# A matter of FACTS
## Deliver more, high quality power

Power and productivity
for a better world™

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# Contents

# Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| DC | Direct Current |
| EAF | Electric Arc Furnace |
| EHV | Extra High Voltage |
| FACTS | Flexible Alternative Current Transmission Systems |
| HV | High Voltage |
| HVDC | High Voltage Direct Current |
| HYBRID STATCOM | SVC Classic+STATCOM |
| kV | Kilovolts |
| LF | Ladle Furnace |
| MMC | Modular Multilevel Converter |
| MOV | Metal Oxide Varistor |
| MSC | Mechanically Switched Capacitor |
| MSR | Mechanically Switched Reactor |
| MV | Medium Voltage |
| MVA | Megavolt Ampères (Apparent power) |
| MVAr | Megavolt Ampères Reactive (Reactive power) |
| MW | Megawatt (Active power) |
| OH | Overhead Line |
| PCC | Point of Common Coupling/Connection |

PWM ................................ Pulse Width Modulation

POD ................................ Power Oscillation Damping

PSS ................................ Power System Stabilizer

SC .................................. Series Capacitor

SC .................................. Synchronous Condenser

SIL .................................. Surge Impedance Loading

SSR ................................ Sub-Synchronous Resonance

STATCOM ........................ Static Synchronous Compensator

SVC ................................ Static Var Compensator

SVR ................................ Syncronous Voltage Reversal

TCR ................................ Thyristor Controlled Reactor

TCSC .............................. Thyristor Controlled Series Capacitor

TL ................................... Transmission Line

TOV ................................ Transient Over-Voltage

TRV ................................ Transient Recovery Voltage

TSC ................................ Thyristor Switched Capacitor

UHV ................................ Ultra High Voltage

VSC ................................ Voltage Source Converter

WTG ................................ Wind Turbine Generator

# 1. Reliable Power Supply for Everyone

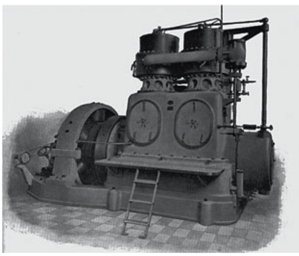
## 1.1 How Our Dependency on Electricity Arose

**WHEN WE PRESS** a button or turn a switch we expect the lamp to light up, the motor to start or the heat to come on. If this does not happen we get irritated. Our accustomed behaviour pattern has been disrupted.

Just 150 years ago we would have been amazed if pressing a button had had such results. We have become so dependent on electric power that we cannot even imagine a life without it.

But, someone may object, we have oil and petrol, after all. Our cars will continue to run and oil would still heat our houses.

Without electricity we would not be able to manufacture the cars of today and the oil-fired boiler would not work. In this manner electric power and control are woven into every aspect of our present-day existence. Why electricity in particular; why not water, oil or gas? There may be several reasons for this, but two of the most important are that electricity is clean and easy to distribute. However, this has not always been the case.



*Steam engine with a generator.*

### Electric power – an expensive, roundabout way?

When electric power was introduced in the latter half of the nineteenth century, there were certainly a great many who had doubts about its future. Why should a simple steam engine giving direct drive be replaced by a steam engine with a generator, copper wires that were dangerous or even lethal to touch, and an electric motor? Installation of such equipment presupposed that electric power was to be generated in the immediate vicinity of the user. The direct current that was generated had such a low voltage that long conveyance distances were out of the question. The number of electricity subscribers a power station could have were naturally limited by this.

For example, the electric power for the arc lighting at important cities' railway stations was generated in a steam power station located just a few blocks away. Electricity was an exclusive and mostly inaccessible form of energy.

*EHV (Extra High Voltage) made it possible to transmit electric power over vast distances without excessive losses.*

## Modern Electric Power

How could this exclusive form of energy become one of the most important building blocks in our modern society?

Around 1880 modern electric power was born. At several places around the world "three-phase alternating current" was introduced. Alternating current made it possible to step up voltage to a high level and down again to a low voltage that could be easily handled. The high voltage made it possible to send electric power several kilometers without excessive voltage drops and losses and the toy railway at home on the kitchen floor no longer needed to have 110 volts between its rails. Suddenly it was obvious how superior the principle of electrical distribution was.

It was no longer necessary to produce electricity in the neighbourhood. Electric power could be produced where it was convenient and the source of energy was to be found. Hydro-electric power could be utilized by other consumers than saw mills and paper mills, and coal-fired power stations could be placed alongside harbours and coal pits. Electricity was available for everyone.

## Available and Thus in Demand

The ready availability of electric power is not merely due to the fact that it can be distributed in a simple manner; it is also easy and convenient to use. Insert a plug into the wall socket and the motor will run, the lamp will light up or the electric heater will glow. If oil is to be converted to corresponding forms of energy, unwieldy and evil-smelling machinery and arrangements are necessary. It is true that the electric motor can in some cases be replaced by an internal combustion engine, the heater by an oil-fired boiler and the lamp by a paraffin lamp, but petrol-powered vacuum cleaners and washing machines are not the sort of thing we would like in our homes.

Its easy availability has made us completely dependent on electric power. We now insist on access to electricity all the time.

## 1.2 Efficient Transportation of Electricity

### A National Grid that is Dependable

Today our lights will not go out because a power station has stopped producing electricity. Other power stations in the nation-wide grid, or electrical network, increase their production, and if that is not enough, we import electricity from our neighboring countries.

However, electric power cannot yet be stored in a cost effective manner. Instead, we have to supply our grid with power from a number of production units. If a sufficient number of power stations are linked in an electrical network, the grid itself can be regarded as a source of power, apparently independent of the individual power stations.

This safety of electric power delivery is however not free of charge. In large, complex power systems, with many and varying kinds of power sources, and also many and widespread kinds of loads, disturbances can occur in a number of ways, due to which grid stability and availability cannot always be taken for granted. To optimize the availability and cost efficiency of the grid, intelligent devices such as FACTS (Flexible AC Transmission Systems) may be required, to keep voltages stable and power quality in accordance to valid Grid Codes, as well as keep power transmission losses at a minimum at all times.

In the FACTS family, SVC (Static Var Compensators), STATCOM (Static Synchronous Compensators) and SC (Series Capacitors) are all available to achive these improvements.

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## 1.3 A Modern Power Supply Network

**SWEDEN IS A NORTHERNLY** situated, highly industrialized country. Both these factors make it very dependent on energy.

Our imports of fossils fuels are insignificant. The major part of our electric energy needs we cover through hydro and nuclear power, a very favourable energy mix from an environmental point of view.

*Electric transmission replaces road tankers wheeling up and down our far-flung country with about two million loads a year.*

## Oil Or Electricity

If we had neither nuclear nor hydro-electric power, we would have to replace these by burning gas, oil or coal. We would need to bring in a medium-sized supertanker each day to our harbours. In order to distribute this quantity of oil to industries and households, road tankers would have to wheel up and down our far-flung country with an extra two million loads a year.

All this energy is today transmitted in the form of electricity in high-voltage lines and cables. Electric power transmission is a real boon, and not only to the environment.


Source: Svenska Kraftnät

# 2. Keeping the Network Stable

## 2.1 A Fragile Distribution Network

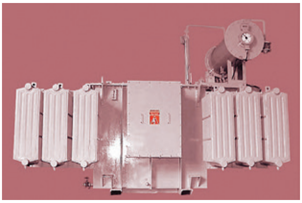
**ADAM B. BROWN ENJOYED** his new life without doubts and worries about electrical blackouts and with the positive atmosphere that nowadays characterized his town.

Even the approaching storm did not make him worry. He knew that nothing would interrupt the supply to his computer and with a steady office lighting there was nothing to remind him of of the days of insecurity a year ago.


*The yellow smoke from the black chimney was embedding the town.*

Yes, it was a dreadful time for the town. They all suffered from the weak electricity supply.

The only days when everything worked in an acceptableway was when the local power station was running, but those days you could not go out as the yellow smoke from the black chimney was embedding the town and the noise made it impossible to have a normal conversation within several blocks of the station. Finally, one and a half years ago, the environmental authority closed it down.



*Increasing the voltage in town by means of the transformer's tap changer was not a good idea...*

After that, the town's energy supplier introduced measures that would "definitely" solve the problems.

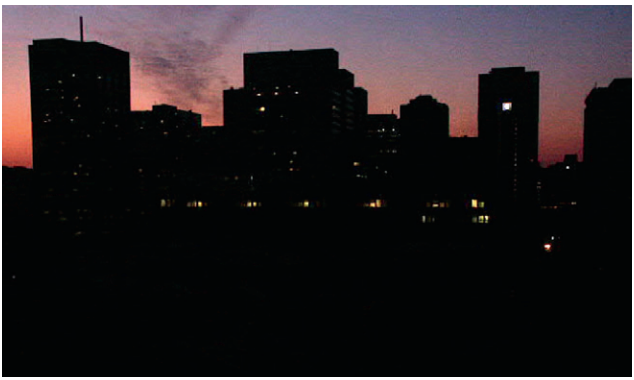
The first measure was to increase the town's voltage by means of the transformer's tap changer. At first the result seemed to be great. The city's lightning became clear and bright. After a few days however, a neighboring factory increased their production for a big order that they had received. This caused a total blackout of the whole area. The factory's production was severely disturbed and most of the material that was in production at the time of the blackout was turned to scrap.

At this time the electricity supplier understood that there was a lack of reactive power. The kind of power that has never done any work, but has to be there so that work can be done.

Capacitors! We need capacitors. The electricity supply company had installed four large capacitor banks at the incoming switch yard. Again the voltage was fine and the network seemed to be strong enough to supply the factories around the town with the electric energy they needed.

The bliss did not last, however. Not this time either. There were complaints from a process industry some miles from the town, that their equipment tripped. When the capacitor banks were switched in and out they had generated severe voltage peaks. The capacitor banks had to be switched in when the city woke up in the morning and out when it went to sleep in the evening.

*A severe blackout had switched off the town again.*



Another, and the worst disappointment came with the storm over the neighbouring mountains. At the time for the storm, the town's network was heavily loaded by factories and air conditioners and one of the external lines tripped out due to a lightning stroke. A severe blackout had switched off the town again.

Now the Town Council had met and a stormy discussion took place on whose responsibility it was and how to find a definite solution to the problem. The Town's future was actually at stake, as there would not be any new industries settling down in an area where the electric network wasn't reliable.

After some hours the discussions had calmed down and he, Adam B Brown, had got the responsibility to lead an investigation of the town's alternatives.

After having ruled out building a new line for both time and economical reasons, there had been two options left. Strengthen one of the feeding lines, and give the town a "super shock absorber" that could see to it that no disturbances would jeopardize the voltage stability.

*SVC works just like a shock absorber.*

He first encountered many suspicious minds but after pointing to results from other installations, the town council was convinced that the main feeding line could increase its capacity by 30 % by means of series compensation, and they had understood that the "shock absorber" for their town was something called SVC (Static Var Compensator) that really could save the town from blackouts at heavy disturbances.

So after all the doubts they had decided to do both. Capacity-increasing series compensation on the most important external feeding line and an SVC to maintain the local network stability.

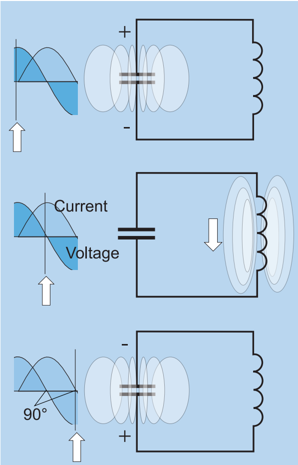
The telephone woke him from his pleasant daydreams.

The southwest region energy office had received the information that the steel works in the area was going to invest in a STATCOM device.

This was really good news. Now even the problem with flickering light in that area of the town would come to an end.

Adam B. Brown sipped his coffee and smiled.

# 2.2 Reactive power




*In the LC-cirquit above, the alternating between electric and magnetic energy makes the angular shift between voltage and current 90°.*

*Active power:*
*U • I • cos 90° = 0*

*Reactive power:*
*U • I • sin 90° = U • I*

### Reactive Power Has Never Done Any Work

Adam B. Brown's town in the last chapter was suffering from lack of controllable reactive power.

Reactive power has never done any work but without it, very little work can be done. Attempts to explain what reactive reactive power is, however can make the reader more confused than enlightened.

This is not because Reactive Power is a badly defined quantity, it is rather because it is a quantity that does not exist in our real world.

### Pure Reactive Power

An electrical circuit with a capacitance and a reactance can be brought into oscillation. The system alternates between energy stored as an electrical field in the capacitor and a magnetic field in the reactor.

The electric field is built up by a voltage over the capacitor. This voltage will drive a current through the reactor. When the electric field over the capacitor is neutralized all the energy is converted to a magnetic field in the reactor.

The current is maintained by this magnetic field until all the energy has been transferred to the capacitor as an electric field, but now with reversed polarity.

The system does not do any work, it just oscillates and will continue doing so infinitely if there is no resist-ance in the system. This is pure reactive power.

A very intuitive reflection on the above is that a capacitor can build up a field supported voltage and an inductor can drain this voltage in order to build up a magnetic field.

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# 2.3 Reactive Power Compen-sated in Different Ways

**A TRANSMISSION LINE'S** voltage level, stability and phase balance can nearly always be maintained by designing the network with an ample margin. However, a network like this would be poorly utilized in normal service and costs would be unnecessarily high.

In reactive power compensation we have a means of control with which we can deal with a number of events in a better manner. By adding and removing reactive power, we can get a heavily loaded network to cope with load variations and other events without any deterioration of the functionality of the grid.

When alternating current is transmitted and converted into mechanical work, reactive power is consumed. If there is a shortage of reactive power, the voltage will drop. If there is a surplus the voltage will rise. The network voltage can thus be very effectively controlled by means of reactive power compensation.

### Dynamic Shunt Compensation provides the grid with controllable reactive power

- The voltage drop over long lines can be kept at a manageable level and voltage variations due to load variations daily as well as yearly can be minimized.
- Sudden over-voltages can be mitigated.
- Voltage collapses can be prevented.
- Lack of symmetry between phases can be compensated.
- Distribution networks can cope with local disturbances caused by complex industrial loads as well as network faults.

### Series Compensation

A transmission line has an inductive reactance, which can be reduced if a capacitor is connected in series with the line.

With series compensation we can achieve:

- Improved transmission capability
- Reduced need to add reactive power
- Reduced risk that generators and other synchronous machines lose synchronism in the event of a serious short circuit in the grid. (Angular stability)
- Improved load sharing between parallel lines.
- Improved grid voltage stability.

# 3. Voltage Stability

## 3.1 A Major Load Area

**NORWAY IS KNOWN** for its hydro power resources. Important resources at the location of some large hydro power stations does not mean, however, that Norway's power network doesn't suffer from stability problems far out in its distant, radial branches.

In such locations increasing demand or a disturbance like a loss of an important power line can lead to voltage collapse. An SVC continuously supervises the voltage level and if need be, quickly restores it.

### Voltage support enables increased power transfer over the grid

As a result of large power demanding industry development in central Norway, the demand in the region has increased dramatically and is expected to grow further. The power import capacity to the region has previously been limited by the risk of voltage collapse. As a remedy, two SVCs (Static Var Compensators) were commissioned in the grid in 2008. With the installation of the two SVCs, the power import capacity to the region has increased by 200-400 MW, depending on the operating conditions.

The SVCs, each rated at -/+ 250 Mvar, were installed at Viklandet and Tunnsjödal substations in the 420/300 kV power transmission network

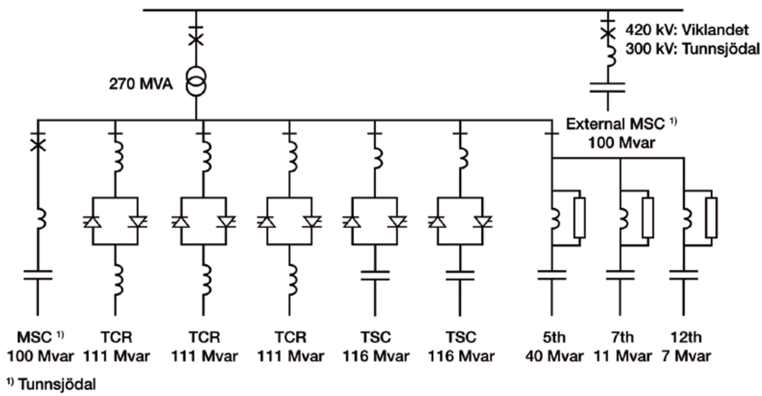
## Main SVC design

The two SVCs are identical in their design, with a 6-pulse configuration with three TCR branches (Thyristor Controlled Reactor), each rated at 111 Mvar, two TSC branches (Thyristor Switched Capacitor), each rated at 116 Mvar, and an array of harmonic filters tuned to the 5th, the 7th, and the 12th harmonic frequency. The overall filter rating is 58 Mvar. The purpose of the SVCs is to perform system control tasks as follows:

- Steady state voltage control at Viklandet 420 kV bus as well as Tunnsjödal 300 kV bus (to be upgraded to 420 kV).
- Enhance damping of system electro-mechanical oscillations by means of POD (Power Oscillation Damping) based on active power measurements (Tunnsjödal SVC).
- Control of an external MSC (Mechanically Switched Capacitor) in the substations. This will reserve a dynamic SVC range to be utilized for system contingencies.

## Power Oscillation Damper (POD)

There are several local-area as well as inter-area power oscillation modes in the Norwegian power system. The Power Oscillation Damper of the Tunnsjödal SVC is equipped particulary to damp a mode with Norway oscillating against the Nordic system at 0,5 Hz.



# 3.2 Old Synchronous Condensers became Silent

**THE POWER SUPPLY** for San Francisco is a typical example of a network that has been built out in many steps comprising generation units within the area and various transmission lines and cables connecting to and from the Greater Bay Area.

*Picture of San Francisco Golden Gate bridge*

In recent years San Francisco has suffered from severe power supply disturbances and studies have shown that the area's current transmission infrastructure is insufficient to accommodate anticipated load growth over the near future. As a result of the studies, a number of alternative solutions have been considered:

- Do nothing and live with the disturbances.
- Add means to stabilize and optimize the network at all different kinds of load and supply situations.
- Build an HVDC submarine link to support the area.
- Build new AC lines

As the area needed a solution quickly, the second alternative was the solution to go for. A key component in the work to stabilize and optimize the network was SVC.

*A Rotating Synchronous Condenser is a synchronous machine that is powered from the grid. It has no physical load and performs both as a generator and absorber of reactive power in the grid.*

Reactive power compensation was not a new means to control the grid voltage. Rotating synchronous compensators had been in use for many years in Newark and Potrero, but as wear as well as the environmental demands made the old, noisy compensators obsolete they were successfully replaced by Static Var Compensators.


*Totally the SVC in Newark, together with the mechanically switched capacitor banks controlled by the SVC, can deliver 425 MVAr and automatically, in a few seconds, switch over to consume 100 MVAr.*

## 3.3 Near Downtown Generation could Shut Down

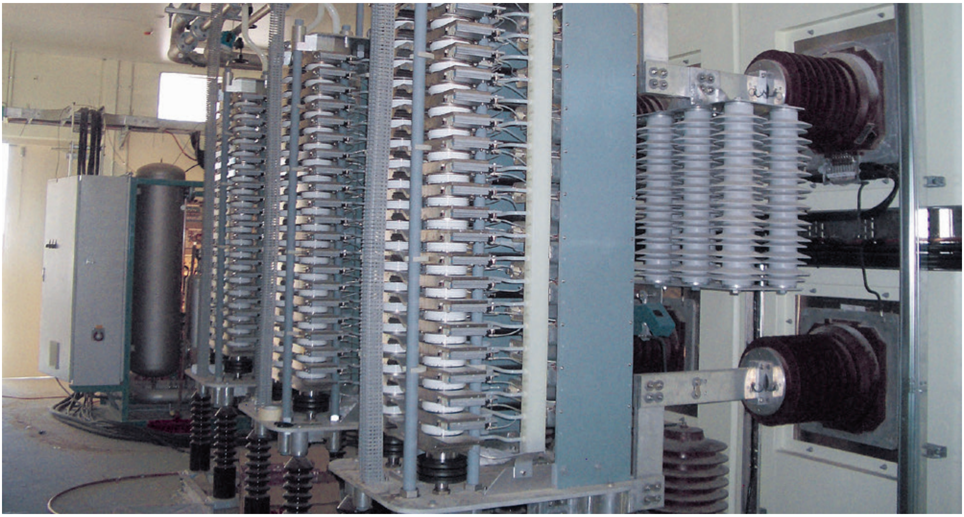
**FOR ENVIRONMENTAL CONSIDERATIONS** Austin Energy had to decommission their old oil and gas-fired power station near downtown Austin. When doing so Austin Energy had to secure the voltage level in the area by some other means. They had to stabilize the voltage on the transmission system feeding the city. In fact that had been the main reason for keeping the Holly power station in operation in spite of the plant's detrimental environmental impact.

In this situation the realistic options were a conventional SVC with extensive dynamic control capacity or a compact STATCOM system. In the urban environment of Austin City, ABB's STATCOM system SVC Light had important advantages. A STATCOM system delivers the same voltage stabilizing effect on the network as a larger SVC system. In addition, the STATCOM system does not need any space-consuming low frequency harmonics filters. All this means that the plant is small enough to be housed in a neat building. As this building is screened all electromagnetic disturbances are eliminated.

## 3.4 An effective option to building a new line

### A cost and time effective option to a 330 kV grid expansion

Power consumption is increasing at a considerable pace in Western Australia due to the resources boom and the associated population increase. Western Power, owner and operator of the grid infrastructure, was studying various options to accommodate increasing levels of power transfer from independent generating facilities in the south-west without destabilising grid voltage levels that may have led to voltage collapse.



*Thyristor valve*

A number of options were considered, including:

- Deferring enhancement of the Network that would require additional generation to be located in the metropolitan area.
- Installing a new 330 kV transmission line, this would have been at a high cost and would have taken a considerable time due to environmental approvals and construction period.
- Installing capacitor banks and synchronous condensers. This did not meet the requirements and was too expensive.
- Installing a Static Var Compensator (SVC).

## SVC: the optimum solution

The SVC alternative was considered the most appropriate, as:

- It met the required network load growth (connection of approximately 525 MW of new generation in the region without compromising system security)
- It was possible to implement within the required time frame
- It was the most cost effective and practical solution.

The SVC, located at the Southern Terminal Station is rated at 132 kV, 100 Mvar inductive to 200 Mvar capacitive (-100/+200 Mvar) and designed to manage grid voltages following an outage of a 330 kV transmission line. It maintains voltage stability, provides flexibility for transmission equipment outages and balances the increased flow of energy entering the network from new generators.

## Meeting the increased energy demand

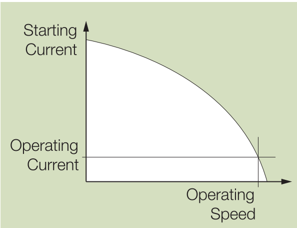
The SVC at Southern Terminal has enabled Western Power to meet the state's increased demand for energy in a timely and cost effective manner by optimising the existing infrastructure for both publically owned and private generators. It has created greater capacity for them to supply electricity to the network and maintained a reliable and quality of power supply for Customers.

As the SVC stabilizes the voltage on the network it has alleviated voltage disturbances to homes and businesses in the southern area of Western Australia. The more secure power supply enables greater levels of productivity for industry and business across Western Australia.

Installing the SVC has deferred the need for a 330 kV line which would have taken up to seven years to implement and resulted in land clearing for hundreds of kilometres for the line easement. The installed SVC and other associated work cost less than 20 per cent of the cost of building a 330 kV line and saved approximately four and a half years of project time.

# 4. Reliable Power Transmission to Every Corner of the Network

## 4.1 Introduction




*Induction motors require a starting current, which may be 6 - 8 times higher than the operating current.*

**A LINE THAT IS** to transmit electric power over long distances cannot do this without suffering losses.

Power losses always occur when we transmit current. Transmitting alternating current, a lack of reactive power can give rise to important voltage drops.

A small deviation from nominal voltage is often acceptable, but even that can cause long-term consequences for the service life of electric motors for instance. If the deviation increases too much, there could be a potential risk for voltage collapse.

### Preventing and Reducing Risk for Voltage Collapse

By voltage collapse is meant that the voltage drops so much that induction motors in the grid stall. A direct restart is impossible unless the grid circumstances are changed since the motors that have stopped require starting currents, which may be 6 - 8 times higher than the operating current.

The result would be an even greater drop in voltage, and the collapse could spread to an even larger part of the grid.

A voltage collapse can be caused by one or more of the following circumstances:

- High transmission reactance
- A supply line drop-out
- Insufficient capacity to supply reactive power
- The load has a large share of asynchronous motors
- Automatic tap-changers on distribution transformers
- Excitation limiters on synchronous machines

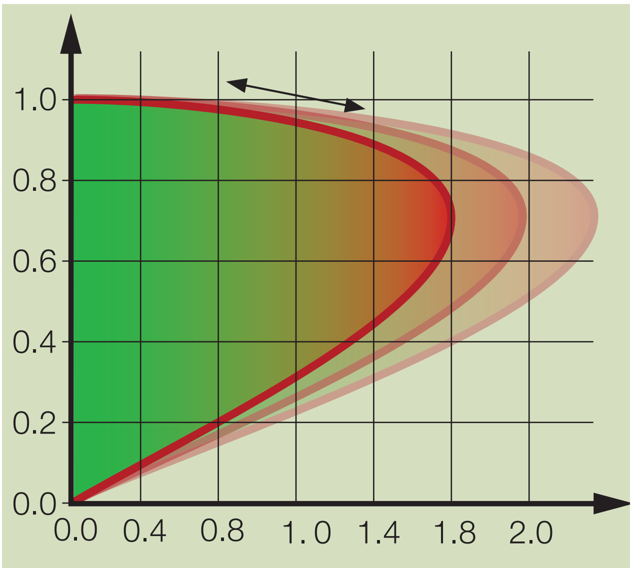
When a voltage collapse occurs, depending on the causes, it can take from fractions of a second up to half an hour before the normal value of the voltage is re-established.

The voltage drop can be compensated by adding reactive power. The reactive power can be added at various locations and using different kinds of devices.

If there is a risk of a collapse, but one which develops slowly, mechanically-switched shunt capacitors are generally sufficient.

If the anticipated collapse is estimated to take place at a faster rate, thyristor-controlled SVCs are the obvious choice.

**Network Compensation in Normal Service**

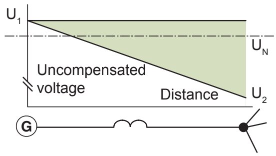


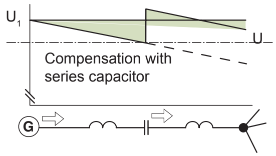

*PU diagram or "nose curve". The upper part of the curve is the working area of the transmission system. The bifurcation point (tip of the nose) represents the point of no return.*

*Often the transmission system is operated down to a voltage of some 95 % of rated voltage. From this working point, the distance down to the bifurcation point is what is left to cope with contingencies.*

*By means of FACTS, the curve can be stretched out, as shown in the figure, thereby allowing for increased transfer of power.*

# 4.2 Long Lines get Shorter




*When alternating current is transmitted in long lines two different kinds of voltage drops arise: active drops due to the line's resistance, I x R, and the reactive drops resulting from the line's reactance, I x X.*

*With series compensation of the line, the voltage profile over the line is improved.*

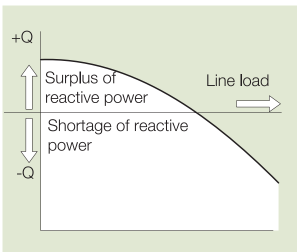
**WHEN NETWORKS WERE** local it was natural that the generator provided the necessary reactive power, but when power networks were developed into country-wide grids, the transmission of the reactive power, which then had to "find room" alongside the active power in the long lines, became a source of major losses and problems.

With the help of rotating synchronous compensators and shunt-connected capacitors, reactive power started to be added locally to an ever greater extent.

Today reactive power compensation is an important means of control in order to maintain a constant and stable voltage in all parts of a network. The need for reactive power in a transmission line depends on the line's length, voltage, current and frequency.

When the current increases, the need for reactive power increases. If, on the other hand, the voltage is high, the line's own shunt capacitance will contribute reactive power and if the voltage is sufficiently high and the current low, the line will produce a surplus of reactive power.

An EHV (Extra High Voltage) line that is not series compensated is not often used for a load much higher than that when the reactive power balance is zero, i.e., when the line's inductance consumes as much reactive power as is generated by the line's own shunt capacitance (Surge Impedance Loading, SIL).




*A long transmission line which is lightly loaded produces a surplus of reactive power.*

*Vice versa, a heavily loaded line creates a deficit of reactive power.*

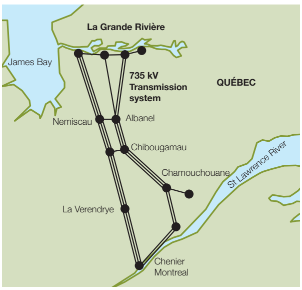
# 4.3 Parallel Lines

**BOTH CANADA AND THE USA** are industrialized countries generating power, but also consuming it at an enormous rate. In Canada the generating capacity has to be matched with the energy requirements for heating households and offices during the cold winter months. In the U.S.A., where it is warmer, it is often the struggle of all the air conditioning equipment against the heat of the summer that determines power needs.

Thus, in summer, Canada has a surplus of energy that can be seized upon by all the power-hungry air conditioners in the U.S.A. In return, the U.S.A. can export power to Canada in the winter months. This is one of the reasons why the limited amounts of transmission networks built across the border between the two countries are so intensively utilized.

## SVCs for long distance transfer of environmentally friendly power

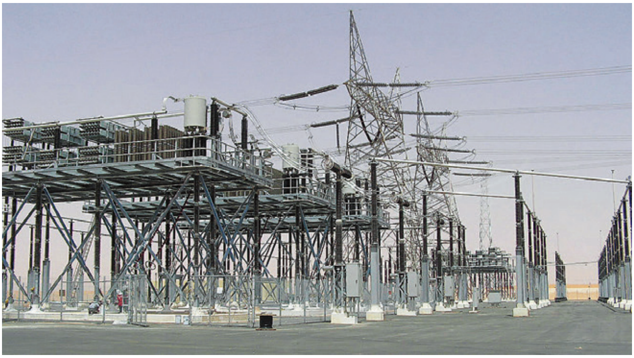
In Canada, Hydro-Québec is operating a total of 12 Static Var Compensators (SVC) in its 735 kV transmission system, commissioned over the period 1984-2016. The 735 kV grid transmits a total of 15000 MVA of environmentally friendly hydro power over six parallel lines from the generating stations along La Grande Rivière at James Bay down to the Montréal area some 1000 km to the south. The SVCs have overall ratings between 440 Mvar and 660 Mvar.




Their purpose is to:

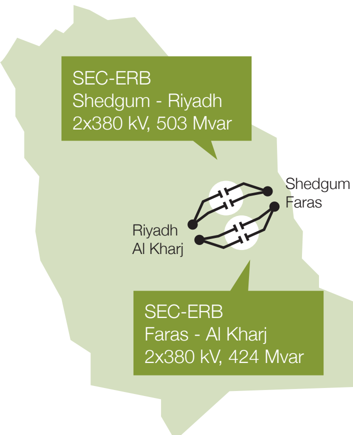
- Regulate and control the 735 kV voltage under normal steady-state as well as contingency conditions;
- Provide dynamic, fast response reactive power following system contingencies such as network short circuits and line and generator disconnections;
- Enhance the transient stability of the grid by maintaining system voltages during large disturbances.

# Increased grid transmission capability from Eastern to Central Saudi Arabia



Saudi Electricity Company (SEC) is operating four Series Capacitors in the 380 kV power transmission corridor interconnecting the Eastern Region with the Central Region of the national grid. The Series Capacitors have the task of increasing the power transmission capability over the interconnector, in order to meet the growing demand for electric power in the Central Region.

The power corridor is about 300 km long and consists of two parallel, double circuit 380 kV lines, Shedgum-Riyadh and Faras-Al Kharj. Each of the totally four lines is series compensated at the midpoint.




Series Capacitor ratings:

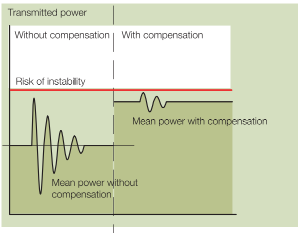
- Shedgum-Riyadh - 2 x 503 Mvar, 380 kV
- Faras-Al Kharj - 2 x 424 Mvar, 380 kV

With the series capacitors on line, the stability limit of the 380 kV circuits reaches about 2.600 MW under double contingency criteria. Installing series compensation was found to be the optimum solution to increase the power flow from the eastern to the central region by about 500 MW.

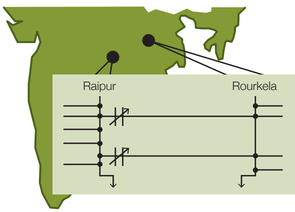
## Minimizing line circuit breaker stress

To minimize transient recovery voltage (TRV) stress on line circuit breakers in conjunction with faults on the lines, the series capacitors are bypassed before the actual opening of the line circuit breakers. This is enabled by means of active communication between line protections and the Series Capacitors.

# 4.4 Damping of Power Oscillations (POD)




*If disturbances in the network result in such large load variations that there is a risk of instability, the mean power transmitted must be lowered. With TCSC, the stability limit is raised.*




## Steady State Stability

Steady state stability implies that a network that includes several generators permits these to maintain synchronous speed without subjecting the rotors to oscillation. The stability limit is the maximum power that can be transmitted with synchronous stability. This figure is often the limiting factor for a line's or a power system's transmission capacity.

It is true that instability may arise spontaneously if the load is very high, but the stability limit is often set at a considerably lower value. The stability limit is often established according to how heavily a network can be loaded without jeopardizing stability in the event of a short circuit.

Power Grid Corporation of India Ltd (PGCIL) has installed two Thyristor Controlled Series Capacitors (TCSC) on the Rourkela-Raipur double circuit 400 kV power transmission interconnector between the Eastern and Western regions of the grid.

The length of the interconnector amounts to 412 km. The TCSCs provide damping of power oscillations between the regions, which would otherwise have limited the power transfer over the interconnector.

# SVC for damping of power oscillations in a 400 kV interconnector

A Static Var Compensator (SVC) rated at 300 Mvar inductive to 300 Mvar capacitive is operated in the 400 kV La Ventosa substation of the CFE (Comisión Fédéral de Electricidad) power transmission grid in Mexico. Among other tasks, the SVC is required to provide damping of active power oscillations over a 400 kV interconnector between Mexico and neighbouring Guatemala.

The SVC is located adjacent to a large wind farm cluster, with a generating capacity close to 2.000 MW at the time of commissioning the SVC. The SVC is also required to provide damping of active power oscillations between the wind farms as well as between wind farms and the grid.

The SVC consists of two thyristor controlled reactors (TCR), each rated at 175 Mvar, two thyristor switched capacitors (TSC), each rated at 125 Mvar, and three harmonic filters, rated together at 50 Mvar.

### Power oscillation damping

Active power oscillations can appear in the grid system (local as well as inter-area oscillations) in the range 0.1 Hz - 2 Hz. The task of the SVC is to damp out such oscillations. After the power oscillations have vanished, the SVC automatically goes into voltage control mode.

For flexibility, three identical POD regulators are implemented, each with different input signals:

- Bus frequency
- Active power sum of the transmission lines in the SVC node
- Active current sum of the transmission lines in the SVC node

**Degraded modes of operation**

The SVC can be operated even with individual reactive power branches temporarily out of operation. The control system is then activated according to the changed characteristics.

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## 4.5 Subsea Cable Transmission

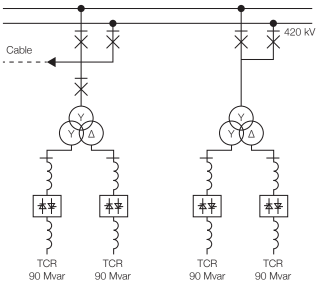
**Long Underground and Submarine Cables**

A ground or submarine cable produces considerably more reactive power than an overhead line for the same voltage. Consequently, considerable amounts of reactive power have to be accomodated, especially at low load.

A common solution is compensation by means of shunt reactors. By utilizing thyristor control of the reactors (TCR), the transmission voltage can be kept at its nominal value, regardless of any load variations of the transmitted power.

### Dynamic voltage control of 420 kV submarine cable grid

In 2008, re-commissioning of the Hasle SVC in 0stfold County in south-eastern Norway was performed after thorough rehabilitation and modernization of the installation which had been in operation in the country's 420 kV power transmission grid since 1981. The SVC, rated at 0-360 Mvar inductive at 420 kV, has the main purpose of controlling the grid voltage adjacent to an oil filled 420 kV subsea cable across the nearby Oslo Fjord. The cable is part of a grid interconnecting the power transmission systems of Norway and neighbouring Sweden. The




interconnector, having an overall transmission capacity of approximately 2.000 MW in either direction, is a key facility for power exchange between the two countries.

The 420 kV line from Hasle to Tveiten consists of the 11.7 km subsea cable across the Oslo Fjord and 35.5 km of overhead line. The reactive power generated in the cable and the connecting overhead line is 355 Mvar. The SVC increases the power export capacity to Sweden, damps electro-mechanical power oscillations over the heavily utilized interconnector, and protects the submarine cable from Hasle across the Oslo Fjord to Tveiten against critical over-voltages in conjunction with switching operations or light loading of the cable. And vice versa, since the cable is located in a mostly heavily loaded area, the capacitive generation of the cable can be put to use by supporting the voltage during high load.

## Main SVC design

The SVC at Hasle consists of two Thyristor-Controlled Reactors (TCR), each rated at 420 kV, 0-180 Mvar inductive, and each TCR subdivided into two 90 Mvar branches. The branches are 12-pulse connected through a 180 MVA power transformer with its tertiary windings in Y/Δ.

One TCR unit is connected directly to the 420 kV station busbar and the other to the 420 kV line from Hasle across the Oslo Fjord to Tveiten. The units can operate independently, or the two TCRs can be run together.

# 5. Industrial applications: Demanding loads on the grid

## 5.1 Reactive Power Compensation in Industry

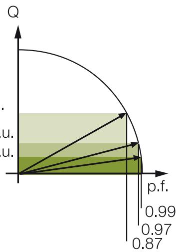
An example:

Permitted Reactive power consumption as part of subscribed power at:

<10kV: 0.5 p.u.

20-40kV: 0.25 p.u.

70-140kV: 0.15 p.u.




*The power factor is used to indicate the useful power content in the power supplied. Note that if the reactive power is 50% of the active power, the power factor (p. f.) is 0. 87.*

**HEAVY INDUSTRIES OFTEN** take their power directly from the transmission network, at 70 to 130 kV or even higher. Agreements with power utilities include a maximum takeoff of both active and reactive power. Additionally the utilities will also put limits on several power quality parameters such as flicker, harmonics and unbalance. If these limits are exceeded, a penalty fee is imposed, or in severe cases the industry might be forced to reduce or even stop its operations. Thus heavy industry can put a price on reactive power and power quality.

### Special Needs for Compensation in Industry

In the mining, and in the steel industry there are certain very special loads that require specially matched reactive power compensation.

Mines are often located at the end of long transmission lines, in weak networks, or even in island operation. This in combination with heavy mining loads create issues with both grid stability and power quality.

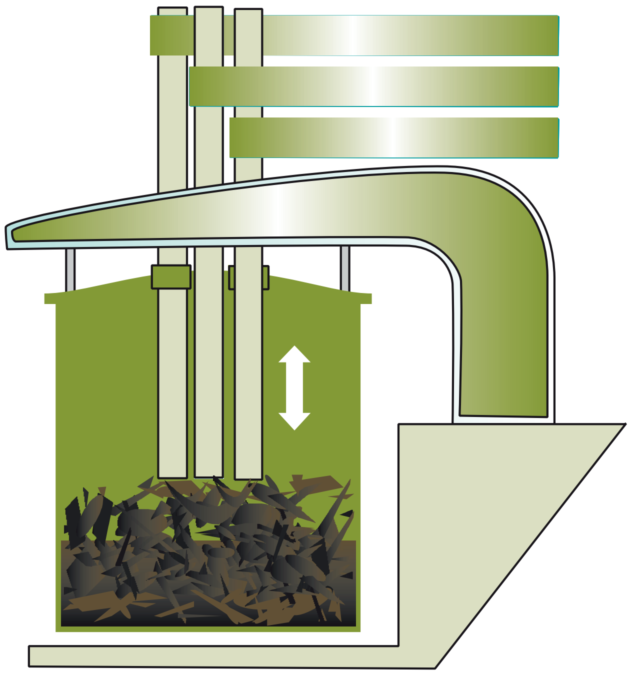
Electrical Arc Furnaces (EAF) require access to large amounts of reactive power. An EAF also gives rise to unsymmetrical loading and therefore has to be compensated phase by phase. The turbulent nature of the EAF also causes light flicker and other disturbances in the grid.

When an induction motor starts up, it can use 6 to 8 times more current than in normal operation, causing voltage dips. Industrial networks with large induction motors are therefore frequently equipped with special shunt-connected starting capacitors.

In addition, if the motors are sufficiently large and started sufficiently often in a weak network, thyristor-controlled compensation by means of SVC is often necessary.

Heavy industry is often a major consumer of reactive power and in an effort to compensate at the point of common coupling rather than load the line with the transmission of reactive power, compensation locally is arranged as far as possible.

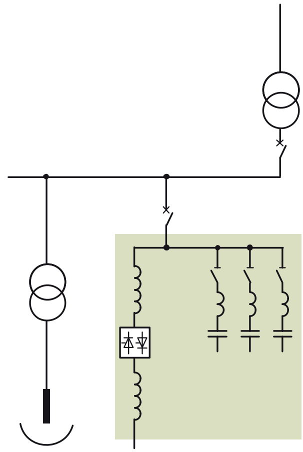
In process industries there is normally a reactive base load consisting of a very large number of AC motors. Within the steel industry, in addition, there are electric arc furnaces that consume a great deal of reactive power. An example of these is the arc furnace used to melt scrap.

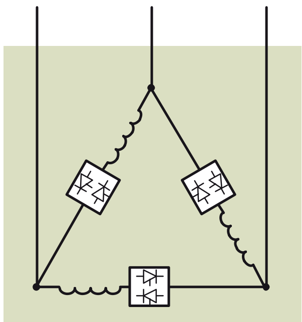


*In the arc furnace the electrodes are "short-circuited" when they are lowered into the electrically conducting scrap. When all the scrap has dropped down into the melt, the electrodes follow, and a new phase with more even loading commences.*

*In non-ferrous metallurgical industry, submerged arc furnaces are employed for extracting metals from raw materials. These furnaces are heavy reactive power loads, often requiring SVC to maintain a high and stable power factor, as well as mitigate voltage fluctuations, harmonics and phase imbalance at the point of common coupling.*

## 5.2 Increased Productivity in the Electric Arc Furnace



*The thyristor bridge in the SVC installation controls the total reactive power; it also distributes it between the phases and in a phase-wise manner for the sake of phase symmetry.*

**TO COMPENSATE FOR** the rapidly fluctuating consumption of reactive power of arc furnaces, an equally rapid compensating device is required. This is the task of the SVC. The purpose of the SVC is to:

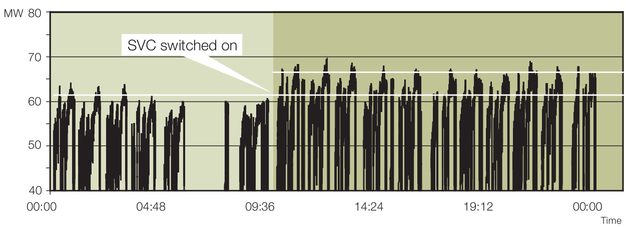
- Keep a good and stable power factor at the point of common connection, independently of the reactive power fluctuations from the furnace loads.
- Reduce flicker at the point of common connection to acceptable levels.
- Filter the harmonics generated by the furnaces.
- Stabilize the system voltage at the EAF load bus.

Stabilizing the voltage at the EAF load bus at a high level usually means an increase of active power into the furnace, compared to the case without SVC. This in turn opens up for increased productivity of the metallurgical process.

### An Example

A steel mill in western USA operates an electric arc furnace rated at 60 MVA. Thanks to effective compensation using SVC, the EAF voltage can be kept at a high level and the melting power can be increase to as much as 69-70 MW. This can be utilized for increasing the steel output, or for producing the same amount as before, but in a shorter time.

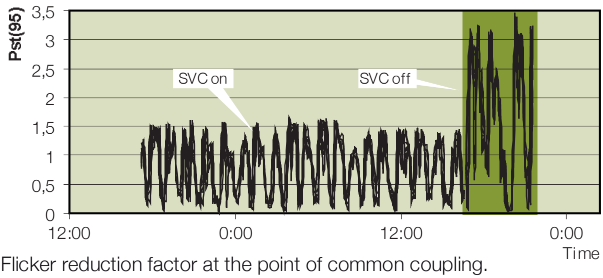
Since the melting time per tonne is reduced in this manner, the electrode consumption per tonne steel will also be lower. Specific losses will decrease, too. Money to be saved! Furthermore, a high and stable power factor at the 230 kV point of common coupling will enable a more favourable power tariff.




*Active power increase in electric arc furnace thanks to SVC.*

## 5.3 Flicker Mitigation

**THE SVC WILL NOT JUST** enable productivity increases and a decrease of specific process costs. It also looks after power quality in the feeding grid. This means that it is for one thing a flicker compensator, performing to decrease the flicker level at the point of common connection with the power grid. In our present case, flicker reduction is achieved by a factor better than two. Another function is as a harmonic mitigator, maintaining an acceptable total harmonic distortion level at 230 kV.




Flicker reduction factor at the point of common coupling.

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## 5.4 The Invisible Arc Furnace

**AN SVC LIGHT® RATED** at 33 kV, 0-164 Mvar capacitive has been installed in a steel plant in the United Arab Emirates for reduction of flicker emanating from the operation of an electric arc furnace (EAF), rated at 130 MVA, and a ladle furnace (LF) rated at 24 MVA. Flicker mitigation is called for due to the considerable size of the EAF in relation to the limited fault level of the feeding grid.

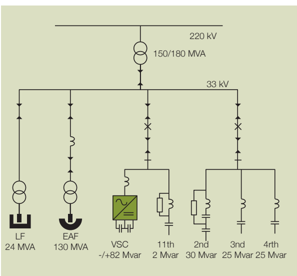
The steel plant takes its power from a 220 kV grid. The fault level varies between 4.800 MVA and 10.000 MVA, depending on grid conditions and winter/summer variations. Considering the substantial rating of the EAF, unless proper measures were taken, strong flicker could have been expected as a result of the operation of the EAF, particularly at minimum fault level of the grid. With the SVC Light operated on the 33 kV EAF bus, efficient flicker mitigation is attained, and the

Grid Code of the feeding grid is fulfilled for all operating conditions. A flicker reduction factor of 7 is achieved with the SVC Light in operation.


### Benefits of the SVC Light installation

With the SVC Light in operation, the following benefits are attained at the 220 kV P.C.C.:

- A flicker reduction factor of 7
- Acceptably low levels of harmonic distortion
- A high  and constant power factor, with no back-feed of reactive power into the grid
- Voltage variations as well as voltage imbalance kept at acceptable levels
- Grid reinforcements kept to a minimum




*Single-line diagram, furnaces and SVC Light.*

### Main circuit design

The compensated load is a joint operation of the EAF and LF. The type of charge of the EAF is 100% DRI (Direct Reduced Iron), continuously charged. For optimal flicker damping, the dynamic range of the SVC Light needs to be higher than the maximum reactive load power. For this application and taking into account the needed flicker reduction, a dynamic rating of 164 Mvar has been chosen.

## 5.5 Mining: Helping reap the rich mountain bounty

**FEEDING SAFE AND RELIABLE** power to mining plants can be a challenging task. Loads such as mine hoists, mining shovels, crushers, pumps, grinding mills, fans, conveyor belts etc are sensitive to fluctuations in the feeding voltage, thereby depending on secure, high quality power supply. At the same time, availability and reliability demands are high (production outages very costly). In terms of profitability the FACTS technology also contributes to a valuable increase in utilization of existing equipment. By investing in an SVC, an iron ore mine in Sweden enabled a double-digit percentage increase in production.

Mining complexes are often forced to operate in environments characterized by one or several of the following factors:

- Remote areas where power supplies are weak or inadequate
- Rough, inaccessible terrain, more or less unsuited for OH feeder line construction
- Island operation, relying on own generation only
- Extreme climatic conditions

Dips and sags are commonly caused by deficit of reactive power. Voltage dips may occur during attempts to start up more or less heavy equipment in a situation where the plant's power supply is inadequate, i.e. the fault level is insufficient for the purpose. The weaker the grid, the worse the situation becomes. This is a severe limitation on the plant's capability to perform, with more or less serious production limitations.

The picture is further complicated by modern industrial drives, harming the power quality of feeding grids, unless proper mitigating measures are taken. As mines get larger as well as more remote and complex, the need for voltage support becomes critical.

FACTS solutions have been proven in the field for more than 40 years and are particularly suitable in mining, with applications requiring rapid dynamic response, ability for frequent variations in output, and/or smoothly adjustable output, all contributing to an efficient mine process.

FACTS controllers keep the voltage levels stable, bringing benefits to grid owners as well as plant owners and operators as follows:

- Dynamic mitigation of voltage dips and fluctuations in feeding grids, thereby fulfilling Grid Codes as far as voltage variations are concerned;
- Dynamic voltage support of load buses, thereby supporting load operation even in cases of weak feeders;
- Improved process economy, where a high and stable bus voltage at all times means higher output, as well as more reliable operation with less outages and higher availability of the plant.
- Protection against over-voltages after load rejection of e.g. a large motor.
- Allowing simultaneous start-up and operation of several loads when the grid is weak.

**Iron ore extraction: an SVC case**

With SVC, stability and power quality are maintained in grids dominated by heavy and complex loads such as mining complexes. The SVC improves network stability and reliability, resulting in more efficient and cost effective mining processes, such as a much improved overall power factor of the plant, saving money on the power bill, as well as increased ore yield and higher refined product output through increased utilization of equipment. It also simplifies plant expansion, since more power can be transmitted over existing lines.

In 2009, an SVC was commissioned in the LKAB iron ore mine at Kiruna in the north of Sweden. The SVC, rated at 0-35 Mvar at 6.3 kV, has the purpose of improving power quality at the 145 kV Point of Common Coupling as well as inside the mine by reducing voltage fluctuations and harmonics. As a direct benefit, with the SVC in operation, the ore hoisting capacity has risen, as well, making the extraction process more efficient than before.

Due to the SVC, the voltage variations have been reduced from typically -/+ 10% down to -/+ 2%. An increase of hoisting capacity by 25-30% has been noted.

## Non-ferrous ore concentrating: an SVC case

Oyu Tolgoi is a copper and gold mine located in the southern Gobi Desert of Mongolia, jointly owned by Rio Tinto, Ivanhoe Mines and the Mongolian government. Production from an open pit and underground shafts is processed in a primary crusher and concentrator. The concentrate is transported to refineries located elsewhere. The site is remotely located, with an elevation more than 1100 m above sea level, and ambient temperatures reaching +40ºC in summer and below -30ºC in winter. At full capacity, the ore concentrate production is expected to reach 170.000 tonnes per day.

Two SVCs went on line in 2012 at the ore mine, each SVC rated at 100 Mvar (inductive) to 100 Mvar (capacitive) at 220 kV system voltage. The purposes of the SVCs are the following:

- Control and regulate the 220 kV mine feeding voltage under normal, steady state as well as contingency conditions;
- Provide dynamic, fast response reactive power following system contingencies such as grid short circuits and line disconnections.
- Enhance first swing stability by maintaining system voltages during large disturbances.

The SVCs are normally run in parallel, yielding a total reactive power range of 200 Mvar (inductive) to 200 Mvar (capacitive). For redundancy, each SVC is designed also to be able to operate individually.

## Series compensation: a case example

Series compensation is a well-established technology primarily used to reduce transfer reactance, in for example long radial lines going to mining complexes. The result is a significant increase in the transient and voltage stability in transmission systems, permitting transfer of more power to the load.

In sub-transmission systems particularly, (voltages typically in the range 66-145 kV), series compensation can be used to advantage for voltage improvement over radial lines. Reduced transmission losses as well as

power factor correction come as valuable byproducts. Typical applications are found in remote industrial areas where one or several plants are powered via long radial feeders.

Thus, a series capacitor was commissioned in the Hydro-Québec network for the purpose of achieving voltage improvement at the receiving end of a 200 km long line feeding power to a mining area at a voltage of 120 kV. The series capacitor, which is rated at 25 Mvar, eliminates the steady-state voltage drop along the line as well as the voltage fluctuations associated with start-up and operation of the large mining loads in the receiving end. As a result, a better quality voltage is secured both for the mines and for other consumers in the area fed from the same network as the mines.

## 5.6 Keep the Nickel rolling

**Nickel metal extraction**

SVCs are widely used in conjunction with electric open arc furnaces for scrap melting in steel making industry. In non-ferrous metallurgy, such as for production of nickel from ore concentrates, submerged arc furnaces are employed. Such smelters are characterized by fluctuating imbalance between phases, large and varying consumption of reactive power, and strong harmonic generation. SVCs come into the picture for voltage support, power factor correction and reduction of harmonics and negative-phase sequence voltages in the three-phase power supply.

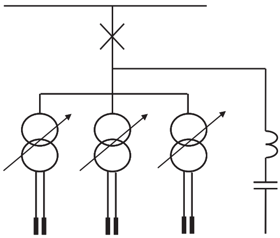
Voltage support of the feeding grid enables increased active power into the furnaces, and thereby increased productivity. Improvement of the power factor saves money on the power bill. Mitigation of load imbalance protects rotating machinery in and around the plant from overheating and mechanical wear. Together with the harmonic filtering, it also fulfils Grid Code demands in the feeding grid.

Nickel finds wide utilization as an alloy metal. For instance, one does not need to be a genius to realize that a substantial part of the metal content in a US

Nickel coin must be nickel. In fact, the nickel content is 25%. What is equally true is that many other coin types around the world also depend on nickel for their proper composition. In other words, nickel is a commodity to be reckoned with.

### An application example

SLN operates a nickel plant in New Caledonia. The plant smelter comprises three submerged arc reduction furnaces, rated totally at 130 MW. The smelter takes its power partly from a small regional power distribution grid, and partly from a local, steam based power supply. The submerged arc furnaces introduce considerable phase imbalance on the three-phase power supply. They are also a source of harmonics. At the same time, the local alternators have limited endurance to phase imbalance, lest they suffer added heating and consequent derating of life span.



*Nickel smelter furnace.*

*SVC hall in the SLN nickel plant.*

To limit the impact of phase imbalance as well as reduce the amount of harmonic distortion entering into the power grid, an SVC has been installed in the smelter, rated at 2 Mvar (inductive) to 66 Mvar (capacitive) at 63 kV. The SVC has been designed to limit the negative phase sequence current in the local generators and improve the power factor to ≥ 0.95. Special precautions were taken to avoid harmful interference between the SVC and existing harmonic filters, as well as between the SVC and the thyristor controlled furnaces.

## 5.7 Oil & Gas: Keep up the good flow

### Voltage support for pipeline drives

Pipelines for oil and gas depend on reliable and properly functioning pump stations, located at regular intervals along the lines. Pump drives require a stable voltage at all times, to avoid irregular operation, sagging, or even outages. At the same time, pipelines are often laid out through remote regions, far from populated areas, and subject to harsh environmental conditions. Power lines feeding the pump stations likewise run through desolate country, far away from roads, and with generation remotely situated. Furthermore, to save costs of infrastructure, power is usually transferred by means of single circuit corridors, at sub-transmission or even distribution voltage. The result is long, weak feeders, with low or even very low fault levels as well as poor or no redundancy.

*SVC for pipeline drive.*

Due to weak lines, voltages will fluctuate, and even minor faults may cause a voltage depression or a collapse. Simultaneously, pump drives, be they of AC or DC type, are voltage sensitive and depend on stable feeding conditions for proper functioning. This is where FACTS is coming in. With SVC, voltages are kept at their rated values for varying load conditions, including start-up of drives.

Alternatively, with Series Compensation, transfer reactances of the power lines are reduced, having a stabilizing effect on voltages. As alternatives to having to reinforce the power corridors by going up in voltage and/or building parallel lines, these are highly cost effective options. They are also time effective, as OH line work typically takes years, while a FACTS device can be in operation in 12-18 months from signing the contract.

*SVC supporting the feeder voltage of an oil field.*

**Improving the availability of oil & gas fields**

Production outages in oil & gas fields are very expensive, and must be prevented at all cost. To reduce production stops due to voltage drops or failures, SVC is a cost and time effective means of eliminating the cause of the problem. SVC will see to it that pump drives and other vital equipment get the voltages they require. The benefit will be stable, uninterrupted operation, enabling steady extraction of oil or gas, as required. At the same time, typically, increased feeder power transfer capability is enabled, thanks to the stabilized system voltage, facilitating possible expansion of the field.

Again, in case of long or very long feeders, Series Capacitors may be considered, as well, as a cost and time effective option to building new lines or going up in system voltage.

**Off-shore installations**

A case in particular is off-shore installations, where oil and/or gas are extracted below the sea floor and brought onto platforms located at sea for further transportation to shore. For powering pumps and other equipment on platform, expensive space can be saved by avoiding platform located power generation, and bringing power from shore through sea cables. The FACTS device required for voltage control will in the typical case be located at the point of common connection on shore.

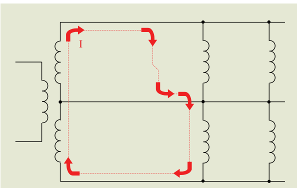
As should not be forgotten in cases like this, AC cable networks call for additional reactive power control. The overall scope of reactive power control should then encompass the platform just as well as the sea cable(s), to bring about a well regulated voltage and reactive power balance of the whole system.

# 6. Traction: Connecting the Railway to the Grid

## 6.1 Trains Take Power Between Phases

**THERE ARE A NUMBER** of different ways to feed traction systems with electric power. The most common scheme used in many electrification systems is to directly supply it by the fundamental frequency of the main power, i.e. 50 or 60 Hz. The transmission or sub-transmission voltages are then directly transformed by a power transformer to the traction voltage. The Auto-Transformer scheme is commonly used for high speed lines.

In the Auto-Transformer scheme, the traction winding is connected to ground in its midpoint. The other two ends of the winding are connected to the catenary wire and the feeder wire respectively. The grounded points are connected to the rail.



*Auto-Transformer Scheme.*

On the transmission network side the power transformer winding is connected between two phases. Frequently, two isolated rail sections are fed from the same feeder station. In this case the power transformers are connected between different phases. The traction load is often relatively large, today it is common with power ratings in the range of 50-100 MW (Pload) per feeding transformer. These loads connected between two phases on the mains will create unbalances in the supply system voltage. By rule of thumb the unbalance, $U_{unbalance}$, is equal to

$$U_{unbalance} = \frac{P_{load}}{S_{sc}}$$

Here, $S_{sc}$ is the short circuit power at the point of common connection. A common requirement is that the negative phase sequence voltage resulting from an unbalanced load should not exceed 1%.

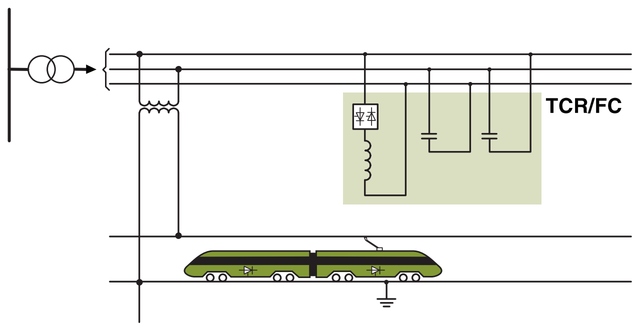
## 16 2/3 Cycles

In 16 2/3 cycles systems, a conversion system transforms 50/60 Hz. The conversion system loads the three-phase system symmetrically. Therefore restoring and maintaining balance between phases is not an issue. However, keeping catenary voltages high and stable, and limiting harmonic distortion, may still be issues to be taken into consideration when designing the system.

For 50 and 60 cycles, X (inductive catenary reactance) dominates over R (catenary resistance). For 16 2/3 cycles, X is diminished and becomes approximately equal to R. This makes voltage control along the catenary less critical. Still, in cases of weak feeding, with feeding points far apart, or with feeding from only one side, trackside, single-phase SVC for 16 2/3 cycles might prove useful, for dynamic voltage support and harmonic mitigation.

## Load Balancing by SVC

It can be shown that conventional SVC, perhaps surprisingly, also has the ability to balance active power flows




*Load balancing and reactive power compensation by SVC.*

even though it only contains reactive elements such as reactors and capacitors.

An SVC is a device providing variable impedance. This is achieved by combining elements having fixed impedances, capacitors, with controlled reactors. In the reactors, the fundamental frequency component of the current is controlled by thyristor valves, giving apparent variable impedance (TCR, Thyristor Controlled Reactor).

**Benefits From Utilizing FACTS in Rail Traction**

By means of FACTS the following important benefits can be brought about for power grids feeding railway systems, as well as for rail traction loads themselves:

- Dynamic balancing of non-symmetrical loads fed between two phases of three-phase grids;
- Dynamic mitigation of voltage fluctuations in feeding grids caused by heavy fluctuations of railway loads;
- Mitigation of harmonics injected into supply grids from traction devices;
- Power factor correction at the point of common coupling, with a high and stable power factor at all times, regardless of load changes and fluctuations;
- Dynamic voltage support of catenaries feeding high power locomotives, thereby maintaining traction capability despite weak feeding, without harmful voltage drops along the catenary;
- Dynamic voltage support of catenaries during outages of feeding points, thereby enabling adequate power infeed into locomotives, or, alternatively, with fewer infeed points required in the system;
- Dynamic voltage control and harmonic mitigation of AC supply systems for DC converter fed traction (typically underground and suburban trains).

**In all these cases, time as well as money can be saved by not having to invest in costly and time-consuming reinforcement of the railway feeding infrastructure such as building new transmission or sub-transmission lines, new power generation, and/or building new substations and infeed points.**

## 6.2 High Speed 1 – the Channel Tunnel Rail Link

**IN THE UK THE** 109 km High Speed 1 (HS1) Rail Link reduces travel time between London and Paris to about two hours, 20 minutes. Similarly, the link reduces travel time between London and Brussels to about two hours.

The railway system is designed for frequently operating high speed trains but also for slower freight traffic. Modern trains have power ratings in the range of 10 MW, thus the power feeding system must be designed for large fluctuating loads. The traction feeding system is a modern direct supply of 50 Hz, 25 kV voltage. The auto transformer scheme is used, giving low voltage drop along the traction lines. Direct transformation from the power grid via transformers connected between two phases is used.

### SVCs for Dynamic Voltage Support and Load Balancing

Each one of the three traction feeding points between London and the Channel tunnel is supported by Static Var Compensators. Three of these SVCs are mainly for voltage support and a fourth is for load balancing.

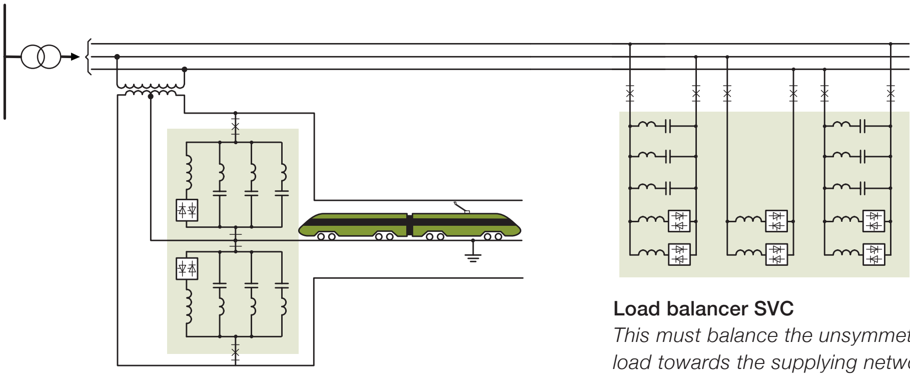
### Dynamic Voltage Support

The SVCs for voltage support are connected on the traction side of the power transformers. There are two identical SVC halves connected feeder to earth and catenary to earth. Each half SVC is rated at 25 kV, -5/+40 Mvar. These SVCs are single phase assemblies. The SVCs have three main purposes:

- Voltage support in case of loss of one feeder station
- Steady state power factor control
- Steady state harmonic mitigation

The prime reasons for the SVCs are to support the railway voltage and to maintain unity power factor seen from the super grid transformers during normal operation. This ensures that a low tariff for the active power can be used. Secondly, the SVCs are installed to mitigate harmonic pollution.

The SVC filters are designed not only to mitigate the SVC generation of harmonics but also harmonic generation from the traction loads. There are stringent requirements on the allowed contribution to the harmonic level at the connection points to the transmission grid from the traction system.



**Load balancer SVC**
*This must balance the unsymmetrical load towards the supplying network.*

**Trackside booster SVC**
*These SVC must provide the railway with single phase, reliable voltage even with one feeder station tripped.*

## Dynamic Load Balancer

Close to one of the feeding stations, the Cross Channel HVDC is located. The railway system is not allowed to contribute to the unbalance of the system voltage at this point. In order to fulfil this requirement, a load balancer has been installed, rated at 33 kV, -80/+170 Mvar.

The traction load of up to 120 MW is connected between two phases. Without compensation, this load would give about 2% negative phase sequence voltage. In order to counteract the unbalanced load, the load balancer (an unsymmetrically controlled SVC) was installed. The load balancer transfers active power between the phases in order to create a balanced load as seen from the grid.

# 6.3 An Underground Railway System


**THE 22 KV AND 11 KV** electrical distribution system provides power to the London Underground Ltd. network. London Underground has closed down its old gas/oil fired power plant as part of a programme for switching over to taking its power from the London public grid. As the Underground load consists to a great extent of diode rectifiers, special measures have had to be taken to ensure that distortion such as voltage fluctuations and harmonics does not reach out into the public grid to become a nuisance to other subscribers connected to the same grid.

## SVCs for Dynamic Voltage Support and Harmonic Filtering

Extensive system studies have been undertaken to map sources of distortion and identify proper measures to be taken. As a result, a total of six Static Var Compensators (SVC) and ten Harmonic Filters have been specified and installed in critical points of the London Underground 22 kV and 11 kV distribution grid.

Due to the scarceness of space and vicinity to underground stations, special measures had to be taken to lay out the hardware in a compact way as well as ensure adequate confinement of noise and magnetic fields. Thus, iron core reactors were utilized for the TCR, which offered a more compact physical design than air core reactors. Likewise, due to the close vicinity of the SVCs to populated parts of the Metropolitan area, magnetic clearance becomes an issue of importance. In this respect, iron core reactors are superiour to air core reactors, as well. The magnetic field is required not to exceed 1.6 mT at the boundary of any of the SVCs. Measurements have confirmed that this requirement is indeed fulfilled.

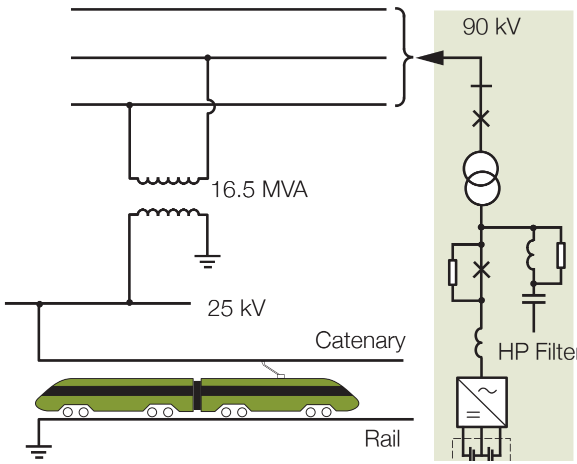
With the SVCs in operation, voltage fluctuations at the points of common connection to the public grid are confined to a specified maximum of 1%.

## 6.4 SVC Light for Active Filtering

**EVRON IS A SUBSTATION** in the French rail system fed from the national power grid. An SVC Light is utilized for dynamic balancing of unsymmetry between phases caused by the mode of traction feeding, single-phase takeoff of power from a three-phase grid. The SVC Light also performs the task of active filtering of harmonics generated by thyristor and diode locomotives. Active filtering is enabled due to the high dynamic response inherent in the SVC Light concept.

The reason for installing the SVC Light was to enable the fulfilling of the demands of the National Grid Code concerning voltage fluctuations, phase unbalance and harmonic distortion at the point of connection to the grid of the traction feeder. The alternative to the SVC Light was building a new transmission line, to increase the fault level of the power grid. In feasibility studies performed before the project, it was demonstrated that the SVC Light approach was less costly as well as less time consuming than building new transmission lines. Not having to build new lines was also very attractive from an environmental as well as concessional point of view.

The ability of the SVC Light to act as an active filter was also an attractive feature of this technical solution, as it eliminated the need for comprehensive installations of passive, shunt filter banks.




*Single-line diagram of the Evron 90 kV SVC Light Load Balancer*

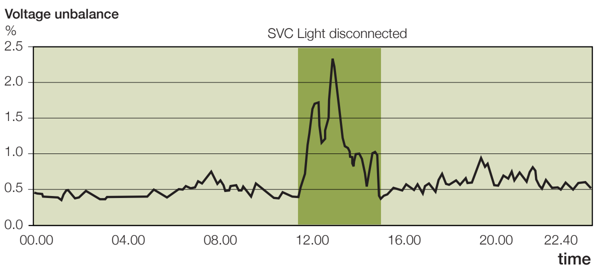
The Load Balancer is rated at 90 kV, 16 MVA. It is rated to accommodate a single-phase active load of ≤ 17 MW. Its task is to confine the grid unbalance at 90 kV as follows:

- ≤ 1% for $S_{SC}$ ≥ 600 MVA (normal network conditions);
- ≤1.5% for 300 MVA ≤ $S_{SC}$ ≤ 600 MVA (abnormal (N-1) network conditions).

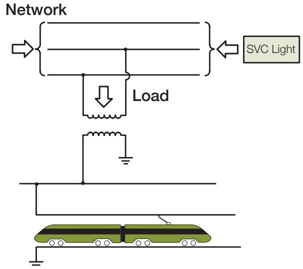
*A site view of the Load balancer*

## Load Balancing

Measurements performed since the installation of the SVC Light have shown a distinct improvement of voltage unbalance. With the SVC Light in operation, the voltage unbalance does not exceed 1%.



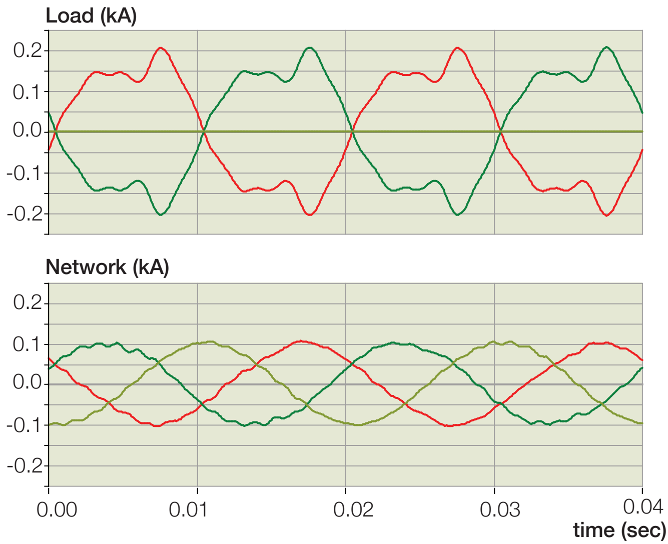

*Measurement of voltage unbalance.*




## Active Filtering

The active harmonic current suppression is based on generating harmonic currents in the SVC Light in phase opposition to the currents from the load.

This is done by modulating the converter terminal fundamental voltages by higher frequencies. Filtering performance and the order of harmonics possible to handle are strongly related to the converter switching frequency. In the Evron case, the active filtering is effective up to and including the 9th harmonic.




*In this upper graph, the total load current in all three phases at the point of common coupling is displayed, ridden with low order harmonics. The current in one phase is zero.*

*This lower graph shows the balanced and filtered currents in the three phases. Please note the three symmetric, 120 degrees displaced phase currents. What remains of distortion in the waveforms is some ripple emanating from the load and from the SVC Light.*

*Load balancing in conjunction with active filtering.*

# 7. Grid Integration of Wind Farms

## 7.1 Wind Farms

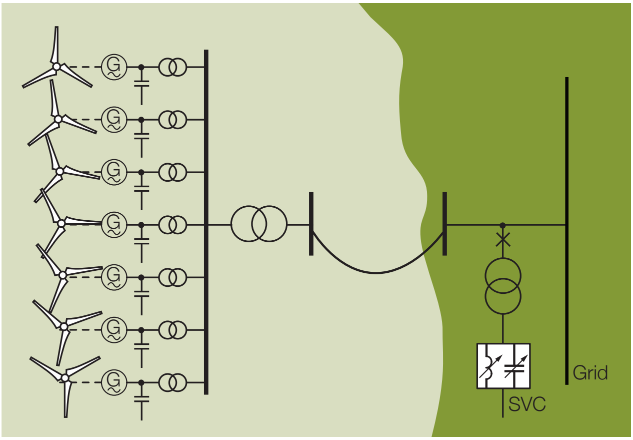
**THE DOMINATING KIND** of wind turbine generator (WTG) is asynchronous, this since it is robust and cost effective. Ideally, they need to be connected to very stiff grids in order not to influence power quality in a detrimental way. This is not the case in reality, however. Quite on the contrary, wind power is usually connected far out in the grid, on sub-transmission or distribution levels, where the grid was not originally designed to transfer power from the system extremities back into the grid.

*Wind turbines produce power as a function of the wind velocity. The need for dynamic voltage control and power factor control motivate equipment that can guarantee the power quality delivered.*

Comprehensive cable networks add another dimension, calling for additional elaborate reactive power control. The overall scope of reactive power control should encompass the wind farm just as well as the cables, to bring about a well-regulated reactive power balance of the whole system, answering to the same demands on reactive power regulation as any other medium to large generator serving the grid.

# 7.2 Grid Integration of Wind Farms

**WHEN A FAULT OCCURS** in a power system the faulty part will be disconnected from the system. Thus if the fault occurs on the feeder to which the wind farm is connected it will be disconnected. But, if the wind farm is connected to the non-faulted part of the system it is desirable that the wind farm stays connected during the fault. As soon as the faulty feeder has been disconnected the wind turbine generators should return into operation in order not to cause consequential loss of generation in addition to generating units connected through the faulty feeder. If consequential loss of generation should occur it may lead to a system collapse.




Therefore the wind farm connection must be designed so that the wind farm is capable of continuous uninterrupted operation during events when the voltage is being depressed during the time required to disconnect a faulty feeder ("fault ride-through capability").

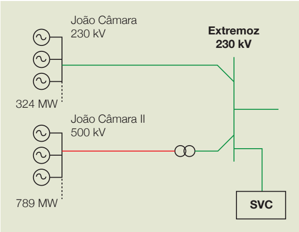
When the electrical network is weak the behaviour of the wind farm at network faults will be strongly improved by reactive power support at the grid connection point. An SVC can be provided as a reactive power source located close to the farm. This approach has a number of advantages:

- Full compensation of wind farm and cable in one system
- Fulfilling the national Grid Code
- Control of reactive power, even without the wind farm in operation
- Lower wind farm complexity
- High wind farm availability
- Improvement of dynamic voltage stability in the grid
- Wind farm plus cable plus SVC act together to offer MW and MVAr in the grid, just like any other major source of generation.

## 7.3 SVC for integration of wind power into a 230 kV grid

**A STATIC VAR COMPENSATOR** (SVC) rated at 75 Mvar inductive to 150 Mvar capacitive (-75/+150 Mvar) at 230 kV is operated at the Extremoz substation belonging to Chesf, a Brazilian transmission and generation utility located in the state of Rio Grande do Norte in North-eastern Brazil. This equipment is part of a transmission system expansion required to facilitate the integration of renewable energy from more than 1.000 MW collected from a multitude of wind turbine generators located in that region.

The wind energy is first collected at two major points in the grid, João Câmara and João Câmara II, and from there further transmitted to the National Interconnected System (NIS) through the Extremoz 230 kV substation and 500/230 kV transformers.



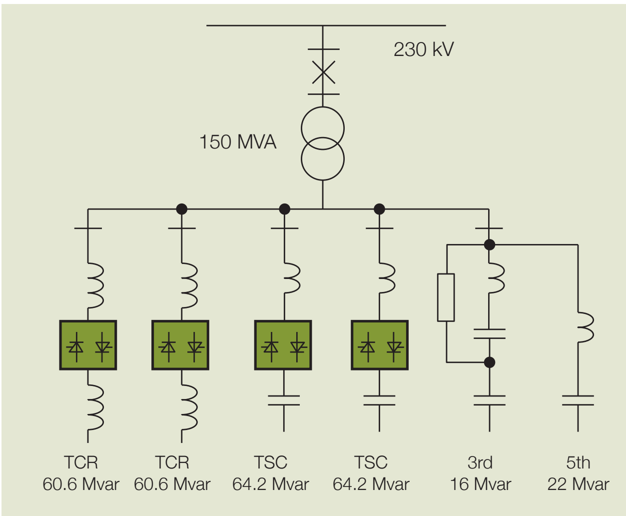

*Extremoz: Wind farms and feeding grid*

The Extremoz SVC has been designed to enable the following actions:

- To perform 230 kV busbar voltage control for steady state and contingencies;
- To provide dynamic, fast response reactive power following system contingencies (e.g. network short circuits, line and generator disconnections);
- To enhance first swing stability by maintaining system voltages within the established limits during large disturbances in the power grid.

The SVC comprises two thyristor controlled reactors (TCR), each rated at 60.6 Mvar, two thyristor switched capacitors (TSC) each rated at 64.2 Mvar, a 3rd harmonic filter rated at 16 Mvar, and a 5th harmonic filter rated at 22 Mvar. A step-down transformer rated at 150 MVA is connecting the SVC busbar to the 230 kV grid. By phase-angle control of the TCRs and switching the TSCs, continuously variable reactive power control is achieved over the entire SVC operating range (-75/+150 Mvar).

The SVC is controlled by a microprocessor based control system.




*Single-line diagram, SVC*

# 7.4 Integration of offshore wind farm

**Westermost Rough offshore wind farm**

The Westermost Rough Offshore Wind Farm is situated 8 km off the Yorkshire Coast, north of Hull and contains 35 turbines of 6 MW capacity, covering a total area of 35 $km^2$ and providing enough electricity to power around 200,000 UK homes per year.

A DRC (dynamic reactive compensation) plant was installed in the onshore substation of Westermost Rough. The DRC, which is connected to the tertiary winding of the supergrid transformer, consists of two containerized STATCOM PCS 6000 units each rated at 25 MVAr, 50 MVAr MSR (mechanically switched reactors) and a GIS (gas insulated switchgear) installed in a container. It provides dynamic reactive power compensation within a compact installation footprint, increasing the resilience of the power generated by the wind farms and helping comply with the stringent requirements of the Grid Code for voltage regulation and power factor performance.

*PCS 6000 (in middle) and MSR (to the right) for Westermost Rough offshore wind farm, UK.*

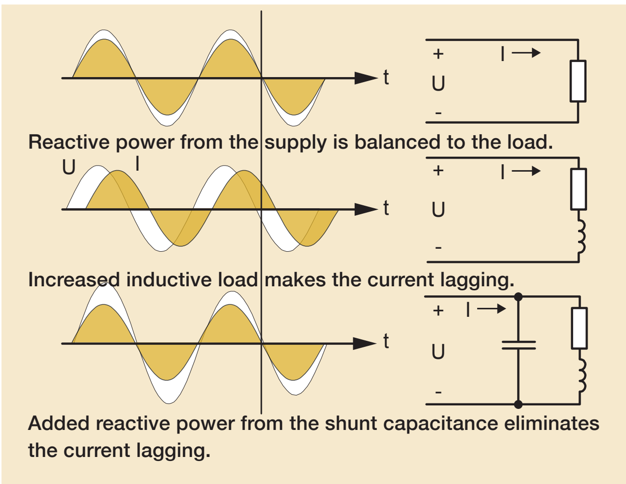
# 8. Static Var Compensation, SVC

## 8.1 Introduction

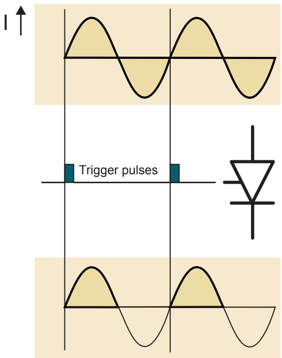
**REACTIVE POWER SHOULD** preferably be balanced locally at the point of consumption. However, this does not mean that the transmission network remains unaffected by local load disturbances. A sudden increase in load at a major consumer of active power leads to the line current increasing as well, and thereby the line's requirement of reactive power too. This load increase should be rapidly compensated, sometimes faster than the operating time of a circuit-breaker. In addition, installation of circuit breaker switched devices for providing an almost continuous control of reactive power is not an economical solution for HV systems. This may lead to the line becoming overcompensated when a single capacitor bank is connected in to the line. Based on this scenario the demand for continuous and fast control of generated or absorbed reactive power is identified.

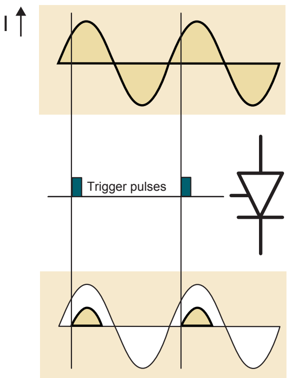
With ABB's SVC, reactive power can be rapidly controlled to meet sudden load changes and system disturbance, or carefully matched for minor adjustments to complex processes.

*With shunt compensation by means of SVC, the system current can be corrected so that it becomes in phase with the voltage.*



## 8.2 A boiling ocean becomes a mere ripple




*Through an electric pulse the thyristor can change over from insulator to conductor in a few microseconds. It is so fast that it can cut away part of the alternating current's half-waves so that the amount of current passing through the thyristor during a certain period is reduced.*

### SVC Fast But "Gentle"

In extensive line networks there are points where producers and consumers of electric power meet. At such Points of Common Coupling (PCC) the risk of disturbances is very great. For example, when a rolling mill starts up; a transmission line opens due to a lightning strike; an arc furnace is put into operation, etc.

SVC is fast enough to compensate the exposed lines with sufficent reactive power that the voltage changes are reduced to a mere "ripple".

In SVC the control is designed for adding as much reactive power as is necessary and it can furthermore be applied "gently".

SVC technology is based on fast switches that are not built up of mechanically moving parts, but of semiconductors. A semiconductor is a material that in certain circumstances conducts electric current and in others serves as an insulator.

In a few microseconds the thyristor can change over from being an insulator to being a conductor.

It is so fast that it can cut away a desirable part of the alternating current's half-waves, so that the amount of current passing through the thyristor during a certain period is reduced.

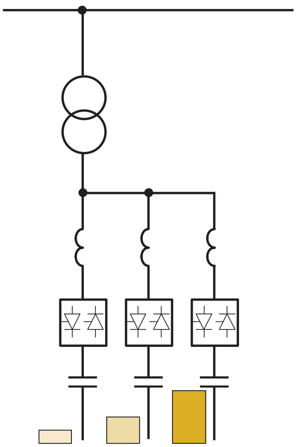
### Building Blocks for SVC

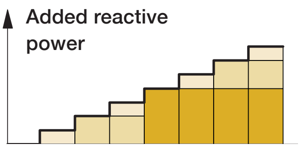
SVC is a concept consisting of various building blocks that can either be used individually or in more or less complex combinations. In this manner, a great number of combinations can be achieved; everything from a simple on/off switched capacitor to steplessly controlled systems with very sophisticated control features in order to provide and absorb finely adjusted reactive power.

As already mentioned, capacitors are used to add reactive power to a network.

# 8.3 Thyristor-Swiched Capacitors TSC

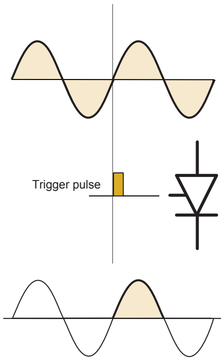
**TSC**






*By combining the connection of capacitor banks, more steps than the number of banks can be achieved. Here three banks give eight steps.*

**WITH THE HELP** of a thyristor bridge a capacitor bank can be switched in and out with an insignificant time-lag. By having several capacitor banks with different reactive capacities, the reactive power added can be controlled in steps. By combining the connection of the banks, more steps than the number of banks can be accomplished; two banks give four steps, three banks give eight steps, etc.

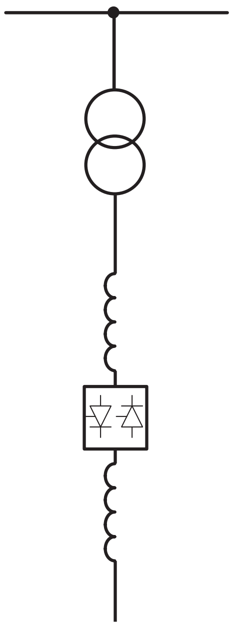



*To get smooth current inception, the thyristors are only fired when the voltage across the valve goes through zero.*

When a capacitor bank is connected to the network, a current surge occurs. To reduce this transient, a small reactor is always placed in series with the capacitor bank and the thyristor bridge. To achieve a smooth transition from a non-conducting to a conducting state, the thyristors are only fired when the alternating voltage across the thyristors passes through zero. This saves the grid from transients.

Using the semiconductor technology, it is possible to switch in/out the capacitor banks without any limitations on the time interval between conductive switchings. This cannot be achieved by using mechanically switched capacitor banks.

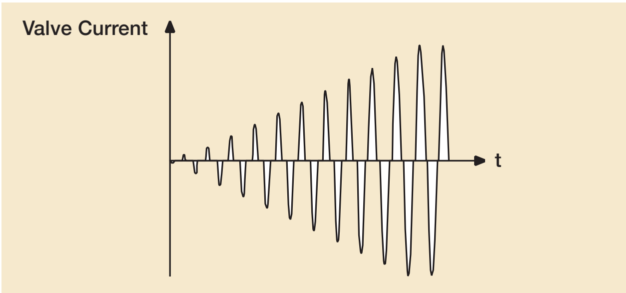
## 8.4 Thyristor-Controlled Reactor TCR



*To protect the thyristor valve from excessive short circuit currents it is placed between the two coils of the divided reactor.*

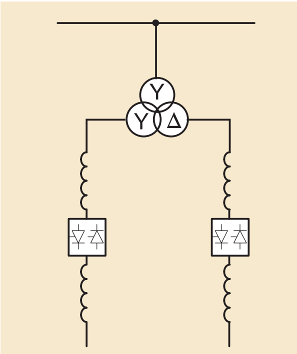
**A REACTOR CONSUMES** reactive power. The reactor is thus connected into the network when there is a surplus of reactive power in the system that needs to be absorbed.

The physics of a reactor does not permit any large current surges. It is therefore very suitable for placing in series with a thyristor valve. The combination of thyristors and reactors even permits the thyristor to be fired outside the current zero-crossings so that an arbitrary part of the current half-wave can be let through. With “smart” control equipment providing firing pulses at the right instant, the amount of reactive power that is




absorbed from the network can thus be controlled step-lessly. However, everything has its price. The thyristor’s distortion of the sine wave current leads to undesirable harmonics.

The harmonics give rise to extra heating in components like transformers and reactors. A three-phase delta -connected TCR reduces the harmonics content to the network, and if we compensate with a 12-pulse connection, subsequent harmonics are further reduced.



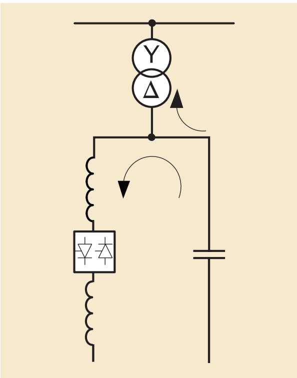

*A 12-pulse-connected TCR results in fewer harmonics in the network.*

## 12-Pulse Compensation Requires Some Explanation

By dividing up the compensation equipment through two secondary windings on the same transformer, one in phase with the primary side and one which displaces the phase by 30°, control using the thyristors can be made more "finely chopped", as twelve firing pulses are then spread over one period. This method is usually called twelve-pulse control and eliminates the need for the 5th and 7th harmonic filters.

## TCR Controlling Reactive Power

By combining the thyristor-controlled reactor with a fixed shunt capacitor providing a surplus of reactive power, reactive power can be continuously controlled. The thyristor-controlled reactor can continuously control how much reactive power generation or absorption is required by the network.




*Single line diagram showing how the reactive current, fed to the grid from an SVC, is controlled.*

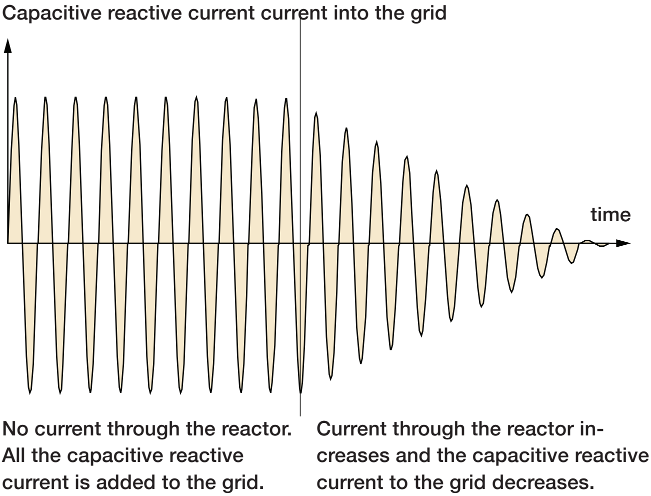
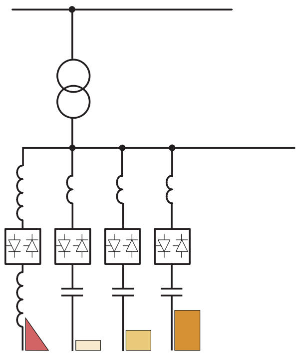



*Diagram showing a sequence where the reactive current, fed to the grid from an SVC, decreases. In this case, the reactor and the capacitor have the same rating, giving an overall dynamic range between zero and fully capacitive.*

# 8.5 Reactors and capacitors working together



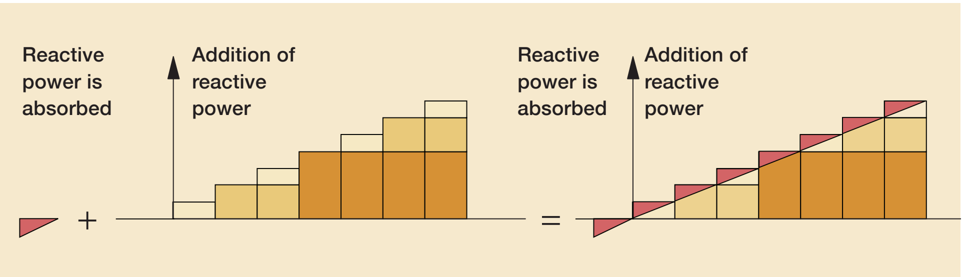
**USING THYRISTOR SWITCHED** capacitor banks, reactive power can be generated to the network in steps, and with the Thyristor Controlled Reactor (TCR) reactive power can be absorbed in a steplessly way.

By combining these two kinds of branches it is possible to add and remove reactive power steplessly.

The TCR and one or more Thyristor Switched Capacitors (TSC) are joined to the network.

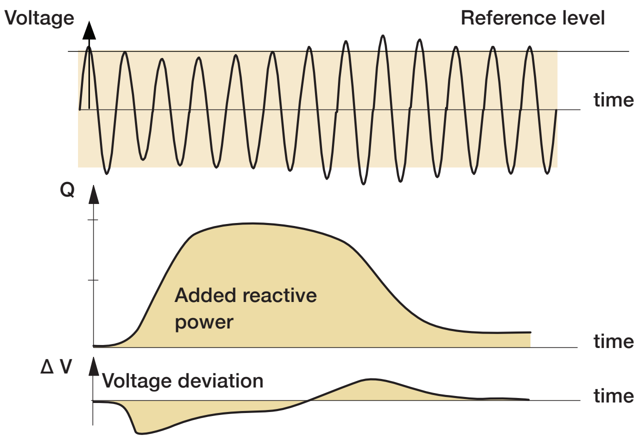
If reactive power is to be absorbed, the TSC thyristors are not fired and the TCR connected to the system does the whole job.

If reactive power is to be generated, one or more TSC branches are switched in. The connected capacitor banks provide as much reactive power as needed. Any surplus is removed using the continous control of the TCR so that the network is provided with exactly the right amount of reactive power.




*Within a couple of cycles (40 ms) SVC has succeeded in compensating for the sudden drop in voltage.*

*When the voltage later recovers, the reactive power surplus is rapidly eliminated and the voltage rapidly reassumes its original level.*



# 9. STATCOM / SVC Light

## 9.1 Introduction

**ELECTRICAL LOADS BOTH** generate and absorb reactive power. Since the load often varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage variations, voltage depression, or even voltage collapse. Similar to the SVC, the STATCOM can provide instantaneous and continuously variable reactive power in response to grid voltage fluctuations, enhancing the grid voltage stability.

Because of the high speed of response, it can also be dedicated to active harmonic filtering and voltage flicker mitigation. STATCOM systems can be comparatively compact; its footprint is normally smaller compared with a standard SVC due to its lack of harmonic filters. ABB has branded this high performance STATCOM concept SVC Light®.

Simplicity in topology and a minimum number of components enables a high degree of prefabrication and in-factory testing, leading to an overall reduction of project lead times and enhanced product quality.

Installing a STATCOM at one or more suitable points in the network will increase the grid transfer capability through enhanced voltage stability while maintaining a smooth voltage profile under varying network conditions. The STATCOM also provides additional versatility in terms of power quality improvement capabilities.

SVC Light is capable of yielding a high reactive input to the grid more or less unimpeded by possible low grid voltages and weakened network conditions while still providing a high degree of dynamic response. This is useful, for instance, for support of weak grids and to improve the availability of large wind farms under varying network conditions, as well as of grids loaded by a large percentage of air conditioners in hot and humid climates. If dictated by application requirements, SVC Light is excellent for hybrid solutions by connecting thyristor-switched reactors and/or capacitors in parallel.

## 9.2 Technology and principle

**THE STATCOM OPERATES** according to the voltage source converter principle (VSC), which together with PWM (Pulsed Width Modulation) switching of IGBTs (Insulated Gate Bipolar Transistors) gives it unequalled performance in terms of effective rating and response speed.

SVC Light can be seen as a voltage source behind a reactance. Physically it is built with modular, multilevel converter (MMC) blocks each operating on a constant, distributed dc voltage. It provides reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a voltage source converter (the grid will see it as a synchronous machine without inertia). This means that shunt capacitor banks and shunt reactors are not needed for generation and absorption of reactive power from the VSC, facilitating a compact design and a small footprint. See Figure 1 for an illustration of how the VSC operates in capacitive and inductive modes relative to the grid volage.

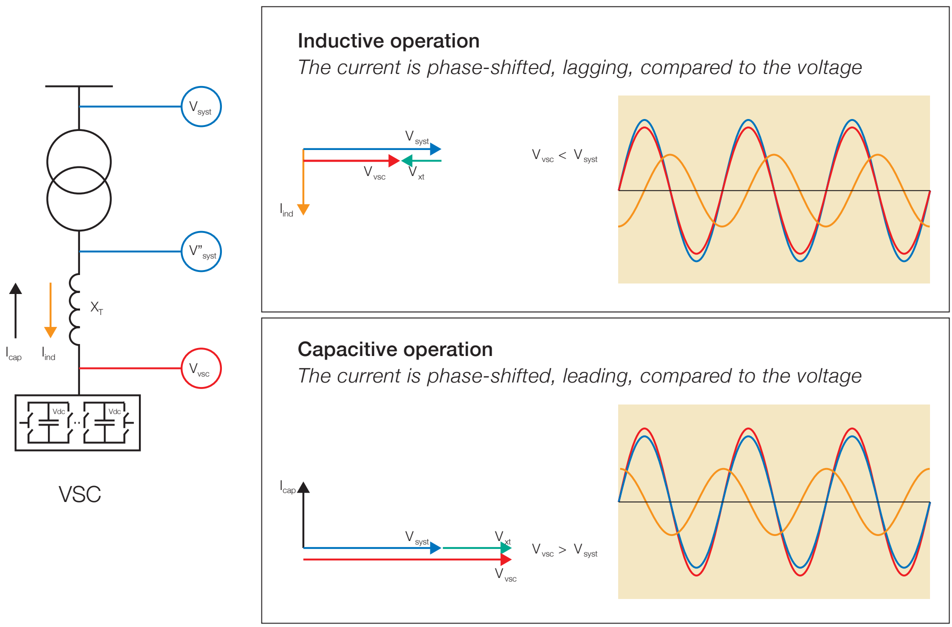


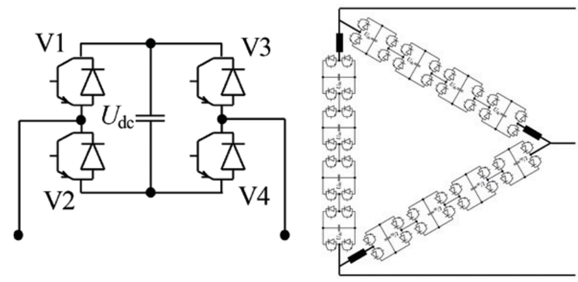

*Figure 1: VSC operation in inductive and capacitive modes*

When the voltage of the VSC (red) is less than the system voltage (blue) as in the top graph, then the VSC will be absorbing reactive power (i.e. operating inductively). On the other hand, when the VSC voltage is higher than the system voltage as in the bottom graph, the VSC will be supplying reactive power (i.e. operating capacitively). Note that in both cases, the VSC voltage is in phase with the network voltage. This ensures that there is no transfer of active power between the grid and the STATCOM. In reality, there must be a small amount of active power transferred in order to maintain the dc voltage of the VSC, but this can be neglected for broad explanatory purposes.

## MMC Technology

The multilevel chain-link solution is built up by linking H-bridge modules in series with one another to form one phase leg of the VSC branch. Figure 2(a) shows a single H-bridge with 4 IGBTs, and Figure 2(b) shows a configuration in which four H-bridge modules make up each of the three phase legs.

In Figure 2(a), there are three possible voltage levels depending on the switching arrangement of the IGBTs: +Udc, -Udc, and a zero-voltage. For the case with 4 modules connected serially as in Figure 2(b), there are 9 possible voltage levels: 4 in the positive direction, 4 in the negative direction, and a zero-voltage, depending on how the IGBTs are switched.



*a)* *b)*

**Figure 2: Multilevel chain-link converter setup**

*a) H-bridge with IGBTs (single phase)*

*b) 3-phase chain-link of H-bridges*

It is noted that the more modules included in the design, the smoother the waveform will be. The number of series-connected modules is primarily determined by the power rating of the STATCOM – the more modules, the more Mvar. Additional modules may be necessary depending on requirements for overvoltage ride-through and harmonic distortion. The waveform can be further synthesized by use of pulse-width modulation (PWM) to reduce the lower level harmonics present. Signals with PWM processing to match a sinusoidal reference can be seen in Figure 4 in the next section.

Practically, the implementation of an MMC converter-based SVC Light can be seen in Figure 3. Note that this implementation shows 8 modules in series as opposed to the 4 shown in the example above. Note that the dc link is distributed into several separate capacitors as can be seen in the single line diagram in Figure 2(b) and in the photograph in Figure 3. Each IGBT is inside of a modular housing which is made up of a number of sub-modules of enhanced Press-Pack type semiconductor chips which have passed rigorous failure mode and safety tests.

**Figure 3:**
*Modular H-bridge units, 2 stacks of 4 modules each*

# Advantages of modular multilevel converters

Early STATCOM installations used 3-level converters to build up the synthesized ac waveform. The use of an MMC solution over 3-level converters provides many advantages. Some important ones are described below.

### Absence of low-order filters

Because of the reduced harmonics at lower orders, it is possible for the majority of cases to exclude low-order filters from the design of a multilevel converter based on VSC technology. This is a great advantage as harmonic filter design can be cumbersome and is heavily dependent on the impedance of the network. This typically requires complex studies to be performed to evaluate harmonic impedances in the network and are only valid for the cases which are studied, which means that if there are major changes to the network the impedance will change and thereby effect the performance of the filters. STATCOM systems based on MMC technology

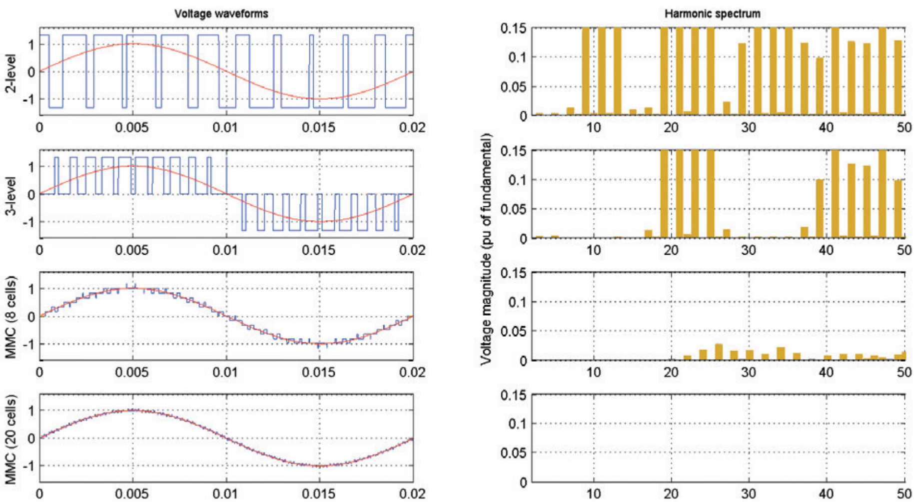



**Figure 4:**
*Left: Voltage reference waveform (red) and synthesized voltage waveform (blue)*
*Right: Harmonic voltage distortion for each type of converter in per unit of fundamental frequency voltage.*

are therefore more network-independent than 3-level STATCOMs or classical SVCs, which typically require low order filter design.

### Reduced footprint

In addition to the reduced complexity of design due to the absence of low-order filters, the reduction in required area (or footprint) for a STATCOM installation using MMC technology is an obvious advantage. Low-order filters require a large space on site, and this space is not necessary for most multilevel chain-link converter STATCOMs. In Figure 5, a typical SVC Light layout can be seen for a ±100 Mvar VSC.

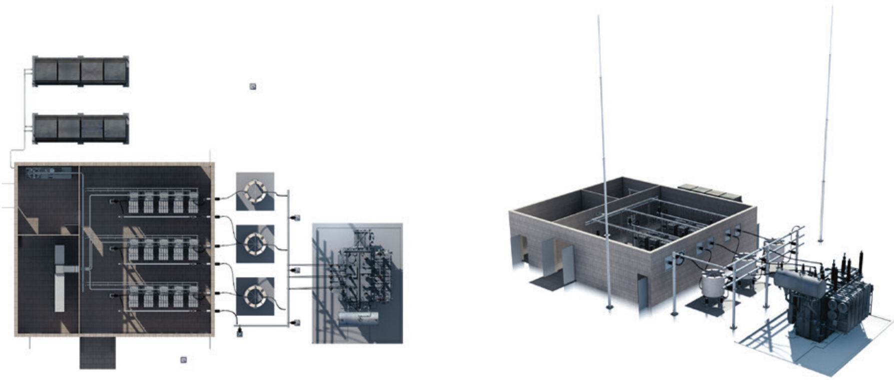


**Figure 5:**
*Example rendering of an SVC Light installation based on MMC technology (±100 Mvar )*

This layout would need to be expanded if using Thyristor Switched Capacitors (TSCs) and Thyristor Switched Reactors (TSRs) to create a Hybrid STATCOM solution as there would be space needed for the thyristor valves and the additional main components and bus work. Hybrid solutions are further discussed in the next section. It is noted that a similar sized classical SVC installation might require nearly twice the area of the VSC-only example in Figure 5.

## Modularity

Another advantage of the lack of low-order filters is the ability to standardize components in the STATCOM system due to less need to rate for harmonic currents and voltages. The valves, buildings, and topologies can all be modularized for specific market needs. Overall, this would reduce cost in the long run for markets which have continued demands for STATCOMs.

## Losses

The multilevel concept can use relatively low switching frequencies to produce a similar switching pattern as a comparable 3-level converter due to the fact that the series modules can stagger their switching patterns to come up with a higher “effective” switching frequency. This means that 10 modules switching in a staggered arrangement would have an effective switching frequency which is 10 times higher than that of the individual IGBT switching frequencies. The main impact of this is on lowering the losses of the STATCOM, as less frequent switching means less switching losses.

# 9.3 Topologies of STATCOM and Hybrid STATCOM systems

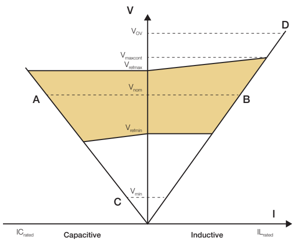
## VI diagrams

The V/I curve is a useful tool to see how a device will operate in the network, and is particularly useful to evaluate under- and over-voltage abilities of the various FACTS devices.

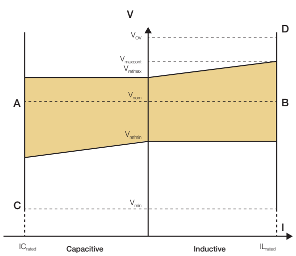
The classical SVC V/I characteristic is plotted in Figure 6(a). V/I diagrams for STATCOM and Hybrid STATCOM solutions can be seen in Figure 6(b) and (c), respectively. For undervoltages, the STATCOM has superior reactive power compensation as compared to an SVC for similar sizing at 1 pu voltage. This can be seen by the fact that the current remains constant at low voltages. For a classical SVC on the other hand, the current decreases linearly as the voltage decreases meaning that the reactive power will be less as compared to the STATCOM by a factor of V (per-unit voltage). On the other side, a classical SVC will outperform a STATCOM during overvoltage disturbances for similar sizing at 1 pu voltage (see the right-hand side of the V/I diagram). For each extra amount of voltage at the SVC point of common coupling (PCC), it will return more current and therefore more reactive power by a factor of V (per-unit voltage) as compared to a STATCOM. A hybrid, then, will combine the two VI characteristics to form what can be seen in Figure 6(c).

**Figure 6**

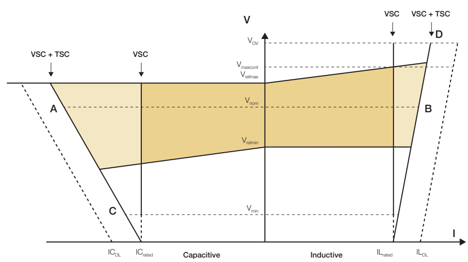
*V/I diagrams for SVC, STATCOM and Hybrid STATCOM*



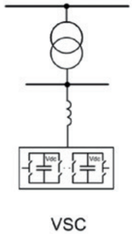

**a) SVC**



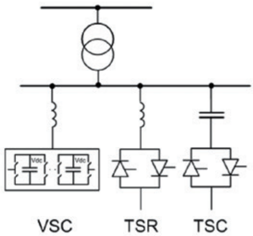

**c) VSC-only STATCOM**



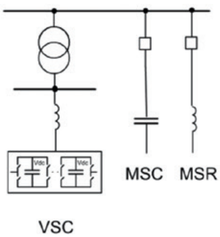

**b) Hybrid STATCOM**




a) STATCOM




b) Hybrid STATCOM
- VSC/TSC/TSR




c) Hybrid STATCOM
- VSC/MSC/MSR

**Figure 7:**
*Example of Hybrid STATCOM layouts.*

**Step-down transformer**

STATCOM or Hybrid STATCOM systems for transmission applications normally make use of a power transformer between the power grid and the medium voltage (MV) busbar. On this bus a VSC is connected in series with a coupling reactor. In addition, thyristor controlled reactors and capacitors or mechanically switched capacitors and reactors can be used. The voltage on the MV bus is typically in the range of 15-30 kV irrespective of the voltage level on the mains. A normal transformer turn ratio is 400/25 kV. This large ratio results in very high short circuit currents on the MV bus, frequently in the range of 50-90 kA (rms symmetrical).

**Thyristor switched shunt (TSS) Hybrid STATCOMs**

It is noted that while a VSC solution may be needed for a particular transmission application, in many cases (especially for very large Mvar operating ranges) the power from the VSC must also be supplemented by added thyristor-switched (TSC/TSR) branches to achieve the desired Mvar output. This creates what is known as a TSS Hybrid STATCOM solution, combining the technologies of SVC classic and STATCOM. In some cases, there could also be some required filter capacitive offset due to telephone interference and network harmonic requirements. This would shift the entire V/I characteristic in the capacitive direction.

Figure 7 shows single line diagrams of several multilevel SVC Light systems. Combining the best of STATCOM technology with conventional thyristor based SVC technology will optimize the power system performance for under-voltage performance, over-voltage performance, transient overvoltage at fault clearing, losses, speed of response, reliability, etc.

**Mechanically switched shunt (MSS) Hybrid STATCOMs**

For applications with less strict dynamic requirements (i.e. reaction time and consecutive number of switching operations), mechanically switched capacitors and/or reactors (MSC/MSR) may be used instead of faster thyristor-switched branches as shown in Figure 7(c). The mechanical shunts provide reactive power support during steady-state conditions and replace one or several TSCs/TCRs/TSRs. It is preferable to locate the MSC or MSR on the primary bus to reduce the size of the transformer and minimize the stress on the breaker elements. Mechanically switched banks have relatively low losses and the capital cost is lower compared to a topology based on thyristor switched elements. Although such external devices are relatively simple and fairly economical, they come with some disadvantages which have to be taken into consideration. Among these are a) the obvious discharge time of MSC banks of several minutes before re-energization, b) the overall limited number of switching cycles of a circuit breaker reducing the overall flexibility of the installation, and c) slower reaction time compared to thyristor-based solutions.

## Case studies

*Figure 8: Holly STATCOM*

**Retired power plant in Texas**

There was an oil and gas fired power plant in Texas that was retired due to reduced use, environmental concerns and the availability of more cost-effective generation elsewhere. SVC Light was commissioned to compensate for the loss of reactive power from the retired plant.

The old plant was located close to a densely populated residential area in Texas. In order to ensure the transmission system's voltage stability, it was necessary to install a reliable dynamic reactive power source as replacement. To make up for the loss of reactive power support in the 138 kV grid, an SVC Light, rated at 80 Mvar inductive to 110 Mvar capacitive, was put into service 2004. Due to the many high tech sensitive loads in the region, the fast response offered by SVC Light to help recover from voltage sags was particularly important to the grid owner.

Also, space was scarce and ambient noise was a concern. SVC Light was chosen because of its minimal footprint, minimal environmental impact and capability to support the grid even more effectively than the old generators. Reactive power support is provided dynamically, quietly and with zero emissions into the air.

*Figure 9: Cerro Navia STATCOM*

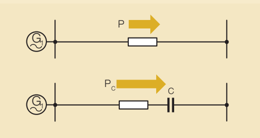
**Dynamic stability in Chile**

After completion of feasibility studies, a grid owner in Chile decided to install FACTS with the aim of increasing the dynamic stability of the system, thereby allowing more power to be transmitted through the grid.

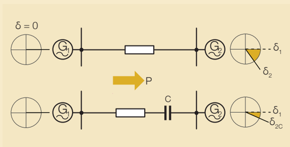
An SVC Light rated at 220 kV, 65 Mvar inductive to 140 Mvar capacitive was put into service 2011, bringing additional power transmission capability to the existing grid. The SVC Light and an ABB SVC are located close to each other. Tests were performed to verify stable control without any harmful interaction between the devices. The performance of the devices and control functions were successfully verified during different operational scenarios.

# 10. Series Compensation (SC) and TCSC

## 10.1 Introduction




**Increased Transmission Capacity**
*Inserting a capacitive reactance in series with a long (typically more than 200 km) transmission line, reduces the impedance and increases therefore the amount of power that can be transferred.*




**Increased Stabillity**
*Inserting a capacitive reactance in series with a long (typically more than 200km) transmission line reduces the angular deviation between sending and receiving ends.*

**SERIES COMPENSATION** is since long the preferred solution when vast bulk transmission corridors are to be optimized. Inserting a capacitive reactance in series with a long (typically more than 200km) transmission line, reduces both the angular deviation and the voltage drop. The result is increased loadability and stability.

The fact that it is the current through the transmission line that directly ”drives” the Mvar output from the capacitor, makes the compensation concept ”self regulating”. This straightforward principle assures that Series Compensation is an extremely cost effective solution.

Squeezing more power out of existing lines can reduce the number of parallel lines in a power corridor and postpone or even eliminate the need to build new lines which all adds up to reduced environmental impact and significant cost and time savings.
Series compensation provides:

- Increased power transmission capacity
- Increased voltage stability of the grid
- Increased transient (angular) stability of a power corridor
- Damping of the first swing
- Optimized power sharing between parallel circuits

Series Compensation schemes involving Thyristor Control allow for rapid dynamic modulation of the inserted reactance. For interconnectors between transmission grids, this can provide strong damping torque on inter-area electromechanical oscillations. Therefore a Thyristor Controlled Series Capacitor (TCSC) rated at some 100 Mvar can make it possible to interconnect grids housing many thousands of MW´s of generating capacity. Often the TCSC is here combined with fixed series compensation in order to increase the transient stability in the most cost effective way.

The TCSC concept can provide inherent immunity against Subsynchronous Resonance (SSR), and thus allow for extended use of series capacitors in specific extended transmission grids comprising thermal generation.

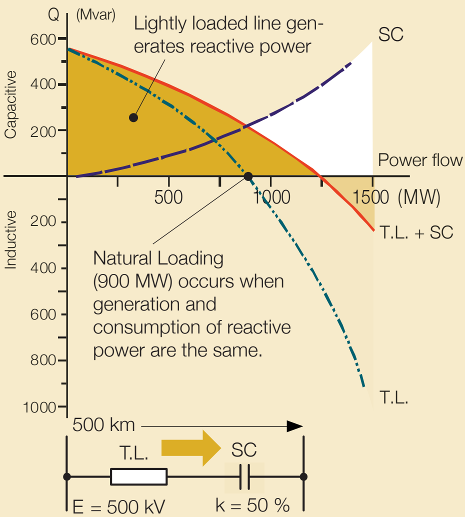
Series compensation can by means of TCSC also provide:

- Damping of active power oscillations
- Post-contingency stability improvements
- Dynamic power flow control

## 10.2 Increased Transmission Capacity and Improved Voltage Stability

**A HIGH VOLTAGE OVERHEAD** line contributes both capacitance and inductance to the circuits. Load and Voltage determine whether the line is consuming or generating reactive power.

Natural Loading occurs when generation and consumption of reactive power are the same. By means of series compensation this occurs at a significantly higher load.




*The figure shows a long lightly loaded 500 kV line generating reactive power; 550 capacative Mvar at 0-load in this specific example.*

*When the load increases, the inductive reactance of the line (T.L.) consumes increasingly more reactive power. The line's Natural Loading (900 MW) occurs when generation and consumption of reactive power are the same.*

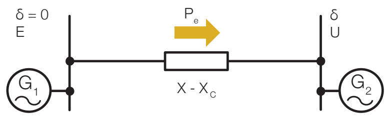
*Series capacitors' generation of reactive power varies with power flow, for which reason the Natural Loading and the transfer capacity of the compensated line (TL+SC) attain a level superior to the capacity of the uncompensated line.*

*Voltage stability may be looked upon as reactive power stability. From the figure it is apparent that a sudden change in the power flow would cause a greater change in the reactive power balance for the steep slope of the uncompensated line than it would for the compensated line.*

*Example showing how series compensation can increase natural loading and transfer capacity of a compensated line.*

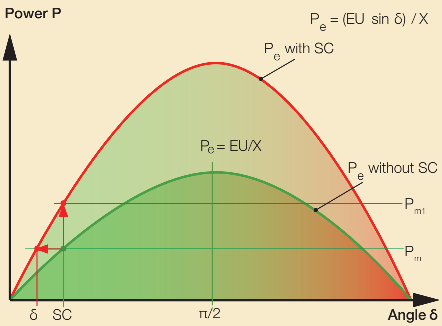
## 10.3 Increased Transmission Capacity and Maintained Angular Stability

**WITH REFERENCE TO** the parameters of the figure below, the approximate transfer equation of a long transmission line may be written $P_e = EU \sin \delta /(X - X_C)$




*Power transfer over transmission line*

*δ = angular difference between E and U*
*E = Sending end voltage*
*U = Receiving end voltage*
*P = Transferred active power*
*X = Line inductive reactance*
*Xc = Compensating capacitive reactance*




*Steady state active power transmission is achieved when the mechanical input power, $P_m$ equals the active power, $P_e$ at the angle $\delta_1$*

*At $\delta_1 = \pi/2$, sin δ equals 1 and this theoretical, maximum of steady state transfer gives a $P_m = P_e = EU/X$, which is not at all a very safe spot for continuous operation, since the system would lose synchronism for angles larger than π/2.*

*As seen in the figure the series compensation allows an increase of steady state transmission from $P_m$ to $Pm_1$ while the same angular displacement $\delta_1$ is kept.*

When power is transferred over long distances, it is essential that the synchronous machines of the receiving end ($G_2$) remain in synchronism with the synchronous machines of the sending end ($G_1$). The line inductance, X which increases with long lines, is a crucial parameter since it displaces the angle between E and U.

If series compensation is inserted in the transmission line, the total line inductance is reduced resulting in an increase in maximum transmittable power.

The operator may instead decide to maintain the same level of transferred power and increase the synchronous stability by reducing the angular displacement to $\delta_{SC}$. Of course, one may also operate the system at values somewhere in between the two above mentioned extremes.

# 10.4 Increased Transmission Capacity and Optimized Power Sharing Between Parallel Circuits

**Load Sharing**

With Series Compensation for Load Sharing of parallel lines, an optimum of active power transfer and minimized transmission losses can be achieved.

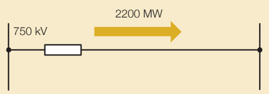
When active power is being transmitted over parallel transmission systems, the power flow will be divided between the systems in inverse proportion to the impedances of the parallel lines.

**An Example:**

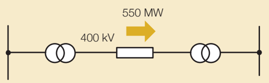
A 400 kV transmission line has a natural loading of some 550 MW which is only 25 % of the natural loading of a 750 kV line.

These two lines are connected as parallel lines between two networks. Assume that the impedance of the 750 kV line is in the order of 80 % of the impedance of the 400 kV line. Full utilization of the 750kV line will be problematic.

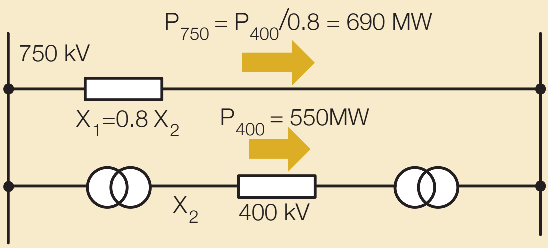
This unfavorable sharing is dictated by the rules of nature and as soon as the line having the lowest power transmission capacity reaches its limit, it automatically blocks the whole system even if other lines have unused capacity.




*The natural loading of a single 750 kV line is typically 2200 MW*




*The natural loading of a single 400 kV line is typically 550 MW or 25 % of the natural loading of the 750 kV line.*




*If the two lines above are arranged as parallel lines, only about 125 % of the power transferred in 400 kV line can be transferred in the 750 kV line.*

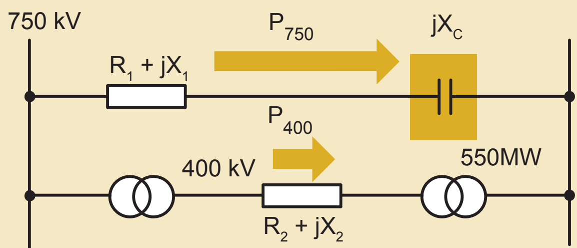
The way to increase the power flow through the 750 kV line is obviously to decrease the impedance in the line ($X_1$) by means of series compensation of the line.

A possible amount of compensation is 70%, i.e. $X_C / X_1 = 0.7$. Using the relation 1. we can get the natural loading $P_1$ of the 750 kV line.

$$\frac{P_1}{P_2} = \frac{X_2}{X_1} \quad \text{.................. 1.}$$

$$\frac{P_1}{550} = \frac{1}{0.8\,(1-0.7)} \; ; \quad P_1 = 550/0.24 = 2290 \text{ MW}$$

Geographical- and electrical map of Sweden. Without series compensation only 2/3 of the power transmitted today would be possible to transmit. In other words there would have to be 12 instead of today's 8 lines.




*By means of SC the full transfer capacity of the 750 kV line could be utilized.*

## Transmission Losses

Poor current sharing over parallel lines may significantly increase power system losses. Again, the series capacitor is the remedy. The total losses are at a minimum when

$$(X_1 - X_C) / X_2 = R_1 / R_2$$

Sweden, with many generation plants up north and major population and industrial areas some 1000 km further south, certainly needed series compensation to optimize transmission over the many parallel long distance lines. However, reduction of transmission losses was the major reason for installing the first series capacitor in the 1950s.

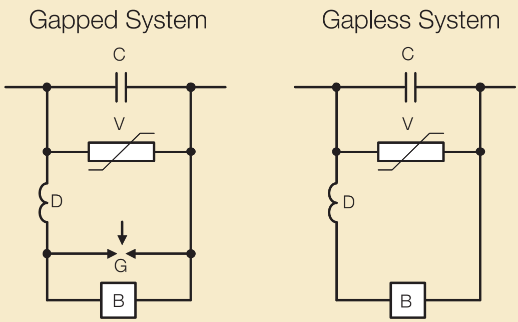
# 10.5 Over-Voltage Protection of Series Capacitors

**How to Handle Fault Currents**
Needless to say, series compensation requires control, supervision and protection to perform in a proper manner. The figure below shows the two basic main circuit diagrams of series capacitors.

V = Metal Oxide Varistor (MOV) protects the capacitors against over-voltage. During ordinary conditions, all the power flows through the capacitor bank and when a fault arises, until fault clearance, the varistor limits the voltage across the capacitors.

**Main circuit diagrams of series capacitor**
*To limit the necessary MOV energy absorption capability, a triggered spark gap is normally used for immediate by-pass of the MOV (and the capacitors) at internal or severe external faults. The gap is normally used at demanding short circuit levels and duty cycles. To extinguish the arc the by-pass switch takes over in some 20 – 25 ms.*

*In weaker locations of a grid and at less severe duty cycles a gapless MOV scheme is sometimes used. Here, the MOV must be designed to harbor the fault until the by-pass switch closes to by-pass the MOV.*




*C: Capacitor, V: MOV, G: Triggered spark gap, B: By-pass switch, D: Damping circuit*

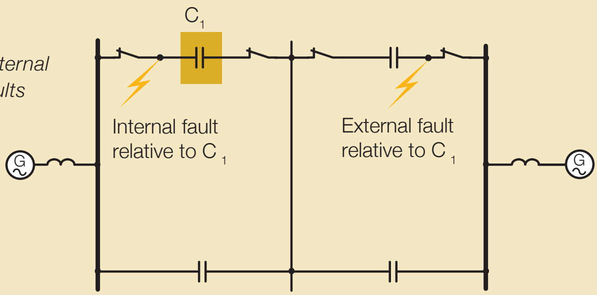
Design and protective requirements of the Series Capacitor depend on power system characteristics and operational principles. Some definitions are useful.

A distinction is commonly made between internal and external faults, defined as follows:

An internal fault is a fault that occurs within the compensated line section.

An external fault is a fault that occurs outside the compensated line section.

*Definitions of internal and external faults*




From a system performance point of view, the line impedance increases if the series capacitor is by-passed to protect the bank from over-voltage.

The effect is not significant for internal faults, since the line section containing the series capacitor is, at least temporarily, removed from service to allow fault clearing.

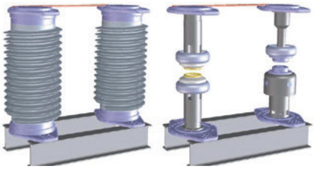
For external faults the impact on system stability is normally under control, after a by-pass, if the capacitor bank returns to operational service within 75 to 100 ms after fault clearance.

Conventional spark gaps will ionize the air gap during operation and some 400 to 500 ms is required for air deionization before the series capacitors can be reinsert-ed without causing flashover in the spark gap. Due to the relatively long time required for deionization, bypass at external faults is generally not recommended with traditional spark gap technology.

For this reason, historically it is common practice not to by-pass the series capacitor for external faults, even though this gives rise to increased component stresses due to transient recovery voltages and additional varistor costs.

With the introduction of a protection system based on a novel, refined approach, external faults can normally be bypassed leaving way for a number of advantages.

This fast protective device, CapThor, allows Series Capacitors to withstand rough environmental conditions and, maybe even more important, it paves the way for a Series Capacitor which copes with growing and evolving power systems.



*CapThor is a switch consisting of two high voltage modules. The modules comprise one Arc Plasma Injector (API) and one Fast Contact (FC) respectively, enclosed in composite insulator housings. The two modules are connected in parallel and are very compact when compared with conventional spark gaps. The two high voltage modules are hermetically enclosed and filled with synthetic air at an over-pressure.*

*The function of CapThor is independent of environmental conditions and designed for high series capacitor protection levels and fault currents.*

This added feature of the protection system may allow bypass and reinsertion of the series capacitor at external faults, without jeopardizing system stability.

Hence the series capacitor will become less sensitive to increasing power system short circuit levels.
Besides this possibility to attain a relative independance of increased fault levels, Cap Thor offers a number of advantages compared to conventional techniques.

- Reduced stresses on system components such as capacitor dielectrics and line breakers caused by Transient Recovery Voltages (TRV), which may be considerable for conventional series capacitors, are added values following from the ability to bypass the series capacitor at external faults.
- Contrary to conventional spark gaps, bypass of a series capacitor with CapThor is practically independent of the voltage across the capacitor bank.
- Last but not least, contrary to conventional spark gaps, the hermetically enclosed design of CapThor, using continuously supervised pressurized air, makes the protection system humidity-safe and resilient to arctic, as well as desert conditions.

# 10.6 Thyristor Controlled Series Compensation, TCSC

**THYRISTOR CONTROLLED** Series Capacitors, TCSC, add controllability, as thyristors are used to dynamically modulate the ohms provided by the inserted capacitor.

TCSC is primarily used to provide inter-area damping of potential low frequency electromechanical oscillations, but it also makes the whole Series Compensation scheme immune to Subsynchronous Resonance (SSR).

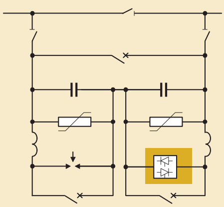
*TCSC platform in the United Kingdom.*

A Series Compensation scheme involving Thyristor Control allows for rapid dynamic modulation of the inserted reactance. On interconnectors between transmission grids, this modulation can provide strong damping torque on inter-area electromechanical oscillations. Therefore a TCSC rated at some 100 Mvar can make it possible to interconnect grids housing many thousands of MW of generating capacity.

Often the TCSC is combined with fixed series compensation in order to increase the transient stability in the most cost effective way.

A TCSC equipped with the ABB developed Synchronous Voltage Reversal (SVR) control scheme comes with inherent SSR (Sub Synchronous Resonance) immunity and thus allows for extended use of series capacitors in specific transmission grids comprising thermal generation.

From a principal technology point of view, the TCSC resembles the conventional series capacitor.



*Often the TCSC is, as here, combined with fixed series compensation in order to increase the transient stability in the most cost effective way.*

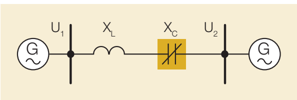
Nearly all the power equipment is located on an insulated steel platform, including the thyristor valve that is used to control the current through the inductor coil connected in parallel with main capacitor bank.

Likewise, the control and protection are located on ground potential together with other auxiliary systems. There are two bearing principles of the TCSC concept:

1. TCSC provides electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line. TCSC provides a variable capacitive reactance.
2. TCSC eliminates a potential subsynchronous resonance by changing its apparent impedance from capacitive to inductive for low frequences as seen by the line current.

Both these objectives are achieved with the TCSC using control algorithms that work concurrently.

The controls will function on the thyristor circuit (in parallel to the main capacitor bank) so that controlled charges are added to the main capacitor, making it a variable capacitor at the fundamental frequency but a "virtual inductor" at subsynchronous frequencies.




### Damping of Power Oscillations by means of TCSC

Interconnections between large generating areas may be subject to low frequency, active power oscillations at line faults and sudden changes in loads or generation. The oscillations may limit the transmission capability making search for suitable remedies necessary.

Power System Stabilizers, PSS on generators, may have difficulties in dealing with the low frequency nature of the oscillations.

### Two large power systems

From the well known transfer equation:

$$P = (U_1\, U_2 \sin \delta) / (X_L - X_C)$$

it follows that the line impedance may be varied and therefore is controllable to counteract the active power oscillation by means of a TCSC.

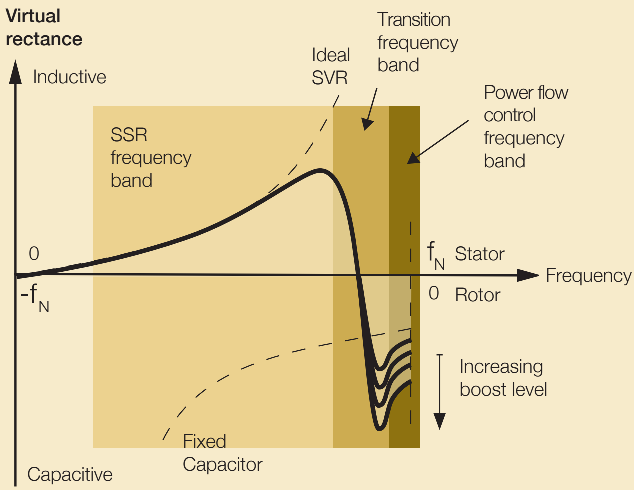
## Mitigation of Sub-Synchronous Resonance

The introduction of series compensation improves power system behavior with respect to voltage stability and angular stability. However, under adverse conditions, system electrical resonance may interact with mechanical torsional resonances in turbine-generator shaft systems. This phenomenon is known as Sub-Synchronous Resonance (SSR). Today the SSR problem is well understood and taken into account when compensation

**Impedance characteristics of a TCSC.**
*TCSC can act like an inductive reactance for the low frequencies where SSR occur.*

*At the power frequencie (50/60 $H_2$) it is still perceived as a capacitance.*

*This is achieved by means of an ingenious control algorithm called Synchronous Voltage Reversal (SVR).*




is planned. Sometimes SSR conditions may even limit the feasible degree of compensation of the series capacitor, in order not to increase the SSR hazard. Use of TCSC with an appropriate control system, such as the SVR, alleviates such restrictions.

The SVR approach offers complete elimination of SSR risk throughout the potential subsynchronous frequency range, by making the apparent reactance of the TCSC inductive in the SSR frequency band.

# 11. Bringing the threads together

**TODAY'S SOCIETY REQUIRES** more and more electric power as we tend to use electrical devices in everything we do. We want to warm our houses in the winter and cool them in the summer. We even want to use electricity for our means of transportation instead of oil and gas. Electric power is a must, and we simply cannot accept a blackout or that the lights flicker because of a nearby heavy industry. That's where FACTS technologies step in, stabilizing and improving the power system and enabling a stable supply of electricity to each of us.

FACTS is an acronym for Flexible AC Transmission System(s), embracing a family of controllable, high power devices, all having in common that they in various ways contribute to the improved, more stable and more economical utilization of power systems.

The FACTS devices treated in this booklet are:

- Shunt devices: SVC and STATCOM
- Series devices: Series Capacitors and TCSC.

In general terms, the shunt devices provide voltage and reactive power control, whereas the series devices provide current and power flow control. It will be found that with this assortment of devices in shunt and/or series with the grid, it is possible to attain important benefits for the economy, performance and utilization of grids, as well as railways and heavy industrial plants. Some examples of the benefits of FACTS are:

- Grid voltage stabilization
- Improved power system stability
- Increased power transmission capability
- Lowered environmental impact
- Shortened construction times
- Improved power quality
- Fulfilment of grid codes
- Improved process economy

FACTS also facilitates the integration of renewable generation in power systems, as well as the implementation of Smart Grid systems.

In cases of green field projects, time as well as money can be saved while being environmentally conscious by implementing FACTS to limit the required number of HV or EHV lines for the transmission of a certain amount of active, useful power from the outset. In cases of upgrading existing installations, FACTS makes a superior alternative to increasing the voltage level or building additional power lines to increase the power transmission capability. Likewise, it is an attractive alternative to raising the fault level of the grid for power quality improvement purposes at the point of common connection (e.g. for a cluster of large industrial process plants).

This booklet has the ambition of giving a brief and popular introduction to these important and widely useful devices within the FACTS family, concentrating on basic design principles as well as on a number of typical and advantageous applications. It is hoped that this work can serve as an inspiration for further penetration into the world of FACTS as well as a door opener to new or alternative ways of solving a variety of power system issues.

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