Enhancement of HVDC performance by means of FACTS devices

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Abstract - **Over the course of three decades of commercial applications, HVDC (High Voltage DC Transmission) has been established as a proven technology in the area of back-to-back and two-terminal long-distance and submarine cable systems up to 2000 MW and higher. Since more than two decades, FACTS (Flexible AC Transmission Systems) devices became a highly reliable, fast and economic means for improving the overall system performance of AC systems. But, up today, only limited HVDC and FACTS systems are operated in parallel in a coordinated manner. However, with increasing complexity of system conditions, e.g. in very weak power systems with enhanced stability requirements, coordinated parallel operation of HVDC and FACTS devices is gaining impetus.**

Key Words: HVDC, FACTS, coordinated operation, system performance

I. INTRODUCTION

In the early years of HVDC, after the transition from mercury-arc valves to thyristor valves, new technologies and new engineering approaches initiated fast HVDC development with both cost reduction and increase of reliability. The high degree of controllability of active and reactive power of the HVDC converters within the rating limits offers the possibility to enhance the overall performance of power systems. Based on over three decades of commercial applications, the HVDC as fully established technique can be used to improve the system performance in the steady state condition through

- steady state power flow control,
- control of the steady state system voltage,
- optimization of spinning reserve sharing

In transient system conditions, HVDC can provide

- damping of power oscillations,
- enhancement of transient stability,
- transient voltage control,
- control of the AC system frequency.

FACTS devices, such as static var compensators (SVC), thyristor-controlled series compensators (TCSC) and thyristor-controlled phase angle regulators as well as unified power flow controllers (UPFC), have the advantage of accuracy, continuity and fast response during their control action, [6]. In comparison to the HVDC, FACTS offer much faster control reactions [7], especially in case of SVC or STATCOM (Static Synchronous Compensator). Hence, due to technical and also economic reasons, FACTS devices are becoming an advanced means for improving overall system performance of AC systems. Most of the FACTS devices use thyristor valves for power converters. In future, the use of GTOs and IGBTs will be increased due to requirements of less space especially in densely populated areas and increased performance in an extended operating range compared to a similar thyristor configuration. STATCOMs with 100 MVar and more are feasible today. High-speed digital controls based on microcomputers and signal processors are the basis for the implementation of advanced control and protection algorithms for FACTS devices and for HVDC.

For comparison, the impact of HVDC and FACTS devices on system performance is shown in Fig. 1.

	SVC/SVG	TCSC	PST	GTO-CSC	UPFC	HVDC
Voltage Control	***	*	*	*	***	*
Load Flow Control (Meshed System)	-	*	***	**	***	***
Transient Stability (Bulk Power System)	*	***	**	***	***	**
Oscillation Damping (Transmission System)	**	***	**	***	***	***
Oscillation Damping (Meshed System)	*	*	**	**	***	***

- very low or no influence
* small influence
** medium influence
*** strong influence

SVC/SVG Static Var Compensator/Generator
TCSC Thyristor Controlled Series Compensatio
GTO-CSC GTO Controlled Series Compensation
PST Phase Shifting Transformer
UPFC Unified Power Flow Controller

Fig. 1 Impact of HVDC and FACTS on system performance

In addition to the standard solutions of the FACTS devices given in Fig. 1, other variations of the FACTS devices have been also developed to meet special system requirements, such as thyristor-controlled voltage limiter and thyristor-controlled braking resistor. These special FACTS devices are usually designed only for a certain problem; they can be used together with other devices e.g. HVDC.

To cover a more wide range of network configurations and operating conditions, a combination of the HVDC and FACTS devices is advantageous. The combination of the HVDC and FACTS can provide the necessary operation characteristics, and thus efficiently improve the system dynamic performance, especially under weak and very weak system conditions.

In this paper, coordinated operations and achievable benefits of the HVDC and various FACTS devices are demonstrated.

II. INTEGRATED OPERATION OF HVDC AND FACTS

The main application of HVDC is the interconnection between AC systems. The types of interconnections are mainly back-to-back stations or long distance transmissions systems, when a large amount of power, e.g. produced by a hydro power plant, has to be transmitted by overhead line or by submarine cable. As it can be seen from Fig. 1, HVDC can provide an excellent load flow control and power damping control. However, it is generally weak in voltage control and transient stability control for an AC system due to the voltage sensibility of converter operations. Particularly, with increasing complexity of system conditions, e.g. in very weak power systems with enhanced stability requirements, the voltage sensibility could cause HVDC outage due to multiple commutation failures.

A commutation failure occurs when the commutation of the current from one phase to the next is not successful. This results in a short circuit on the DC-side and a momentary loss of DC-power. Commutation failures are mostly caused by events in the AC system. For example, voltage drops or phase angle changes in the AC system caused by switching events and system faults can often lead to commutation failures in the HVDC system.

Under normal system conditions, a single commutation failure is a rare event and the controls provide fast recovery, so it is only a transient problem for the overall system. Under weak system conditions, the risk of commutation failures due to the AC system sensitivity and the resulting voltage fluctuation increases significantly. To measure the strength of the AC system involved, the ratio between the AC system short circuit capacity (SCC) and the DC power, the so-called short-circuit ratio (SCR) is adopted

$$SCR = \frac{SCC(MVA)}{P_{DC}(MW)} \tag{1}$$

For strong system conditions e.g. SCR > 3, no major problems are to be expected. In case of weak system conditions e.g. SCR < 2, problems may occur such as increased number of, or repetitive, commutation failures.

Under severe conditions, if the recovery after the first commutation failure is not successful, multiple commutation failures can occur. This can normally not be tolerated and countermeasures have to be taken to provide stable operation of the DC link. Temporary increases in the commutation margin during disturbed AC system conditions are a practical measure. Modified control strategies during the recovery reduce the stress on the weak AC system when DC power is fed into the network again.

For multi-infeed configurations, where separate DC links are connected to a system with low electrical distances between the converter stations, the weak system condition can be reached very quickly. Insufficient decoupling increases the chance of simultaneous commutation failures of all or almost all converters in the area. These situations and the effect on the AC system has to be studied carefully, as a disturbance to a number of links might stress the whole network beyond its limits. Under all circumstances consecutive or multiple commutation failures have to be avoided.

To improve the performance of HVDC in weak system conditions, FACTS devices can be adopted to operate coordinated with the HVDC involved. For example, the improvement of voltage control can be provided by an additional SVC and the enhancement of the transient stability can be achieved by using a TCSC.

Transmission systems will have to be operated more and more to their thermal and dynamic stability limits because of economic and environmental reasons resulting in higher loading. The increased loading may have impact on

- overloading of the equipment and lines during outages
- voltage stability
- transient stability
- oscillatory stability

The impact may be aggravated when high-power HVDC systems are combined with weak ac systems. Thus, careful and detailed planning with powerful planning tools such as NETOMAC is needed to find an appropriate solution [5]. Often the combination of HVDC and FACTS will be the most economic solution that at the same time fulfills reliability and operational requirements. To minimize costs and size of the power electronic equipment the approach has to take into account the combined and parallel operation of power electronic equipment. The different controllers in the system have to be coordinated to avoid interference and to achieve optimum system operation and minimum response times. In the next chapters selected examples on coordinated operation of HVDC and FACTS are given.

III. EXAMPLES OF INTEGRATED OPERATION OF HVDC AND FACTS

A. HVDC and SVC

Use of an SVC close to an HVDC transmission system can improve voltage quality and system stability during and after faults and increase the transient stability. In 1995, a major 500 kV transmission system extension has been carried out to increase the power transfer capability between Arizona and California in USA [8]. As shown in Fig. 2, the extension includes two series compensated lines and two equally rated SVCs, which will operate together with the existing HVDC system. Two SVCs of each 388 MVar have been installed at Mead Adelanto and Marketplace in the 500 kV series compensated WSCC network. Both SVCs are designed mainly to improve the transient stability of the transmission system and to reduce voltage dips on the bus where the inverter station of the 1920 MW HVDC long distance transmission line is connected.

The SVCs use thyristor switched capacitors (TSC) in combination with a special control, that provides voltage stabilization and power swing damping facilities only by use of 500 kV bus voltage measurement with no need for additional power or frequency measurement. In Figure 3, the benefits of the SVC installation for the overall system stability after severe disturbances by providing fast reactive power support are demonstrated clearly: Without SVC in Fig. 3a), the system is unstable with one of the main generators falling out of the step. In Fig. 3b), both SVCs are in voltage control mode, which already provides stability to the system. In Fig. 3c), the coordinated control with power swing damping features is now activated and it achieves much faster return to stability by the improved control.

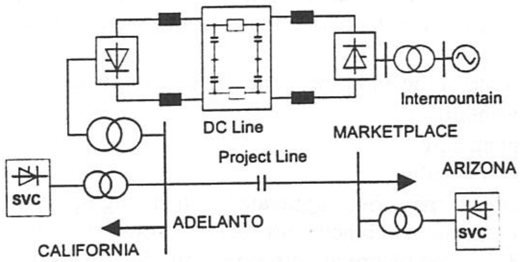

Fig. 2 Mead-Adelanto AC-DC system

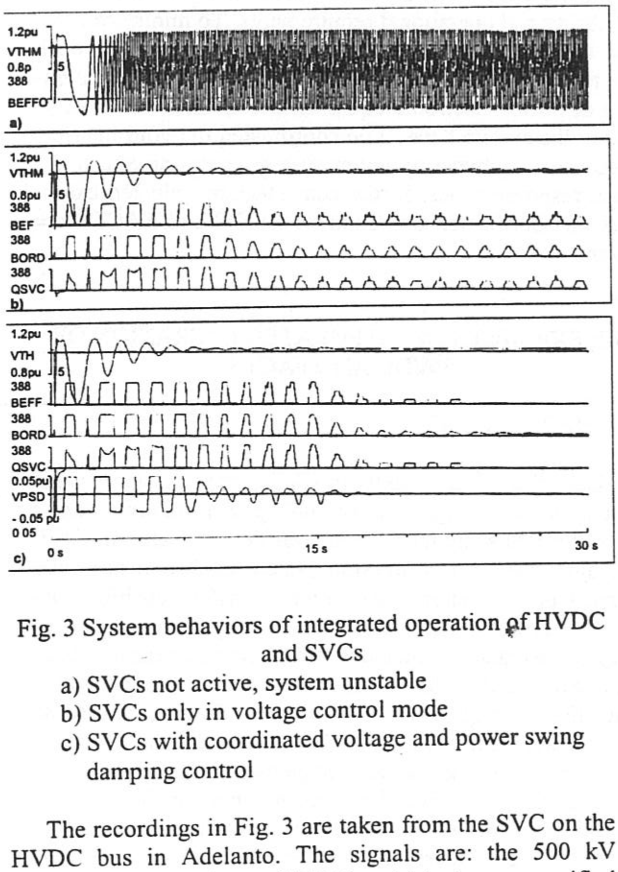

Fig. 3 System behaviors of integrated operation of HVDC and SVCs

a) SVCs not active, system unstable
b) SVCs only in voltage control mode
c) SVCs with coordinated voltage and power swing damping control

The recordings in Fig. 3 are taken from the SVC on the HVDC bus in Adelanto. The signals are: the 500 kV equivalent bus voltage VTHM, which is a magnified equivalent system voltage used for the voltage and power swing controller in combination with the SVC status signal BEFFO. BEFFO is the momentary susceptance value of all activated SVC branches on a phase individual basis (fast evaluation circuit), and it subtracts "virtually" the SVCs own influence from the measured 500 kV bus voltage in order to avoid TSC chattering. BORD is the SVC susceptance output and QSVC the measured and filtered voltage dependent SVC reactive power output (500 kV side). VPSD (in Fig. 3c) is the damping controller output signal.

Figure 4 gives an example of the 500 kV voltage stabilization in case of HVDC disturbances. A five-pulse duration commutation failure is applied on the inverter side of the IPP HVDC, which affects the 500 kV bus voltage significantly. The commutation failure leeds to a long duration of HVDC transformer saturation that needs to be compensated by the SVCs, which do this very well. The oscillograms represent the Adelanto SVC; the Marketplace SVC shows a similar, but smaller reaction due to the larger distance to the event.

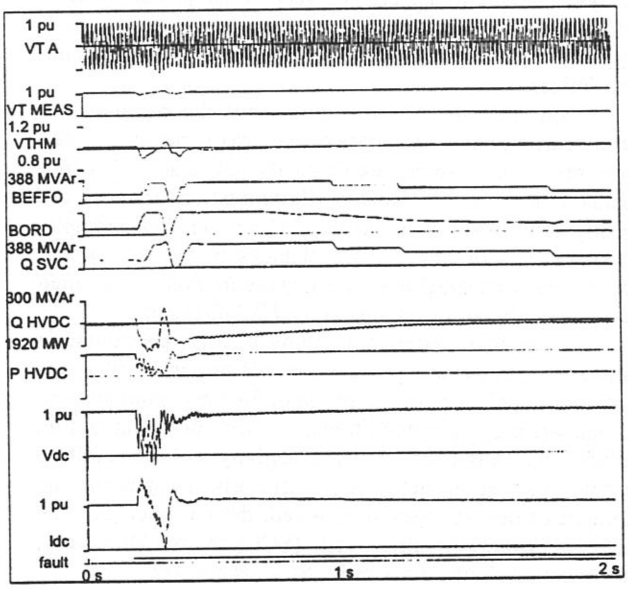

Fig. 4 Simulation of transient HVDC-FACTS Interaction for a severe DC Commutation Failure

B. HVDC combined with Breaker- or Thyristor-Switched Voltage Limiter (BSVL, TSVL)

Overvoltage limiters can be designed either as mechanically or thyristor-switched power arrester. The selection of the optimum version depends upon the specific transient overvoltage sensitivity of the power system. If very fast protection of sensitive electronic devices is required a thyristor-switched limiter is needed. As an example, an integrated operation of a BSVL with a back-to-back HVDC is discussed [1].

The 200 MW back-to-back HVDC has been installed between Sidney and Nebraska to provide an energy-interchange between eastern and western US power grids. Although the AC systems are geographically large, both AC networks are relative weak, e.g. at Sidney converter station where the SCR is below 2.25. Especially, faults in the AC systems close to the HVDC bus and subsequent disconnection of the faulted line can lead to extremely weak network conditions. At blocking of the DC link under these conditions a temporary overvoltage of over 2.0

p.u. is expected that would last until the DC link restarts or, if it remains blocked, until the AC filters and shunt capacitor banks are disconnected.

Due to the need to limit the temporary AC system overvoltage and due to AC system voltage regulation requirements, a special FACTS device, a breaker-controlled voltage limiter (BSVL) was installed at Sidney to ensure a safe operation of the HVDC system. The BSVL consists of parallel-connected metal oxide arresters (MOV). As an equipment to limit the temporary overvoltage, the MOV arresters would be overloaded if they are continuously connected to the system voltage. The BSVL is therefore inserted only when critical faults are detected. During system recovery, the temporary overvoltage is quickly reduced and then the MOV is switched off.

An additional measure of the coordinated BCVL-HVDC control is to provide an HVDC bypass operation in the event of a fault close to the converter bus. When the DC link would block during faults, the undisturbed bus of the link would bear the full load rejection, which would lead to a high overvoltage. To avoid this, the bypass is initiated on the faulted side, the firing angle of the undisturbed side is automatically adjusted approximately to 90°and the DC current is reduced to keep the reactive power of the undisturbed side nearly constant, thus keeping the system voltage constant.

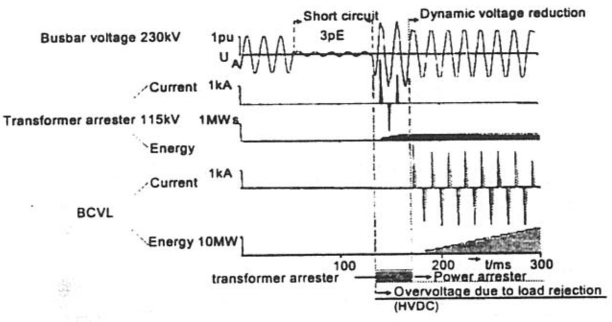

Fig. 5 Application of Thyristor- or Breaker Switched Overvoltage Limiter

Fig. 5 shows the results of a real-time simulation for a 3-phase fault on the HVDC bus followed by a load rejection (loss of HVDC). It can be seen that the local AC voltage is limited very effectively by the BSVL following the defined fault, thus providing protection to existing plant arresters (transformer etc.). Using TSVL, the switching delay (1 or more periods of the breaker) could be reduced to a minimum.

C. HVDC with Thyristor-Controlled and Thyristor-Switched Braking Resistor (TCBR, TSBR)

Thyristor-controlled Braking resistors can quickly absorb large amounts of generated energy when major loads are rejected during severe system disturbances, thus preventing an HVDC system or generator tripping. Breaker switched resistors allow only a relatively slow switching sequence, whereas thyristor-controlled braking resistors can be operated very rapidly and with much more flexibility in a linearly controlled mode or in a stepwise switched mode, e.g. for power oscillation damping. As an example of such a solution, the Cahora Bassa AC/DC system [2] is presented.

Fig. 6 shows the actual AC/DC network concept of Cahora Bassa - Zimbabwe - South Africa interconnection. A 330 kV AC-link interconnects Cahora Bassa and Zimbabwe, whereas the integration of the Zimbabwe network into South Africa is realized via a 400 kV AC-link. The AC/DC interconnection between Songo and Apollo improves of the dynamic behavior of the network substantially by utilizing DC power to rapidly control the voltage angle difference between Songo and Apollo. In case of an insufficient DC power being available, a braking resistor with up to 720 MW is activated. This results in a safe system operation with a voltage angle difference in the order of 60°.

Disturbances from the DC side such as commutation failures at Apollo and the DC line faults affect the AC system significantly. The operational requirements during contingencies are as follows:

- no loss of rotor angle stability,
- damping of power oscillations in the AC link,
- limitation of transient voltage drops,
- avoid switching operation (busbar splitting) at Songo due to disturbances.

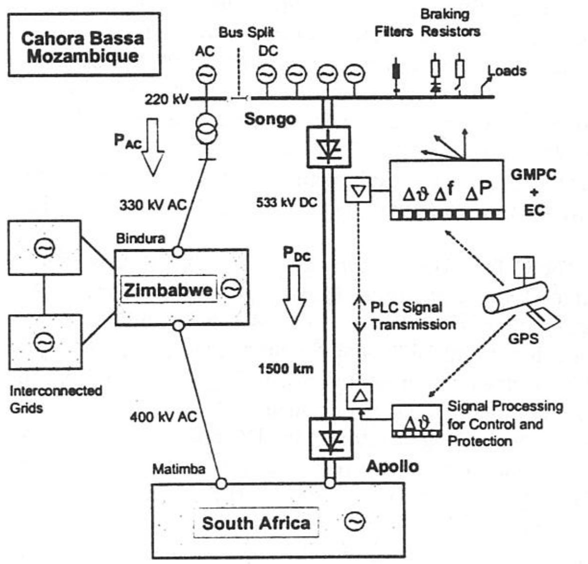

Fig. 6 Power grid of Cahora Bassa - Zimbabwe - South Africa

The stability requirements can be achieved by the Grid Master Power Controller (GMPC) applying the following sequential measures:

- use of 480 MW thyristor switched braking resistor,
- use of 240 MW breaker-switched braking resistor,
- control voltage angle difference by braking resistor and DC power modulation,
- dynamic busbar splitting (only in exceptional cases),
- Bindura line tripping (only in exceptional cases),

- Tripping of generators (only in exceptional cases).

In this AC/DC system, the AC link is very weak. The power change rate is in the order of only 7 MW per degree of the voltage angle. Thus, the AC link can absorb only a small amount of the load deficit caused by faults on the DC transmission. Braking resistors are therefore necessary to keep the power balance at Songo. Apart from stabilizing the AC link, the braking resistors prevent also frequent generator tripping which is undesirable with respect to the service and life-time of the generators. A typical thyristor-switched braking resistor arrangement is shown in Fig. 7.

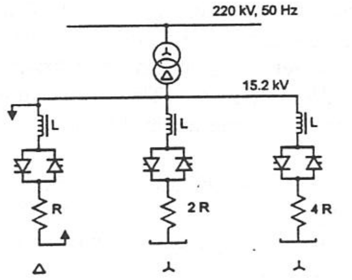

Fig. 7 Thyristor switched braking resistor

The total braking resistor power required is 720 MW where 480 MW is provided by the thyristor-switched resistors in steps of 70 MW. The TSBR is chosen for its superior ability to follow dynamic load rejection profiles. The remaining 1/3 is mechanically switched by a circuit breaker. To demonstrate the effectiveness of the TSBR,

Fig. 8-9 show the system behavior in case of a DC line fault on Pole 1 (close to Songo), on which the HVDC reacts with fast pulse blocking, the healthy pole remains in operation. In the pre-fault condition, the GMPC operates in angle control mode with the AC and DC systems coupled.

The Cahora Bassa power generation is 500 MW via the Songo-Bindura line (corresponding to a Songo-Apollo AC system angle of 72 degree.), 130 MW is taken for the local Songo loads and 1470 MW for the HVDC (7 out of totally 8 DC bridges are in operation). In Fig. 8, the braking resistor is de-activated, thus causing AC and DC bus splitting and trip of 1 generator on the DC bus due to the excess of frequency (at 1,2 Hz in this case) and angle tolerance (120 degree). The voltage dip at Bindura is severe and unacceptable. Hence, for comparison, the braking resistor is activated and compensates the energy surplus during the fault very effectively as shown in Fig. 9. So, no generator in Songo needs to be tripped and the AC and DC bus remains in coupled mode.

D. HVDC and Thyristor-Controlled Series Capacitor

Concepts of series-compensated converters for HVDC has been newly proposed. These concepts are based on the insertion of series compensation between converter transformer and the valve [3]. The solution offers advantages for HVDC feeding in AC systems with extremely low SCR. By reducing the voltage sensitivity in AC systems at load changes, an improved transient stability of the system can be ensured. In the mean time, demands of the HVDC system on shunt compensation can be accordingly reduced.

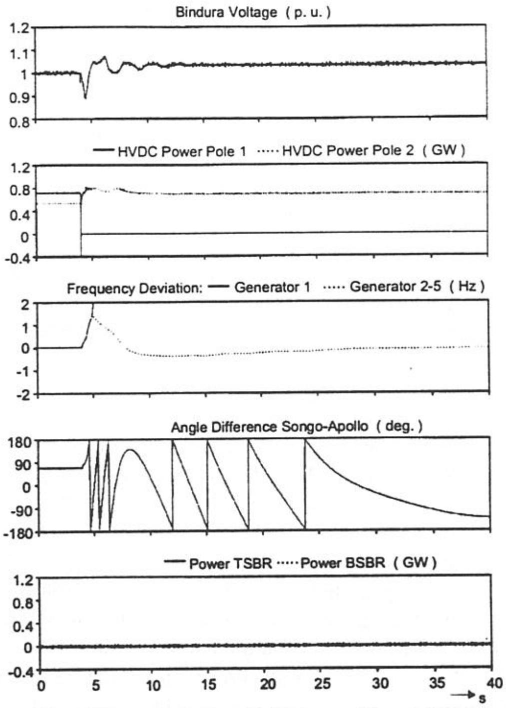

Fig. 8 Songo Busbar Splitting without TSBR

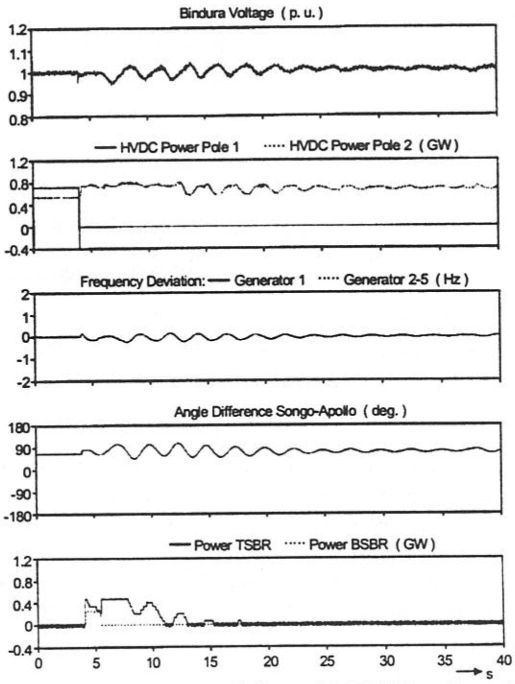

Fig. 9 No Busbar Splitting with TSBR activated

However, overall costs, technical risks and the benefits of such a solution depend upon the application.

Especially, care must be taken to avoid the risk of subsynchronous resonances (SSR). Proposals with parallel inductors to the series capacitor (connected either permanently and/or temporarily by mechanical switches) have been made to avoid this potential risk of series-compensated schemes. Damping effects can also be obtained by a temporary series resistor insertion. However, the parameters of all of these solutions can only be tuned to certain system configurations and operating conditions. If pre-selected conditions change, an SSR free operation of the AC/DC system cannot be ensured.

In this situation, the successful operation of the Thyristor Controlled Series Compensation (TCSC) [4] leads to an innovative concept: Combining TCSC technology with conventional HVDC. Thus, subsynchronous resonances can be avoided easily by dynamically tuning the series compensation circuits to uncritical frequencies. The configuration of a conventional HVDC compared with the standard capacitor commutated converter (CCC) and the thyristor-controlled series capacitor converter (CSCC) is shown in Fig. 10.

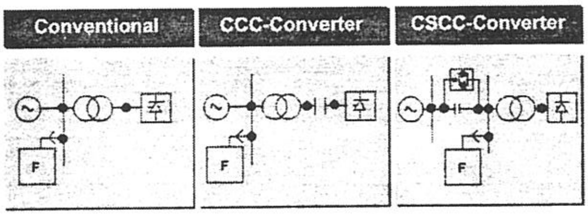

Fig. 10 Configurations of Series-compensated HVDC Converter

The benefits of both versions are summarized in Fig. 11. It can be seen that the combination of TCSC and HVDC offers additional advantages, which cannot be achieved by use of a passive series compensator. The basic benefit of capacitor-coupled HVDC schemes is the possibility to move the extinction angle (α) closer towards 180 degree due to the series compensation, and thus reducing the need for conventional reactive power compensation from usually 50 % of the nominal power to the smaller amounts of remaining harmonic filter requirements.

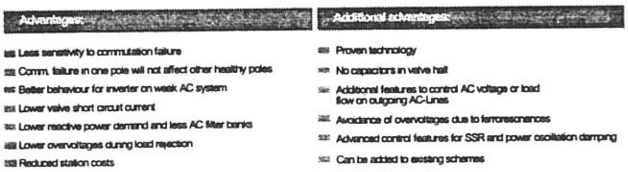

Fig. 11 Benefits of Capacitor-commutated Converters

IV. CONCLUSION

Operation requirements on AC and DC transmission systems will strongly focus on reliability and quality of the electrical energy. HVDC and FACTS technology has been established as advanced means for improving the overall power system performance. To cover a wide range of network configurations and operation conditions, a combination of the HVDC and FACTS devices can be very advantageous. This combination can provide the necessary operation characteristics, and thus efficiently improve the dynamic system performance, especially under weak and very weak system conditions.

The second generation of FACTS technology is based on gate-turn-off thyristors (GTO) and a third generation with IGBTs is currently introduced into the market. This technology offers a lot of technical and operational advantages not achievable with conventional thyristor technology, thus expanding the options for parallel operation with the HVDC. Furthermore, the combination of HVDC and TCSC can avoid the problem of subsynchronous resonances that may occur in the traditional CCC concept.

From the case studies demonstrated in this paper, it can easily be seen that the evaluation of the performance of the HVDC and the FACTS installations is extremely important in the planning stage when analyzing the feasibility of the project. Such studies can be very complex and need multifunctional computer programs such as NETOMAC [5].

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