Benefits of SVC and STATCOM for Electric Utility Application

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***Abstract*--** **Examination of the behavior of SVCs and STATCOMs in electric power systems is presented. The paper is based on analytical and simulation analysis, and conclusions can be used as power industry guidelines.**

We explain the principle structures of SVCs and STATCOMs, the models for dynamic studies, and the impact of these devices on steady state voltage and transient voltage stability. Sensitivity analysis is provided which shows the impact of SVCs and STATCOMs with regard to network strength. Harmonic issues, space requirements, and price discussions are also briefly addressed.

***Index Terms*—Dynamic Compensators, SVC, STATCOM, Short Circuit Capacity, Gain Sensitivity, Short Term Voltage Stability, Harmonics**

I. INTRODUCTION

SHUNT-connected static var compensators (SVCs) are used extensively to control the AC voltage in transmission networks. Power electronic equipment, such as the thyristor controlled reactor (TCR) and the thyristor switched capacitor (TSC) have gained a significant market, primarily because of well-proven robustness to supply dynamic reactive power with fast response time and with low maintenance.

With the advent of high power gate turn-off thyristors and transistor devices (GTO, IGBT, …) a new generation of power electronic equipment, STATCOM, shows great promise for application in power systems [3,4].

This paper aims to explain the benefits of SVCs and STATCOMs for application in utility power systems. Installation of a large number of SVCs and experience gained from recent STATCOM projects throughout the world motivates us to clarify certain aspects of these devices.

II. BASIC DESCRIPTION

This section explains briefly the basic configuration of SVCs and STATCOMs:

A. SVC

Fig. 1 shows a schematic diagram of a static var compensator. The compensator normally includes a thyristor-controlled reactor (TCR), thyristor-switched capacitors (TSCs) and harmonic filters. It might also include mechanically switched shunt capacitors (MSCs), and then the term static var *system* is used. The harmonic filters (for the TCR-produced harmonics) are capacitive at fundamental frequency. The TCR is typically larger than the TSC blocks so that continuous control is realized. Other possibilities are fixed capacitors (FCs), and thyristor switched reactors (TSRs). Usually a dedicated transformer is used, with the compensator equipment at medium voltage. The transmission side voltage is controlled, and the Mvar ratings are referred to the transmission side.

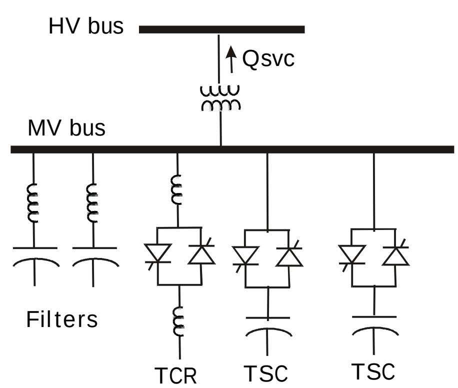

Fig. 1. Schematic diagram of an SVC

The rating of an SVC can be optimized to meet the required demand. The rating can be symmetric or asymmetric with respect to inductive and capacitive reactive power. As an example, the rating can be 200 Mvar inductive and 200 Mvar capacitive, or 100 Mvar inductive and 200 Mvar capacitive.

B. STATCOM

The voltage-sourced converter (VSC) is the basic electronic part of a STATCOM, which converts the dc voltage into a three-phase set of output voltages with desired amplitude, frequency, and phase. Fig. 2 shows the simplest implementation of a STATCOM.

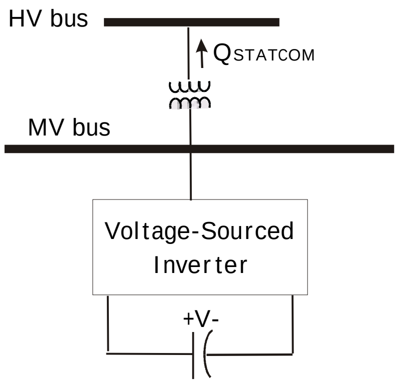

Fig. 2. Schematic diagram of a basic STATCOM

There are different methods to realize a voltage-sourced converter for power utility application. Based on harmonics and loss considerations, pulse width modulation (PWM) or multiple converters are used.

Inherently, STATCOMs have a symmetrical rating with respect to inductive and capacitive reactive power. For example, the rating can be 100 Mvar inductive and 100 Mvar capacitive. For asymmetric rating, STATCOMs need a complementary reactive power source. This can be realized for example with MSCs.

III. MODELING

This section describes the appropriate models for dynamic studies:

A. SVC [2]

An SVC is in principle a controlled shunt susceptance. The voltage measurement converts the fundamental three-phase waveforms to a RMS value. The conversion and filtering can be represented by an analog lag with around 10 ms time constant.

The voltage regulator determines a value for B_{ref} to make the error signal zero in the steady state. The voltage regulator is often purely integral control. The current may be obtained by multiplication of B_{ref} and V_{meas}. The susceptance regulator limits are determined by the physical size of the SVC (B_{min} and B_{max}). Today, the controls are digital so that various strategies can be implemented. For example, the "other signals" inputs to summing junction could be damping control.

The slope is defined as the ratio between the change of voltage and the change of the SVC current over the whole control range. It determines the steady-state operating point and is normally set between 2–5%.

The thyristor susceptance control module is normally modeled by a time delay (T_{d2}) of about 4 ms. An SVC might include a undervoltage strategy which forces the susceptance to the lowest level to prevent contribution of the SVC to overvoltage following fault clearing. (In Fig. 3 the parameter V_{CL} can become zero based on the selected values for V_L and V_H). A current limiter is normally provided to reduce the TCR current within a predefined time (T_4 is about 1 second).

B. STATCOM

Fig. 4 shows the STATCOM model for transient stability studies. STATCOM is in principle a controlled voltage source. In a real installation, the magnitude of the source voltage is controlled through dc voltage across the capacitor. Since this loop is very fast, the dc capacitor does not need to be modeled for dynamic stability studies. The regulator keeps the STATCOM current within the current limit (I_{MAX}).

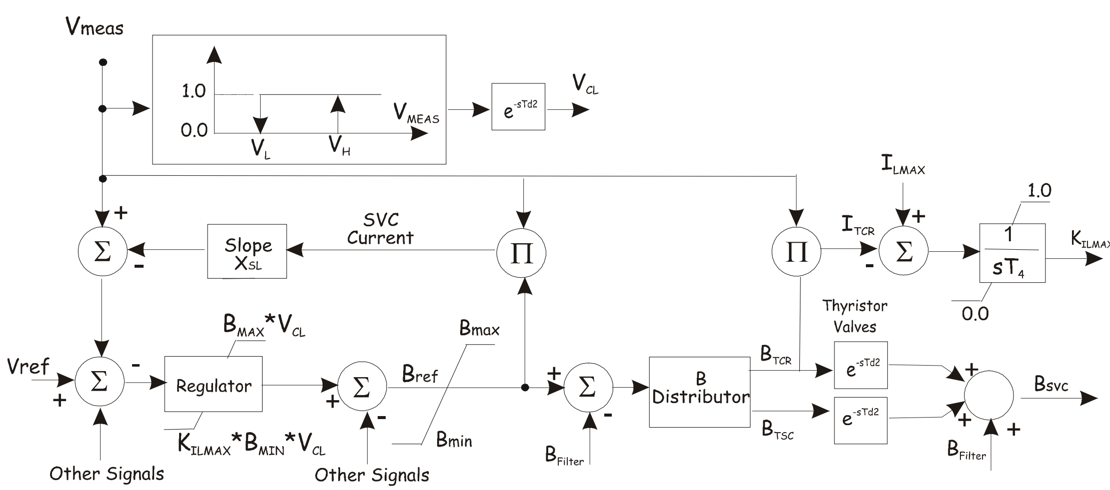

Fig. 3. SVC model for dynamic studies

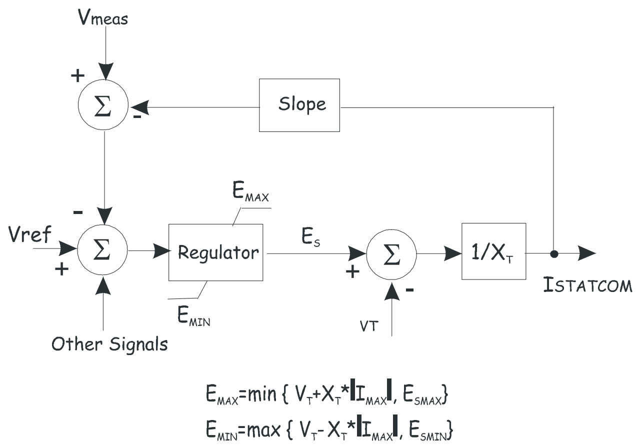

Fig. 4. STATCOM model for dynamic studies

IV. Voltage Regulation

SVCs and STATCOMs respond to changes in power system operating conditions fast and continuously. Normally, the size of the reactive compensators (S_Q) is decided by the network short circuit capacity (S_{SC}). A ratio of 5% (S_Q/S_{SC}) is normally selected. This section demonstrates the impact of SVCs and STATCOMs on the bus voltage for deviation of the network strength from the nominal point. In the studied model the nominal S_{SC} is 10 p.u. The size of the dynamic compensator is 0.5 p.u. A fixed capacitor is provided near the load to fix the load voltage at 1 p.u. for normal operation. The size of the load is *2.3+j0.8* p.u. Fig. 5 shows the schematic diagram for the studied system.

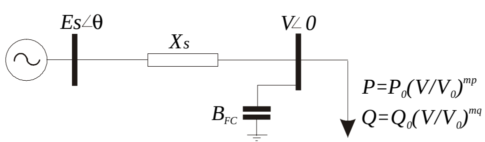

Fig. 5: Uncompensated system

The following equations are valid for power flows in Fig. 5:

$$P = \frac{E_S V}{X_S}\sin\theta \tag{1}$$

$$Q = B_{FC}V^2 - \frac{V^2 - VE_S\cos\theta}{X_S} \tag{2}$$

Eliminating the angle θ, we get the following non-linear equation for calculating the terminal voltage V.

$$\left[P_0 V^{mp} X_S\right]^2 + \left[Q_0 V^{mq} X_S + (1 - X_S B_{FC})V^2\right]^2 = (E_S V)^2 \tag{3}$$

Fig. 6 shows the model power system with an SVC:

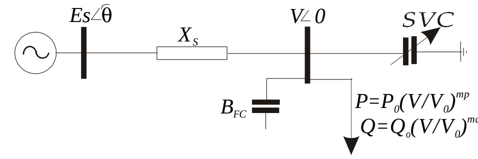

Fig. 6: Single-line diagram of the studied power system with SVC

The following equation yields the node voltage:

$$\left[P_0 V^{mp} X_S\right]^2 + \left[Q_0 V^{mq} X_S + (1 - B_{FC}X_S - B_{SVC}X_S)V^2\right]^2 = (E_S V)^2 \tag{4}$$

Fig. 7 shows the model power system with a STATCOM:

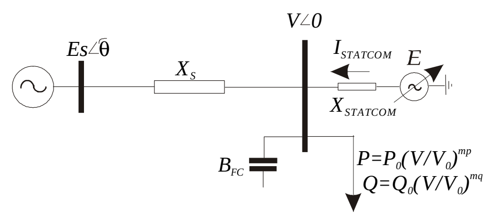

Fig. 7: Single line diagram of the studied power system with STATCOM

The following equation gives the voltage:

$$\left[P_0 V^{mp} X_S\right]^2 + \left[Q_0 V^{mq} X_S + (1 - X_S B_{FC})V^2 - I_{STATCOM} V X_S\right]^2 = (E_S V)^2 \tag{5}$$

A. Undervoltage Case

To see the impact of voltage regulation provided by the dynamic compensators on the undervoltage case, the three non-linear equations (Eqs. 3–5) are solved with respect to the variation of X_S ($1/S_{SC}$) from the nominal value (0.1 p.u.). Fig. 8 shows the variation of voltage for different compensators. In the simulations $m_p=1$ and $m_q=2$.

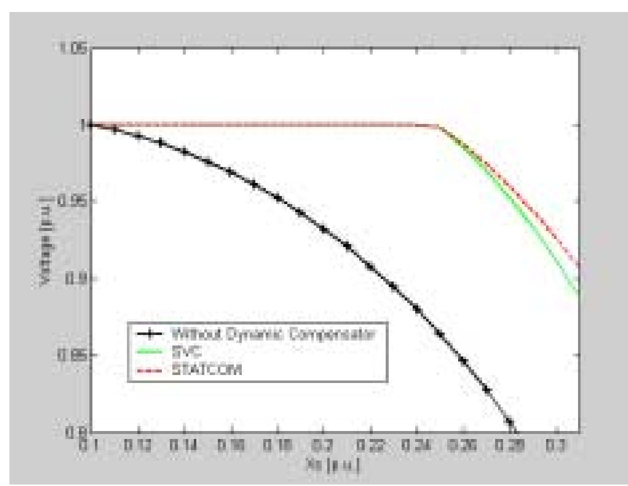

Fig. 8. Voltage variation with change in source reactance

Fig. 8 shows how a dynamic compensator reacts with increase of network reactance (decrease of S_{SC}). In this example, SVCs and STATCOMs regulate the load voltage up to a value about X_s=0.25 p.u. Above this level, both compensators hit the limit. SVCs work as a shunt capacitor and STATCOMs work as a constant current source. It is seen that if the S_{SC} decreases to one-third of the nominal value (for example, outage of parallel lines), STATCOMs contribute to the voltage regulation more than SVCs by a factor about 1.7%.

B. Overvoltage Case

The same network in used to illustrate the influence of SVCs and STATCOMs on reducing overvoltage. To create the overvoltage scenario, the S_{SC} is kept at the nominal level but the load level is reduced. To show more clearly the behavior of SVCs and STATCOMs with respect to overvoltage, the load size is selected to be 4 p.u. and the fixed capacitor is increased to 2.5 p.u. from 1.1 p.u.

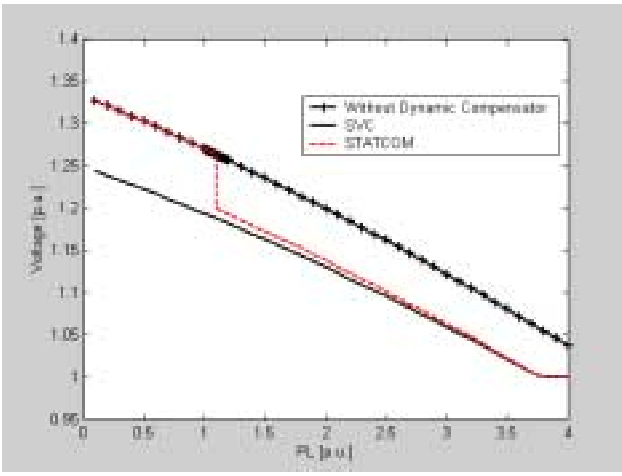

Fig. 9. Illustration of overvoltage for the simple power system

The explanation of the impact of SVCs and STATCOMs on the system voltage during an overvoltage is as follows (The selected voltage limit values are based on current practices):

- SVC

At a sudden voltage rise up to less than 1.3 p.u., the TCR current is allowed to increase as determined by the TCR reactance. A limiting function having a time constant of 1.0 second will then reduce the current down to the allowable maximum continuous current, i.e., the current at 1.1 p.u. voltage.

At a sudden voltage rise exceeding 1.3 p.u., the TCR current will increase as determined by the reactor impedance. In this case, no current limitation is possible, resulting in disconnection of the SVC after 1 second.

- STATCOM

STATCOMs absorb reactive current to reduce the voltage. When the voltage goes higher than a certain value (say 1.2 p.u.), the VSC voltage amplitude must increase to limit the current to the maximum value. For a typical STATCOM with reactance of 10% and with a maximum voltage of E_S equivalent to 1.1 p.u., the maximum allowable net voltage will be about 1.2 p.u. If the voltage rises beyond this limit, the STATCOM should be disconnected to protect the valves.

The above examples show that with the same reactive power rating, STATCOMs contribute to voltage regulation more effectively than SVCs during undervoltage situations, while SVCs contribute to voltage regulation more effectively than STATCOMs during overvoltage situations.

V. Sensitivity of Stability Loop

An interesting consideration in the application of SVCs and STATCOMs is the impact of the network reactance on the stability of the control loop. The simple network in Fig. 5 is used for analytical examination of the amplification factors, which are equivalent to the sensitivities of the node voltage with respect to the control variables.

A. Sensitivity of node voltage to SVC susceptance

Differentiating Eq. 4 with respect to B_{SVC}, yields the sensitivity.

$$\frac{dV}{dB_{SVC}} = \frac{X_S V^2 (k_1 V^2 + Q_0 X_S V^{mq})}{m_p P_0{}^2 X_S^2 V^{2m_p-1} + \left(Q_0 X_S m_q V^{m_q-1} + 2K_1 V\right)\left(K_1 V^2 + Q_0 X_S m_q V^{m_q}\right) - E_S{}^2 V} \tag{6}$$

where

$$K_1 = 1 - X_S\left(B_{FC} + B_{SVC}\right) \tag{7}$$

The sensitivity is determined at the operating points for B_{SVC} which regulate the node voltage at 1 p.u.

B. Sensitivity of node voltage to STATCOM voltage

Differentiating Eq. 5 with respect to voltage source *E* yields the sensitivity.

$$\frac{dV}{dE} = \frac{K_3 b_{STATCOM} X_S V}{m_p P_0{}^2 X_S^2 V^{2m_p-1} + k_3 (2K_2 V + m_q Q_0 X_S V^{m^q-1} - b_{STATCOM} E X_S) - E_S^2 V} \tag{8}$$

where

$$K_2 = 1 - X_S\left(B_{FC} + B_{STATOM}\right)$$

$$K_3 = K_2 V^2 + X_S Q_0 V^{mq} - b_{STATCOM} EVX_S \tag{9}$$

The sensitivity is determined at the operating points for E which regulate the node voltage at 1 p.u. Fig. 10 shows the sensitivities of the load voltage to SVC susceptance and STATCOM voltage with respect to variation of the network reactance. The two curves are scaled which result in 1 p.u. sensitivity at the nominal operating point.

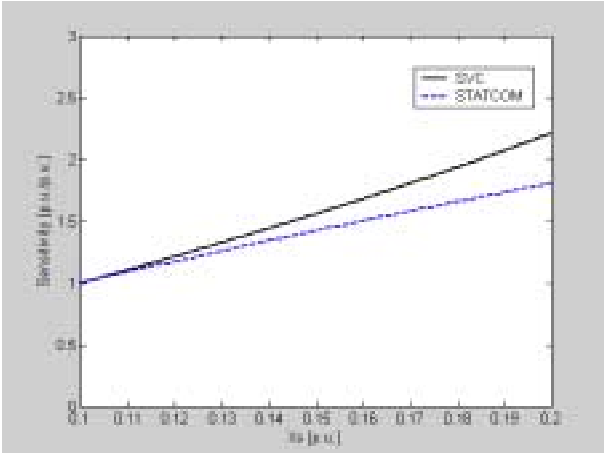

Fig. 10. Sensitivity of the load voltage to the SVC and STATCOM control variables

Fig. 10 shows that SVC and STATCOM sensitivities increase with respect to the network weakness. The variation of sensitivity is less for STATCOMs. In practice, for SVC applications, a gain supervisor and optimizer reduces the control gain when the sensitivity goes beyond a limit.

This observation reveals that a STATCOM stability loop is more robust than an SVC with respect to the variation of the network capacity.

VI. Short Term Voltage Stability

In this section we consider an equivalent of a typical power system, and examine short-term (transient) voltage stability focusing on the impact of SVCs and STATCOMs on voltage recovery.

Fig. 11 shows the studied system. A 600 MW load is served from a large system over two 230-kV lines, each 113 km long. The system is heavily stressed and heavily shunt compensated. The load is half motor and half resistive. A LTC transformer controls the voltage at the load. The data for the system is given in Ref. [1]. We apply a three-phase fault at the midpoint of one of the lines. The fault is cleared after 80 ms by permanently opening the line. We simulate this case with SVC and STATCOM with the rating of 200 Mvar located at the REC 230-kV bus. The SVC blocking scheme for undervoltage is not modelled.

Figures 12–14 show simulation results. As expected, the STATCOM solution allows faster voltage recovery compared to a conventional SVC.

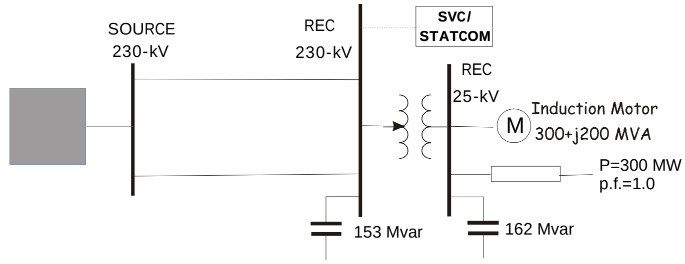

Fig. 11. Equivalent system studied for short term voltage stability

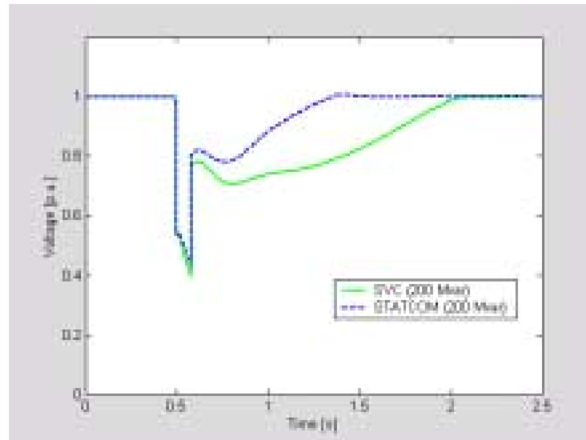

Fig. 12. Voltage variation with SVC and STATCOM

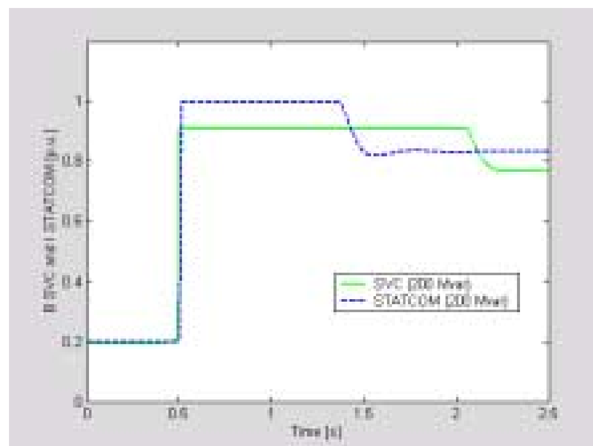

Fig. 13. Variation of SVC susceptance and STATCOM current

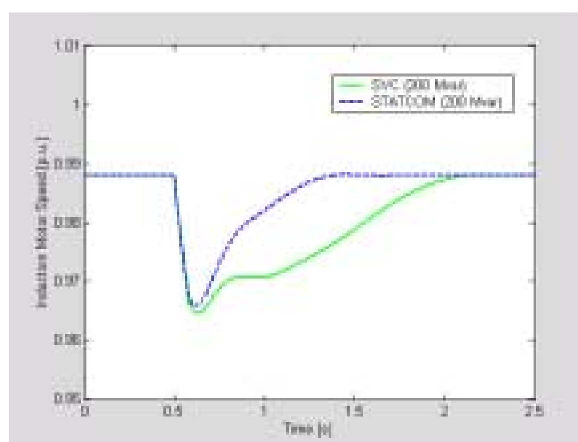

Fig. 14. Variation of induction motor speed

VII. THE FUNCTIONAL RATING CONCEPT

Traditionally, SVCs of a common design have been used to handle different types of network problems. The trend today, however, is to tailor SVCs for their intended use. This is important in order to make SVCs cost efficient.

For steady state voltage support, i.e., to follow the daily load pattern, bulk reactive power combined with stepless smooth voltage control is desired. Vernier voltage regulation can be provided by a TCR running in parallel with harmonic filters. The bulk reactive power is provided by mechanically switched capacitor banks (MSCs) or reactors (MSRs) governed by the SVC controller. Thus SVCs serve the purpose of continuously maintaining a smooth voltage, piloting the MSC switching.

If the task is to support a system limited by post contingency voltage instability or unacceptable voltage levels, a large amount of quickly controllable reactive power is needed for a short time duration. An SVC with additional TSCs is an excellent choice. Post recovery voltage support may also be necessary—this is then preferably provided by MSCs governed by the SVC.

For temporary overvoltages, large inductive reactive power is needed for a short period of time. The standard TCR has some short-time overcurrent capability. This capacity can easily be extended by lowering its steady state operating temperature and by "undersizing" the reactors.

A. Enhanced SVCs

The SVC characteristic at depressed voltage can be efficiently improved by adding an extra TSC. This branch is intended to operate only during undervoltage conditions. It can be added without introducing additional cost in other parts of the SVC. Most important is that the current rating or the voltage capability of the power transformer does not need to be increased. Power transformers allow large overcurrent during limited time (IEEE C57-115 can be used as a guide for available capacity). In many cases three times overload in current for 10 seconds is available. The additional TSC rating is typically in the range of 50 to 100% of the SVC rating.

B. SVC Short Term Overload

The maximum power from an SVC at a given voltage is determined by its reactance. No overload capacity is available unless the reactance is lowered, e.g., by adding a TSC. For overvoltages, however, the SVC reactance is no longer the limiting factor; instead the current in components defines the limit. In most cases the thyristors set the limit. The design is made so that the thyristors are running at a maximum allowed temperature at maximum steady state system voltage. A margin to destructive temperatures is reserved in order to handle fault cases. The Forbes 500 kV static var system near Duluth Minnestoa USA is an interesting example of an Enhanced SVC [5].

C. STATCOM

In STATCOMs the maximum current is given by the difference in voltage between the converter terminal voltage and the power system voltage, and by the phase reactance. A normal design of the converter is such that it can withstand a current corresponding to about 10–15% voltage difference across the phase reactance. The control system must ensure that the converter terminal voltage is kept high enough not to overload the plant. At full current (rated power) the converter semiconductors, IGBTs, IGCTs or GTOs, work at their maximum allowed steady state temperature. A margin to destructive temperature must be left for uncertainties and for fault cases. There is also a maximum instantaneous current that the semiconductors can turn off. The same principle is used here; a margin must be left for uncertainties and for fault cases. The conclusion is that a STATCOM does not have short time overload capacity unless its power rating is de-rated initially. Using the above mentioned margins for planned short time operation would jeopardize the plant security.

D. Short Term Voltage Stability with Enhanced SVC

To demonstrate the performance of an Enhanced SVC, the 200 Mvar SVC used in the Section VI is enhanced to 260 Mvar. The rating of the transformer is unchanged, but the SVC rating is increased by adding a TSC. Figures 15–17 show the affect of the SVC enhancement on the short-term (transient) voltage stability. The figures reveal that with 30% increase of the TSC capacity, the performance of the Enhanced SVC is comparable to a STATCOM for short-term voltage stability.

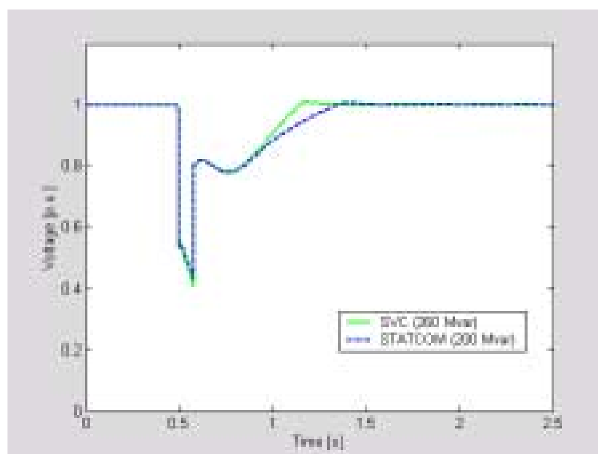

Fig. 15. Variation of bus voltage with Enhanced SVC STATCOM

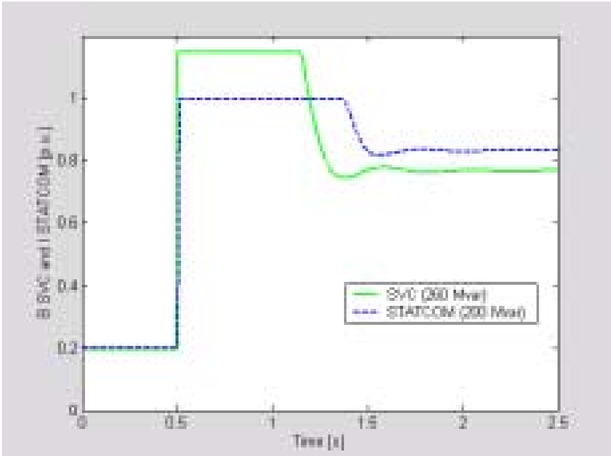

Fig. 16. Variation of Enhanced SVC suseceptance and STATCOM current

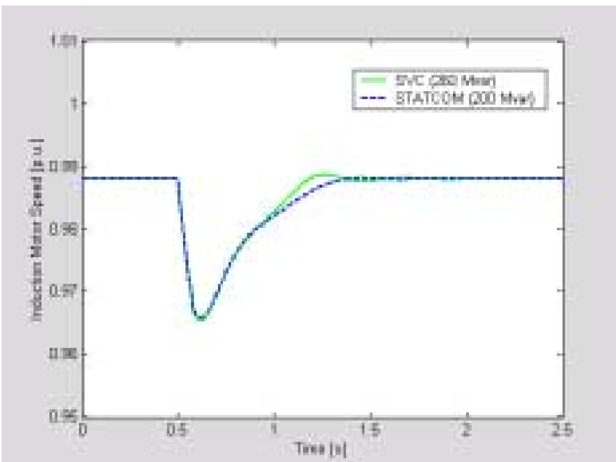

Fig. 17. Variation of induction motor speed with STATCOM and Enhanced SVC

VIII. Harmonics

Both SVCs and STATCOMs generate harmonics. The TCR of an SVC is a harmonic current source. Network harmonic voltages distortion occurs as a result of the currents entering the power system. The STATCOM is a harmonic voltage source. Network voltage harmonic distortion occurs as a result of voltage division between the STATCOM phase impedance and the network impedance.

The major harmonic generation in SVCs is at low frequencies; above the 15th harmonic the contribution is normally small. At lower frequencies the generation is large and filters are needed. SVCs normally have at least 5th and 7th harmonic filters. The filter rating is in the range of 25–50% of the TCR size.

STATCOMs with PWM operation have their major harmonic generation at higher frequencies. The major contributions are at odd multiples of the PWM switch frequency; at even multiples the levels are lower. The harmonic generation decays with increasing frequency. STATCOMs might also generate harmonics in the same spectra as the conventional SVCs. The magnitudes depend on converter topology and the modulation and switching frequency used. In most cases STATCOMs as well as SVCs require harmonic filters.

IX. Footprint

More and more frequently the footprint available for prospective STATCOMs or SVCs is restricted. The trend is, as in many other fields, more capacity on less space. Requirements for extremely tight designs, however, result in higher costs. In general the footprint issue seems not to hinder the utilization of STATCOMs or SVCs, but occasionally, STATCOM has been preferred based on anticipated smaller footprint.

When comparing SVCs with STATCOMs, it is tempting to assume that the latter will fit within a much smaller footprint, as the passive reactive elements (air core reactors and high voltage capacitor banks) are “replaced” with semiconductor assemblies. In the authors’ opinion, this assumption however remains to be practically proved. The main reason for this is that the voltage sourced converter concepts applied in STATCOMs to date have been built with several (even as many as eight) inverter bridges in parallel. This design philosophy implies many current paths, high fault currents and complex magnetic interfaces between the converters and the grid. All in all, not all STATCOMs come out as downsized compared to SVCs. Also the higher losses in the STATCOM will require substantially larger cooling equipment. However, as the STATCOM technology evolves, including the use of very compact inverter assemblies with series connected semiconductor devices, and with pulse width modulation, there is a definite potential for downsizing.

In the case of SVCs, the industry has a long product development where, when necessary, measures have been taken to downsize the installation. Such measures include elevated design of apparatuses, stacking of components (reactors and capacitors), vertical orientation of busbars and use of non-magnetic material in nearby structures. In a few extreme cases iron core reactors have been utilized in order to allow installation in very tight premises. In addition the development of much higher power density in high power thyristors and capacitors contributes to physically smaller SVCs.

X. Life Cycle or evaluated costs

It is the authors’ experience that the investment cost of SVCs is today substantially lower than of comparable STATCOMs. As STATCOMs provides improved performance, it will be the choice in the cases where this can be justified, such as flicker compensation at large electrical arc furnaces or in combination with active power transfer (back-to-back DC schemes). The two different concepts cannot be compared on a subsystem basis but it is clear that the cost of the turn-off semiconductor devices used in VSC schemes must come down significantly for the overall cost to favor the STATCOM. In other industries using high power semiconductors, like electrical traction and drives, the mainstream transition to VSC technology is since long completed and it is reasonable to believe that transmission applications, benefiting from traction and drive developments, will follow. Although the semiconductor volumes in these fields are relatively small, there is potential for the cost of STATCOMs to come down."

Apart from the losses, the life cycle cost for STATCOM and SVCs will be driven by the efforts required for operation and maintenance. Both technologies can be considered maintenance free—only 1–2 man-days of maintenance with a minimum of equipment is expected as an annual average. The maintenance is primarily needed for auxiliary systems such as the converter cooling and building systems. In all, the difference in the cost for these efforts, when comparing STATCOM and SVC, will be negligible.

XI. Losses

The primary losses in SVCs are in the "step-down" transformers, the thyristor controlled air core reactors and the thyristor valves. For STATCOMs the losses in the converter bridges dominate. For both technologies the long-term losses will depend on the specific operation of each installation. The evaluation of investments in transmission has also increasingly included the costs during the entire life cycle, not only the initial investment. Losses will then be increasingly important. With a typical evaluation at $3000/kW (based on 30 years), and additional average evaluated losses of say 300 kW (compared to an SVC), the additional burden on the STATCOM is significant. The evaluated losses at full output will contribute significantly to this, but with less weight on these the difference will be much smaller. Here the evolution does not help the STATCOM as its adequate performance is assumed to be achieved with high frequency PWM, implying that the losses will be quite high even at small reactive power output.

We expect most utilities to operate their facilities close to zero Mvar output, in order to have SVCs or STATCOMs available for dynamic voltage support. In these cases both technologies will operate with well below 0.5% losses (based on "step-down" transformer rating). However the losses will typically increase quite rapidly should the operating point be offset from zero. This is valid for both SVCs and STATCOMs. SVCs will frequently operate with both switched capacitors and controlled reactors at the same time, while converter losses of STATCOMs will increase rapidly with output current. The losses of STATCOMs at rated output will be higher than for comparable SVCs.

XII. Conclusions

We have examined the performance of SVCs and STATCOMs in electric power systems. Based on the analytical and simulation studies, the impact of SVCs and STATCOMs on the studied power system is presented. It was shown that both devices significantly improve the transient voltage behavior of power systems. Though SVCs and STATCOMs work on different principles, their impact on increasing power system transmission capacity can be comparable. Specifically, we describe " enhanced" SVCs with voltage recovery performance similar to STATCOMs. Other issues such as losses, footprint, harmonics, etc., must be examined for each scenario for an optimum investment.

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