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Use of Local and Remote Information in POD Control of a VSC-HVdc

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***Abstract*—VSC-HVdcs have shown to be effective means to increase margins of stability in transmission systems. An appropriate control strategy and a correct selection of input signals allow VSC-HVdcs to enhance transient stability, damp power oscillations and provide voltage support in a significant way. In this paper the use of local and remote information in control strategies for POD in the control of a VSC-HVdc are studied. Two main control strategies are considered one of them based on linear control and the other one based on nonlinear control. As local signals current through transmission lines and frequency at connecting nodes of the VSC-HVdc are used. Rotor angles and speed of the generators are used as remote signals.**

***Index Terms*—Remote Information, POD, Transient Stability, VSC-HVdc.**

I. Introduction

The benefits of Voltage Source Converters technology and the fast development of power electronics with higher rated capacity are making VSC-HVdc systems to be considered as an important option among possible solutions when transmission grid owners plan to increase the transfer capacity of the system or interconnect two independent transmission systems.

VSC-HVdcs have shown to be effective means to stabilize transmission systems with resulting higher energy transfer capability and reduced risk of line trips. Different studies have shown the capability of VSC-HVdc enhancing the stability of power systems [1], [2] and providing voltage support [3], [4] just to mention some references. This type of transmission of energy enables power grid owners to increase the existing transmission network capacity while improving the operating margins necessary for grid stability. As a result, a more reliable service can be provided.

Local signals have traditionally been common candidate input signals for POD. In the case of Power System Stabilizer (PSS) shaft speed, real power output or terminal frequency in generators are typical input signals [5]. When a supplementary control for POD is added to FACTS devices or HVdcs systems, signals such as real/reactive power flows, line currents in adjacent lines or deviation of voltage are the most common local input signals used [5], [6].

The use of remote signals in feedback controllers for POD have become more feasible thanks to the development in communication systems [7], [8]. Remote signals, also referred as “global signals”, contain information about overall network. PSSs with remote signals as input have a higher effectiveness than local signals in the damping of interarea oscillations. Interarea modes are not as highly controllable and observable in the generator’s local signals as the local modes [9]. Local signals lack of good observability of some significant interarea modes [10].

This paper analyzes the use of remote and local information in the control strategies of a VSC-HVdc. The different control strategies of the control are intended to provide damping and improve stability in a power system. The aim of the analysis is to compare the damping of the interarea mode of a power system when the POD controllers are input with different signals based on information available at the nodes of connection of the VSC-HVdc or from the generator stations.

II. Controllability and Observability

The total linearized system model of a multimachine system can be represented by the following equation:

$$\begin{aligned}\Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x\end{aligned} \tag{1}$$

where A is the state matrix, B is the input matrix and C the output matrix. Δx is the state vector, Δy is the output vector and Δu the input vector.

Let us define Λ as the diagonal matrix of eigenvalues, Φ as the matrix of right eigenvectors and Ψ as the matrix of left eigenvectors. The modal controllability matrix and modal observability matrix are respectively defined as:

$$\begin{aligned}B' &= \Psi B \\ C' &= C\Phi\end{aligned} \tag{2}$$

A mode is uncontrollable if the corresponding row of the matrix B' is zero. A mode is unobservable if the corresponding column of the matrix C' is zero. If a mode is either uncontrollable or unobservable, a feedback between the output and input does not have effect on the mode.

Controllability of a oscillatory mode is dependent on the location of the electrical equipment. A higher controllability of a critical mode results in a small variable compensation requirement for a given modal damping.

Observability of a oscillatory mode is dependent on the selection of the feedback signal.

Residue is a measurement that depends on both controllability and observability. A higher residue magnitude of residue implies higher sensitivity of the corresponding eigenvalue to controller gain [11]. It is then desirable to have a high controllability and high observability of a mode of oscillation to achieve high damping.

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III. Control Strategies

A. Nonlinear Theory

The control strategy is based on Control Lyapunov Functions. Some authors have used nonlinear theory in the derivation of control strategies for shunt FACTS devices in order to enhance the transient stability [12] - [16]. The control strategy used in this paper has specific application for VSC-HVdc systems [17]. Although the main application of this control strategy is for enhancing transient stability, in this paper it is used for POD.

$$\Delta P_i = k_t(f_i - f_j) \tag{3}$$

where:

- i, j: nodes of connection of the VSC-HVdc
- k_t: positive gain
- f_i: frequency measured at node i
- f_j: frequency measured at node j

B. Linear Theory

A large number of authors have used linear theory in the derivation of control strategies for POD. Some authors have specifically studied VSC-HVdcs in the increase of power oscillation damping. Studies in small signals analysis and its application in VSC-HVdcs to increase damping in power systems can be found in [2], [18] - [22].

In this paper, the POD controller used in the control of the VSC-HVdc consists of a wash out filter, lead-lag filter and a gain as shown in Fig. 1. The time constants of the lead-lag filter are tuned by following the residue technique [23] and the gain determined by Nyquist plots.

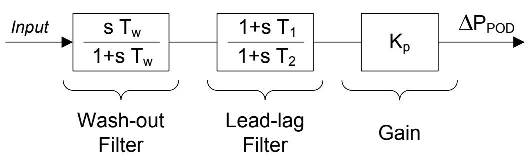

Fig. 1. POD regulator

C. Voltage Support and POD

The control strategy for voltage support is simply based on a PI-controller that tries to keep the voltage at the connecting nodes of the VSC-HVdc (or nearby nodes) as close as possible to a reference value.

A supplementary control strategy for POD is included in the control of reactive power in the VSC-HVdc. The controller has the same structure of the POD controller described in section III-B. The lead-lag filter is also tuned by using the residue technique.

IV. Nordic 32A - Cigré Test System

The Nordic 32A consists of four main parts. The north part which is characterized by high hydro generation and low load consumption. The central part with high demand of electric energy and mainly thermal power generation. The south west part with a few thermal units and low load consumption. Finally the external part, which is connected to the north part and has a mixture of generation and load.

The network is rather long. The major transfer section is from the north part to central area. The south west part is rather loosely connected to the rest of the system. Fig. 2 shows a single line diagram of the system and Fig. 3 illustrates the transfer of power between the areas in a peak-load condition. A detail description of the system can be found in [24].

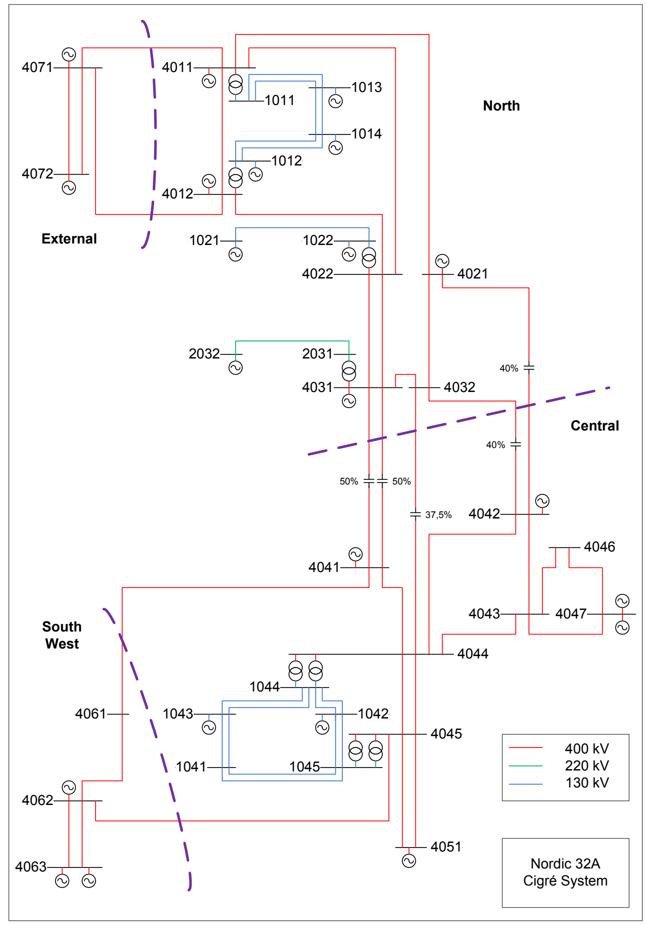

Fig. 2. Nordic 32A Power System

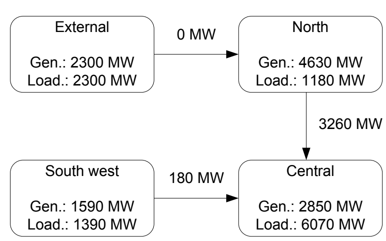

Fig. 3. Transfers of power. Peak-load condition

Linear analysis of the interconnected system shows the presence of two main modes of oscillation. The first mode shows a strong interarea mode between the external and the south west parts. The second mode shows a group of synchronous machines of the central part oscillating against the generators in the south west. These two modes of oscillation have a low, but acceptable damping ratio (7-8%). All generator units have been equipped with PSSs.

V. Location of the VSC-HVdc

The installation of a VSC-HVdc is mainly determined by the need for increasing the transmission capacity in areas where the flow of power has practically reached its maximum allowed transfer. However the purpose of this paper is to show the capability of a VSC-HVdc providing damping by using local and remote information. For this reason the location of the VSC-HVdc is based on analysis of controllability and observability of the interarea mode between external and south west parts.

First the controllability of the interarea mode is calculated by connecting the VSC-HVdc in different parts of the power system. Since the transfer of power is essentially from north to center, the location of the VSC-HVdc is mainly studied in this area.

Table I displays the nodes of connection of the added VSC-HVdc in the system and the respective magnitude of the controllability.

TABLE I
Controllability at different locations

Loc.	Nodes of Connection	Controllability
1	4011-4021	9.0697
2	4011-4022	3.0501
3	4011-4032	4.5058
4	4012-4022	3.1920
5	4021-4032	0.8840
6	4022-4031	2.9885
7	4031-4032	1.7495
8	4031-4041	1.7049
9	4032-4042	0.6576
10	4032-4044	1.3425

Table I shows that higher controllability can be obtained by connecting one of the nodes of the VSC-HVdc in the nodes at the north, i.e., node 4011 or node 4012. The closer to the central part of the power system (farther from north part) the VSC-HVdc is connected, the less controllability of the interarea mode is achieved.

Next the observability is calculated for the selection of the local signal. The line current and active power signals are studied in the five locations with highest controllability. Initial calculations showed that only the current either through the parallel ac line or injected into the VSC-HVdc resulted in very low values of observability. For this reason, the total current/power that flows from north to south at the node of connection of the VSC-HVdc is considered as the local signal.

Table II shows the lines where the signal is measured and the respective magnitude of the observability.

Even though the location of the VSC-HVdc between nodes 4011 and 4021 gives the highest controllability (twice the second highest controllability), the observability is very low which results in a low residue. The location and the feedback local signal are chosen from the calculation of the residue. Table III summarizes the results

From the results of the residue, it is decided to connect the VSC-HVdc between nodes 4011-4032. The feedback input signal for POD is the total current that flows from node 4011 to the central part of the power system, i.e., ac lines 4011-4021 and 4011-4022 and the current injected into the VSC-HVdc.

TABLE II
Observability

Loc.	Measured in line	Observability	
		Current	Power
1	4011-4021 + 4011-4021(dc) + 4011-4022	0.4377	0.3737
2	4011-4021 + 4011-4022 + 4011-4022(dc)	0.8319	0.7866
3	4011-4021 + 4011-4022 + 4011-4032(dc)	1.6959	1.5969
4	4012-4022 + 4012-4022(dc)	0.5223	0.5062
6	4022-4031 x 2 + 4022-4031(dc)	0.9872	0.9485

TABLE III
Residue

Nodes of connection	Current	Power
4011-4021	3.9698	3.3894
4011-4022	2.5373	2.3992
4011-4032	7.6414	7.1953
4012-4022	1.6672	1.6158
4022-4031	2.9502	2.8346

VI. Numerical Example

1) VSC-HVdc Model: The model of VSC-HVdc used in simulations is a model available in the software of simulation SIMPOW [25]. The model is intended for system analysis of power flows and electromechanical transients in electrical systems, for which the influence of harmonics may be neglected. The model is based on parameters and rating values of VSC-HVdc systems currently in operation.

A. Input Signals Control Strategies

1) Nonlinear Theory: In this control strategy local and remote signal are considered. As remote signals, the speed of the generators with highest participation in the interarea mode are selected. They are: 4072G (external area) and 4063G (south west area). An adaptive gain is included in the control strategy (3). This gain is a function of the rotor angles of the machines and is calculated as: $|\sin(\delta_1 - \delta_2)|$. When the difference of the angles is large, the gain will have a high value. If the difference of the angles is small, the gain of the control strategy is low. The absolute value of the adaptive gain makes the gain to be always positive, as it is required by the control strategy.

This signal is denoted as δ, ω and it is used for POD when active or reactive power is modulated.

$$\Delta P_{\delta,\omega} = k_{rem}(\omega_{4072G} - \omega_{4063G})|\sin(\delta_{4072G} - \delta_{4063G})| \quad (4)$$

As local signal, the frequency at the connecting nodes of the VSC-HVdc is considered. The signal is denoted as f_{ij}

$$\Delta P_{f_{ij}} = k_{loc}(f_{4011} - f_{4032}) \quad (5)$$

2) Linear Theory: As concluded from the residue results, the input signal for POD is the total current that flows from node 4011 to the central part of the grid. The notation used for the signal is I_{line}. This signal is used for POD when either active or reactive power is modulated.

B. Fault Cases

The Nordic 32A system is a strong-meshed system. Except for few faults at terminal nodes of generators in the north part, the power system remains in synchronism under $n-1$ conditions.

Four fault cases are defined. All of them consist of faults under $n-1$ condition which means we are simulating the $n-2$ condition of the power system. The plots show the time window result for the $n-2$ condition.

1) Case 1: Disconnection of transmission line 4061-4062 in south west part. 60 s later a three phase short circuit is connected for 100 ms in transmission line 4012-4071, close to node 4012. The fault is cleared by tripping the transmission line. Fig. 4 shows the rotor angle of the generator with highest participation in the mode in Sweden (4063G).

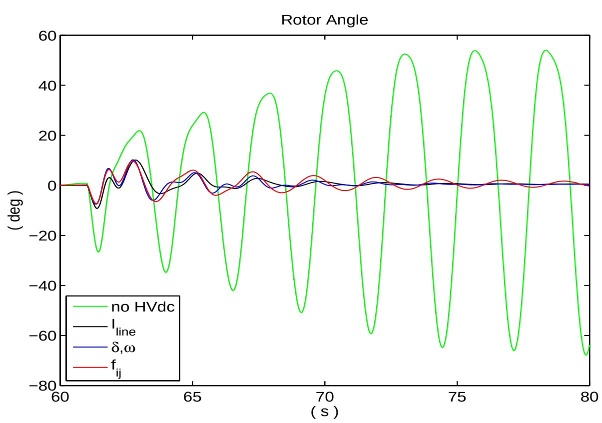

Fig. 4. Rotor angle generator 4063G. Case 1

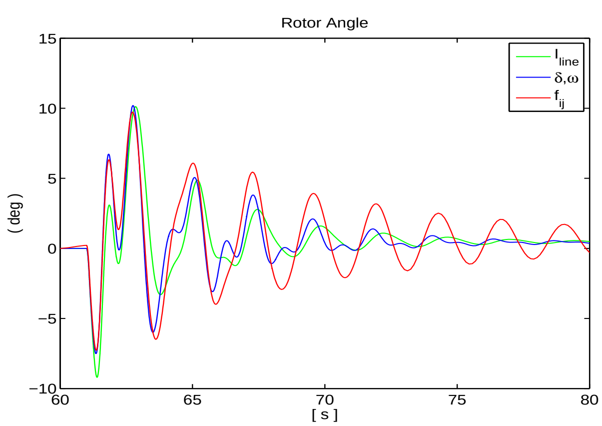

Fig. 5. Comparison damping control strategies. Case 1

When there is no HVdc connected, the system shows large oscillations. Although the time window in Fig. 4 shows a negative damping, the oscillations reach their maximum amplitude some seconds later and then become damped. The system does not lose synchronism.

When the VSC-HVdc is included in the system, the oscillation are dramatically reduced. Fig. 5 compare the damping obtained in the system for the three control strategies. The local signal, I_{line} provides as much damping as the remote signal δ, ω. The second local signal f_{ij} provide also damping but in a lower scale.

2) Case 2: A three phase short circuit is connected in transmission line 4032-4042 close to node 4032. The fault is cleared 100 ms later by tripping the transmission line. After 60 s again the second fault of case 1 is connected. Fig. 6 shows the rotor angle of the generator 4063G and Fig. 7 a detailed comparison of the damping.

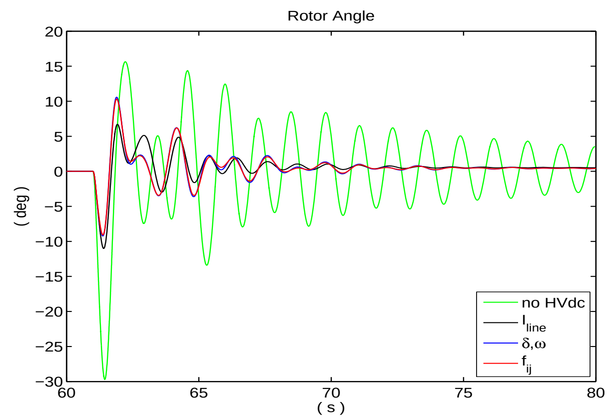

Fig. 6. Rotor angle generator 4063G. Case 2

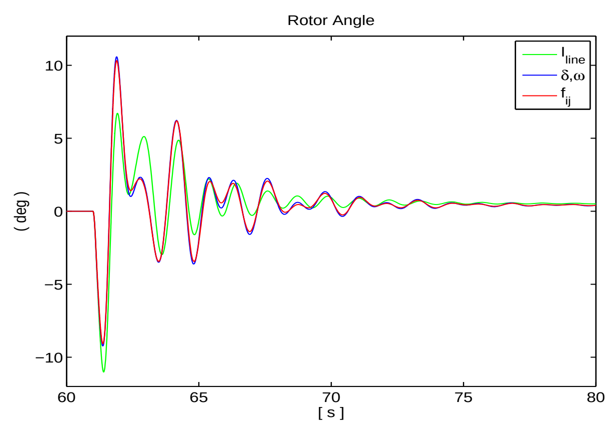

Fig. 7. Comparison damping control strategies. Case 2

There is no much difference between the damping provided by the local feedback signal I_{line} and the remote signal. The local signal f_{ij} follows the same pattern as the remote signal, which is expected due to the location of the VSC-HVdc.

3) Case 3: The transmission line 4031-4032 with high transfer of power is disconnected. After 60 s the transmission line 4021-4042 is three phase short circuited. 100 ms later the faulted line is tripped. Fig. 8 shows the voltage at the connection node of the VSC-HVdc in the central area.

This is a case of voltage instability as Fig. 8 shows. When there is no HVdc in the transmission grid the voltage remains close to 1 p.u. after the first disturbance. However after the short circuit and respective disconnection of the faulted line in the second fault, the system cannot achieve stability. The higher transfer of power through the corridor that interconnects north and central area makes the voltage to fall and the power system becomes voltage unstable.

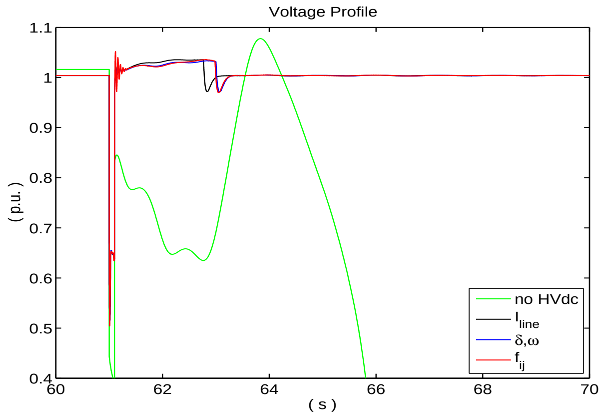

Fig. 8. Voltage profile at node 4032. Case 3

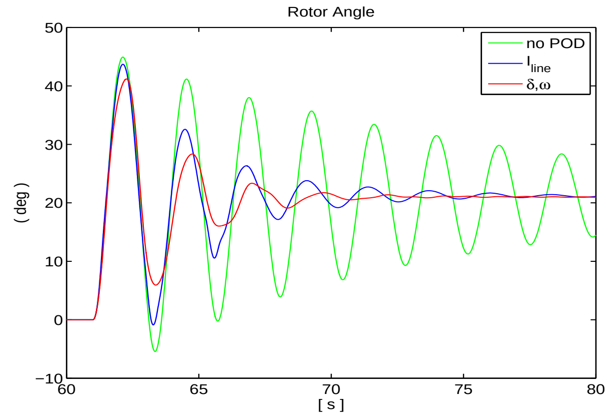

Fig. 10. Rotor angle generator 4063G. Case 5

Thanks to the capability of the VSC-HVdc to consume or generate reactive power independent of the transfer of active power, the power system remains in synchronism after the second fault. Fig. 9 shows the modulation of the reactive power in the VSC connected at node 4032. The combination of damping by modulating the active power and voltage support by generating (in this case) more reactive power the system gives a higher margin of stability in the power system. The VSC decreases its consumption of reactive power from 2.3 p.u. to practically zero.

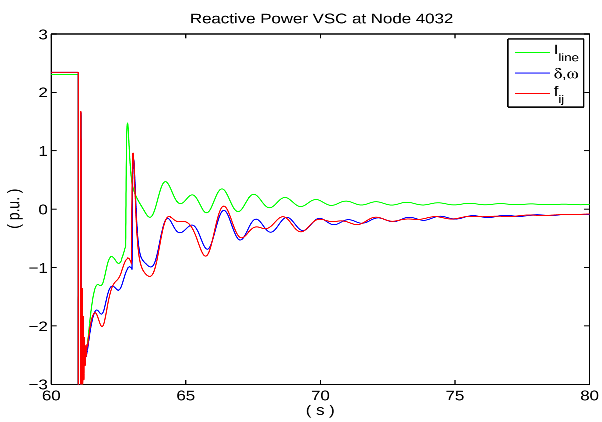

Fig. 9. Comparison voltage support. Case 3

4) Case 4: The purpose of this case is to observe the damping provided by the converters when there is no possibility to transmit dc power. A short circuit is connected in one of the dc nodes for 100 ms in the north converter (node 4011). Even though the VSC-HVdc is able to transmit energy with one single pole, both poles are disconnected. There is no transmission of dc power, but the converters remain in operation. 60 s later the transmission line 4061-4062 is disconnected. Fig. 10 shows the simulation results.

When there is no POD in the Q-control, the system is stable after the fault and an acceptable damping can be observed. Next, the control strategy is connected to the Q-control in the rectifier converter (node 4011). Under this condition the VSC-HVdc has modulation of reactive power due to the POD signal and modulation of reactive power at the inverter side due to the voltage support (U_{ac}-control). This mode of operation makes the oscillations in the system die out much faster. A somewhat higher damping is observed when the remote signal is used.

VII. Discussion

In this paper local signals have shown to be appropriate feedback signals in the control of a VSC-HVdc. The damping provided by these local signals was very close to the damping provided by the remote signal. This result was expected since the location of the VSC-HVdc was specifically determined to obtain the maximum controllability of the interarea mode. The right location of the VSC-HVdc can be confirmed by comparing the damping provided by the signal f_{ij} which follows the same pattern of the remote signal δ, ω. Furthermore the feedback local signal was specifically chosen so that the highest residue magnitude was achieved.

If the VSC-HVdc is connected in some other part in the system, local signals are not as effective as remote signals. A VSC-HVdc connected in the south west part, for instance, provides little damping if the local signal f_{ij} is used. The frequency variation in one node of connection of the VSC-HVdc is very close to the change of frequency in the other node. This similarity makes the difference $f_i - f_j$ to become practically zero and therefore have a low impact in damping. On the other hand the remote signal always has the same information independent of the location of the VSC-HVdc.

One relevant assumption in this paper was that there was no time delay in the remote signals. The inclusion of time delay in the control strategies might result in lower damping. However this is part of future work.

VIII. Conclusions

A comparison between local and remote signals in different control strategies for POD in the control of a VSC-HVdc were analyzed. The location of the VSC-HVdc and the selection of the local feedback signal for POD were purposely determined so that a high residue magnitude of the interarea mode was achieved. This allowed local signals to provide as much damping as remote signals. However, for different location of the VSC-HVdc the damping is lower when the feedback input signal is local.

The independent modulation of active and reactive power allowed the VSC-HVdc to provide higher margins of stability in the power system.

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BIOGRAPHIES

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