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FACTS to Enhance Availability and Stability of AC Power Transmission

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***Abstract*-Recent blackouts have focused on the critical importance of secure and reliable power supply. Traditionally, strengthening power grids has involved the construction of new transmission lines, usually at considerable cost and in the face of public objections. Power technology developments in recent years, however, are now offering new methods for stable, cost effective, bulk transfer of power over existing transmission lines.**

Furthermore, into focus is coming the need to provide adequate reactive power balance for various system conditions, including disturbances. Recent years´ unbundling of power generation and transmission has brought new aspects into the picture, as grid companies no longer can be certain to rely on generators to have their need for reactive power satisfied. In other words, transmission suppliers may have to provide their own vars. This brings to the agenda the question what kind of var supply devices are available, and for what uses, and at what cost. This paper will dwell on the issue, particularly highlighting state of the art devices such as SVC (Static Var Compensators) and STATCOM, as well as their application in power transmission.

***Index terms* –** BCT, FACTS, IGBT, SVC, STATCOM, Transient stability, Voltage stability.

I. INTRODUCTION

Recent blackouts in the USA and Europe have focused attention on the importance of secure and reliable supply of power to homes, public institutions and industry. It is now recognized that a significant number of grids are plagued by under-investment, exacerbated by the uncertainty of roles and rules within the electricity supply industry brought about by on-going de-regulation.

For instance, recent years´ unbundling of power generation and transmission means that grid companies no longer can be certain to rely on generators for reactive power, i.e., transmission suppliers may have to provide their own vars.

A vital characteristic of FACTS (Flexible AC Transmission Systems) is just this, i.e. the ability to provide reactive power in grids for a variety of situations, thereby helping to maintain, or, in the most difficult cases, restore grids to stable operating conditions.

The rapid increase of wind power penetration in several regions of the world may also have a destabilizing effect on the grid and is likely to place more emphasis on the resilience of transmission networks.

Traditionally the strengthening of power grids has involved the construction of new transmission lines, usually at considerable cost and in the face of substantial public objections. This may in many cases not be the best way, however. With FACTS, power technology developments in recent years are offering new methods for stable, cost effective bulk transfer of power over existing transmission lines.

FACTS make up a family of devices that are applied in power systems in shunt, in series, and in some cases, both in shunt and series. SVC (Static Var Compensators), and STATCOM are both shunt devices.

II. DYNAMIC VOLTAGE STABILITY

Behind a voltage collapse, there is usually a deficit of reactive power, as typically, reactive power is needed to maintain proper voltage levels in a power system.

However, reactive power cannot/should not travel over long distances, because it is associated with voltage gradients as well as power losses. Therefore, reactive power should be provided where it is needed (load centres). Reactive power is consumed by loaded lines. When a fault occurs in a power system, such as a short circuit, the faulted line is disconnected, whereupon remaining lines pick up flow from the disconnected line(s). Reactive power is then consumed to an increasing degree. If reactive power supply is limited, the increased line loading will cause a voltage drop over the system. Then, if reactive power is not provided at the receiving end, the voltage can fall precipitously. At which point, the transmission system can no longer transfer electrical energy. There is a system blackout.

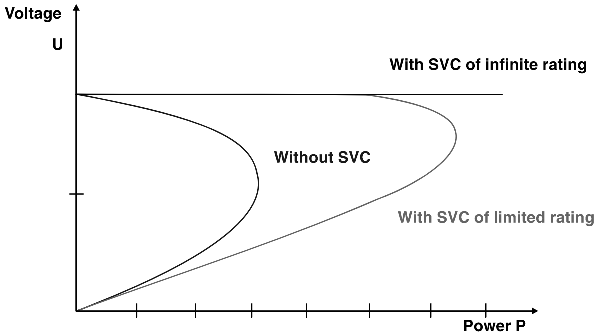

Fig. 1. Voltage variation at a load busbar as a function of loading, with and without SVC.

It is obvious that providing reactive power at the right instant and at the right location(s) will be a potent way of preventing, or at least limiting, blackouts. Providing an SVC at the load point will, within its range, maintain the load voltage within design rating limits (Fig. 1). If,

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however, the SVC had unlimited rating, as shown in the figure, it would be possible to hold constant voltage at the load busbar for any load condition. In reality, the SVC must be sufficiently rated to be able to cope with the most severe case of loading in a given situation.

III. FAST VARS, SLOW VARS

Not only SVC and STATCOM, but also MSC (Mechanically Switched Capacitors) can supply reactive power. There are, however, some vital distinctions to be made. Whereas SVC and STATCOM provide fast vars, MSC is a provider of slow vars. This means that MSC is very useful in situations where there are no particular requirements on dynamic response or frequent operations, such as steady state voltage support to follow 24 hours load patterns. For more demanding applications, MSC falls short, and SVC or STATCOM will be needed. More about this in the paper.

To summarize things so far:
SVC and/or STATCOM should be the natural choice in cases where the following qualities are required:

- Rapid dynamic response
- Ability for frequent variations in output
- Smoothly adjustable output.

IV. TRANSIENT STABILITY IMPROVEMENT

The angular difference between the ends of a line, δ, is a key quantity for power transmission:

$$P = \frac{U_S U_R}{X_L} \sin\delta \qquad (1)$$

We can see that for a certain power transmission level (P), there will be a certain angular separation, δ, everything else unchanged. This separation, for the sake of system stability, should never be allowed to grow too much, lest it grow out of hand during system disturbances. At the same time, as will be demonstrated, an SVC suitably located has beneficial influence on the angular behaviour of a disturbed system. In a dynamic sense, this means that SVC increases the system stability in the way that it keeps the system in synchronism for more or less severe disturbances, where, if uncompensated, the system would have been lost. We call this an increase of angular, or transient, stability of the system. With improved angular stability, availability of the power system is increased in the sense that it gets less disposed towards falling out of synchronism as a consequence of faults in the system.

In Fig. 2a and 2b, the improvement of transient stability by means of an SVC located at midpoint of the power system is illustrated [1]. The power transfer P as a function of angular displacement δ is shown for two cases: with no compensation (a), and with SVC (b). At a certain moment, a fault is incepted in the system, during which the transmitted electrical power P becomes zero, while the mechanical input power to the generator remains constant, P_m. As a consequence, the sending-end generator accelerates until the fault has been cleared and the line reclosed. During this process, the angular difference of the system will have increased from its steady-state value δ_1 to a higher value, δ_2. After reclosure of the system, the transmitted power exceeds the mechanical input power and the sending-end machine decelerates. Since there is a difference in angular velocity between the machine rotor and the system, the angular difference continues to grow until the excess energy built up in the rotor has been discharged into the system.

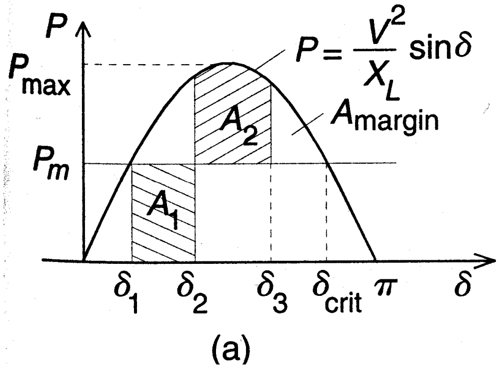

Fig. 2a. Equal area criterion, uncompensated.

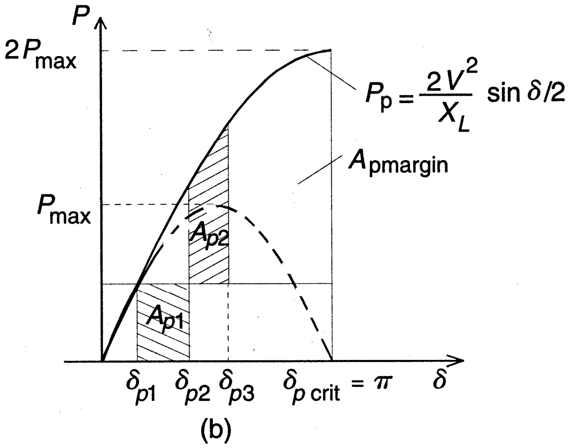

Fig. 2b. Equal area criterion, compensated.

The critical condition for post-fault system stability is that the angular displacement does not exceed δ_{crit}, because if it does, the system cannot get back to equilibrium, and synchronism is lost. We can find the location of the maximum angular displacement δ_3 in both cases shown in Fig. 2 by recognizing that the areas A_1, A_{p1} represent the accelerating energy and areas A_2, A_{p2} the decelerating energy during and after the fault, and letting these areas be equal. The ”stability margin” in each case will then be given by the area locked in between P_m and P(δ) in the interval to the right of δ_3, δ_{p3}. From the graphs, it is obvious that the SVC improves the ”stability margin”, by how much will depend of the SVC size in each case.

V. STATIC VAR COMPENSATION

An SVC is based on thyristor controlled reactors (TCR), thyristor switched capacitors (TSC), and/or Fixed Capacitors (FC) tuned to Filters. Two common design types, both having their specific merits, are shown in Fig. 3a and 3b.

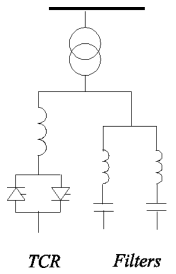

Fig. 3a. TCR / FC configuration.

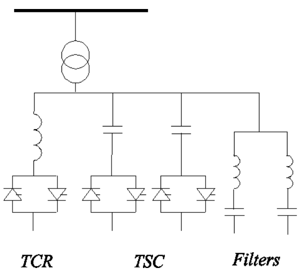

Fig. 3b. TCR / TSC configuration.

A complete SVC based on TCR and TSC may be designed in a variety of ways, to satisfy a number of criteria and requirements in its operation in the grid. In addition, slow vars by means of MSC can easily be incorporated in the schemes, as well, if required.

The fast var capabilities of SVC make it highly suitable for fulfilling the following functions:

- Steady-state as well as dynamic voltage stabilisation, meaning power transfer capability increases and reduced voltage variations.
- Synchronous stability improvements, meaning increased transient stability and improved power system damping.
- Dynamic balancing of asymmetric loads.

A. SVC characteristics

A typical terminal voltage versus output current of an SVC is shown in Fig. 4. Usually, the terminal voltage is allowed to vary in proportion to the compensating current, in accordance to a set slope.

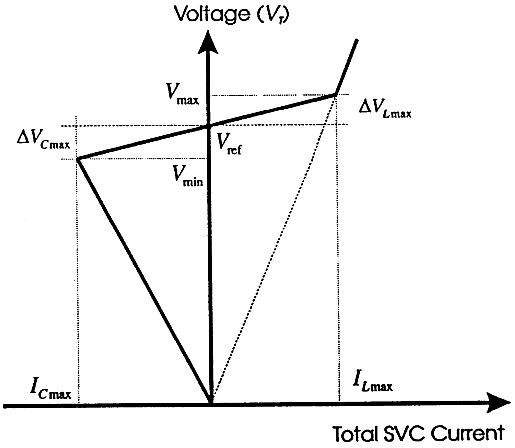

Fig. 4. V-I characteristics of SVC.

The voltage at which the SVC neither generates nor absorbs reactive power is the reference voltage V_{ref}. This reference voltage can be adjusted within a certain range. The slope of the characteristic represents a change in voltage with the compensator current and can therefore be seen as a slope reactance X_{SL}. The SVC response to a voltage variation will then be given by

$$V_T = V_{ref} + X_{SL}\, I_{SVC} \qquad (2)$$

In Fig. 5, the voltage correcting effect of the SVC is demonstrated for three different load cases by letting the SVC characteristic intersect with system load lines for the said cases (Slope: X_s):

1: Nominal voltage & load
2: Undervoltage, e.g. due to generator outage
3. Overvoltage, e.g. due to load rejection.

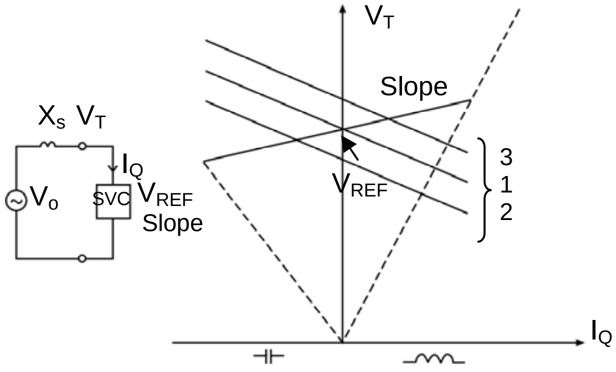

Fig. 5. System voltage correction by means of SVC.

The SVC of TCR / TSC type is very useful as a means for dynamic voltage control in a number of situations such as mitigation of voltage fluctuations which are not too rapid and preventing of voltage collapses in conjunction with grid faults as discussed above. Its dynamic response is limited by the maximum switching frequency of ordinary grid commutated power thyristors, i.e. 100 Hz.

B. SVC control

The main objective of the control system is to determine the SVC susceptance needed in the point of connection to the power system, in order to keep the system voltage close to some desired value, cfm. eq. (2). This function is realised by measuring the system voltage and comparing it with the set (reference) value. In case of a discrepancy between the two values, the controller orders changes in the susceptance until equilibrium is attained.

The controller operation results in a susceptance order from the voltage regulator which is converted into firing orders for each thyristor. The overall active SVC susceptance is given by the sum of susceptances of the harmonic filters, the continuously controllable TCR, and the TSC if switched into operation. The control system also includes supervision of currents and voltages in different branches. In case of need, protective actions are taken.

C. Thyristor valves

The thyristor valves consist of single-phase assemblies (Fig. 6). The thyristors are electrically fired. The energy for firing is taken from snubber circuits, also being part of the valve assembly.

Between thyristors, heat sinks are located. The heat sinks are connected to a water piping system. The cooling media is a low conductivity mixture of water and glycol. In the most recent SVCs supplied, the thyristor valves are equipped with Bi-Directional Control Thyristors (BCT). In such devices, two thyristors are integrated into one wafer with separate gate contacts. Thus, the valves comprise only one thyristor stack in each phase instead of two, which enables considerable compacting of the valve design.

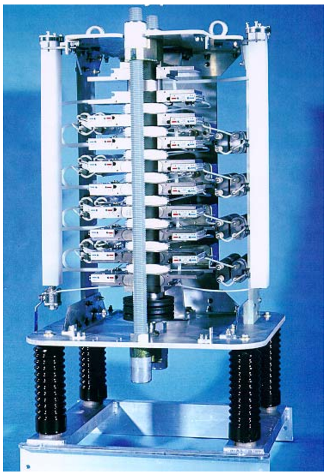

Fig. 6. Thyristor valve of BCT design.

VI. SVC VS MSC: A COMPARISON

An issue frequently raised is how SVC and MSC compare as tools in a grid as far as functionality, capabilities and operational characteristics are concerned. The obvious difference is the speed and repeatability with which the SVC can influence the stability and/or voltage level and/or power factor in a transmission grid. The **SVC** can be used to provide the following performance benefits, based on its practically unrestricted capability to vary its Mvar output:

- High speed voltage stability enhancement
- Improved voltage control
- Improved damping of inter-area power oscillations.

Numerous SVCs worldwide provide each one of the above-listed advantages to the grid owners, assuring optimal behaviour of the transmission systems.

MSCs on the other hand normally are used to compensate for slow variations in the reactive power consumption of downstream sub-transmission and distribution systems. Therefore they are often more advantageously located at lower voltages, and rarely with automatic control.

From the grid system operator point of view, it is often considered the optimum to supplement MSCs and OLTCs (On-Line Tap Changer) with an SVC that assures that the grid voltage level behaves in a safe and predictable way also under scenarios where the grid is severely weakened.

VII. STATCOM

SVC Light® is a STATCOM device, based on VSC (Voltage Source Converter) technology and equipped with IGBTs (Insulated Gate Bipolar Transistor) as semiconductors. A typical voltage-current characteristic of an SVC Light is shown in Fig. 7. It is worth noticing that the SVC Light is capable of yielding a high reactive input to the grid more or less unimpeded by possible low grid voltages.

With SVC Light, the following benefits will be attained in power systems:

- Increased voltage stability
- Improved power quality

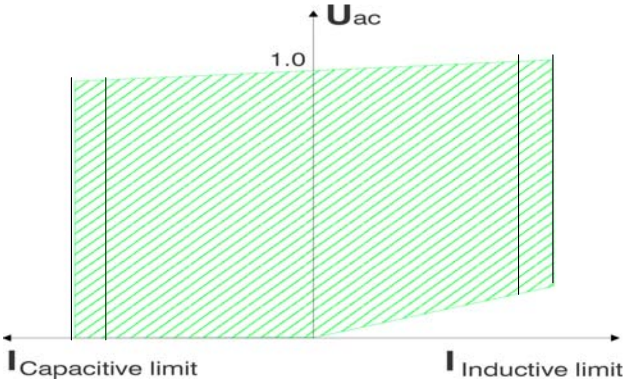

Fig. 7. SVC Light voltage/current characteristic.

From a practical point of view, the SVC Light technology brings further benefits such as:
-Reduced area requirements, due to the replacing of passive reactive components by compact electronic converters;
-Modular, factory assembled units, reducing site works and commissioning time and costs;
-Natural relocatability, due to modular, compact design as well as low harmonic interaction with the grid.

A. Voltage source converter

The function of a VSC is a fully controllable voltage source matching the system voltage in phase and frequency, and with an amplitude which can be continuously and rapidly controlled, so as to be used as the tool for reactive power control (Fig. 8). In the system, the VSC is connected to the system bus via a small reactor. With the VSC voltage and the bus voltage denoted U_2 and U_1 respectively, it can be shown that the output of the VSC can be expressed as follows:

$$P = \frac{U_1 U_2}{X} \sin\delta \tag{3}$$

$$Q = \frac{U_1 U_2}{X} \cos\delta - \frac{U_1^2}{X} \tag{4}$$

P: Active power of the VSC
Q: Reactive power of the VSC
U_1: Bus voltage
U_2: VSC voltage
δ: Phase difference between the voltages
X: Reactance of the coupling reactor.

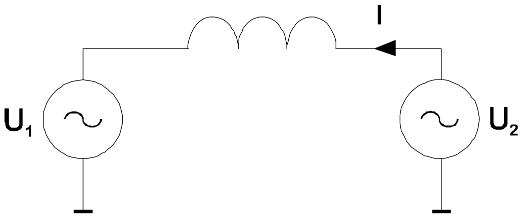

Fig. 8. VSC: a controllable voltage source.

From equations (3) and (4) it can be seen that by choosing zero phaseshift between the bus voltage and the VSC voltage (δ = 0), the VSC will act as a purely reactive element. (In reality, a small phase shift is allowed, in order to make up for the VSC losses.) It is further seen that if U_2 › U_1, the VSC will act as a generator of reactive power, i.e. it will have a capacitive character. If U_2 ‹ U_1, the VSC will act as an absorber of reactive power, i.e. it will have an inductive character.

B. Converter valve

A VSC of three-level configuration is built up as in Fig. 9. One side of the VSC is connected to a capacitor bank, which acts as a DC voltage source. The converter produces a variable AC voltage at its output by connecting the positive pole, the neutral, or the negative pole of the capacitor bank directly to any of the converter outputs.

By use of Pulse Width Modulation (PWM), an AC voltage of nearly sinusoidal shape can be produced without any considerable need for harmonic filtering. This contributes to the compactness of the design, as well as robustness from a harmonic interaction point of view.

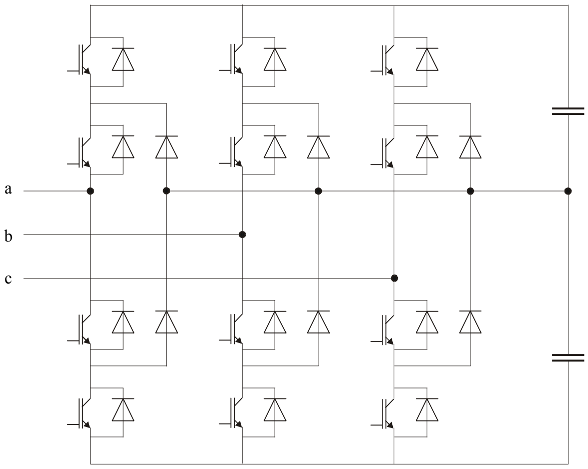

Fig. 9. 3-level VSC configuration.

C. Valve assembly

For SVC Light the IGBT has been chosen as the most appropriate power device. IGBT allows connecting in series, thanks to low delay times for turn-on and turn-off. It has low switching losses and can thus be used at high switching frequencies. Nowadays, devices are available with both high power handling capability and high reliability, making them suitable for high power converters. Thus, by series connecting IGBTs, VSC ratings of more than 100 Mvar are achieved without any need for parallelling devices.

Water cooling is utilized for the IGBT valves, giving a compact converter design and high current handling capacity (Fig. 10). IGBTs capable of handling close to 2000 A_{RMS} are a reality today.

VIII. GRID IMPROVEMENT BY MEANS OF FACTS

In the following, several successful examples of SVC and STATCOM applied for grid improvement are presented:

- Dynamic voltage control of a load centre remotely located from power generation;
- Transient stability improvement of a long power transmission corridor;
- Power oscillation damping in transmission interconnector;

Fig. 10. Converter valve assembly.

- Dynamic voltage stabilization of a grid with a high degree of air conditioning loads;
- Stabilization of voltage in a grid with heavy wind power penetration.

A. SVC for dynamic voltage control of load centre

SVCs located in load centres are primarily installed in order to mitigate the effect on sensitive loads by disturbances in the grid. The disturbances may be short circuits and/or loss of important power lines. The load centres may be located either at the end of a radial network, or in a meshed system. The common characteristic for both locations is that the loads are located far away from large capacity power stations. One example of an installation in a meshed network is an SVC close to the city of Oslo in the southern parts of Norway. This plant is rated at +/- 160 Mvar and is connected to the 420 kV system at a substation southwest of the city (Fig. 11).

Fig. 11. 420 kV, -160/+160 Mvar SVC in Norway.

During a transmission network incident the SVC detects the resulting voltage depression on the 420 kV system. The result of the SVC action during and following the fault is that the loads in the city area notice virtually no voltage change. Effectively the SVC has isolated the city from the impact of the remote system fault.

B. SVC for transient stability improvement

The power system in Thailand is undergoing strong expansion. Increased generating capacity in different parts of the system augments demands on the transmission system and on transfer of power over long distances.

A weak part of the bulk system is an interconnecting corridor linking Bangkok with a major generating area in the south by means of a twin circuit 230 kV line and a twin circuit 115 kV line. The length of this interconnector is 700 km, and an SVC is located at Bang Saphan, half way in between (Fig. 12).

Transient stability is a limiting factor for power transmission over this interconnector. The purpose of the SVC is to increase the transient stability, thereby increasing the power transmission capability of the existing system. At the same time, the SVC provides continuous voltage control under various operating conditions. Mechanically-switched capacitor banks were considered but ruled out due to high demands on control dynamics, requiring a response time well below 50 ms. Also, continuous var control efficiently eliminates step-wise voltage changes, which since the system is weak could violate the grid owner´s requirement that voltage changes do not exceed 3% at 230 kV.

Fig. 12. Power interconnector, Thailand.

The overall dynamic range of the SVC is 50 Mvar (inductive) to 300 Mvar (capacitive) (Fig. 13).

The SVC at Bang Saphan has enabled considerable increase of the power transmission capability up to Bangkok, with no need for more lines. Without the SVC, the transmission capacity was limited to below 200 MW. With the SVC, the capacity has been raised to well over 300 MW, i.e. a more than 50% increase of transmission capability over the existing lines.

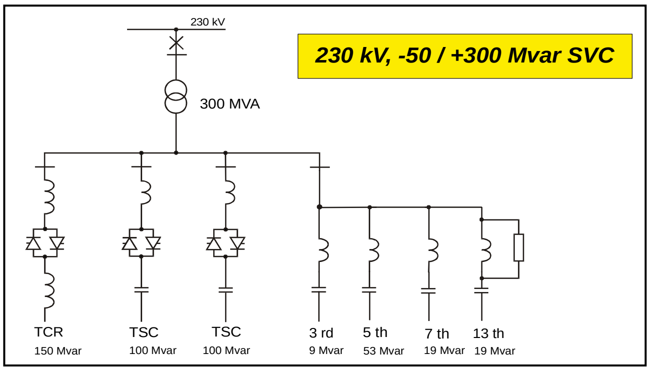

Fig. 13. Single-line diagram, SVC at Bang Saphan.

C. Power oscillation damping of a transmission corridor

An SVC rated at 100 Mvar inductive to 200 Mvar capacitive at 330 kV is in operation in the Matimba-Insukamini 600 MW power interconnecting corridor between South Africa and Zimbabwe. It is located at the ZESA Insukamini 330 kV substation in Zimbabwe, close to the coupling point for the 400 kV interconnection to South Africa. This 405 km long line forms part of an AC connection running in parallel with the Cahora Bassa HVDC link (Fig. 14).

Fig. 14. Matimba-Insukamini 600 MW power interconnection.

The single 400 kV interconnection between Matimba and Insukamini is relatively weak, and unless proper measures are taken, poorly damped, low frequency (‹ 0,5 Hz) active power oscillations tend to appear between South Africa and Zimbabwe. The SVC is there to mitigate these power oscillations (Fig. 15). With the SVC in operation, stability and power transfer margins have been increased by approximately 150 MW in the existing power corridor, without any need for additional power lines. It should be pointed out in this context that the alternative to the SVC, i.e. the building of an additional line, would have taken longer as well as cost considerably more money. Additionally, the eliminating of the need for an additional line has brought benefits to the environment which cannot so easily be quantified, but which nevertheless are very important, as well.

Fig. 15: The Insukamini SVC.

D. STATCOM for dynamic grid voltage control

A utility plans to decommission an old oil- and gas-fired power plant near downtown Austin, Texas. The power plant was constructed in the 1960s. In addition to providing the generation capacity, an important reason the plant has been kept in operation is to stabilize the voltage on the transmission system. Retirement of the power plant without a reliable dynamic reactive source would have a negative impact on the transmission system voltage stability. FACTS technology was considered as a possible solution for the problem. A special requirement in the present case is the recovery from voltage sags where a fast response is necessary at low voltages. Physical limitations of the urban site included low electro-magnetic fields and audible noise emissions, which were specified as special requirements of the installation.

An initial study showed that the needs could be met using a compact STATCOM [2]. A STATCOM is particularly suited for supplying full compensating current at very low AC network voltages and has the ability to compensate for unbalances. The STATCOM design features also include minimum footprint and effective electro-magnetic screening, both of which were required in this application.

The STATCOM consists of a VSC inherently symmetrically rated at +/- 95 MVA as well as 15 Mvar of harmonic filters as seen from the 138 kV bus. In total this gives an operating range from 80 Mvar inductive reactive power to 110 Mvar capacitive reactive power. There are also three 138 kV mechanically switched capacitor banks (MSC) each rated at 31.2 Mvar for providing steady-state reactive power support to the grid. Including the three 138 kV MSC, the reactive power range is 80 Mvar inductive to just above 200 Mvar capacitive. The dynamic portion of this is two times the VSC rating of 95 Mvar, or 190 Mvar.

Fig. 16 shows a simplified single line diagram of the STATCOM (including the dual redundant step-down transformers and the three 138 kV MSC).

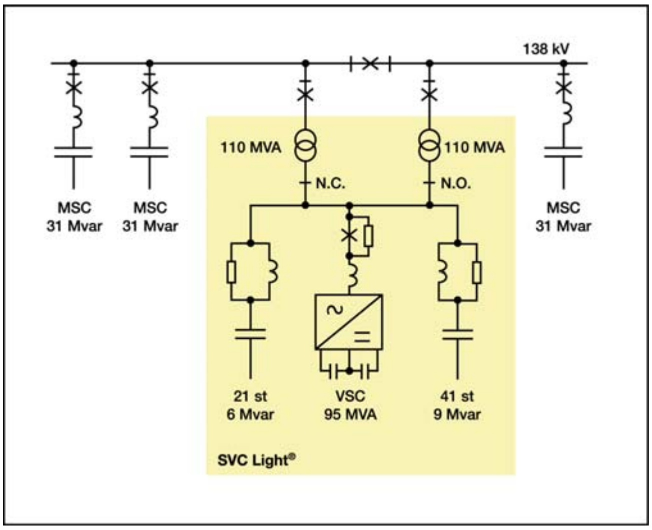

Fig. 16. Single line diagram, STATCOM plus MSC.

Operating strategy The STATCOM controller inherently has the capability to automatically take actions for switching in and out the three 138 kV mechanically switched capacitor banks. This operating strategy forces the MSC to be the major producer of reactive power support during slow varying conditions in the system. The strategy leaves the STATCOM ready to rapidly respond with dynamic reactive power support to disturbances occurring during power system contingencies. This applies to both over-voltage suppression and under-voltage support.

The entire installation can be seen in the site photo shown in Fig. 17.

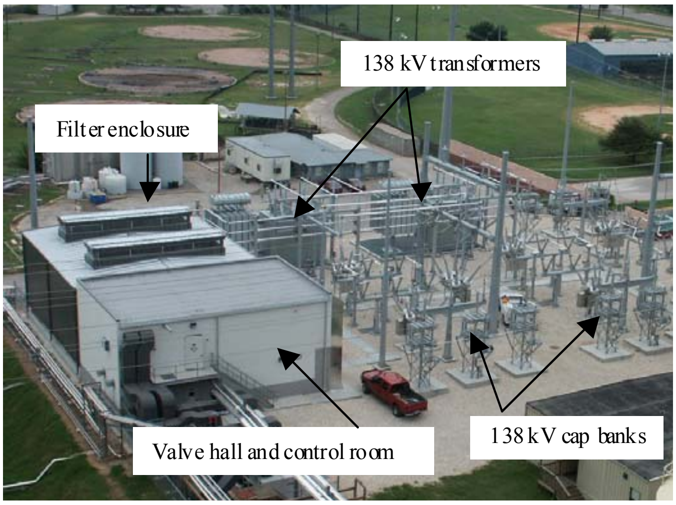

Fig. 17. Site view, STATCOM and MSC.

E. SVC for stability improvement in grid with strong wind power penetration

The McCamey Area is a sparsely populated part of west Texas where the penetration of wind power production has grown to 750 MW and is expected to grow to well over 1 GW in the next few years [3]. This corresponds to some 80% wind power penetration. To improve and maintain system stability, four SVCs have been installed in the area, each rated at -40/+50 Mvar and directly connected to grid nodes at 69 kV or 35 kV. The primary function of the devices is to provide reliable reactive power support to the wind farms under steady state conditions as well as transient disturbances in the network.

In the planning stage, two possible approaches to fulfil the dynamic var demand were investigated: either a number of distributed, small SVCs, or few, larger SVCs at selected key points in the grid. The latter option was chosen, for several reasons:

- Few, larger SVCs cost less than many small SVCs.
- Less total area demand.
- Less total need for service and maintenance.

A key benefit in the project was that all four SVCs could be connected to the grid without any need for step-down transformers. This was true not only for 35 kV, but also for 69 kV (Fig. 18).

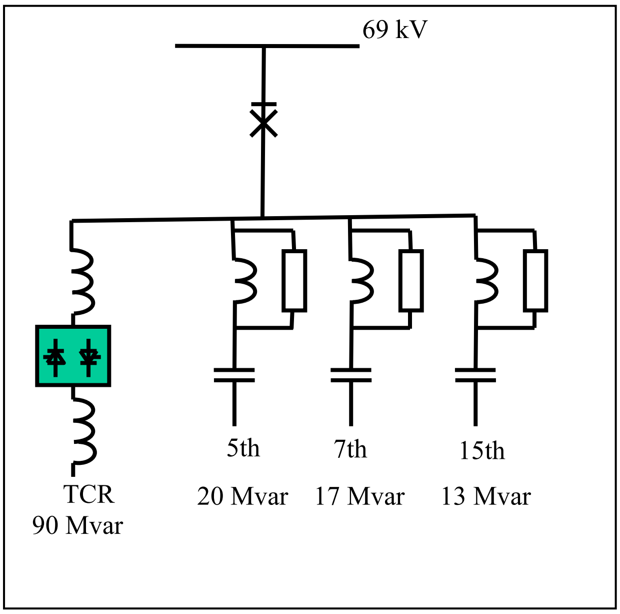

Fig. 18. Single-line diagram, 69 kV, -40/+50 Mvar SVC.

In Fig. 19, a site photo of one of the SVCs is displayed, directly connected to 69 kV.

Fig. 19. 69 kV, -40/+50 Mvar SVC.

IX. CONCLUSION

For HVAC grids, several kinds of system stability need to be looked after:

- Angular stability, i.e. the maintenance of synchronism in the system;
- Synchronous stability, typically electromechanical damping and the control of power oscillations;
- Dynamic voltage stability, i.e. the avoidance of voltage collapses.

These things need to be re-assessed and safeguarded in a changing grid environment, which several big blackouts in recent years in various parts of the world are bearing witness about. For example, the unbundling of power generation and transmission seen in the last decade means that grid companies no longer can be certain to be able to rely on generators to supply their need for reactive power. In other words, transmission suppliers may have to provide their own vars.

Another factor is connected with the growing focus on power transmission across state borders, encouraged by the European Union. In cases where the power transmission capacity of existing cross-border connections is insufficient, there will be a need for fast and cost effective grid reinforcements.

And thirdly: the growing impact of wind power is placing new demands on the grid infrastructure, to ensure that grid stability is maintained as wind power penetration increases.

A vital characteristic of FACTS (Flexible AC Transmission Systems) is the ability to provide reactive power in grids for a variety of situations, thereby helping to maintain, or, in the most difficult cases, restore grids to stable operating conditions. Furthermore, this is typically done at a cost level and time expenditure by far less than with traditional means such as building new transmission lines.

From an environmental point of view, FACTS enables the transmission of power over distances with less right-of-way impact than would otherwise be possible. Furthermore, the saving in transmission losses may well bring a corresponding decrease in need for generation, with so much less toll on the environment.

FACTS make up a family of devices that are applied in shunt, in series, and in some cases, both in shunt and series. In this paper, SVC and STATCOM, both shunt devices, are treated.

X. REFERENCES

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XI. BIOGRAPHY

Rolf Grünbaum (M’2001) was born in Gothenburg, Sweden. He received his M.Sc. in Electrical Engineering from the Chalmers University of Technology, Gothenburg, Sweden.
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