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POWER SYSTEM STABILITY BENEFITS WITH VSC DC-TRANSMISSION SYSTEMS

Stefan G Johansson*
ABB Corporate Research
(Sweden)

Gunnar Asplund, Erik Jansson & Roberto Rudervall
ABB Power Systems
(Sweden)

The power system is dependent of a stable and reliable control of active and reactive power to keep its integrity. Loosing this control may lead to a system collapse. Voltage Source Converter transmission system technology such as HVDC Light™ has the advantage of being able to almost instantly change its working point within its capability curve. This can be used to support the grid with the best mixture of active and reactive power during stressed conditions. In many cases is a mix of active and reactive power the best solution compared to active or reactive power only. VSC transmission systems can therefore give added support to the grid. Some small 'text-book' grid examples are used to show that for asynchronous infeed, active power modulation damp ~4 times better than reactive power modulation and that local loadability can increase with ~2 times installed converter MVA size. In a parallel case where the VSC transmission system is connected in parallel with the AC system, the VSC transmission system can damp ~2-3 times better than reactive shunt compensation and increase loadability ~1.5 times installed MVA converter size. The benefits with a VSC transmission system during a grid restoration can be considerable since it can control voltage and stabilize frequency when active power is available in the remote end. The frequency control is then not limited in the same way as a conventional power plant where boiler dynamics may limit the operation during a grid restoration.

Keywords: High Voltage Source Converter - Transmission system – HVDC Light - Power System Stability – Voltage Stability – Rotor oscillation damping - Black start – Grid Restoration

1. INTRODUCTION

Since ABB introduced its Voltage Source Converter DC-transmission system 'HVDC Light' in Hellsjön 1997, the rating has increased 100 times to 330 MW presently operating in the Cross Sound cable connection. A number of projects has now been commissioned and are showing good operating experience. The transmission capacity and converter sizes of a VSC transmission system are becoming large enough to also play a role in system stability improvement. Different applications will make good use of the high controllability of active and reactive power considerably improving system stability. Three basic grid configurations will be discussed, parallel AC and DC systems, series connected AC and DC systems and asynchronous connection of a DC system between two AC systems.

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*) SE-721 78 Västerås, SWEDEN, email: stefan.g.johansson@se.abb.com

Transmission line bottlenecks caused by system stability limitations form one particular area of interest. Series and shunt compensation may have been used already to alleviate the congestion and right of way problems may prohibit new transmission lines. A VSC transmission system can be laid (cable) and installed in parallel with the AC system without lengthy right of ways discussions alleviating the bottleneck constraints.

In case of asynchronous infeed of power where the two ends of a VSC transmission system do not have any mutual coupling the control of the VSC transmission can improve stability further in the connection point.

The VSC transmission system can also be connected in series with a (long and/or weak) AC-line. Methods to utilize the weak AC line as high as possible will also be discussed in the paper.

This paper treats symmetrical three phase stability problems related to fundamental power transfer in the power grid. A VSC Transmission system is also capable of influencing unsymmetrical grid conditions, power quality and harmonic problems. These issues are not covered further in this paper. A more thorough presentation of the technology discussed can be found in [1].

We start with a presentation of different stability issues that are treated with regard to the specific characteristics of a VSC transmission. The strategies for some applications are discussed followed by simulation results in a ‘text-book’-type example. Note that many of the proposed strategies will be applicable for temporary solving instability situations. Criterions like (N-1) or similar are used to establish the maximum amount of load that a critical grid section can transfer. If a large generator or transmission line trips, the VSC transmission can change its operating mode and temporary strengthen the grid until other remedial actions restore grid security.

2. THE CAPABILITY CURVE OF A VSC TRANSMISSION SYSTEM

There are mainly three factors that limit the capability seen from a power system stability perspective. The first one is the maximum current through the IGBT:s. This will give rise to a maximum MVA circle in the power plane where maximum current and actual AC voltage is multiplied. If the AC voltage decreases so will also the MVA capability.

The second limit is the maximum DC voltage level. The reactive power is mainly dependent on the voltage difference between the AC voltage the VSC can generate from the DC voltage and the grid AC voltage. If the grid AC voltage is high the difference between the maximum DC voltage and the AC voltage will be low. The reactive power capability is then moderate but increases with decreasing AC voltage. This makes sense from a stability point of view.

The third limit is the maximum DC current through the cable.

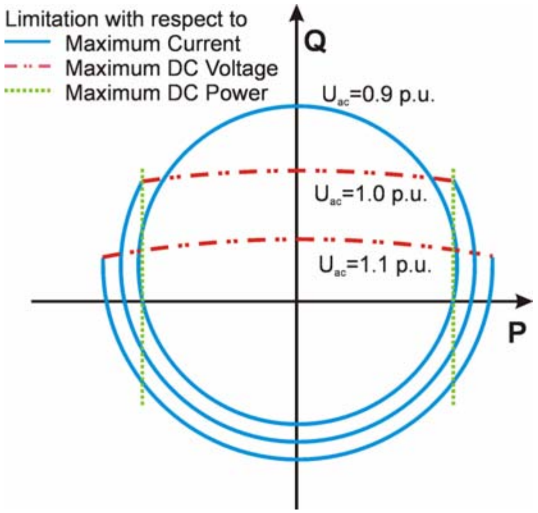

Figure 1 The capability curve

The different limits are shown in Figure 1. For a decreasing AC voltage level the maximum DC voltage level will vanish and the maximum current level will decide the capability. The small bias in Q-axis direction is due to the line reactor and the filter capacitance within the VSC transmission system [1]. Smaller adjustments in the calculations presented below will therefore be necessary when evaluating the qualitative results of a VSC transmission. Also the tap changer on the converter transformers will play a role during certain cases. Note the similarities with this capability curve and a capability curve for a generator. Maximum DC voltage level corresponds to maximum field current in the rotor winding and IGBT current corresponds to armature current.

A VSC transmission system can virtually instantly take any working point within the capability chart. Instant active power flow reversals are also possible since the VSC transmission system changes DC current direction and not DC voltage polarity. The XLPE-based cable technology used will handle such current reversals without any problem. Any limitations in the maximum power changing rates of the connecting AC grids must naturally be taken into account.

3. DIFFERENT STABILITY ISSUES AND VARYING GRID CONFIGURATIONS

There are two different aspects to consider. Firstly, the type of power system stability issue that the VSC transmission system can be exposed to. Two phenomena are voltage stability and rotor angle stability. Secondly, the grid configuration in which the VSC is configured to the AC system. Three basic types can be identified:

- Series connection of the VSC converter and the AC-system
- Parallel connection of the VSC transmission system and the AC-system
- Asynchronous infeed from the VSC converter into the AC-system

3.1. *Strategy for series connection and voltage instability*

A typical situation can be illustrated as in Figure 2b. Illustrating the power flow equations for the receiving end in a power circle diagram [4] combined with the (mirrored) capability curve of the VSC transmission system shown in Figure 2a will immediately reveal the maximum transferable active power. The crossing between the capability curve of the VSC transmission and receiving end circle will indicate the stable solution for that particular voltage level. If sending end voltage drops it is possible to immediately establish the new stable solution in the power circle plane by recalculate the figure.

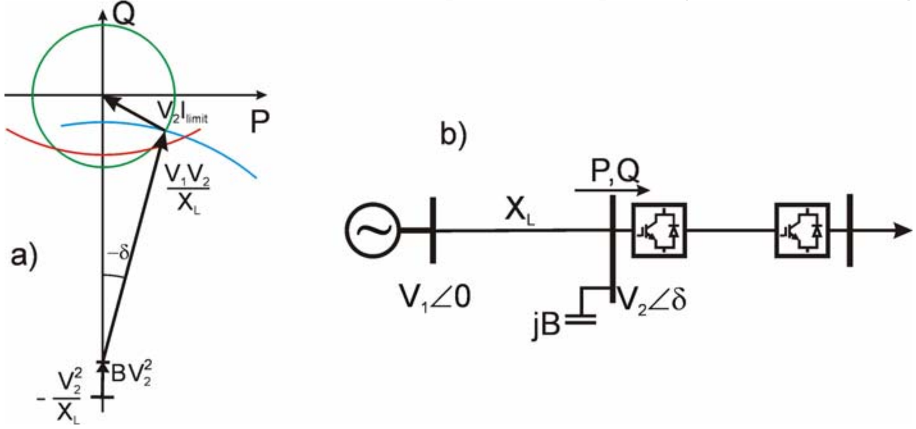

Figure 2 The receiving power circle plane, a) for a VSC transmission in series with an AC line, b)

3.2. *Strategy for parallel connection and voltage instability*

If the VSC transmission system is connected in parallel to an AC line the control of the VSC transmission will have impact on the AC flow. By varying the power factor of the DC transmission we will be able to utilize the AC system better. In order to enhance system operation we must pick the best power factor operation for the VSC transmission when the system becomes stressed. Figure 3a)-b) shows a parallel case with the associated power circle plane [4]. If we begin studying the receiving end circle we can see the power flow on the AC-line (following the arc with angle δ) to which the power flow via the VSC transmission is added (the vector within the smaller circle). In this example, the AC line is requiring some reactive power which is fed from the VSC system. In the figure, the MVA circle (the small one) is valid for the VSC transmission. We see that the MVA capacity is at its maximum point for the DC system i.e. we can not transfer more power over the combination. An increase of DC flow or AC flow (requiring more reactive power to keep AC voltage) would violate the capability curve. If we now decrease DC-power transfer and are able to inject more reactive power one can see that it is possible to transfer more active power over the combination. A best choice is made according to:

$$P_{dc} = I_{\text{limit}} \cdot V_2 \sin(\delta_1 - \delta_2) \qquad \text{and} \qquad Q_{dc} = I_{\text{limit}} \cdot V_2 \cos(\delta_1 - \delta_2) \tag{1}$$

where I_{limit} is the maximum steady state current allowed in the converter. If the maximum DC voltage level limit is included in the figure its role is directly disclosed in the drawing.

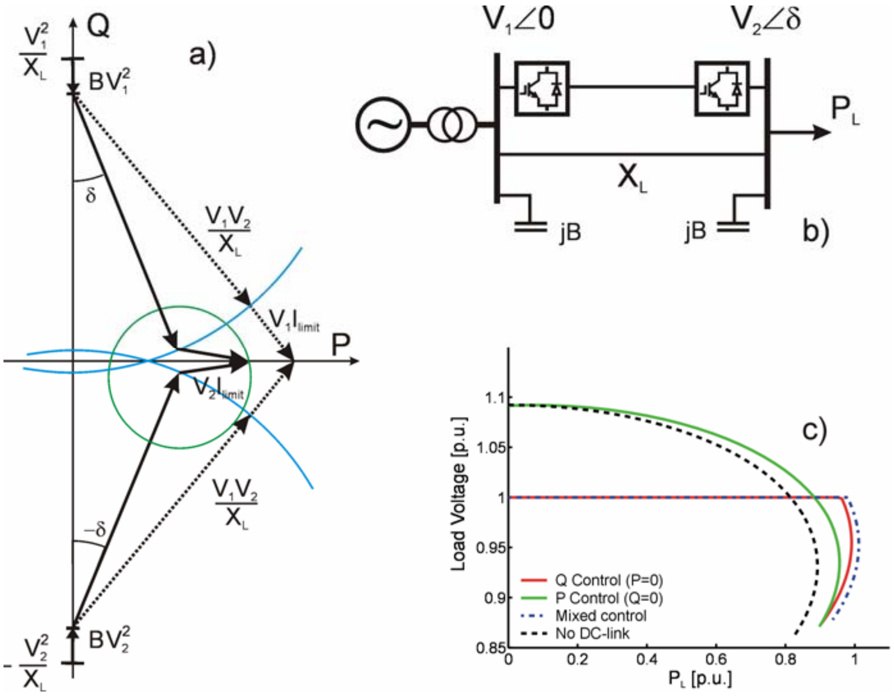

Figure 3 A parallel case b) with a power circle plane, a) to indicate 'best' solution. PV curve in c). Key grid parameters are X_L=0.5, B=0.2, (SIL=0.872 p.u.), X_t=0.2 p.u. and converter size=0.08 p.u.

The associated PV-curve is plotted in Figure 3c). It shows three different ways to utilize the capacity in the VSC transmission system. The first one is active power transfer only, the second is only reactive power generation in each end (STATCOM operation) and the third one is a mixture according to the best choice described above. Point of Maximum Loadability, P_{max} for the three possibilities are indicated in Table I. The best choice in this example increases the point of maximum loadability with 149% of installed MVA capacity.

Table I Loadability as a function of different control strategies

Method	P_{max} [p.u.]	Gain [p.u.]	Gain/Converter size
No DC	0.8923		
P Control	0.9561	0.0638	-20%
Q Control	0.9908	0.0985	+23%
Mixed Control	1.0117	0.1194	+49%

3.3. Strategy for asynchronous infeed and voltage instability

Many HVDC links are connected between asynchronous grids operating with different frequency. In the connection point where active power is fed into the AC grid VSC transmission can add improved performance. If we study a thevenin equivalent of an infeed shown in Figure 4 the qualitative behavior of changing power factor in the VSC transmission can be studied. Compare the solid and dotted vectors in the diagram. By aligning the vectors by changing power factor we achieve maximum loadability. A study for generators where a similar structure was investigated can be found in [2].

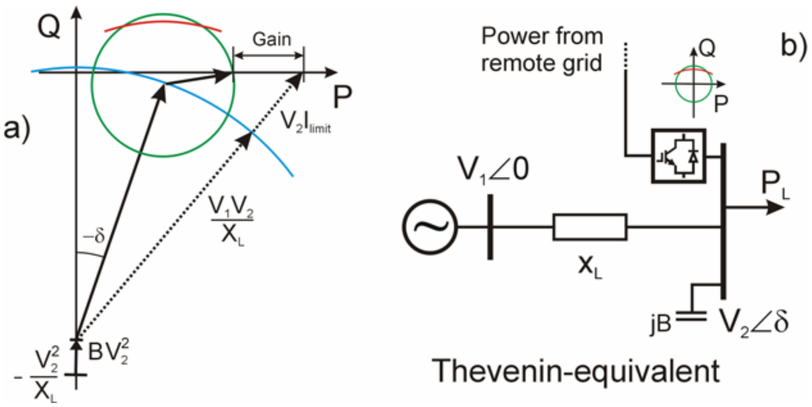

Figure 4 **Asynchronous infeed b) and enhanced loadability shown in the diagram a)**

The loadability P_L as a function of P_{dc} is plotted to the left in Figure 5. The working points are indicated in the schematic power circle planes to the right of Figure 5. Note the point A, where we only transfer active power (similar to Classic HVDC) and the optimum point B where the loadability has increased more than the installed MVA capacity in this numerical example. It means that from SIL transmission level of 0.87 p.u. we have increased power transmission capacity to 1.04 p.u. i.e. a gain of 0.17 p.u., twice the installed converter capacity of 0.08 p.u. If active power is not available remotely the loadability is increasing to point C in the figure (assuming that maximum DC voltage has not limited reactive power output).

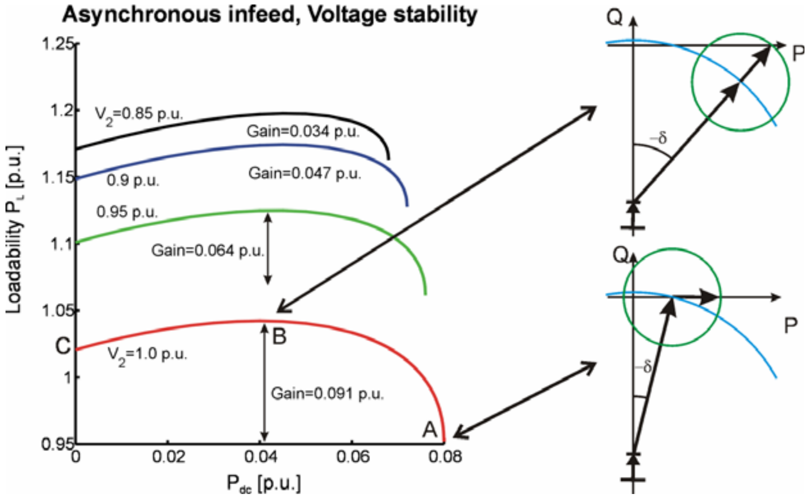

Figure 5 **Loadability as a function of injected DC voltage. Key grid parameters are X_L=0.5, B=0.2 (SIL=0.872 p.u.) and converter size=0.08 p.u.**

Two things are important to remember. The study has not taken the maximum DC voltage level limit into account and the power angle δ can be too high for certain parameter combinations. Nevertheless, it is clearly observed that the grid in a stressed situation is best supported by a mixture of active and reactive power. The gain will decrease with decreasing voltage. A critical bottleneck with a VSC based transmission system in the remote end can be equipped with controls alleviating an (N-1) contingency with up to 2 times its installed capacity. A VSC transmission system of 330 MW can roughly cover the loadability loss of a 400 kV line contingency (SIL around 500 MW) in certain grid configurations.

3.4. Strategy for rotor angle oscillation damping with VSC transmission

There are two basic methods of damping rotor angle oscillations. The first one is to adjust transmission capability between the oscillating generators. This is either done with a series or shunt element. Basically one tries to strengthen the transmission system when the rotors are diverging (going apart) and weaken the system when they are coming together. The second method is by taking out and injecting kinetic (oscillating) energy from/to the oscillating system and either store it in an energy storage or temporarily put it into an asynchronous grid (with different oscillating modes). The VSC transmission can operate in any of the following strategies:

- Modulating active power and keeping AC voltage as constant as possible
- Modulating active and reactive power achieving best possible damping
- Modulating reactive power keeping active power constant (SVC-POD mode)

3.4.1. Asynchronous infeed

When an asynchronous grid is involved it is important that that the two systems do not have the same frequency on the oscillation modes. If not, we can use the other AC-grid to temporary store or discharge energy to damp rotor oscillations. Figure 6a) shows such a case when the AC system is exposed to a fault in the vicinity of the generator. The fault is cleared after 100 ms and the corresponding rotor angle response is plotted in b) for active power modulation and compared to what a pure reactive power modulation method can achieve.

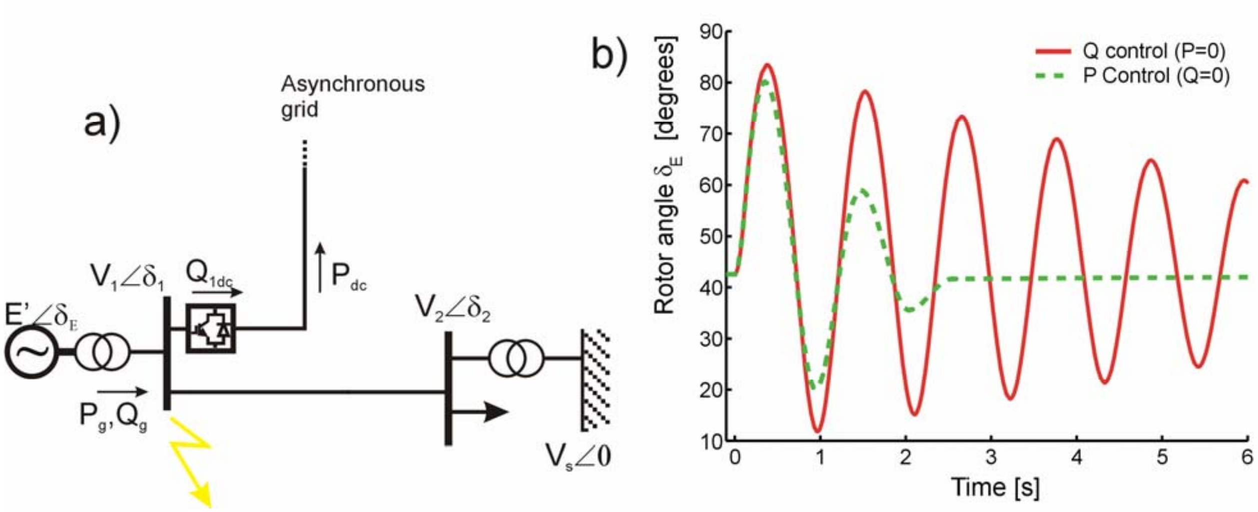

Figure 6 Asynchronous infeed, a) and rotor angle oscillation damping after fault, b).

The difference in damping capability is clearly shown in the power-angle curve shown in Figure 7a). A thin arrow has been drawn showing the working point trajectory during the fault and the initial damping period. Active power modulation is much more efficient and a comparison was made between active power and reactive power modulation. In this 'text-book' example is active power 4 times as effective as reactive power for damping the oscillation. The comparison is shown in the right part of Figure 7. In reality a number of added factors must come into play to establish the qualitative gain. Note, however, that we have the freedom to design any modulation depending on, for instance, local PSS response or local load characteristics.

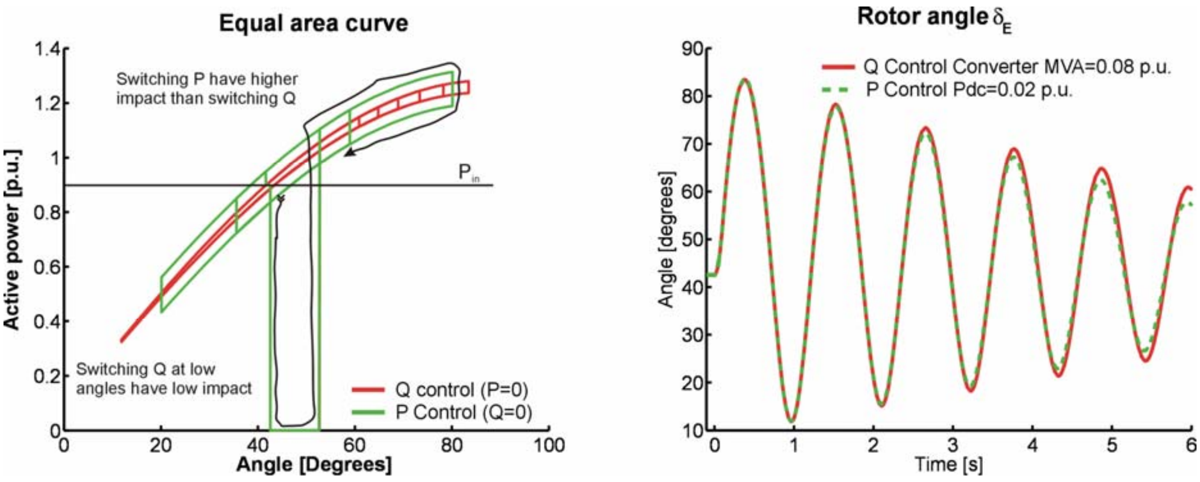

Figure 7 **Equal area curve and comparison between different ratings**

3.4.2. Parallel connection

A slightly different tactic is used when a VSC transmission is connected in parallel with the AC transmission system compared with the voltage stability scenario presented above. A simple and fairly robust modulation can be achieved with:

$$P_{dc} = I_{\text{limit}} \cdot \min(V_1, V_2) \cdot \cos(\delta_1 - \delta_2) \cdot sign\left(\frac{d\delta}{dt}\right) \quad \text{and} \quad Q_{dc} = \pm I_{\text{limit}} \cdot V \cdot \sin(\delta_1 - \delta_2) \cdot sign\left(\frac{d\delta}{dt}\right) \qquad (2)$$

where I_{limit} is the maximum steady state current allowed in the converter. The sign for the reactive power in the respective end is chosen so it supports damping. A grid example and a simulation are illustrated in Figure 8. A fault applied on 'node 1' is cleared after 100 ms. The rotor angle oscillations is presented for three different control strategies for the VSC transmission where the Mixed control described by equation (2) give the highest damping.

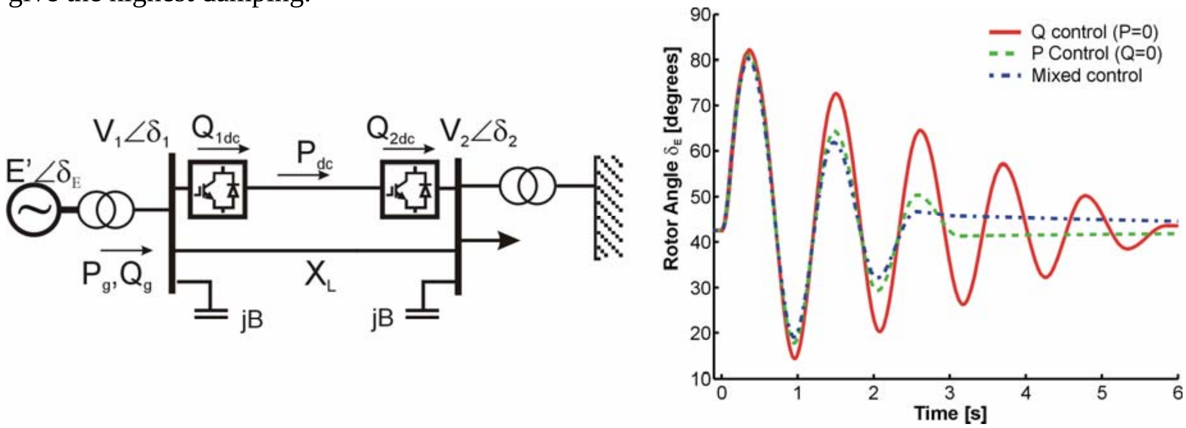

Figure 8 **AC line fault cleared after 100 ms and the associated rotor oscillation for three different strategies for VSC transmission. Key grid parameters are X_L=0.5, B=0.2 (SIL=0.872 p.u.), H=4 and converter size=0.08 p.u.**

The problem is rather complex even in its simplest version presented here. The difference in damping between the methods will vary and a thorough investigation is necessary before the benefits for a specific case can be determined. For one parameter setup a mixed control with a third of the rating of Q control had the same damping i.e. a gain of 3. For another setup the gain was a factor 2. A more complex grid will have many aspects to consider before the actual benefits are established but VSC transmission systems do have a possibility to significantly improve damping for certain grid configurations.

4. EMERGENCY POWER AND BLACK START CAPABILITY

A VSC transmission system will be a very valuable asset during a grid restoration. It will be available almost instantly after the blackout and does not need any short circuit capacity in order to become connected to the grid. The benefits will differ if one or both ends are exposed to the blackout. The following list highlights some aspects:

- Black start capability if equipped with a small diesel generator feeding auxiliary power (or power from another grid).
- Fast voltage control is available in both ends virtually instantly after the auxiliary power is back.
- Can energize a few transmission lines at a lower voltage level avoiding severe Ferranti-overvoltage and allow remote end connection of transformers/reactors at a safer voltage level. When the remote end is connected to the reactor/transformer the voltage can be ramped up to its nominal value.
- When active power is available in the remote end the VSC connection can feed auxiliary power to local plants making sure that they have a stable voltage/frequency to start on.
- When the local plants are synchronized to the grid they can ramp up power production at a constant and safe speed and do not initially have to participate in frequency control. Thermal time constants and control issues in the boiler can then be handled. The VSC transmission system is taking care of frequency variations via power exchange to the remote grid. This will increase the likelihood of a successful startup. Islanding operation of a single power plant is seldom tested beforehand and the operation is therefore not reliable. The VSC transmission system does not have thermal/mechanical systems that are affected by rapidly changing active power demand and will therefore be a safer and tested way to use for frequency control. It can also temporarily export power from the island meaning that we can have a considerable overproduction available in the island before we start to connect load.
- When the power production margins are safe we can start connecting load. The system is now ready to handle phenomena as cold load pickup and varying AC voltage in the transmission grid. More generation is fed with auxiliary power and then connected.
- Classic HVDC can be started when the short circuit capacity is sufficient.

The buildup scheme has the potential of being quite robust and fast especially if the remote VSC system end is connected to a strong grid. Speed and robustness during the buildup should be very valuable since the consequences in the society significantly differ if the blackout is 15 minutes or 6 hours.

5. CONCLUSIONS

The best support from a VSC transmission system is for many grid configurations and stability problems a mixture of active and reactive power control. A VSC DC transmission system is able to support the AC grid with a suitable power factor and hence improve stability. One can say that it works as a 'distributed' FACTS-unit connecting two (or more) points in the grid. The paper presents a few basic aspects of the benefits. More information can be found in [3].

6. REFERENCES

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