} - U_v \cdot \cos(\delta))}{X} \end{cases}$$

Figure 6. Control of VSC-Based Transmission System

3. VSC BASED PROJECTS

Table 1 lists the VSC based transmission projects in operation or under construction, their ratings and the rationale for selecting VSC technology. Certain aspects, unique features or attributes of five of these projects will be described below. These are HVDC Light transmission projects Murray Link, Cross Sound Cable Interconnector, and Troll A and SVC Light reactive power compensation projects Polarit and Holly STATCOM.

VSC Project	Rating	VSC Rationale
Hellsjön	3 MW, ±10 kV 10 km	Development
Hagfors	0-44 MVAR	EAF flicker mitigation
Gotland	50 MW, ±80 kV 70 km underground	- Wind power - Environmental - Voltage support - Stabilize AC lines
Tjæreborg	7 MW, ±10 kV 4 km underground	- Wind power testing - Variable frequency - Voltage support
Directlink	3 x 60 MW, ±80 kV 65 km underground	- Asynchronous Tie - Weak systems - Environmental - Permitting
Moselstahlwerk	0-38 MVAR	EAF flicker mitigation
Eagle Pass	36 MVA	- Weak system - Voltage support - Asynchronous Tie - Black start
Cross Sound Cable Intercon.	330 MW, ±150 kV 40 km submarine	- Controllability - System interface
Murray Link	200 MW, ±150kV 180km underground	- Asynchronous Tie - Weak systems - Environmental - Permitting
Polarit	0-164 MVAR	EAF flicker mitigation
Evron	0-36 MVAR	- Load balancing - Active filtering
Troll A	2 x 40 MW, ±60 kV 70 km submarine	- Offshore platform - Var. speed drive - Environmental - Black start
Holly	-80/+100 MVAR	- Voltage support - Retired generator - Cap bank control - Small site

Table 1. VSC Based Projects

3.1 Murray Link – HVDC Light

At 180 km, Murray Link is the world's longest underground cable transmission. Murray Link is rated to deliver 200 MW at a dc transmission voltage of ± 150 kV. Cable conductor cross section is 1400 mm^2 Al, overall outer cable diameter is 83.7 mm and cable weight is 7.8 kg/m.

Figure 7. Murray Link – Berri Station

Figure 8 shows the result of a negative 10 MW step response test during commissioning of Murray Link. The link is operating with power control at Red Cliffs and both terminals in ac voltage control. Ac voltage remains constant during the power step. Figure 9 shows the result a two percent ac voltage step response test at Red Cliffs during which the ac power remains constant.

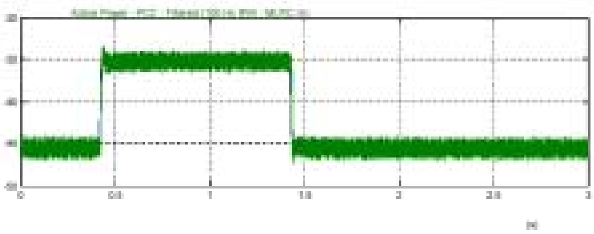


Figure 8. Murray Link – Power Step Test

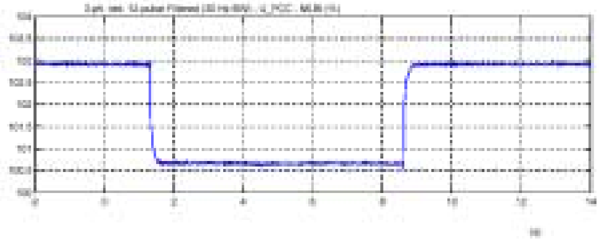


Figure 9. Murray Link – AC Voltage Step Test

3.2 Cross Sound Cable – HVDC Light

The Cross Sound Cable provides a directly controllable merchant interconnection between the New England and Long Island systems bypassing the congested New York City transmission network. The interconnection is rated 330 MW, ± 150 kV. The 40 km submarine cable is buried on the sea bottom. The Cross Sound Cable increases regional reliability by increasing the ability of the New England and New York networks to share generating capacity. It can also reduce the overall cost of power to consumers as well as reduce overall CO_2 emissions by allowing the shared use of more efficient generation units. The attributes of HVDC

Light^{TM} transmission simplify system operation and the interconnection’s interface with each regional system.

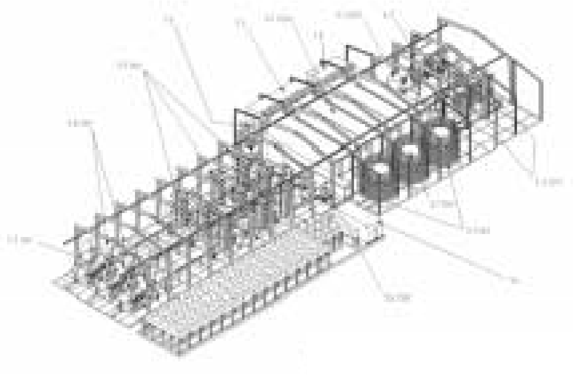


Figure 10. Cross Sound – Station Design

Figure 10 illustrates the design of for the Cross Sound converter stations. The IGBT valve stacks, control and protection system, valve-cooling package and auxiliary power system are enclosed in pre-fabricated housings. These housings along with the ac and dc filters are installed inside a warehouse-like metal building. The only outdoor equipment consists of power transformers, liquid-to-air heat exchangers and PLC filters.

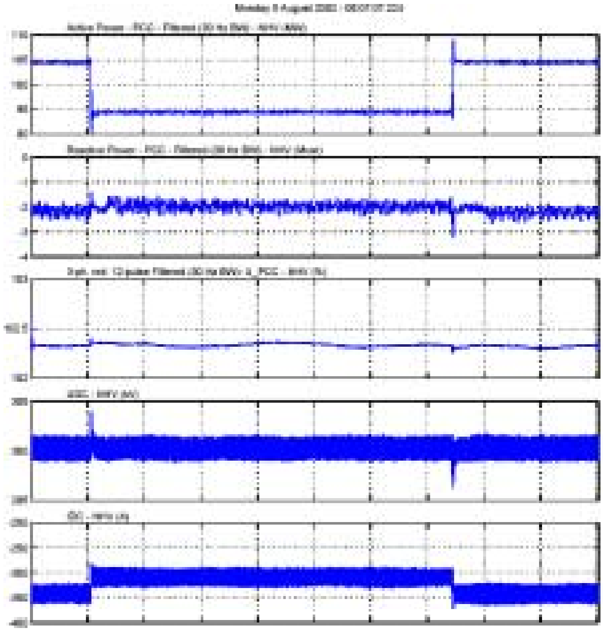


Figure 11. Cross Sound – Power Step Test

Figure 11 shows the result of a -10 % power step response test at the New Haven terminal. The step was entered on the direct axis component of the current order (ID_ORDER). The quadrature axis component of the current order (IQ_ORDER) was not changed. Time divisions are one second. The top trace is active power, the second trace is reactive power, the third trace is ac voltage, the fourth trace is the dc voltage and the bottom trace is the DC current.

3.3 Troll A – HVDC Light

The Troll A Project consists of 2 x 40 MW, ± 60 kV dc bipolar HVDC transmission links to an offshore production platform in the North Sea 70 km from the Norwegian coast. The power supply will be produced more efficiently on the mainland thereby substantially reducing CO_2 emissions and associated taxes. The VSC inverters used for transmission will directly control variable-speed, pre-compressor drive motors for efficiency and ease of starting. High voltage, cable-wound motors will be used to eliminate large power transformers on the platform.

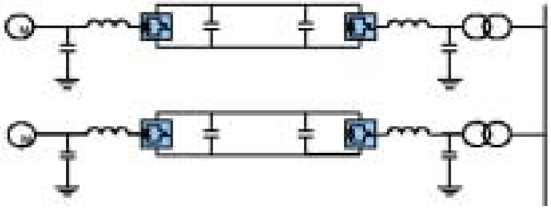


Figure 12. Troll A 2 x 40 MW Offshore Supply

The offshore dual inverter terminal is designed for compactness in a marine environment. The AC side of each inverter is directly connected to its respective motor via a breaker and AC cables. The motor shafts are coupled though a gearbox to the compressors.

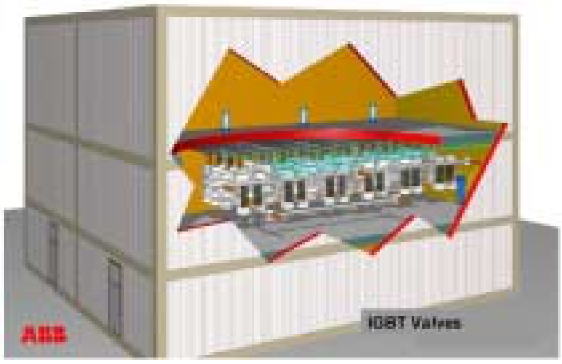


Figure 13. Troll A Platform Housing with Valves

Factors influencing the selection of HVDC Light transmission are listed below:

- Power level and distance
- Fewer submarine cables
- Better conductor utilization
- Independent power and voltage control
- Variable frequency for motor speed control
- Black start capability

- High voltage motor drive

3.4 Polarit – SVC Light

Polarit is an SVC Light installation in Finland used for reactive power compensation and flicker mitigation for an electric arc furnace (EAF). The flicker level was established by the local utility to assure that the steel mill did not cause any adverse effects while operating the EAF. The compensation consists of a ± 82 MVAR VSC, 10.8 MVAR of switching frequency filters and 79.2 MVAR of lower order harmonic filters for the EAF. The compensation is directly connected to the 33 kV arc furnace bus. The dynamic range for the net compensations scheme is approximately 0 - 164 MVAR.

The top trace in Figure 14 shows the EAF MW and MVAR consumption along with reactive power exchange with the network. The second trace shows the 33 kV EAF bus voltage. Operation with and without the SVC Light STATCOM is shown. The required flicker reduction is well over 3. Polarit was commissioned and taken into commercial operation in the fall of 2002.

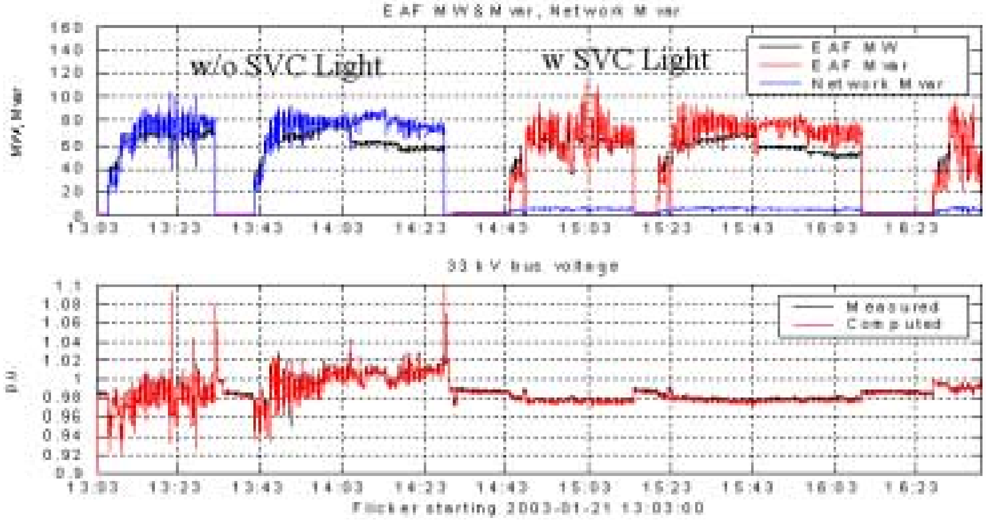


Figure 14. EAF Flicker Mitigation

3.5 Holly STATCOM – SVC Light

The VSC used in the Holly STATCOM located in Austin Texas is based on the Polarit design described in Section 3.4. It consists of a single ± 95 MVAR, 32 kV VSC and 15 MVAR of high frequency filters for the PWM switching harmonics. This combination gives a continuous dynamic range from –80 MVAR to +100 MVAR plus a short time capacitive overload of 10 percent. The VSC has built in redundancy. Three 31.2 MVAR, 138 kV mechanically-switched capacitor banks are included and controlled to shift the VSC dynamic range depending on system operating conditions.

The Holly STATCOM provides the voltage regulating capability and contingency voltage support thereby allowing retirement of an older inefficient power plant without sacrificing system reliability. A fully rated standby transformer is provided. The unit is under construction and commissioning is scheduled for October 2004.

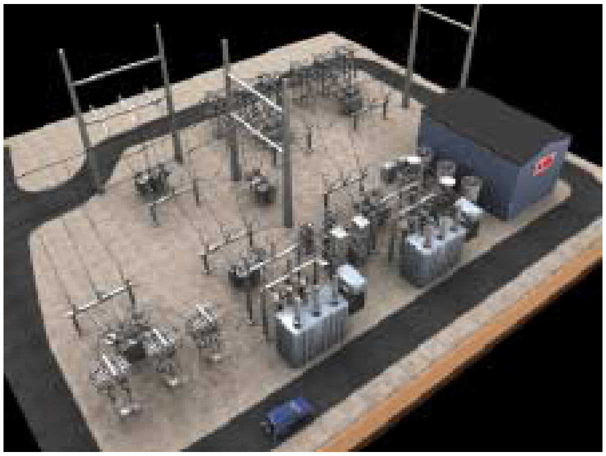


Figure 15. Holly SVC Light STATCOM – Artist’s Impression

4. CONCLUSION

Recent projects have demonstrated that VSC-based transmission technology has come of age both for HVDC transmission schemes and for enhancing performance of ac transmission through application of new FACTS devices. Although VSC-based schemes may not always be the most economical solution for the higher rated transmission applications, their special attributes and ease of application provide special benefits which merit serious consideration. In some applications, VSC transmission may be the only solution. As the technology matures and ratings increase, more applications can be expected.

5. REFERENCES

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