

## Reactive power compensation

Installation of new reactive power compensation equipment on RTE's grid in France

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## Abstract

This report describes, in the first section the studies conducted in order to define the reactive power compensation equipment needed to support the voltage on the 225 kV networks in two regions in France. In the second section, the design studies of this equipment are presented, and details are given on the main components as well as on the erection on site.

## References

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# System needs for reactive power compensation

**The inductive series impedance of high voltage overhead lines results in a reactive power consumption increasing with the square of the current. Due to this reactive power, the flowing active power capability of the line is reduced and voltage drop appears, leading also to a reduction of the power transmitted to the load. To limit these effects, reactive power compensation equipment, such as shunt capacitor banks, is usually installed.**

These devices reduce the reactive current flowing on the lines and the subsequent losses. However, a current limit value exists for which, in the case of an important load, the voltage diminishes faster than the increasing current needed to maintain the active power level. This phenomenon results in a decreasing of the transmitted power and in a voltage collapse. This value mainly depends on the network impedance and of the network configuration: if a line trips due to a fault, it is necessary to ensure that, after the fault, the current is kept under the new current limit value. Switching on shunt compensation is a means to increase this limit value. In the case of a severe voltage drop, it is also very important to block the load tap changers of the transformers so they will not try to maintain the voltage and thus the power constant, which would maintain or amplify the voltage drop.

Voltage studies on the French network made by RTE in 2002 and 2003 have shown that, considering the increasing power consumption:

- The risk of severe voltage drop on the Brittany network was due to happen in 2006-2007 if both a cold winter and line tripping occurred. It is important to keep in mind that only 5% of the electricity consumption in Brittany comes from local power plants, so this kind of situation is still an issue.
- For 2008, very low voltage levels could have been reached in the Parisian region because of the decommissioning of several 250 MW thermal power plants in this area, and the dismantling of many capacitor banks with PCB contamination on the Distribution grid. In this case, the consequence of a line tripping was not a voltage collapse but a huge reduction of the margin between the maximum transmissible active power and the load.

Additional stability network studies led by RTE helped to identify the optimal means of compensation, allowing an increase in the flowing active power limits for both of these areas.

## Brittany study

It was found to be necessary to install about 840 Mvar, which meant doubling the existing reactive power compensation equipment. The usual means of operating the shunt capacitor banks is to switch on the necessary volume in a preventive manner, taking into account line tripping. The aim is to keep a positive margin between active power capacity and the load power consumption for every scenarios. However, considering the important need for reactive power, this means of operating the network would create an excessive operating voltage during normal conditions, e.g. with all the lines in service. Thus it was decided to share the 840 Mvar compensation between capacitor banks (540 Mvar) and 2 Static Var Compensators (SVC) of 200 Mvar (capacitive) and 100 Mvar (capacitive) each. SVC are comprised Thyristors Switched Capacitors, allowing them to connect very quickly on voltage criteria when a fault appears on the network. The fast response time of the SVC avoids tap-changer blocking.

Compared to a basic solution with only capacitor banks, SVC will also limit the tripping of many wind farms in the case of faults on the 400 kV or 225 kV network. Indeed, the SVC will manage to bring back very quickly the voltage stability after the fault clearance, and then avoid the protection operation of the wind turbines (over-speed or overvoltage protections). In such a case, the situation turns from easy pre-fault conditions with low loaded lines, high voltage profile, low level of thermal production and reactive compensation, to critical conditions where all the loads are imported from the lines with a very high reactive power consumption (1 Mvar per MW imported) and a lack of time to start thermal production and to adjust the reactive power for the region. The risk for voltage collapse is then increased. Moreover, the SVC will help to reduce the voltage drop during faults, which help the wind farms to reconnect. The studies showed that it was useful for the SVC to be able to also absorb between 100 and 150 Mvar in order to control the voltage during low loaded periods, or in the case of a high level of distributed generation. At the end of 2003 it was decided to commission the 540 Mvar shunt capacitors by the end of 2004 and the 2 SVC by the end of 2006.

## Parisian region study

It was found necessary, through the studies, to install about 800 Mvar. In contrast to the Brittany project, SVCs were not required and having only capacitor banks was sufficient. By the end of 2005, it was decided to commission the 800 Mvar of capacitor banks between October 2007 and July 2008.

# Studies to design and implement the compensation equipment

## Capacitor banks in Brittany

In the past — RTE installed 30 Mvar capacitor banks connected to the 63 kV and 90 kV networks. 30 Mvar rated power corresponds to the optimal value to limit the voltage changes when the capacitor bank is switched in, when the short-circuit current ( $S_{cc}$ ) of the substation is low. These capacitor banks have an isolated neutral. Indeed, for a 63 kV network, grounded neutral can not be used since the impedance of a 30 Mvar capacitor bank (about 130 ohms capacitive) is rather close to the equivalent zero impedance of a typical 63 kV substation of the South Brittany network (50 ohms inductive). The connection of the neutral to the ground would change the impedance seen by the protection relay, as well as the equivalent resistance of the fault. In such a case, this could have negative effects on the protection selectivity for fault clearance. For these reasons, 30 Mvar rated power with isolated neutral is required for the installation of the new capacitor banks.

In a substation, a maximum of three standard capacitor banks can be installed. In the 90's, a damping circuit (DAR) [1] was designed in order to:

- Limit the frequency and the amplitude of the voltage oscillations on the bus bar when several capacitor banks are switched on back-to-back. These oscillations were generating overvoltages on the extremity of the dead end line connected to the busbar.

To avoid such situations, the line circuit breakers cut the current during the first ms in the elimination of a fault close to the substation, and to ensure that the transient recovery voltage does not exceeds the standardized gauge. Besides, in the case of circuit breaker re-striking, the discharge currents of the capacitor in the fault are limited by this damping circuit to avoid high-frequency zero crossing of the current.

These risks must also be taken into account for the new capacitor banks to be installed. Furthermore, the implementation of 540 Mvar (18 capacitor banks) has increased the risk of disturbing the transmission of the signals that are used in France to change the customer's electricity tariff. These 175 Hz 3 phases voltage signals (TCFM) are connected in series on the 20 kV network. Their amplitude is 2.3% of the 50 Hz voltage. When the Short Circuit current ( $S_{cc}$ ) on the busbar is infinite, this TCFM voltage is applied entirely on the 20 kV loads. On the other hand, if the upstream network has a weak  $S_{cc}$ , the generated voltage is shared between the upstream network and the targeted 20 kV loads. This phenomenon is amplified when plain capacitor banks are installed on the 63kV network. As a rule of thumb we estimate that the apparent  $S_{cc}$  is reduced by about 100 MVA when the 10 Mvar capacitor bank is connected to the bus bar. On Figure 1, we represent a 63 kV busbar supplied by a 1240 MVA  $S_{cc}$  source on which are connected in parallel:

- Three capacitor banks (20 + 3x30 Mvar)
- One 63/20 kV and 36 MVA transformer supplying a 35 MVA load which is compensated by a 8.3 Mvar capacitor bank. On the secondary of the transformer a TCFM generator is connected in series,
- Three 36 MVA transformers (108 MVA) supplying a 53 MVA load compensated by a 12 Mvar capacitor bank.

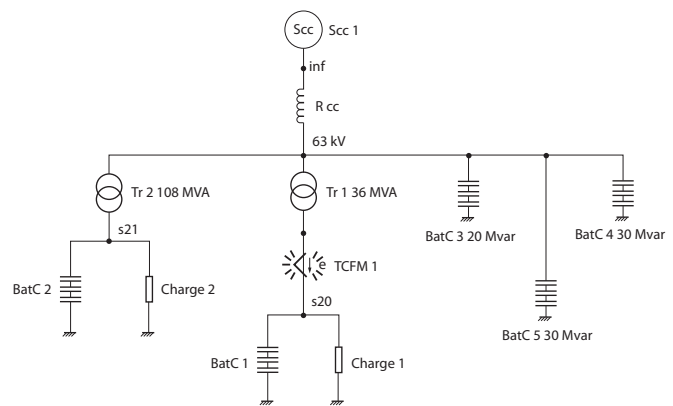


Figure 1  
Transmission of the TCFM signals

The calculation results show that the 175 Hz voltage level is lower than 1.5% on the applicable 20 kV busbar (S20), which means a high risk of mis-operation of the targeted relays. Furthermore, the 175 Hz voltage level exceeds 0.4% on the 63 kV grid and will be erroneously propagated to non-concerned 20 kV bus bars (S21).

For that reason it was decided to design the capacitor banks as a filter tuned on 175 Hz in order to lower the network impedance. This leads to the choice of a C-type filter configuration, represented on Figure 2 which has already been used on other networks [ 2 ]. In this type of filter, the L, C2 branch is tuned on 50 Hz, which makes it equivalent to the C1 capacitor for the fundamental frequency. In addition the second L, C1, C2 branch is tuned on the 175 Hz frequency. The R1 resistance is used to damp the harmonic voltages of the network.

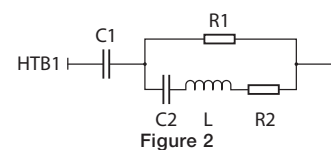


Figure 2  
Scheme of a C type filter

The calculations of the 175 Hz voltage level on bus bars S20 and S21 were made for the three following configurations:

- Case A — 3 x 30 Mvar plain capacitor banks without any filter structure.

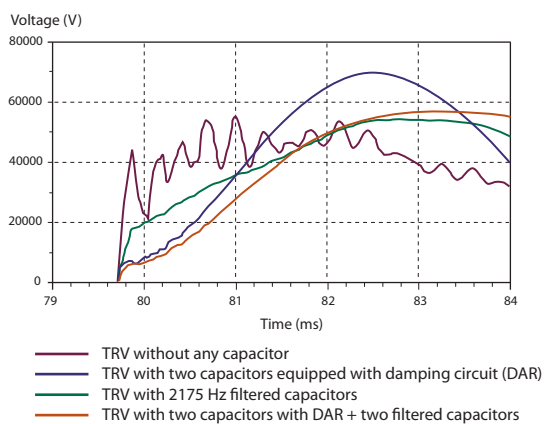
- Case B — Two plain capacitor banks and one 30 Mvar capacitor banks designed as a filter.
- Case C — 2 x 30 Mvar capacitor banks are filtered.

The results are given in this table:

	Case A	Case B	Case C
<b>S 20</b>	1.917%	2.278%	2.429%
<b>S 21</b>	0.861%	0.483%	0.334%
<b>63 kV</b>	0.724%	0.406%	0.280%

We notice that, for this typical configuration, two filtered capacitor banks are necessary to avoid propagating the TCFM signals on S21. Substations with new capacitor banks, have been studied with these criteria. From this study, it was found necessary to have 13 filtered capacitors banks, the remaining 5 being standard plain capacitor banks with a damping circuit.

Once this configuration was chosen, simulations were made with EMTP to determine whether if the TRV (Transient Recovery Voltage) across the line circuit breakers were acceptable, allowing fault clearance without any CB restriking. Figure 3 shows the TRV obtained in four configurations:



**Figure 3**  
TRV at the terminals of the line circuit breaker

We can observe that, compared to plain capacitor banks, the filtered capacitor banks improves the situation for circuit breakers, since they maintain the stiffness of the front of the TRV in the first ms consecutive to the fault clearance and reduce the TRV peak value in the following ms.

Finally it was verified that the pre-existent harmonic voltages in Brittany, in particular the 3rd harmonic, were not significantly amplified with the installation of that type of capacitor banks. According that the tuned frequency of the filter was not corresponding to a characteristic harmonic of the network, it was decided to specify the new capacitor bank to handle the maximum harmonic voltages, authorized by the connecting decree as follows:

Harmonic	2	3	5	7	9	11	13
Vh/V1 (%)	3	4	4	4	2	3	3

### Parisian region capacitor banks

Taking into account the lack of space in the 63 kV and 90 kV substations in this region, it was necessary to foresee the installation of 225 kV capacitor banks. The specified rated reactive power of these capacitor banks is 80 Mvar at 225 kV in order to limit the amplitude of the voltage changes during switching below 3%.

In these substations, the short-circuit power is about 7 to 10 GVA with a possible minimum of 3.5 GVA in N-1 configuration. When installing an 80 Mvar capacitor bank, the upstream network impedance is only slightly modified as seen from the 20 kV network where TCFM signals are generated. Adding to the fact that we have two steps of transformation between these two voltage levels, no specific measure was required regarding the 175 Hz signals transmission, on the contrary of the 63 kV and 90 kV compensation.

EMTP simulations were also made to check the effect of the 225 kV grounded-neutral shunt capacitor bank switching on the PX distance protection relay. Using the diagram in Figure 4, calculations of the PX measurements were made with different type of links (over head line, single-phase cable, three phases oil cable) between substations A, B and C with and without capacitor banks installed in A and B.

In every case we noticed that the direction of the fault between upstream and downstream was not changed and that there was little difference for the PX between the configurations with and without the capacitor banks.

Considering all the previous points, we have concluded that 80 Mvar/225kV capacitor banks without any filter structure tuned on 175 Hz and with grounded neutral were suitable. However, issues with the 5th harmonic voltage (H5) were detected by pre-existent harmonic voltage measurements made in the substations as well as simulations showing the evolution of harmonic rate after the capacitor banks, implementation. Indeed, in some substations the rate was already higher than 2% and would reach 3.6% after the installation of standard capacitor banks. The other harmonic voltages levels remained lower than 1% both before and after the installation of capacitor banks.

Consequently it was decided to install filtered capacitor banks tuned on the 5th harmonic. The choice of a damping type C filter as was used in Brittany was made to avoid creating any pronounced anti-resonance below 250 Hz while also ensuring the filtering of higher-rank harmonics.

# Studies to design and implement the compensation equipment

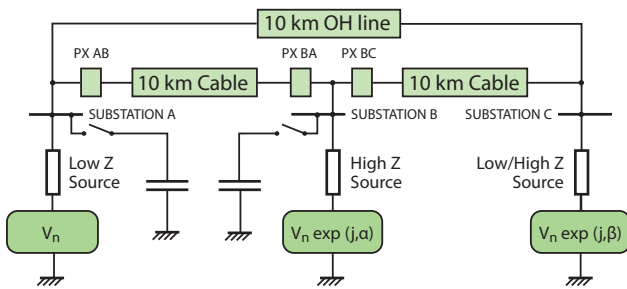


Figure 4  
Diagram for the protection studies

Another advantage of the filtered capacitor banks is to avoid the installation in series of a damping circuit. Indeed, simulations have shown that, due to the reactor of the filter, TRV during a line fault clearance was in accordance with the 225 kV line circuit breaker performances.

Nevertheless, choosing a tuning frequency for the filter on a characteristic harmonic of the network had an impact on the rated current for the design of the components. To have, like in Brittany, that we have the maximum harmonic voltages authorized in the connecting decree on the terminals of the filter, was not reasonable. Indeed, this philosophy would have led to design the capacitor banks for a 5th harmonic current (H5) 3 or 4 times higher than the fundamental current, depending of the choice of the damping (R value). We thus modeled the harmonic impedance of the network supplying the busbar where the capacitor banks were connected, and we have determined the harmonic current sources needed to generate on the busbar the maximal authorized harmonic voltages without the filtered capacitor banks connected.

Once this source was defined for each characteristic harmonic, we switched on the capacitor banks and measured the part of the harmonic current flowing into the filter. This value was linked to the filter damping. We chose R equal to 1000 ohms because it was the optimum value regarding filtering performances for the harmonics with a rank equal to or higher than 5, while at the same time not amplifying too much the 3rd harmonic.

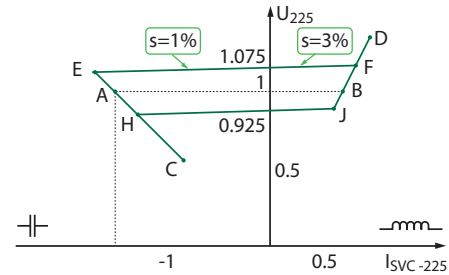
With this method, the calculated harmonic currents (taking into account factors that will modify the tuned frequency of the filter like tolerances, temperature, fault on internal fuses) were the following:

Harmonic	H2	H3	H5	H7	H9	H11	H13
Current (A)	16	50	150	60	20	20	15

These values are quite important for the design of the components, nevertheless they are still lower than the fundamental capacitor banks current (223 A for 245 kV).

## Static Var Compensators (SVC)

The SVCs are designed for operation according to the voltage-current characteristic shown in Figure 5.



Points	A	B	C	D	E	F	H	J
U (p.u.)	1	1	0.5	1.33	≈1.065	≈1.09	≈0.89	≈0.93
I (p.u.)	-1	0.5	-0.5	-	-	-	-	-
V <sub>ref</sub> (p.u.)	-	-	-	-	1.075	1.075	0.925	0.925
Slope (%)	-	-	-	-	1	3	3	1
Duration	∞	∞	10s	5s	∞	∞	∞	∞

U<sub>BASE</sub>=225 kV S<sub>BASE</sub>=100 MVA at Plaine Haute | S<sub>BASE</sub>=200 MVA at Poteau Rouge

Figure 5  
SVC voltage/current characteristics

The rated reactive power of the SVC installed at Poteau- Rouge substation is in a range from: 100 Mvar (inductive) to 200 Mvar = 1 pu (capacitive) at 225kV (1 pu). At Plaine-Haute, the second SVC has half the rated power for both the inductive and capacitive values. In the technical specification, the SVC configuration was not defined. The purpose of the SVCs is to control the voltage in the 225 kV network, both dynamically and in steady state. The SVCs also had to be designed to fulfill the harmonic requirements according to the following table:

Harmonic order	Maximum allowed harmonic current	
	Plaine Haute SVC	Poteau Rouge SVC
2	5 A	10 A
3	10 A	20 A
5	15 A	30 A
7	15 A	30 A
11	10 A	20 A
13	10 A	20 A
Total	15 A	30 A

Finally, it was specified that the response time to a voltage step shall not exceed 75 ms. As the SVCs comprised several large reactors, noise and magnetic fields limitations were imposed at the border of RTE's substation. It was foreseen that the SVCs could operate in two different modes: a standby mode, for which the SVC automatically starts to run on in the case of a fault on the network; and a regulating mode, where the SVC controls the voltage continuously.

# Filtered capacitor banks study

ABB has designed, manufactured, erected and commissioned filter banks for RTE's Bretagne and Paris region compensation projects. In order to meet RTE's requirements, the following activities have been performed.

## Filter component data

The filters for the Paris region have been designed in order to fulfill the following system requirements:

Description	63 kV filter	90 kV filter	225 kV filter
<b>Nominal data</b>			
Nominal system voltage (kV)	63	90	225
Rated power at nominal system voltage (kV)	30	30	80
Tolerance of the rated power at nominal system voltage (%)	± 2.5	± 2.5	± 2.5
Type of filter C	Ungrounded neutral	Ungrounded neutral	Grounded neutral
Tuning frequency (Hz)	175	148	245
<b>Voltage variations</b>			
Maximum continuous operating voltage (kV)	66	95	245
Minimum continuous operating voltage (kV)	54.4	78	200
8 hours temporary overvoltage (kV)	72	100	250
10 seconds temporary overvoltage phase-phase (kV)	91	130.5	300
10 seconds temporary overvoltage phase-ground (kV)	63	90	205
<b>Frequency variations</b>			
Minimum continuous frequency variations (%)	± 1	± 1	± 1
10 minutes temporary frequency variations (%)	- 6 / + 4	- 6 / + 4	± 2
60 minutes temporary frequency variations (%)	± 2	± 2	- 6 / + 4

RTE has also specified the individual and total harmonic voltage distortion that the filters should withstand as follows:

Harmonic order	2	3	5	7	9	11	13	THD
Vh/V1 %	3	4	4	4	2	3	3	6

In the cases of the 90 kV and 225 kV filters for the Paris region, calculated harmonic filter currents have also been specified by the RTE. Based on the RTE specifications, the connection schemes of the filters have been developed as follows:

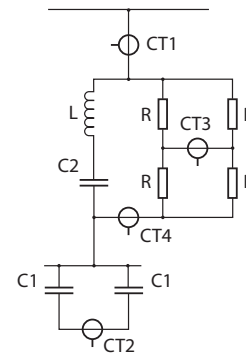


Figure 6  
Single line diagram, 63 and 90 kV filters

Where

C1	Main capacitor bank
C2	Tuning capacitor bank
L	Filter reactor
R	Filter resistor
CT1	CT for overload protection
CT2	Current transformer for unbalance protection of capacitor bank C1
CT3	Current transformer for unbalance protection of resistor R
CT4	Current transformer for overload protection of resistor R

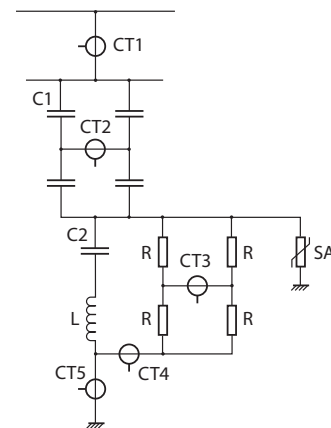


Figure 7  
Single line diagram, 225 kV filters

Where

C1	Main capacitor bank
C2	Tuning capacitor bank
L	Filter reactor
R	Filter resistor
CT1	CT for overload protection
CT2	Current transformer for unbalance protection of capacitor bank C1
CT3	Current transformer for unbalance protection of resistor R
CT4	Current transformer for overload protection of resistor R
CT5	Current transformer for differential protection
SA	Surge arrester for resistor and reactor protection

# Filtered capacitor banks study

In order to meet the specifications' requirements, the nominal data for filter components have been determined as follows:

Description	Value	Value	Value
Rated capacitance of capacitor C1 (μF)	24.06	11.79	5.03
Rated capacitance of capacitor C2 (μF)	270.7	91.5	115.7
Manufacturing tolerance of capacitor C1 (%)	± 2.5	± 2.5	± 2.5
Manufacturing tolerance of capacitor C2 (%)	± 2.5	± 2.5	± 2.5
Rated inductance of reactor L (mH)	37.4	110.7	87.54
Manufacturing tolerance of reactor L (%)	± 2.0	± 2.0	± 2.0
Adjustment taps on reactor L (%)	± 2.0, ± 4.0	± 2.0, ± 4.0	-4, -2, 0, +2, +4
Rated resistance of resistor R (W)	214	900	1000
Filter earthing	Ungrounded neutral	Ungrounded neutral	Grounded neutral

- Capacitance deviation of C2 due to operation of internal fuses prior to operation of unbalance protection.
- Inductance deviation due to manufacturing tolerances.
- Inductance correction by adjustment tap.
- Resistance deviation due to manufacturing tolerances.
- Resistance deviation due to temperature variations.

As an example of the obtained results, nominal characteristics at 20 °C for the 63 kV filter are shown in Figures 8 and 9.

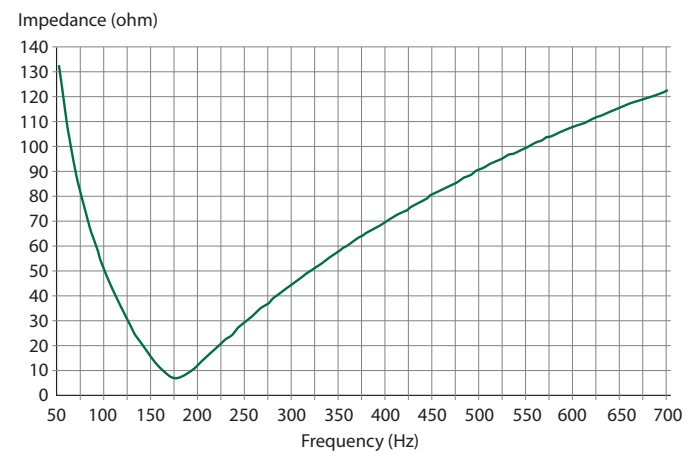


Figure 8  
Nominal filter impedance. Modulus vs. frequency.

## Impedance study

The characteristics of the filters have been verified by calculation of impedance modulus and phase angle versus frequency, as well as calculations of tuning frequency and generated power for the following cases:

- Nominal impedance characteristic at 20 °C.
- Worst-case negative component deviation
- Worst-case positive component deviation
- Impedance of two filter banks connected in parallel at 20 °C with maximum de-tuning.

When calculating the worst-case negative and positive component deviations, the following factors have been considered:

- Capacitance deviation of C1 and C2 due to manufacturing tolerance.
- Capacitance deviation of C1 and C2 due to temperature variations.
- Capacitance deviation of C1 due to operation of internal fuses prior to operation of unbalance protection.

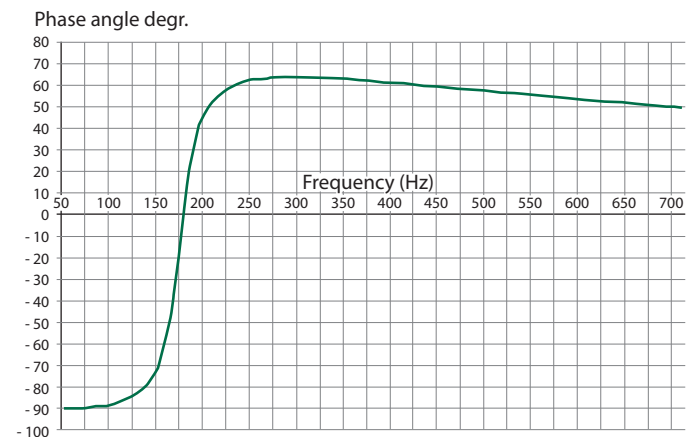


Figure 9  
Nominal filter impedance. Angle vs. frequency.

The summaries of the calculations' results are presented in Tables 1 to 3.

#### 63 kV filter

Case	Description	fres	Qgen
1	Nominal components values	175.0	30.0
2	Worst-case negative component deviation	178.1	28.6
3	Worst-case positive component deviation	172.5	31.3

**Table 1**  
Maximum deviations of tuning tolerances and reactive power.

#### 90 kV filter

Case	Description	fres	Qgen
1	Nominal components values	148.0	30.0
2	Worst-case negative component deviation	150.7	28.5
3	Worst-case positive component deviation	145.9	31.4

**Table 2**  
Maximum deviations of tuning tolerances and reactive power.

#### 225 kV filter

Case	Description	fres	Qgen
1	Nominal components values	245.0	80.0
2	Worst-case negative component deviation	248.5	77.0
3	Worst-case positive component deviation	241.4	83.4

**Table 3**  
Maximum deviations of tuning tolerances and reactive power.

The calculation results have demonstrated that the filter characteristics will meet RTE requirements with respect to tuning frequency and generated power during various operation conditions.

#### Determination of rated values of filter components

The filter component rating study has been performed by calculating currents and voltages across each component for the following cases:

	63 kV	90 kV	225 kV	Δf %	Components	Duration
1	66	95	245	0	Nominal component values	∞
2	66	95	245	-1	Worst-case negative component deviation	∞
3	66	95	245	1	Worst-case positive component deviation	∞
4	72	100	245	-1	Worst-case negative component deviation	8 h.
5	72	100	245	1	Worst-case positive component deviation	8 h.
6	72	100	250	-6	Worst-case negative component deviation	10 min.
7	72	100	250	4	Worst-case positive component deviation	10 min.
8	91	130.5	355	-1	Worst-case negative component deviation	10 sec.
9	91	130.5	355	1	Worst-case positive component deviation	10 sec.
10	109	155.9	-	-1	Worst-case negative component deviation	10 sec.
11	106	155.9	-	1	Worst-case positive component deviation	10 sec.

In addition to the steady-state calculations, transient calculations have been performed for the following cases:

- Re-energization of a single bank at maximum short-circuit level 5 minutes after disconnection.
- Re-energization of a filter bank with one parallel bank in operation 5 minutes after disconnection.
- Single-phase earth-fault at RTE busbar.
- Two-phase earth-fault at RTE busbar.

The rated voltage of the filter capacitors is carefully selected. It takes in consideration the theoretically maximum value of the fundamental frequency, the variations due to the harmonic loads, both voltage and frequency.

Under transient conditions, the chosen voltage of capacitors shall also withstand the characteristic according to IEC 60871-1, (voltage and current versus time characteristics.)

The filter reactors and resistors have been designed to withstand the calculated steady-state and transient currents.

# Filtered capacitor banks study

## Protection

The protection is based on ABB's one REF 543 system, one SPAJ 141C protection and three SPAJ 110C protections as follows:

### – Capacitor overload and under-voltage protection

The capacitor overload and under-voltage protection is arranged by using block OL3Cap of REF 543. The three-phase overload protection is used for protection of the capacitor bank against overload produced by harmonic currents and over-voltage. The function includes overload alarm stage and tripping stage. The alarm stage  $I_a$  is RMS-value sensitive and has a definite time characteristics. The trip stage  $I_b$  has a peak value sensitive invert time characteristics (IDMT) that corresponds to the capacitor's withstand characteristics according to capacitor standard IEC 60871-1.

The undercurrent protection is intended for detection of capacitor disconnection and includes breaker reconnection inhibit function for enabling the complete capacitor discharging time to pass before re-closing.

### – Reactor over-load protection.

The reactor protection is arranged using thermal overload function block TOL3Dev of RTE543. The settings of the protection is selected to obtain a protective characteristic of the relay similar to the overload withstand capability of the actual reactors.

### – Resistor over-load protection.

The resistor overload protection is arranged in two stages by using the three-phase, low-set phase over-current unit and the three-phase, high-set phase over-current unit of the SPAJ 141C relay.

### – Short-circuit protection

The short-circuit protection is arranged by using function block NOC3High of RTE543 connected to the secondary windings of the current transformers CT1. The three-phase non-directional over-current function blocks NOC3High are designed to be used for non-directional two-phase and three-phase over-current and short-circuit protection.

### – Earth-fault protection

The earth-fault protection is arranged by using function block DEF2Low of the RTE543 connected to the secondary windings of the current transformers CT1. The earth-fault protection function block is designed to be used for directional or

non-directional earth-fault protection whenever the DT characteristic or, as concerns DEF2Low, the IDMT (Inverse Definite Minimum Time) characteristic is appropriate.

### – Capacitor C1 unbalance protection, 63 kV and 90 kV filters

The unbalance protection of the capacitor bank C1 is arranged by connecting the bank in double Y with a current transformer connected between neutral points of the two Y connected groups. In normal conditions, the current through unbalance CT is negligible, but a failure in one of the capacitor groups will result in an unbalance current through the CT. The protection is arranged in two stages, one for alarm and one for trip, using the function block CUB1Cap of RTE543 connected to the secondary winding of the current transformer.

### – Capacitor C1 unbalance protection, 225 kV filters

The unbalance protection of the capacitor bank C1 is arranged by connecting each phase of the bank in a Wheatstone Bridge with the current transformer connected between the midpoints of the bridge. In normal condition, the current through CT is negligible, but a failure in one of the capacitor groups will result in an unbalance current through the CT. The protection is arranged in two stages, one for alarm and one for trip.

### – Resistor unbalance protection

The resistor unbalance protection is arranged by connecting each phase of the resistor in a Wheatstone bridge with current transformer CT3 connected between the midpoints of the bridge. In normal condition, the current through CT3 is negligible but a failure in one of the resistor branches will result in an unbalance current through CT3. For this protection, three relays type SPAJ 110C are used.

### – Under voltage detection

The under voltage detection is arranged using the voltage module UV3 Low of the REF 543.

### – Overvoltage detection

The over voltage detection is arranged using the voltage modules OV3 Low and OV3 High of the REF 543.

### – Filter differential protection

The purpose of the differential protection is to detect phase-phase and ground-fault failures within the filter bank. The protection is arranged by measuring the difference of filter current

at the line terminal and ground terminal in each phase. For this protection the differential relay type SPAD 346C is used. The input signals to the relay are obtained from the current transformers CT1 and CT5. The relay type SPAD 346C is stabilized for switching transients and the 2nd and 5th harmonics, which will prevent unjustified tripping operations.

#### – Surge arrester protection

The surge arrester protection is intended to ascertain that the resistors and reactors will not be exposed to lightning or transient over voltages exceeding their design insulation level. The protection is arranged using ABB's ZnO arresters type EXLIM connected between the low-voltage terminal of the capacitor C2 and ground.

#### Erection and commissioning

The erection and commissioning tests consisted of the following main activities:

- Visual inspection of the installation
- Capacitance measurement of all capacitor units
- Selection of reactor taps based on the capacitance measurements and actual reactor data

- Test of protection function and protection settings by injection of current to the primary side of each current transformer
- Measurements of line voltages
- Measurements of filter currents
- Measurements of resistor currents
- Measurements of unbalance current of C1
- Measurements of unbalance current of C2
- Measurements of unbalance current of filter resistor R
- Measurements of line voltage harmonic spectrum
- Measurements of filter current harmonic spectrum
- Measurements of resistor current harmonic spectrum
- Measurements of filter impedance versus frequency characteristics
- The results of the commissioning test have verified that the supplied filters fulfill the contractual requirements:
- The manufacturing tolerances are within the specified limits
- The capacitor banks and resistors are well-balanced and the initial unbalance currents are negligible
- The fundamental- and harmonic filter load is below the rated data of filter components
- The measured impedance characteristics comply with the theoretical curves presented in the Impedance study report.



Figure 10

An example of a complete 63 kV filter bank is shown in figure 10

# CSPR (TSC, TCR and Transformer)

**ABB has designed, manufactured and commissioned two SVCs for connection to the 225 kV network in Poteau Rouge and Plaine Haute, respectively.**

## Main component design

For Poteau Rouge the specified SVC rating and harmonic requirement is fulfilled with a 150 Mvar TCR (Thyristor Controlled Reactor), a 150 Mvar TSC (Thyristor Switched Capacitor) and a 50 Mvar filter tuned to the 5th harmonic. This gives the SVC a dynamic range from 100 Mvar (inductive) to 200 Mvar (capacitive) at 225 kV. The SVC in Plaine Haute consists of a 75 Mvar TCR, a 75 Mvar TSC and a 25 Mvar filter tuned to the 5th harmonic, resulting in a dynamic range from 50 Mvar (inductive) to 100 Mvar (capacitive) at 225 kV. The SVCs have identical configurations, only the rated power of the branches differ. The single line diagram is shown in Figure 11. By a combination of phase-angle control of the TCR and switching of the TSC, the SVCs can be continuously controlled over their entire range.

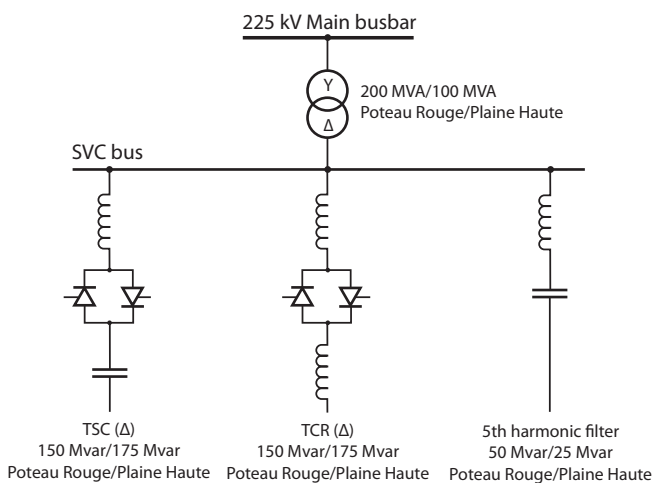


Figure 11

Single line diagram of Poteau Rouge SVC and Plaine Haute SVC

## Transformer

Saturation is the major characteristic that differentiates for SVC transformers than from standard design units. The transformer is designed for continuous operation at 1.18 p.u. secondary voltage.

## Reactors and capacitors

All the reactors of the SVC (TCR reactor, TSC inrush current limiting reactor, harmonic filter tuning reactor) are of epoxy-impregnated, fibre glass insulated, air core design, a technology totally adopted for SVC applications for many reasons. Capacitors are of the full-film, non-PCB and internally fused type.

## Thyristor valves

The thyristor valves consist of single-phase assemblies (Figure 12). The thyristors are electrically fired. The energy for firing is taken from snubber circuits, also being part of the valve assembly. The order for firing the thyristors is communicated via optical light guides from the valve control unit located at ground potential. Between thyristors, heat sinks are located. The heat sinks are connected to a water piping system. The cooling media is a low conductivity mixture of water and glycol.

The TCR and TSC valves each comprise a number of thyristors in series, to obtain the voltage blocking capability needed for the valves. One thyristor is redundant, allowing the SVC to maintain operation with one thyristor level shortened.

The Poteau Rouge SVC uses thyristors of PCT (Phase Control Thyristor) type. This type of thyristor conducts in one direction only. Each thyristor valve comprises two stacks of anti parallel connected thyristors. For the SVC, close to 140 single thyristors are in use, each with a voltage rating of 6.5 kV.

The Plaine Haute SVC uses thyristors of BCT (Bi-directional Control Thyristor) type. In such a device two anti-parallel thyristors are integrated into one wafer with separate gate contacts, allowing conduction in both directions. The thyristor valves comprise only one thyristor stack in each phase instead of two, which enables a more compact valve design. 75 thyristors are in use for the SVC, each with a voltage rating of 6.5 kV. A BCT thyristor allows approximately half the current of a PCT thyristor.

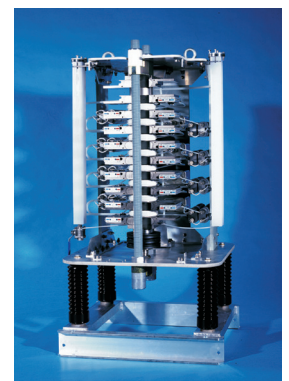


Figure 12  
BCT valve

## Control system

The major objective of the control system (Figure 13) is to determine the SVC susceptance needed in the point of connection to the 225 kV system, to keep the system voltage close to the desired value. This function is realized by measuring the system voltage and comparing it with a set reference value. In case of a discrepancy between the two values, the controller orders changes in the susceptance until equilibrium is attained. Controller operation results in a susceptance order from the voltage regulator which is converted into firing orders for each thyristor. The overall active SVC susceptance is given by the sum of susceptances of the harmonic filter, the continuously controllable TCR, and the TSC if switched into operation. The protective actions are taken.

### Additional control functions

**Loss minimizing:** When the SVC is operating close to the TSC switching point, two operating modes are possible: either with the TCR controlled to a high current balancing the TSC, or with the TSC switched off and a low TCR current. As the losses are higher in the first-mentioned mode, a special control function will prevent long-duration operation in this mode, and after a preset time delay, switch the SVC into the low loss operating mode. This function has no impact on the response time.

**TDCC:** A specific control device, TCR Direct Current Control (TDCC) is included in the SVC control system, in order to minimize negative effects of possibly occurring even harmonic voltage. In such cases, the TDCC prevents DC currents from appearing in the TCR.

**Gain Supervisor and Optimizer:** In case of large changes of the impedance of the connected grid, a Gain Supervisor will automatically reduce the gain of the voltage regulator of the SVC. This is to prevent the SVC output from becoming unstable as a consequence of the gain being too high for the new power system impedance. A Gain Optimizer operates together with the Gain Supervisor, to bring the voltage regulator gain back towards the preset value, when this is appropriate.

### Overvoltage and undervoltage strategies

At system overvoltages and undervoltages, different actions will be taken by the SVC, according to preset strategies.

**Overvoltage strategy:** The SVC is designed to be controllable up to 1.33 p.u. voltage. For all overvoltages above 1.33 p.u. and overvoltages below 1.33 p.u. with duration exceeding 5 seconds, the SVC will be tripped. During overvoltages the normal voltage control will control the SVC to inductive operation. The TSC is designed to allow blocking up to 1.5 p.u. voltage.

**Undervoltage strategy:** If the primary voltage, due to some fault on the 225 kV line, drops to a low value, the normal voltage control will control the SVC to full capacitive output, to support the system voltage. The SVC is designed for operation at 0.8 p.u. voltage during 90 minutes and 0.5 p.u. voltage during 10 seconds, and for voltage between 0.5 and 0.8 p.u. a time duration varying linearly from 10 seconds to 90 minutes. This results in special requirements on the thyristor valve cooling system, as the cooling systems pumps must be able to operate during these severe undervoltage conditions. For voltage below 0.5 p.u. the thyristor valves are blocked, resulting in SVC output equal to the filter output.

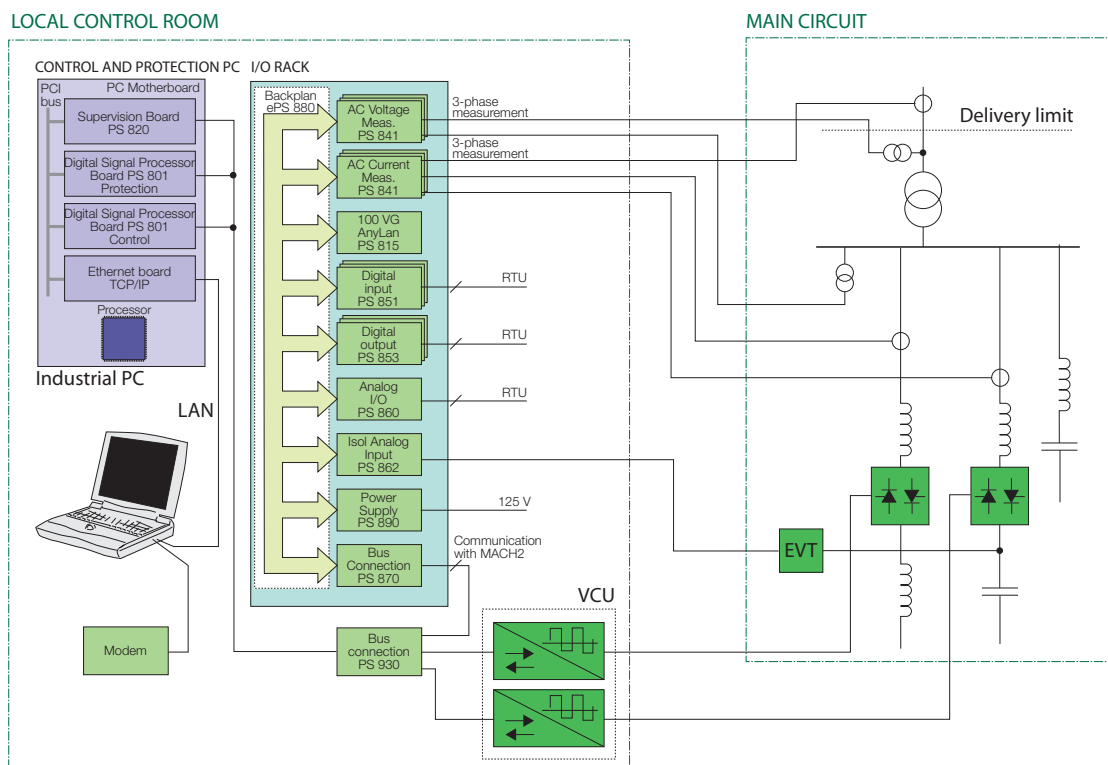


Figure 13  
SVC control system

## SVC Light

SVC Light® is a STATCOM type of device developed by ABB [3]. A typical voltage-current characteristic of an SVC Light is shown in Figure 14. It is worth noting that SVC Light is capable of yielding a high reactive input to the grid even for possible low grid voltages.

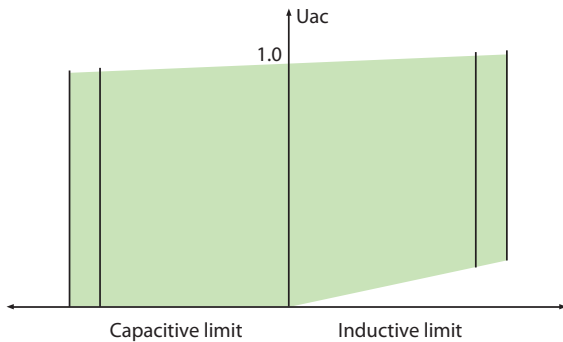


Figure 14  
SVC Light voltage/current characteristics

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

### – Increasing voltage stability

This enables a maximizing of system availability as well as of power transmission capability over existing as well as new lines.

### – Improvement of power quality

This enables the operation of heavy industry such as steel-works and mines without violation of power quality requirements, without the need of reinforcing the grid just to meet power quality demands and without causing nuisance to other consumers in the grid. Other cases of growing importance are dynamic balancing of unsymmetrical loads emanating from high speed traction fed from AC grids, and conditioning of in-feed of wind power.

### – Voltage source converters

SVC Light is based on voltage source converter (VSC) technology. The function of an VSC is a fully-controllable voltage source matching the system voltage in phase and frequency, and with an amplitude which can be continuously and rapidly

controlled, so as to be used as the tool for reactive power control. With the VSC voltage and the bus voltage denoted  $U_2$  and  $U_1$  respectively, it can be shown that by choosing zero phase-shift between the bus voltage and the VSC voltage, the VSC will act as a purely reactive element. (In reality, a small phase shift is allowed, in order to make up for the VSC losses.) If  $U_2 > U_1$ , the VSC will act as a generator of reactive power, i.e. it will have a capacitive character. If  $U_2 < U_1$ , the VSC will act as an absorber of reactive power, i.e. it will have an inductive character. The reactive power supplied to the network can be controlled very quickly. The response time is limited mainly by the switching frequency and the size of the reactor.

### – The converter valve

A VSC of three-level configuration is built up as in Figure 15. One side of the VSC is connected to a capacitor bank, which acts as a DC voltage source. The converter produces a variable AC voltage at its output by connecting the positive pole, the neutral, or the negative pole of the capacitor bank directly to any of the converter outputs. By use of Pulse Width Modulation (PWM), an AC voltage of nearly sinusoidal shape can be produced with only little need for harmonic filtering. This contributes to the compactness of the design, as well as robustness from a harmonic interaction perspective.

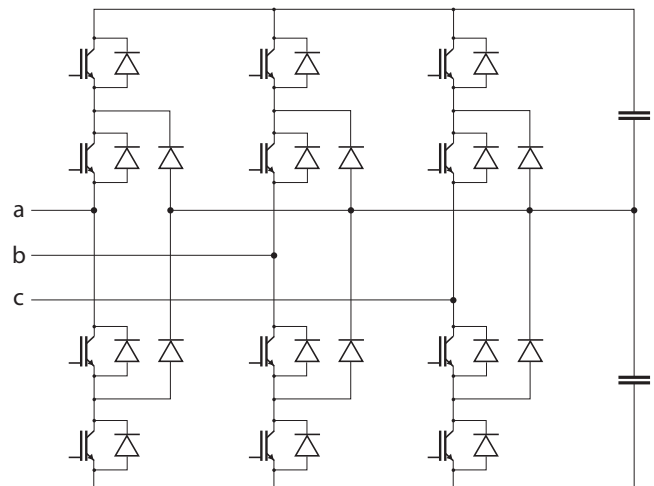


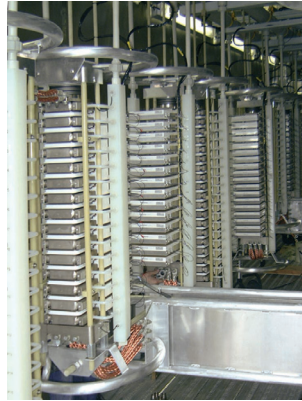
Figure 15

# Conclusions

## – Valve assembly

For SVC Light, IGBT (Insulated Gate Bipolar Transistor) has been chosen as the most appropriate power device.

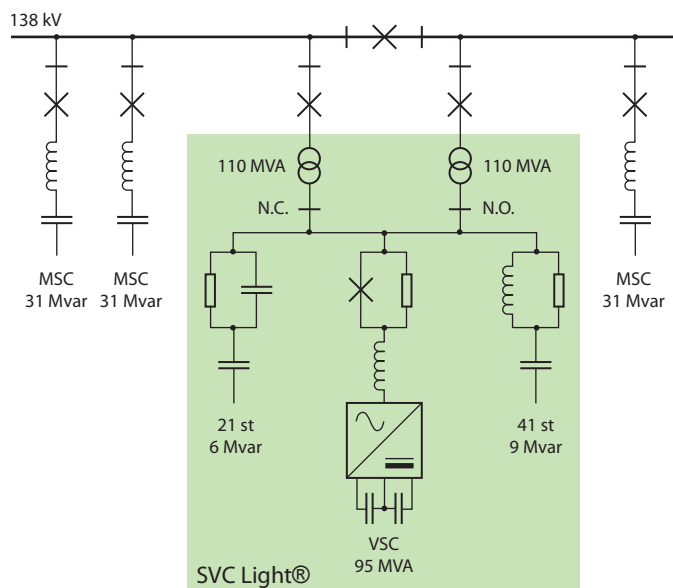
IGBT allows connecting in series, thanks to low delay times for turn-on and turn-off. Nowadays, devices are available with both high power handling capability and high reliability, making them suitable for high power converters. Thus, by series connecting IGBTs, VSC ratings well over 100 Mvar are achieved without any need for paralleling devices. Water cooling is utilized for the IGBT valves, giving a compact converter design and high current handling capacity (Figure 16). IGBTs capable of handling about 2000 ARMS are a reality today.



**Figure 16**  
Converter valve assembly

## – STATCOM for dynamic grid voltage control

An example of a recently installed SVC Light for dynamic control of a 138 kV grid voltage is shown in Figure 17. Including three 138 kV MSC (Mechanically Switched Capacitors), also controlled from the SVC Light, the reactive power range is 80 Mvar inductive to just above 200 Mvar capacitive. The dynamic portion of this is twice the VSC rating of 95 Mvar, or 190 Mvar.



**Figure 17**  
Single-line diagram, STATCOM plus MSC

Shunt capacitor banks have been widely used to compensate reactive power on transmission network. They still represent an economical solution to solve voltage problems. Nevertheless, their insertion in the grid requires detailed studies since shunt capacitors will modify the impedance of the network, and attention must be paid to the amplification of the harmonics, line protections and signal transmission. Last, transient recovery voltages across circuit breakers will also be affected by shunt capacitors, and care must be taken that their performances are not over passed.

Static Var Compensators (SVC) are easier to insert in the network since they are connected to the grid through a power transformer. SVCs are the key solution when the transmission system is pushed to its limits and needs a continuous voltage control with a short time response in a contingency situation. More over with the new SVC, based on voltage source converters, it is possible to support the system during faults or to improve power quality and grid controllability, thanks to the use of fast IGBT combined with latest information technologies.

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