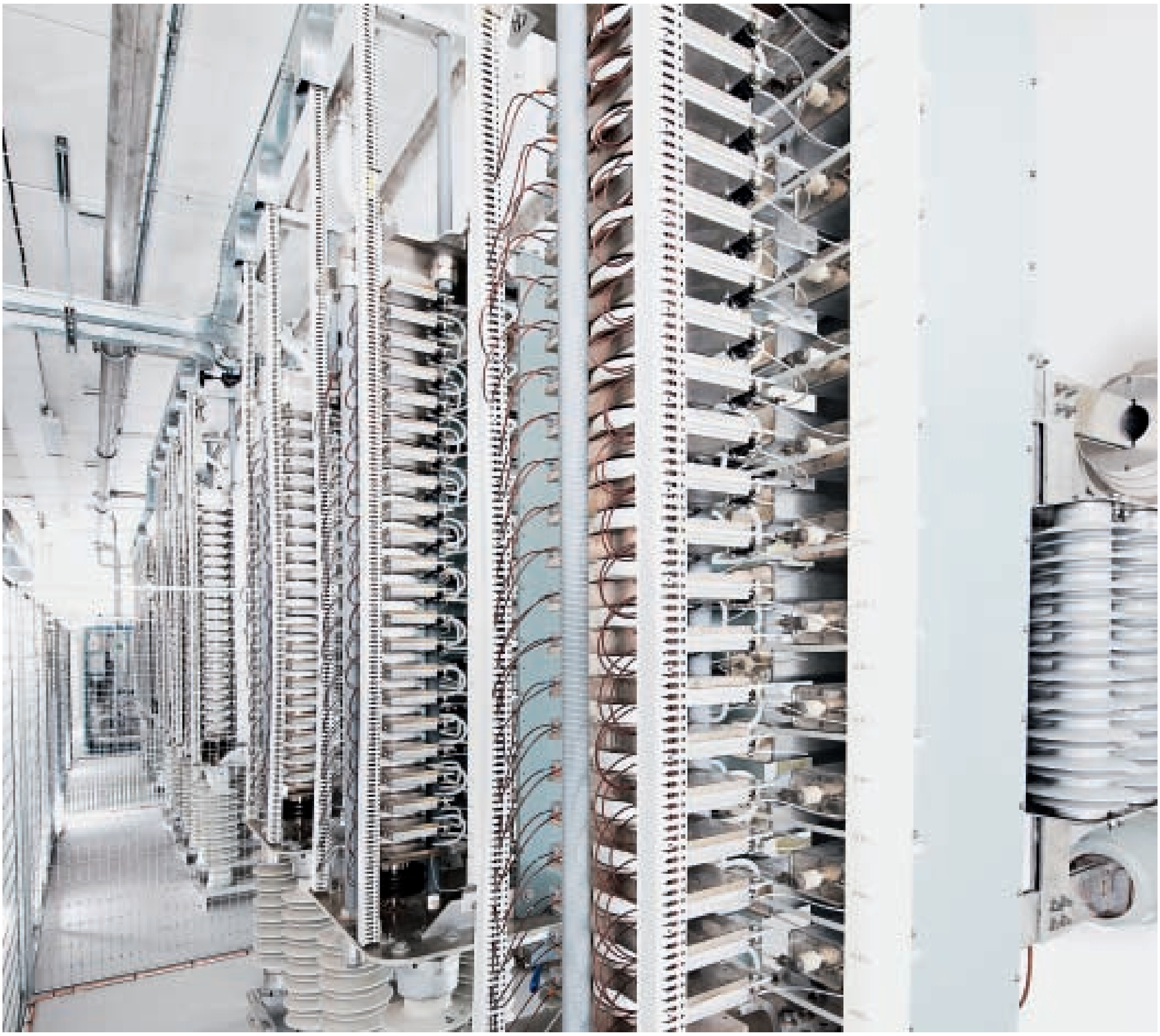


# Securing power

## Mitigation of voltage collapses in large urban grids by means of SVC

ROLF GRÜNBAUM, PETER LUNDBERG, BJÖRN THORVALDSSON
– Recent blackouts in Europe as well as the United States have focused attention on the importance of a 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 underinvestment, exacerbated by the uncertainty of roles and rules within the electricity supply industry brought about by deregulation. For instance, the unbundling of power generation and transmission in recent years has meant that grid companies can no longer rely on generators for reactive power, ie, transmission suppliers may have to provide their own var (volt-ampere reactive). The fast and adequate supply of reactive power is required to maintain stable voltages, especially when high percentages of induction motor loads, such as those created by air conditioners in urban areas, are dominant in the grid and during system faults. SVCs (static var compensators) are a solution well adapted to meet the challenges in question.

A vital characteristic of the SVC is its ability to provide reactive power in grids for a variety of situations, thereby helping to maintain, or, in the most difficult cases, restore stable operating conditions to grids. The article focuses on a current case where SVCs are used successfully for dynamic voltage stabilization in power grids dominated by heavy loads with a large percentage of induction motors for air conditioning.

SVCs are part of the FACTS (flexible AC transmission systems) family of devices that are applied to power systems for a variety of tasks, with the aim of improving grid performance.

A shortage of reactive power is often the cause of a voltage collapse in the power grid. Typically reactive power is needed to maintain proper voltage levels in a power system. However, reactive power cannot – nor should it – travel over long distances, because it is associated with power losses as well as voltage gradients. Reactive power should therefore be provided where it is needed (ie, at load centers).

Reactive power is consumed by loaded lines. When a fault occurs in a power system, such as a short circuit, the affected line is disconnected and the remaining lines pick up the flow. Reactive power is then consumed to an increasing degree. If the reactive power supply is limited, the increased loading on the line will cause a voltage drop over the system. If reactive power is not provided at this time, the voltage can fall precipitously. The transmission system can no longer transfer electrical energy and a system blackout will follow.

It is apparent that provision of the right kind of reactive power (with proper dynamic characteristics) at the right moment and at the right locations provides potent methods to prevent, or at least limit, blackouts. This is where ABB's SVC can play a critical role.

## Fast var, slow var

Reactive power can be supplied, not only by SVC, but also by MSCs (mechanically switched capacitors). There are, however, some vital distinctions to be made. While the SVC provides fast vars, an MSC is a provider of slow vars. This means that the MSC is very useful in situations where there are no particular requirements on dynamic response or frequent operation, such as steady-state voltage support to follow 24-hour load patterns. For more demanding applications, MSCs fall short, and SVCs (or indeed STATCOMs [1] will be needed.

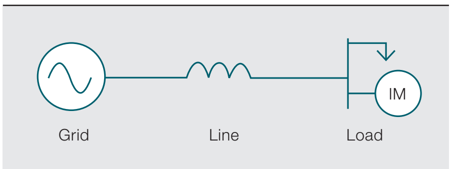
## Dynamic voltage stability

The introduction of an SVC at a critical load point will serve as a powerful tool for dynamic voltage support that will enhance the stability margin. The ability of an SVC to maintain a constant voltage at the load point of a certain grid configuration is dependent on the SVC rating and the size of the load. This relationship is shown in → 1.

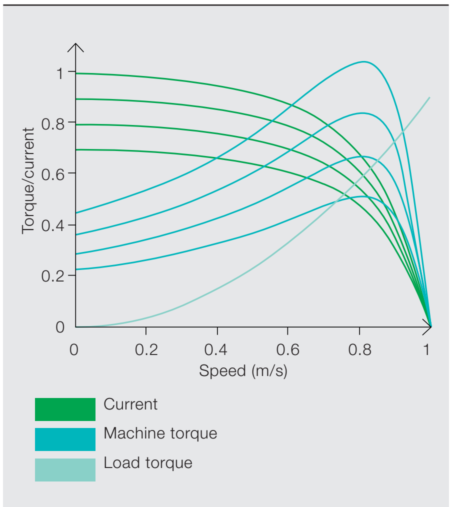
Controlling the undervoltages produced by faults and overvoltages produced during light or no-load conditions are key features of SVC operation. A generic case is shown in → 2. The load center is fed through a transmission line and the load consists, to a large extent, of induction motors (IM), which are sensitive to undervoltage situations. In this case both active and reactive power to the load must be supported through the transmission line. Quite apart from the ohmic losses this will generate in the system, it will also show up as a variety of challenges during faults in the system. In the following section, these challenges are described.

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

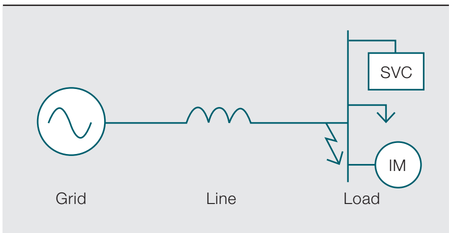

2 Single-line diagram of generic system




3 Load torque and machine torques as functions of speed and machine currents




4 SLG close to the load




**Footnote**

1 A STATCOM (static synchronous compensator) is a power electronics voltage-source converter used on alternating current electricity transmission networks that acts as either a source or sink of reactive power.

### Undervoltage control

Undervoltage situations can occur at generator outages or faults in adjacent feeders. These faults are typically temporary, clearing after 100 to 150 ms. During the fault, the voltage will drop by a varying degree. Two main cases of undervoltage can develop: one case during the fault, and the other directly after the fault has cleared.

If the SVC is very close to a three-phase fault, it cannot do much to help alleviate the voltage drop during the fault. For more remote faults or for single line-to-ground (SLG) faults, however, it might also be possible, to some extent, to support the voltage situation in the vicinity of the SVC since the SVC will continue to generate reactive power in the grid during the fault. Undervoltage situations are especially difficult when the load consists of a large percentage of asynchronous machines, such as motors for pumps or air conditioners. The steady-state relationship between the load torque and the produced electrical torque as a function of speed is shown in ➔ 3.

During the fault the asynchronous machines will slow, which will affect the system when the fault is cleared. In the most severe cases voltage recovery may be prevented in the grid after this kind of fault. Assume, for example, that an SLG fault occurs close to the load center as indicated in ➔ 4. With the help of an SVC that dynamically supports the situation during the fault by means of reactive power generation, the case can be solved. The SVC will give strong support to the grid, especially after the fault has cleared.

### Overvoltage control

The overvoltage control works in a similar fashion to the undervoltage control, but is vital in load-rejection cases, where sudden loss of loads generates overvoltages due to reactive surplus from the generators, lines and cables in the system. The control speed of the SVC enables full support within one fundamental cycle and the SVC will consume reactive power to limit the voltage in the system. As soon as the load is back in the system the SVC will return to its original set point and support the system once again.

## Static var compensator

An SVC is based on thyristor-controlled reactors (TCR), thyristor-switched capacitors (TSC), and/or fixed capacitors (FC) tuned to filters. A common design type is shown in ➔ 5.

A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. TCR reactors are generally of air core type, glass fiber insulated and epoxy resin impregnated.

A TSC consists of a capacitor bank in series with a bidirectional thyristor valve and a damping reactor. The reactor also serves to detune the circuit to avoid parallel resonance with the network. The thyristor switch acts to connect or disconnect the capacitor bank for an integral number of half cycles of the applied voltage. The TSC is not phase controlled, which means it does not generate any harmonic distortion.

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

### SVC characteristics

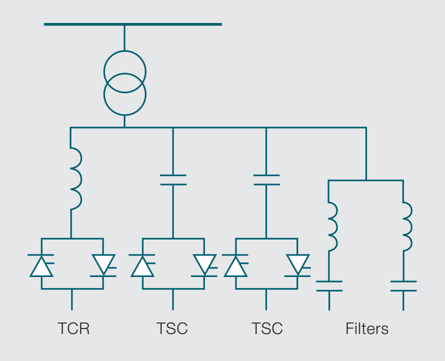
An SVC has a steady-state and dynamic voltage-current (V-I) characteristic as shown in ➔ 6. The SVC current/susceptance is varied to regulate the voltage according to a slope characteristic. The slope setting along with other voltage control equipment is important in the grid. It is also important when determining the voltage at which the SVC will reach the limit of its control range. A large slope setting will extend the active control range to a lower voltage, but at the expense of voltage regulation accuracy.

The voltage at which the SVC neither generates nor absorbs reactive power is the reference voltage Vref. This reference voltage can be adjusted within a certain range.

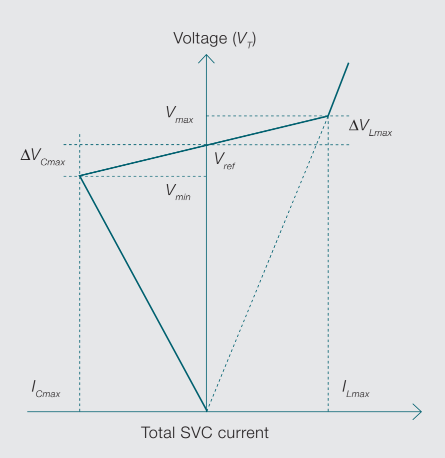
## Preventing voltage collapse

The Saudi Electricity Company of the Western region of Saudi Arabia operates a power transmission system comprising 380 kV overhead (OH) lines and underground cables. There are numerous 380 kV / 110 kV bulk supply stations, feeding local 110 kV / 13.8 kV substations through mostly underground cable circuits. A simplified form of the grid is shown in ➔ 7.

5 SVC of TCR/TSC/Filter configuration

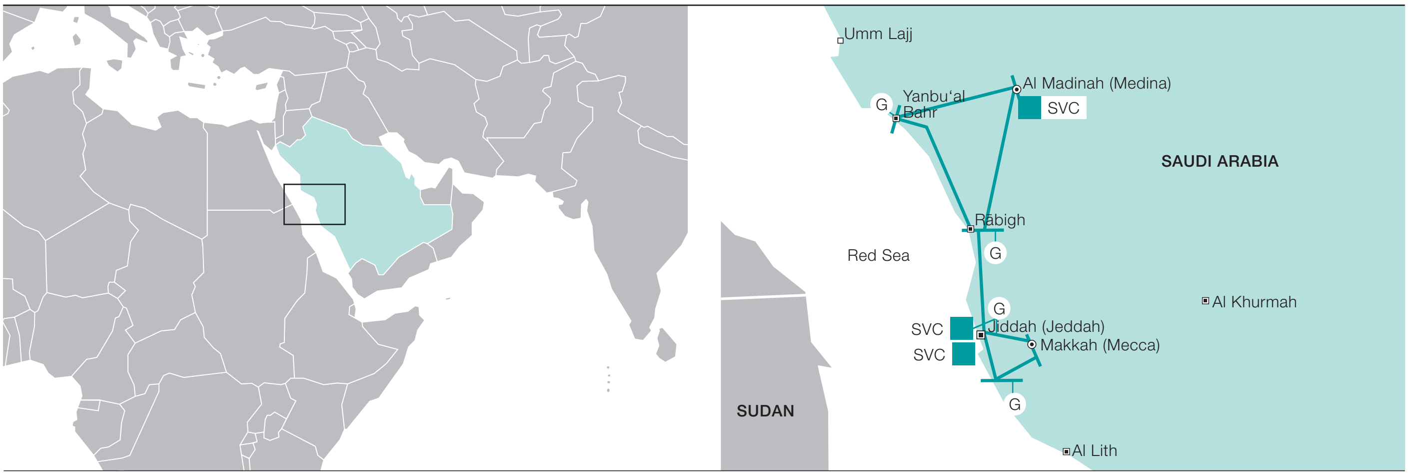



6 V-I characteristics of SVC




A shortage of reactive power is often the cause of a voltage collapse in the power grid. ABB's SVC can play a critical role in the provision of reactive power to prevent or limit blackouts.

7 Simplified grid of SEC Western region




Operating conditions in the Saudi power grid are special due to the hot climate, with up to 80 percent of the total load consisting of air conditioners. From a grid point of view, air conditioning is a particularly demanding kind of load, with slow voltage recovery, motor stalling or even voltage collapse in conjunction with short circuits in the transmission or subtransmission network. In the Western region, especially near the Red Sea, and with the major city of Jiddah and the cities of Makkah and Al Madinah as dominant load centers, grid stability is strained, particularly in summer and during the Hajj pilgrimage. Simulations have shown that the power system may not survive even SLG faults close to the load center during peak load conditions. To stabilize the situation, three large SVCs have been installed, with the explicit purpose of keeping the grid voltage stable as air conditioners all around the region are running at full speed ➔ 7 [1].

The power system has a few specific characteristics:
- A large difference between minimum and maximum (annual and daily) load
- Extremely high concentration of air-conditioning load
- High impedance 380 kV / 110 kV and 110 kV / 13.8 kV power transformers, to limit short circuit currents
- Somewhat remote generation

These characteristics affect the operation of the system. System performance and operational problems experienced were:
- Voltage control between peak load and off-peak load conditions
- Unacceptable voltage recovery after faults at medium-load conditions
- Voltage collapse situations at peak load conditions

A comprehensive reactive power planning study encompassing 380 kV, 110 kV and 13.8 kV levels was performed. The most important conclusions affecting the system planning and operation were:
- Faster fault clearing, where possible, reduces the dynamic reactive power requirement.
- AC motor stalling for SLG faults can be avoided by installing dynamic reactive power support.
- Dynamic reactive power support is needed only for a short period: during the fault and for about 1 s following fault clearing.
- Reactive power support is needed to counteract voltage fluctuations due to daily load variations.

The total dynamic reactive power demand was calculated at 3,000 MVAr (Megavolt-ampere reactive). Installing five SVCs with a rating –60 MVAr / +600 MVAr each (ie, 60 MVAr inductive to 600 MVAr capacitive) at five different 110 kV buses would solve the AC motor-load stalling problem and satisfy the daily load voltage control.

The first three SVCs at the Al Madinah South, Faisaliyah and Jamia substations were taken into service in 2008 and 2009. The remaining two SVCs are still to be purchased. Site views of the Faisaliyah ➔ 8 and Jamia SVCs are shown in ➔ 9.

## Problem definition

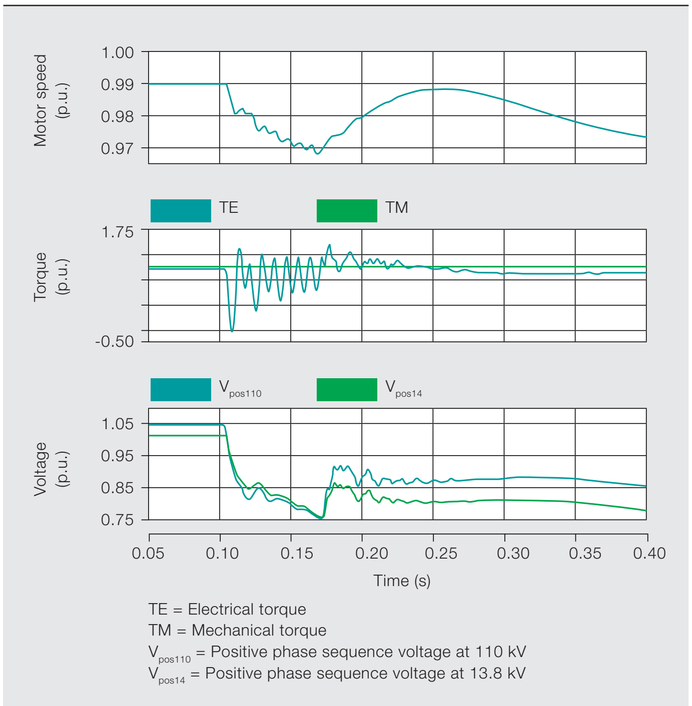
At an SLG fault in the vicinity of the city of Jiddah, on the 380 kV system or directly in the 110 kV system, the positive phase sequence voltage initially drops to 0.7 to 0.8 per unit (p.u.). Air-conditioner induction-motor flux decays and the motors lose electrical torque. Almost instantaneously the motors lose speed as the transient electrical torque becomes negative. During the rest of the fault time the electrical torque oscillates due to the imbalance, but with an average value below the load torque due to the reduced voltage. The loss of speed continues but with a smaller rate of change. At fault clearing the motors need to both remagnetize and reaccelerate. The resulting large active and reactive components in the load current give a big voltage drop in the source impedances. A large part of the impedance is in the 110 kV / 13.8 kV power transformers. In case of peak load conditions, the motors will have lost too much speed to be able to reaccelerate

SVCs provide a fast and adequate supply of reactive power to maintain stable voltages, especially when large induction motor loads, such as those created by air conditioners, are dominant in the grid.

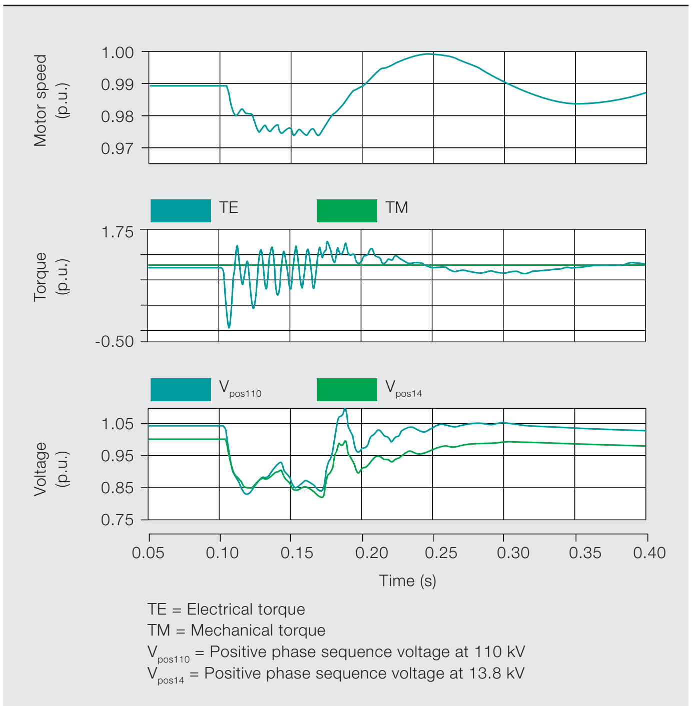
8 Faisaliyah SVC

9 Jamia SVC

10 Motor speed, torque and 110 kV / 13.8 kV without SVC: unsuccessful voltage recovery




11 Motor speed, torque and 110 kV / 13.8 kV with SVCs: successful voltage recovery




following fault clearing, and voltage recovery is unsuccessful ➔ 10.

## Countering motor stalling with SVCs

The way to prevent the motors from stalling is obviously to reduce the voltage drop during the fault and to restore the voltage as quickly as possible after fault clearing. Such a task requires a lot of reactive power support during a short period of time. Voltage support applied close to the motors gives the best results. The most efficient locations are in each 110 kV / 13.8 kV distribution substation on the 13.8 kV level. This would require installing a very large number of rather small SVCs. The practical solution is to install a limited number of large SVCs on the 110 kV level.

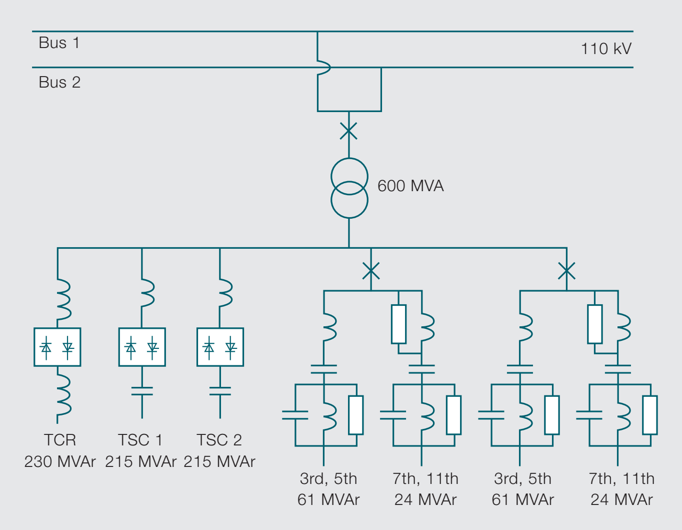
The initial drop in speed for the induction motors cannot be avoided by SVCs. It will take 1.5 cycles before the SVCs are fully compensating the voltage drop. With sufficiently large SVCs the voltage can be supported to such an extent that the motors do not continue to lose speed following the initial drop ➔ 11. A new "stable" operating point is reached. During the fault, it is very difficult to increase the voltage to the point at which the motors accelerate. It is important to stop or slow down the speed drop as quickly as possible. The sooner it stops the easier it becomes to reaccelerate the system following fault clearing. A shorter response time for the SVC means that fewer Mvars are needed. It has been shown in studies that the motors are almost impossible to reaccelerate after fault clearing in cases where the SVCs were not operating during the fault.

Directly at fault clearing, the voltage jumps upwards in a step. The reactive current to the motors increases instantaneously. In addition, a large active current is needed for reacceleration. In cases where the voltage at the motors remains severely depressed, the active current needed cannot flow and the voltage recovery in the system will be slow. In the worst case the motors will get stuck. By supporting the voltage, a more rapid recovery is made.

## SVC performance

The three SVCs each have a rating of 60 MVAr inductive to 600 MVAr capaci-

12 SVC single-line diagram




tive power. They are connected to gas-insulated switchgear (GIS) substations on 110 kV. The nominal voltage on the SVC medium-voltage bus is 22.5 kV. There are two TSCs rated at 215 MVAr each, and one TCR rated at 230 MVAr → 12. The harmonic filters rated at a total of 170 MVAr are divided into two separate branches. The branches are connected to the MV bus by circuit breakers. Each filter branch consists of two double-tuned filters covering the 3rd, 5th, 7th and 11th harmonics.

**Speed of response**

When it comes to the speed of response for an SVC it is important to differentiate between "large signal" and "small signal" behavior. The large signal response is when the SVC responds to network faults causing a large system voltage change. This is typically a line-to-ground fault in the vicinity of an SVC, or a more distant three-phase fault. The small signal response is for minor changes in the system voltage such as the effect from tap changer action or connection/disconnection of a line reactor or a capacitor bank. For the utility-type of SVC, it is mainly the large signal speed that is of interest.

A utility SVC primarily controls the positive phase sequence voltage and in some special cases the negative phase sequence voltage. For control, the instantaneous voltage measurements have to be separated into sequence values and the harmonic components in the voltage must be removed. Both these actions require time. As a first approximation, the voltage processing can be seen as a first-order low-pass filter with a time constant of about 10 ms; the slope is the positive phase sequence current multiplied by a constant. Control action is by a PI (proportional and integrating) regulator (in many cases just an I regulator). It works on the difference between a set voltage and the actual voltage modified by the slope. The output is a signal that can be seen directly as a susceptance order to the main circuit. Thyristor valves can switch only once per half cycle and phase. A three-phase valve assembly can be modeled by an average time delay.

Typically, a response in the range of two cycles is achievable. This fulfills the requirement by the utility that the response time be no longer than 40 ms in a strong network. (In Saudi Arabia, the grid frequency is 60 cycles, ie, two cycles correspond to 33.3 ms.)

The stability of the control must be maintained at varying network strengths. Typically the short-circuit capacity varies by a factor of two between the strong and weak conditions. The regulator is trimmed to give a fast response at the weakest network condition. It is accepted that the SVC will be slower at the strongest network. In case the system becomes even weaker, automatic gain-reduction algorithms are activated.

The major task for a utility SVC is to quickly supply Mvar at severe voltage drops at network faults. The most frequent fault is a line-to-ground fault. The positive sequence voltage typically drops to 0.7 p.u. for a nearby fault and to gradually higher values for more remote faults. At such a large voltage deviation the SVC regulator very quickly (in about one cycle) reaches its limit. This time is essentially the same irrespective of regulator gain. The TSC valves will switch on at the appropriate point on wave [2] and the TCRs will cease conducting. The SVC will be fully conducting in 1.5 cycles. The TSC switch-on time may be longer depending on its precondition (charged or discharged). The most common condition is discharged capacitors.

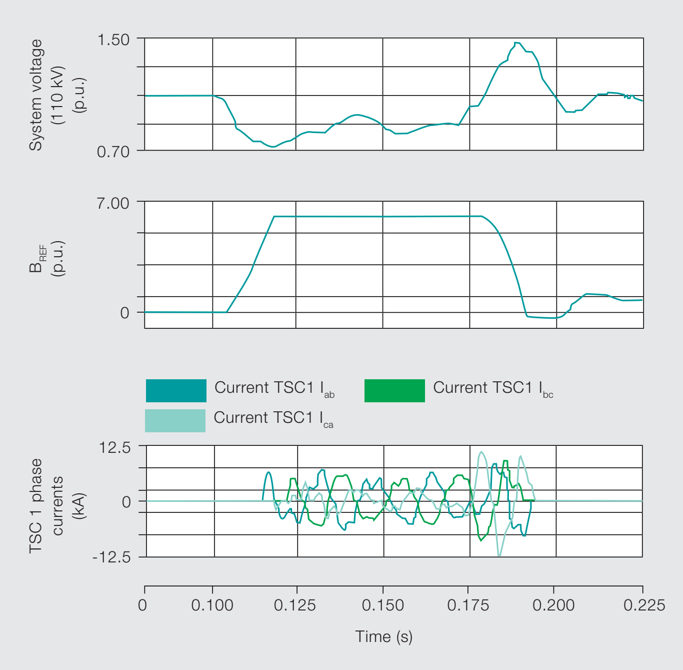
**New control for faster voltage recovery**

During a short circuit in the power grid the positive phase sequence voltage is depressed. The SVC runs fully capacitive. In case of a lightly loaded system, a temporary overvoltage may occur at fault clearing. The primary reason for the overvoltage is that the power system cannot absorb the reactive power generation from the SVC. A standard control system has to wait until the voltage has exceeded its set voltage before the regulator can start reducing the susceptance order to the main circuit. This inevitably results in an overvoltage with a duration of at least one cycle. In the studied system, voltages in excess of 1.5 p.u. may occur. Many SVCs around the world do not run in capacitive mode until after fault clearing because there were no efficient ways to solve this problem at the time when they were installed.

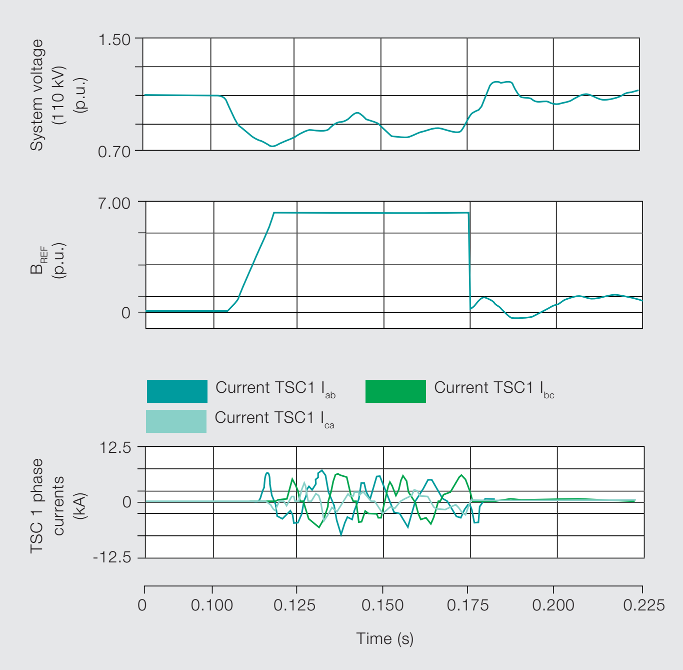
A simulation of the temporary overvoltage is shown in → 13. The need to switch the TSC out faster is evident. To improve the situation, a new control function was developed and implemented in the three Saudi SVCs where the TSCs are blocked at the first current-zero crossing following fault clearing. This approach has been shown to be efficient in simulations, however real data is still to come. The results obtained with the new control function are shown in → 14.

Motors are almost impossible to reaccelerate after fault clearing in cases where SVCs were not operating and in those cases where they were, fewer Mvars were needed when the SVC response time was short.

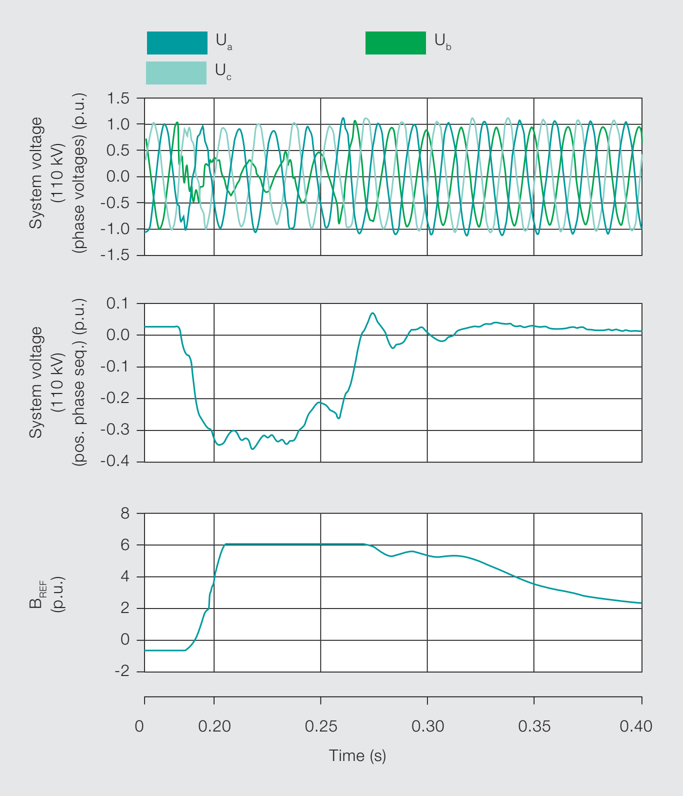
13 Temporary over-voltage: 1.4 p.u. over-voltage; TSC blocking at the 4th current zero crossing



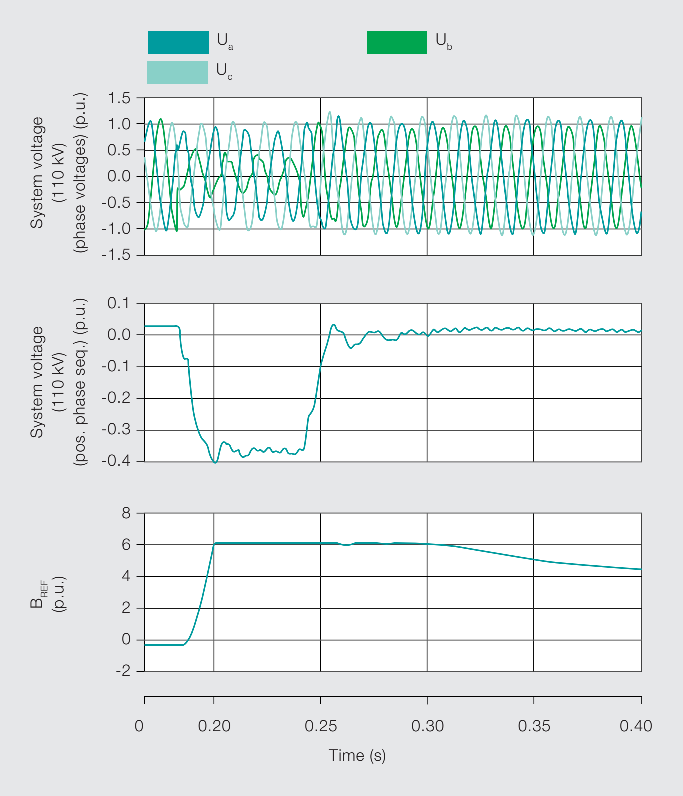

14 New TSC blocking function: over-voltage reduced to 1.1 p.u.; TSC blocking at the 1st current zero crossing.




15 TFR recording at Faisaliyah SVC




16 TFR recording at Al Madinah South SVC



## 17 Saudi SVC project

Several important conclusions can be drawn from the Saudi SVC project:
- Motor stalling or voltage collapse problems are evident in power systems with large induction motor loads such as those produced by the frequent use of air conditioners.
- SVCs provide efficient support for the positive phase sequence voltage during faults. The speed of induction motors can then be maintained at reasonable levels.
- SVCs must run at a high capacity during faults. The quicker the SVC response, the smaller the ratings needed. Very large ratings are required when the SVCs become active only after fault clearing.
- A short time rating is sufficient, ie, only a few seconds of operation is required.
- SVCs are robust and can run during faults and during fault clearing.
- The SVCs must be able to block TSCs immediately after fault clearing to prevent temporary overvoltages during light load situations.
- The typical SVC large-signal response time (from zero to full output) is 1.5 cycles with discharged capacitors.
- The typical SVC small-signal response time is 2.5 cycles for a strong power system, resulting in two cycles in the weak system without retuning.

Operational experience shows that the SVCs are efficient in supporting the positive phase sequence voltage during and following single-line-to-ground faults.

## Operational experience

Three line-to-ground faults were experienced in the grid system in the summer of 2008, ie, during the peak load season. Two of the faults were in the Jiddah area (Faisaliyah) ➔ 15 and one in Al Madinah ➔ 16.

The SVC responded quickly to the fault, and became fully capacitive in 1.5 cycles. During the fault, the system voltage was constant or even increased slightly. It was noted that the fault-free phase voltages did not drop much after the initial dip. At fault clearing the faulted phase recovered instantaneously. The SVC reduced its output somewhat (about 100 MVAr) and ran at 500 MVAr for about four cycles; thereafter it gradually reduced its output to about 200 MVAr during the next five cycles. It remained at this output throughout the recorded period of 30 s. It is interesting to note that the faulted phase did not fully recover to its prefault value within the 30 s time period.

At the time of the fault, the phase B to neutral voltage instantaneously dropped. The measured positive phase sequence voltage in the SVC dropped with a time constant of about 10 ms. This is the time needed for phase sequence separation and harmonic filtering. The voltage regulator went fully capacitive in just a little more than one cycle. The time for the main circuit to run fully capacitive on all three phases was 1.5 cycles. The delay is due to the sampling effect – each phase can only start conducting on the zero crossing of their voltages. The TSCs started to conduct with a minimum of transients. At fault clearing the TSCs remained in service. The currents still contained a minimum of transients.

The fault in Al Madinah was similar to the one in Jiddah ➔ 14. The major difference was that the fault in Al Madinah occurred at 8:45 a.m., compared with 4:45 a.m. in the previous case. At this later time the load in the system was heavier. There was larger asymmetry during the faults and one of the fault-free phases was depressed, while the third one remained unaffected. The recovery was somewhat slower and the SVC stayed at full output for a longer period of time. It should be noted that full capacity was needed only during some tenths of a second.

Operational experience shows that the SVCs are efficient in supporting the positive phase sequence voltage during and following SLG faults. The SVC reaction time is short and the TSCs behave correctly during the disturbances. Supporting the positive phase sequence voltage most efficiently means running all SVC phases fully capacitive. The disadvantage is that also the fault-free phases may be raised above the maximum continuous voltage. Such a rise could saturate the SVC power transformer; however, this problem did not develop as a result of the fault ➔ 17.

### Grid stability with fast SVC response

Power systems with large induction motor loads, such as air conditioners, present a high risk of voltage collapse or motor stalling, particularly in conjunction with faults. They tend to consume large amounts of reactive power, which should not be transmitted over large distances, since this increases the risk of voltage drops and causes active power losses. To maintain voltage stability in such circumstances SVCs can be used. To provide voltage stability in the grid, particularly in conjunction with fault situations, a fast dynamic response from the SVC is essential. There is typically a trade-off between dynamic response and the Mvar rating, ie, an increase in dynamic response offers possible savings in Mvar ratings while attaining the same favorable impact on grid stability.

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**Footnote**

2 Point on wave is a kind of synchronous switching where there is an active choice of moment in the cycle when the switching is made.

**Reference**

[1] Al-Mubarak, A. H., Bamsak, S. M., Thorvaldsson, B., Halonen, M., Grünbaum, R. (2009, March). Preventing voltage collapse by large SVCs at power system faults. IEEE PSCE, Seattle, WA.