Return to Session

FACTS FOR OPTIMUM UTILISATION OF CABLE NETWORKS IN POWER SYSTEMS

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ABSTRACT

An important line of development in power transmission is the growing importance of cable networks. In particular, the increasing use of offshore installations such as oil and gas platforms, as well as large offshore wind farms, will see a growing use of undersea cables for connection to mainland grids.
FACTS is a powerful means to come to grips with a number of challenges associated with the proliferation of cable networks in power transmission. The paper gives an introduction to FACTS, therein primarily SVC and series compensation, as well as elaborates on various applications to address the challenges in cable networks as presented below.

KEYWORDS

XLPE Cables, Reactive power, FACTS, SVC, Series Compensation, Voltage control, Load balancing.

INTRODUCTION

There is a direct connection between reactive power control in power transmission systems and control of system voltage. In networks more or less dominated by HV and EHV cables, the large reactive power generation associated with cables will inevitably set its mark on voltage regulation. At low load, unless remedied, cable generation may give rise to unwanted voltage rises. At high load, on the other side, cable generation can be used to benefit for voltage support. A common measure to avoid over-voltage at low load is to provide cables with shunt reactors at their ends. This is a crude measure, however, since it loads the cable at all times and prevents it from being fully utilized at high grid load. A better way is to apply reactive power compensation with dynamic control, thereby enabling reactive power balance in the grid at all times. Several benefits to grid operation follow from this, which are the subject of this paper.
Another cable specific characteristic is its low series impedance in comparison with overhead lines. Unless properly dealt with, serious mismatch between load flows in cables and overhead lines may follow. As is shown, FACTS can mitigate or even eliminate this mismatch and thereby improve power transmission capacity in grids.
The term “FACTS” (Flexible AC Transmission Systems) covers several power electronics based systems used for AC power transmission [1]. Given their nature, FACTS solutions are particularly beneficial in applications requiring one or more of the following qualities:

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

Important FACTS devices are SVC (Static Var Compensators), STATCOM, and Series capacitors.

XLPE CABLES IN NORMAL OPERATION

An increasing number of land and submarine links are supposed to be built in Europe in the near future [2]. A considerable part of these links may be built as cable systems, due to mainly environmental concerns associated with OH-lines. Extruded cable transmission links, either operated at AC or DC voltage, must then be able to transmit power reliably and with full control over short and long distances across borders and undersea.
When integrating XLPE cables into the existing transmission network one has to know how the cable itself and the rest of the network react on such integration. A key issue is then to have power flow and voltage control. Consequently, the impedance characteristics of cables must be known.

Line/shunt impedance of XLPE cables

Compared to an OH-line, an XLPE cable has much higher capacitance but normally a lower line inductance. The latter is however also true for single-core submarine cables even if the spacing is large since the sheath/armouring is both ends bonded. Thus, the inductance may for single-core submarine cables be defined solely between conductor and sheath/armour.
The positive sequence impedance for XLPE cables is defined according to equation 1:

$$Z_1 = R_c + \frac{X_s^2}{R_s^2 + X_s^2} \cdot R_s + j\left(X_c - \frac{X_s^2}{R_s^2 + X_s^2} \cdot X_s \right) \quad [1]$$

Equation 1 may be written:

$$Z_1 = \left(R_c + \alpha \cdot R_s\right) + j\left(X_c - \alpha \cdot X_s\right) \quad [2]$$

R_c	resistance of conductor
R_s	resistance of sheath/armour
X_c	reactance between phase conductors
X_s	reactance between conductor-sheath/armour

From equation 2 it can be noticed that we have two extremes:

1. $X_s >> R_s$: $\alpha \rightarrow 1$
2. $X_s << R_s$: $\alpha \rightarrow 0$

Case 1 may be an extreme situation for a submarine single-core cable having a large armour cross-section, i.e. with sheath/armour bonded at both ends or continuously connected to earth via the water, i.e. the magnetic field is enclosed between conductor and sheath/armour. Case 2 may be a land cable installation with single point or cross-bonded sheaths, i.e. the magnetic field affects adjacent conductors outside the cable.

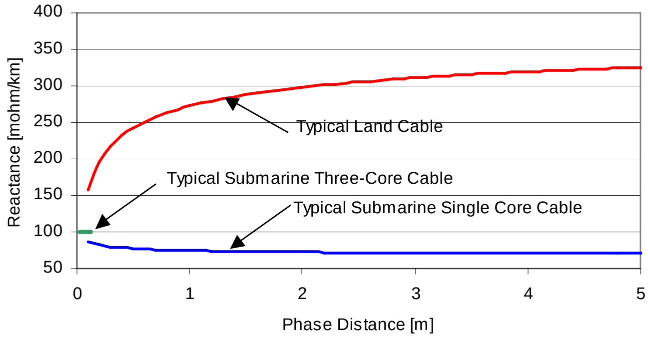

Figure 1. Reactive inductance for typical sub-marine and land XLPE cables.

It is worth noting that a submarine cable designed with a large cross-section of armour will have a low and close to constant reactive inductance. On the other hand, a cross-bonded land cable design may have an inductance close to that of some OH-lines if the phase distance is big enough.

The resistance of the cable can also be obtained from equation 1. Losses will be present in both conductor and sheath/armouring. Submarine single core cables will have an extra loss compared to land cables systems, which normally have single point or cross-bonded sheaths.

Moving further to the capacitance of XLPE cables, it is much higher than for OH-lines. This has a big impact on the maximum length, power loss and voltage swing for long links of XLPE cables. The capacitance may vary between 0.15 to 0.35 μF/km for HV and EHV XLPE cables.

Optimal operation

It is rather clear from the foregoing discussion that XLPE AC cables cannot be optimally operated when they become so long that the capacitance increases the power loss and/or causes the voltage to be uncontrolled.

An ideal state of operation would be to operate long HV or EHV XLPE cables at their natural load, i.e. when the absorbing of reactive power in the cable inductance equals the generation of reactive power in the capacitance of the cable. This never happens, however, since the cable reactive power generation is much bigger than the absorbtion. FACTS devices with shunt inductive compensation can be installed at suitable locations, however, in order to absorb the reactive power generation from the cable. This measure will improve the rating of the link. The natural load or "SIL load" is defined in equation 3:

$$P_{nat} = \frac{U^2}{Z_o} = U^2 \cdot \sqrt{\frac{C}{L}} \qquad [3]$$

U is here the system voltage of a three-phase system and Z_o is the characteristic impedance of the cable or transmission link, in general. For submarine XLPE cables, the characteristic impedance is between 25 and 45 Ω and for other XLPE cables such as land cables it will typically be in the range of 25 to 85 Ω.

There is, however, also a thermal limit, P_{th} of a transmission link, which ideally should be as close to P_{nat} as possible. For AC cables the gap between P_{nat} and P_{th} is large and increases further if the capacitance is high. One optimal way to keep this gap stable and also to get control of reactive power flows and voltages in the network is to use FACTS devices connected to the cable ends.

The ratio between P_{nat} and P_{th} increases with voltage and approximate figures are listed in Table 1 below:

Table 1. Ratios of P_{nat} and P_{th} for normal operation and short lengths of XLPE cables.

Voltage	$P_{nat}/P_{th.}$
110 kV	2-3
150 kV	3-4
220 kV	4-7
400 kV	8-12

Values of maximum lengths, powers and voltages are largely affected by the design of the cable (conductor cross-section, capacitance, inductance etc). However, for various system voltages and lengths, inductive shunt compensation is needed to limit either the maximum allowed voltage swing, or to decrease power losses and balance the capacitive current generation in the cable system.

DYNAMIC COMPENSATION OF REACTIVE POWER: BENEFITS FOR CABLE SYSTEMS

FACTS is a powerful means to come to grips with a number of challenges associated with the proliferation of cable networks in power transmission:

- o As mentioned, an HV or EHV cable is a considerable contributor of reactive power (Figure 2). By means of FACTS, this reactive power generation can be turned to advantage, making it work to the benefit of the grid rather than the opposite. Thus, during high load, the extra vars can be utilized for voltage support, while for low load conditions, the excessive reactive power will be absorbed to prevent overvoltage.

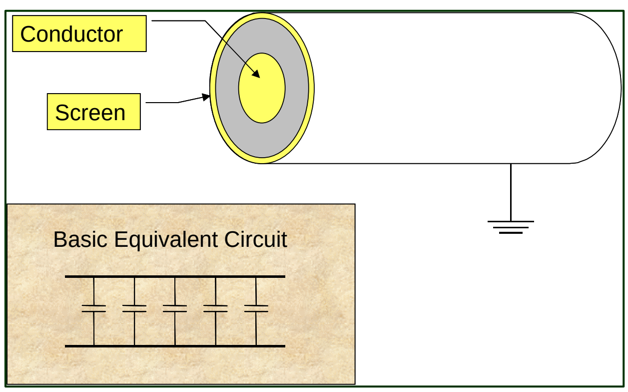

Figure 2: EHV cable: large generator of reactive power

- o With FACTS, the disadvantage of voltage steps associated with mechanical switching of shunt reactors is eliminated altogether, and smooth voltage control is provided over the entire range of cable loading (Figure 3). Moreover, mechanical wear of switching devices is avoided, together with the associated need for regular maintenance of the same.

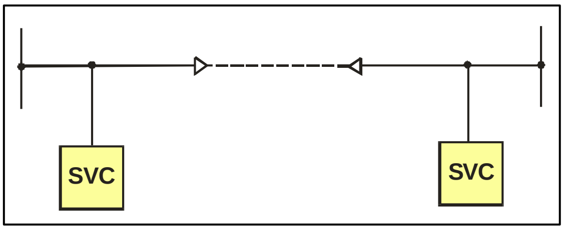

Figure 3: Smooth reactive power control of cable grid

With smooth, dynamic control of reactive power, the following benefits are attained:

1. Maximizing active power transfer capability
2. Voltage support during high load conditions
3. Preventing over-voltage during low or no load
4. Preventing switching over-voltages.

- From a dynamic point of view, cables for power transmission are transparent to possible events in the grid on either sides of the cable link(s). This means that, unless properly remedied, phenomena such as active power oscillations may be propagated through the cables. FACTS devices offer effective means for countering this, thereby contributing to an increase of dynamic stability in the grid.
- From a transient point of view, power cables are subject to over-voltages in conjunction with energizing and switching, presenting potential hazards to the cables as well as surrounding parts of the grid. With FACTS as an integral part of the scheme, such transient over-voltages will be damped or eliminated altogether, saving the cables and the system from potential damage.
- With increasing cable penetration in grids, load division between parallel circuits of cables and overhead lines is becoming an issue of growing importance. Thus, more than one grid company has campaigns running where overhead lines for power transmission and sub-transmission are gradually replaced by underground cables. Here, the dynamic qualities of FACTS enable optimum load balancing for various operating conditions of the grid, thereby ensuring the best possible division of load between parallel circuits (Figure 4).

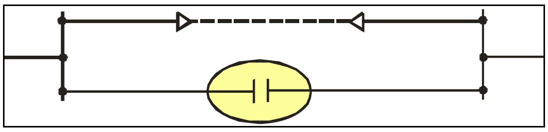

Figure 4: Balancing unmatched cable and OH line

- Comprehensive sea cable networks add another dimension, calling for elaborate reactive power control (Figure 5). In case of off-shore wind farms, the overall scope of reactive power control should encompass the sea cables just as well as the wind farm itself, to bring about a well regulated reactive power balance of the whole system, answering to the same demands on reactive power control as any other medium to large power generator serving the grid.
To fulfill valid grid codes, the reactive power control should also enable the setting of power factors within some certain, given range at the point of connection.

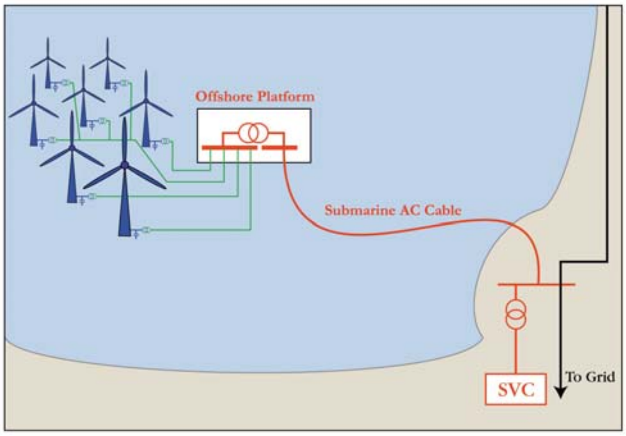

Figure 5: Dynamic compensation of sea cable and off-shore wind farm

FACTS DEVICES

SVC

An SVC is based on Thyristor Controlled Reactors (TCR), Thyristor Switched Capacitors (TSC), and/or Harmonic Filters. Two common design types are shown in Figure 6a and 6b.

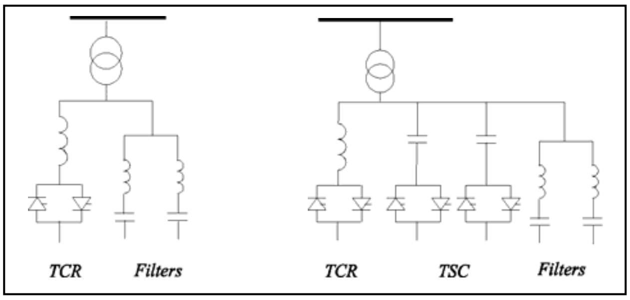

Figure 6a: TCR / Filter configuration (left);
Figure 6b: TCR / TSC configuration (right)

Basic diagrams of one phase of a TCR and a TSC are shown in Figure 7a and 7b. A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. TCR reactors are as a rule of air core type, glass fibre insulated, epoxy resin impregnated.
A TSC consists of a capacitor bank in series with a bi-directional thyristor valve and a damping reactor, which also serves to de-tune the circuit to avoid parallel resonance with the network. The thyristor switch acts to connect or disconnect the capacitor bank for an integral number of half-cycles of the applied voltage. The TSC is not phase controlled, which means it does not generate any harmonic distortion.
A complete SVC based on TCR and TSC may be designed in a variety of ways, to satisfy a number of criteria and

requirements for its operation in the grid.

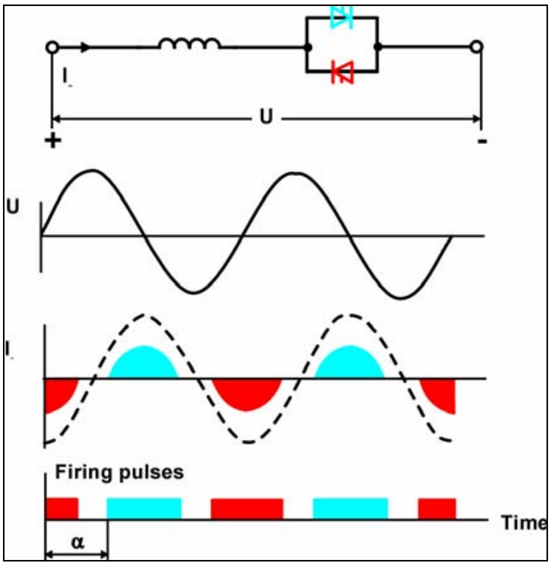

Figure 7a: Operating principle of TCR

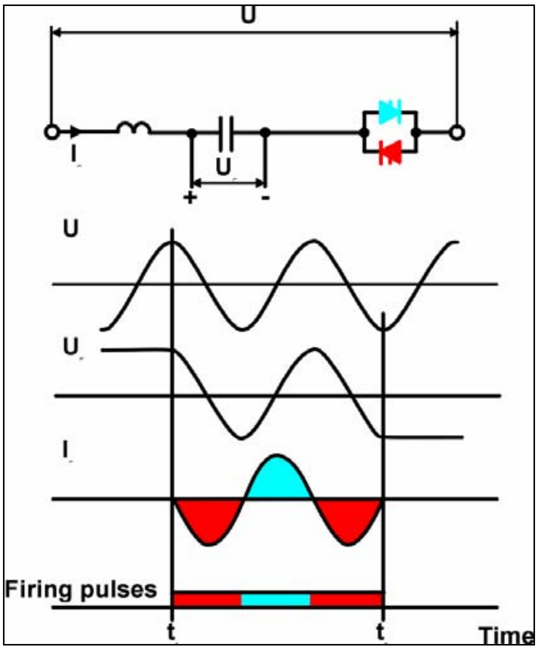

Figure 7b: Operating principle of TSC

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

- Steady-state as well as dynamic voltage stabilisation, meaning power transfer capability increases and reduced voltage variations.
- Synchronous stability improvements, meaning increased transient stability and improved power system damping.
- Dynamic balancing of unsymmetric loads, a feature most useful for protecting wind generators from damage caused by grid unsymmetry.

Thyristor valves

The thyristor valves consist of single-phase assemblies (Figure 8). Each valve comprises two stacks of antiparallel connected thyristors. 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 application. One thyristor is redundant, allowing the SVC to maintain operation with one thyristor level shortened.

Figure 8: TCR valve (one phase out of three)

Series Capacitors

Series compensation has been utilized for many years in AC power transmission with excellent results in a number of countries all over the world. The usefulness of the concept can be demonstrated by the well-known expression relating to active power transfer:

$$P = V_1 V_2 \sin\psi \,/\, X \qquad [4]$$

Here, V_1 and V_2 denote the voltages at either end of the interconnection, whereas Ψ denotes the angular difference of the said voltages.

X is the reactance of the transmission circuit, while P and Q denote the active and reactive power flow.

From [4] it is evident that the flow of active power can be increased by decreasing the effective series reactance of the line. In other words, if a negative reactance is added in the denominator, a corresponding increase in power transmission is enabled without having to increase the angular separation of the end voltages, i.e. with the angular stability of the link unimpeded.

Influencing transmission reactance by means of series compensation also opens up for optimizing load sharing between parallel circuits, thereby bringing about an increase in overall power transmission capacity again. Likewise a valuable feature, active losses associated with power transmission can be decreased, as well.

The impact of series compensation of a transmission circuit can be illustrated as in Figure 9.

Return to Session

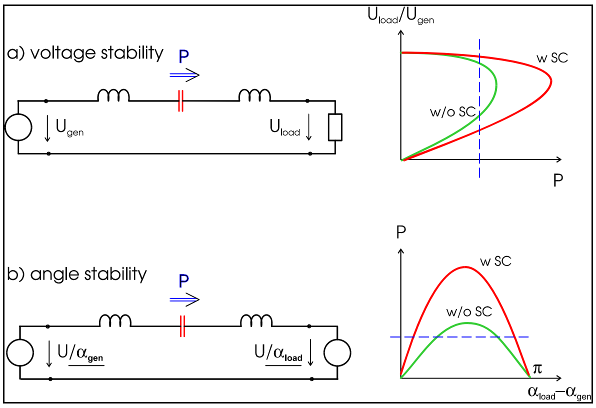

Figure 9: The impact of series compensation

With the reactance of the capacitive element, i.e. the series capacitor equal to X_C and the inductive reactance of the line equal to X_L, we can introduce a measure of the degree of series compensation, k:

$$k = X_C / X_L \qquad [5]$$

In power transmission applications, the degree of compensation is usually chosen somewhere in the range $0{,}3 \leq k \leq 0{,}7$.

The main circuit diagram of a state of the art series capacitor is shown in Figure 10. The main protective device is a varistor, usually of ZnO type, limiting the voltage across the capacitor to safe values in conjunction with system faults giving rise to large short circuit currents flowing through the line.

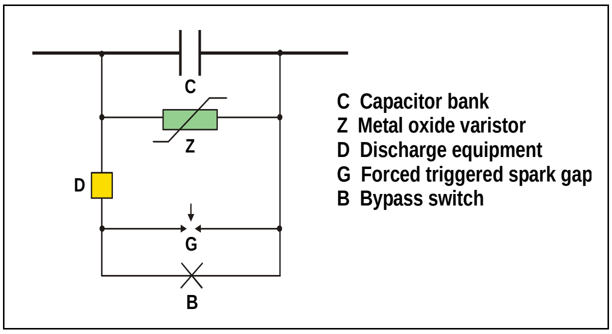

Figure 10: Series capacitor: main circuit configuration

A spark gap is utilized in many cases, to enable by-pass of the series capacitor in situations where the varistor is not sufficient to absorb the excess current during a fault sequence. Finally, a bypass switch is incorporated in the scheme to enable the switching in and out of the series capacitor as needed. It is also required for extinguishing the spark gap, or, in the absence of a spark gap, for by-passing the varistor in conjunction with faults close to the series capacitor.

FACTS APPLICATIONS IN CABLE SYSTEMS

Sea cable power transmission corridor

In Norway, a 12 km, 420 kV underwater oil-filled cable is bridging the Oslo Fjord. The cable is part of the Nordel grid, connecting the power transmission systems of Norway and neighbouring Sweden. The interconnector, having an overall transmission capacity of more than 2.000 MW in either direction, is a key facility for power exchange between the countries.

The underwater cable has a reactive power generation exceeding 350 Mvar. It is equipped with a TCR rated at 360 Mvar (inductive). The purpose of the TCR is to eliminate excessive voltage rise during abnormal conditions and during light load in the power system. The TCR is also of benefit in reducing voltage surges in conjunction with switching operations in the grid (Figure 11).

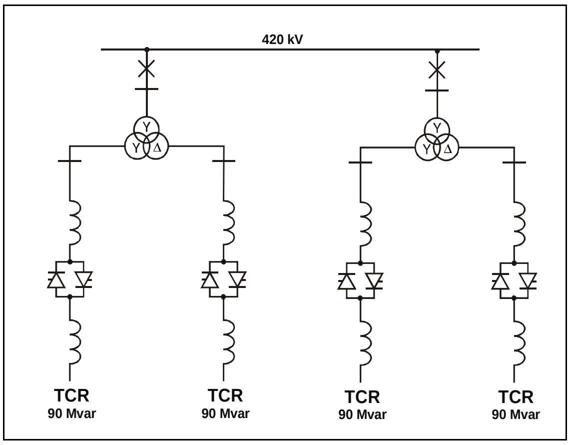

Figure 11: 420 kV, 360 Mvar TCR for sea cable compensation

Furthermore, as it is located in a mostly heavily loaded part of the grid, the capacitive generation of the cable is utilized to support the voltage when needed.

The TCR has been in successful operation for many years, and its owner has recently made a decision to invest in modernizing the installation.

Urban EHV cable grid

For a number of years, one of the Asian main metropoles has been operating two SVCs of TCR type in its 230 kV urban cable transmission network. One SVC is rated at 0-100 Mvar (inductive) and the other is rated at 0-50 Mvar (inductive) (Figure 12).

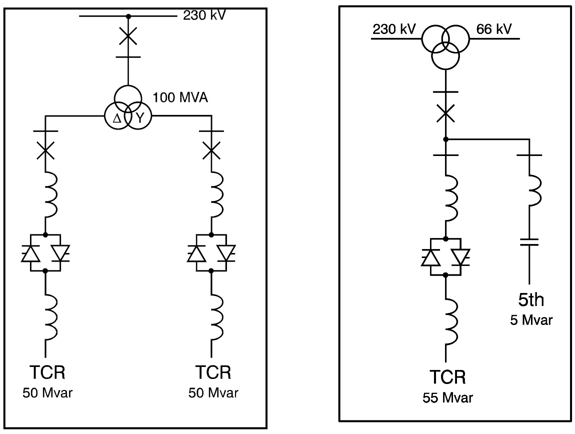

Figure 12: Two TCR, 230 kV, 0-100 Mvar and 0-50 Mvar

The network in question is 100% cable based, with heavy reactive power generation as a consequence. The need for

absorption of surplus reactive power is considerable, as well as complex, due to the variations in reactive power balance during varying load conditions ranging between peak load and light load.
Before the advent of TCR, the need for reactive power absorption was solved by extensive use of shunt reactors at key points in the network, fixed as well as mechanically-switched. This had mainly the following disadvantages:

- Frequent switching of reactors, with the associated switching transients, circuit breaker wear, and requirements for breaker maintenance.
- Limited dynamic capability in situations where fast operation of reactors would be advantageous from a system point of view.
- Only stepwise switching of reactive power possible, which imposed step voltage changes in the grid and did not enable optimum utilization of the power system with respect to loss minimizing and active power carrying capability.

In order to improve the system behaviour of the 230 kV cable network, it was decided to install the two TCR (Figure 13). Their capability to continuously and quickly vary the reactive power absorption yield the following benefits to the grid:

- Continuous compensation of load variations, enabling optimum utilization of the power system with respect to losses and active power carrying capability.
- No need for circuit breaker operations, enabling savings of maintenance costs as well as increased operational reliability.
- Smooth grid voltage control.

Figure 13: 230 kV, 0-100 Mvar TCR

Load sharing between cables and overhead lines

In European countries, to a growing extent legislation is adopted to the effect that new overhead power lines can be erected only provided a corresponding length of already existing lines are converted to underground cables. Likewise, there are urban infrastructure projects going on or at the planning stage implying that overhead line feeders with voltage ratings all the way up to 400 kV are replaced by XLPE cables. The result, to a varying degree, is power corridors with underground cables and overhead lines running in parallel. As series reactances of cables and overhead lines are typically different, mismatch of power sharing is usually the result. This will become more and more common in the future.
Against this scenario, series compensation is studied to improve the load sharing between underground cables and overhead lines. Assuming that in the typical case, it is the overhead line that will be series compensated, the series capacitor rating Q_{SC} will depend on the line current, I_L, and the line reactance, X_L as follows:

$$Q_{SC} = 3kX_L I_L^2 \qquad [6]$$

Impedance matching is done by proper selection of the degree of compensation, k.
So far, mostly in sub-transmission networks this technology has been assessed and found basically useful. What has hampered the application to become real till this day, however, is the fact that at sub-transmission voltage levels (60 kV to 150 kV), circuit lengths (X_L) and current ratings (I_L) have shown to be too small to result in series capacitors of commercially viable sizes. With further development of series compensation in the direction of this area, however, the application will become attractive.
Also, in a certain perspective, series compensation will come into the picture to improve load sharing between 220 kV and 400 kV cables and overhead lines. Here, too, series compensation will prove a viable solution.

CONCLUSION

EHV cables are considerable generators of reactive power. They also display smaller series reactances compared to overhead lines of equal lengths. These qualities need to be properly addressed for cables to operate in harmony with other parts of power transmission grids.
By means of FACTS and more specifically SVC, the reactive power generated by cables can be put to use for voltage support in high load situations, while at the same time, over-voltage is contained at low load.
Frequent switching of shunt reactors can be replaced by smooth reactive power control by SVC, thereby avoiding step voltage changes in the grid. Also a benefit, mechanical wear and frequent maintenance of circuit breakers are avoided by this means.
By means of Series Capacitors, mismatch of loading between cables and overhead lines can be mitigated, or eliminated altogether, thereby achieving larger overall power transmission capability of the system.

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