SUMMARY

In this paper, several interesting features of VSC-HVDC have been demonstrated. It shows that these features can greatly improve the reliability and transfer capability of the power systems. The fast power run-back and instant power reversal can be used if the transfer capability of the interconnected power systems is limited by transient stability. By implementing a damping controller, VSC-HVDC can be used to mitigate inter-area low frequency oscillations. The ability of simultaneously modulating active and reactive power makes the damping effect of VSC-HVDC less dependent on its converter location and transmission line connection schemes. In contrast to the conventional HVDC technology, where the converter stations always consume reactive power, VSC-HVDC is able to supply reactive power to the grid independent of its active power transmission.

KEYWORDS

Power system reliability, Transfer capability, VSC-HVDC, Transient stability, Low frequency oscillations, Voltage stability
1. INTRODUCTION

For reliable service, a bulk power system must remain intact and be capable of withstanding a wide variety of disturbances. Therefore, it is essential that the system be designed and operated so that the most adverse possible contingencies do not result in uncontrolled, widespread and cascading power interruptions [1]. A common practice in transmission system operation is that the system does not transfer more power than it is still possible upon failure of a single equipment or lost one transmission line, namely the N-1 criterion. A today existing but less common method is to change the operation of another component in the system after a failure to maintain the stability in the system. The voltage-source-converter (VSC)-based power transmission technology HVDC Light© has the advantage of being able to almost instantly change the active and reactive power [2][4]. To the grid, it behaves like an ideal power generator with flexible working point and no inertia.

2. CONTROL PRINCIPLE OF A VSC-HVDC LINK

Figure 1 shows the basic main circuit and control structure used for VSC-HVDC. A VSC-HVDC transmission consists of at least two forced-commutated voltage source converters (VSCs) and a common dc link, including dc capacitors and dc cables, or lines. As an integrated power transmission system, the control of active power in the converter station should be coordinated. The coordination of active power control between the stations is realized by designating only one converter controlling the dc side voltage whereas the other converters control the active power. A constant dc voltage control gives a “slack bus” which will result in an automatic balance of active power flow between stations. Controlling ac voltage or reactive power, however, is independent for each station. Depending on the requirement, it can be switched between “AC voltage control” or “Reactive power control”.

![Figure 1: Main circuit and control structure of VSC-HVDC](image)

3. TRANSIENT STABILITY IMPROVEMENT BY VSC-HVDC

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance [1]. The fundamental mechanism with this type of instability is that the kinetic energy accumulated in generator rotors during system fault cannot be released with the first power swing if the system fault is not cleared in a short enough time (critical clearing time). This excessive kinetic energy causes a group of generators going out of step from the main grid after the fault is cleared. This phenomenon is often illustrated by the so-called equal area criterion (EAC) [2].

2
3.1 The example system

Figure 2 A four machine, two area network connected by VSC-HVDC

Figure 2 shows a modified four machine system originally proposed by [1]. In this example, G3 represents a big system which gets electrical power supply from two generator units of G4. G4 has 1400MW power capacity in total. However, the power transfer capability between G3 and G4 is 1060MW, which is limited by the 100ms fault critical clearing time, if one of the double circuits between bus 10 and bus 11 is tripped following a system fault on bus 12.

A VSC-HVDC link (Rated 350MW) is planned to connect the two power areas A and B. The planned link initially is used to transfer power to supply the load on bus 9.

3.2 Case studies

In the studied scenario, the planned VSC-HVDC transfers 350MW power from Area A to Area B. This power is initially balanced by the load at bus 9. Thus, there is no power transfer between bus 9 and bus 10. This case is so designed to show the concept how a standby VSC-HVDC helps another system with transient stability. However, this is not necessarily the pre-condition.

In this example, the fast power run-back capability of VSC-HVDC is very useful in helping the system from transient instability after a system fault. As we described above, the generator out-of-step is due to the excessive kinetic energy accumulated in the generator rotor during the fault. Immediately after the fault is cleared, VSC-HVDC can quickly release the energy to the other healthy system area A, provided area A has enough capacity to take the power unbalance. In the case of VSC-HVDC, the instant power reversal ability of VSC-HVDC makes it possible to change up to two times the power of its rated value. Figure 3 shows a simulation example that VSC-HVDC prevents the system from transient instability by its instant power reversal ability.
Two cases have been run. In case I, given power transfer 1060MW from bus 10 to bus 11, compare fault critical clearing time by VSC-HVDC reduced power to 10% rated power (35MW) and full power reversal (-350MW). The reduction to 10% power is the minimum limit for the operation of conventional HVDC. Table I shows that the critical clearing time is extended from 100ms to 260ms by instant power reversal. This example shows that the instant power reversal capability of VSC-HVDC can greatly improve the reliability of power systems.

<table>
<thead>
<tr>
<th>HVDC Light action</th>
<th>No action</th>
<th>Reduced to 10% rated power</th>
<th>Full power reversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical clearing time</td>
<td>100ms</td>
<td>190ms</td>
<td>260ms</td>
</tr>
</tbody>
</table>

In case II as shown in Table II, the critical clearing time is assumed to be fixed to 100ms, the allowed power transfer from G4 and G3 is improved by the instant power reversal capability of VSC-HVDC from 1060MW to 1270MW.

<table>
<thead>
<tr>
<th>HVDC Light action</th>
<th>No action</th>
<th>Reduced to 10% rated power</th>
<th>Full power reversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowed power transfer</td>
<td>1060MW</td>
<td>1140MW</td>
<td>1270MW</td>
</tr>
</tbody>
</table>

4. INTER-AREA LOW FREQUENCY OSCILLATIONS IMPROVEMENT BY VSC-HVDC

Low-frequency oscillations have been a concern for large interconnected power systems for decades. Whereas power system stabilizers (PSS) are widely applied and useful in reducing local mode oscillations, they are less effective for inter-area oscillations with frequency below 0.3Hz [1]. Due to its fast active and reactive power controlling capability, VSC-HVDC can be used to mitigate such oscillations in the grid by active or reactive power modulation. The ability of simultaneously modulating active and reactive power makes the damping effect of VSC-HVDC less dependent on its converter location and transmission line connection schemes.

4.1 Damping control by active power modulation

One way to use VSC-HVDC to damp the ac system low frequency oscillation is done by modulating the active power output. For a system with parallel connection of ac ties with a VSC-HVDC link,
oscillations on the ac ties can usually be damped by modulation of the power of the VSC-HVDC link. This is the classical way of using conventional HVDC links for inter-area oscillations damping. If two separate ac systems are connected with an HVDC link, the conditions are different, as no inter-area oscillations (i.e. classical ac system electro-mechanical oscillation) can exist between these asynchronous systems. However, HVDC can be used to provide damping effect when one of the systems has oscillation mode between two generator groups. In such case, HVDC has the best damping effect if the converter station is electrically close to one of the oscillating generator group [6]. Figure 4 A) and B) show the two types of connection scheme. Figure 4 C) shows an example that VSC-HVDC provides damping effect to an inter-area oscillation by implementing an active power damping controller. The frequency measurement is used as the input signal of the damping controller.

![Figure 4](image-url)

**Figure 4 Low frequency oscillations damping by active power modulation**

- A) Parallel connection scheme
- B) Asynchronous connection scheme
- C) Active power between bus 3 and bus 4 (MW). Dashed line: without damping controller; Solid line: with damping controller

### 4.2 Damping control by reactive power modulation

One of the important features of VSC-HVDC is to control active and reactive power independently. Figure 5 shows an example that VSC-HVDC provides damping effect to an inter-area oscillation by implementing a reactive power damping controller. VSC-HVDC link is connected to Location 4 (the middle point) from a third area, which is asynchronous to the in-feed area. A lead-lag type damping regulator has been applied on VSC-HVDC, which provides a 90° leading phase shift on the interested frequency range. This 90° leading phase is essential for reactive power damping, which make sure the damping effect is in phase with the machine speed. The input signal is the current measurement of the transmission line between bus 3 and bus 4. The output of the damping controller adds a modulation signal on the reactive power reference of VSC-HVDC.

Regarding the converter location, the best location for reactive power damping is the electrical middle point between the oscillating generator groups [6]. Comparing to the active power modulation location, we found that active power and reactive power modulations are complementary, which implies that a VSC-HVDC link has greater opportunity for damping low-frequency oscillations than conventional HVDC and SVC.
5. VOLTAGE STABILITY IMPROVEMENT BY VSC-HVDC

Voltage instability or collapse is another challenge facing power-system design and operation. Inadequate reactive power support from generators and transmission lines leads to voltage collapse, which have resulted in several major system failures in recent years [3]. In contrast to the conventional HVDC technology, where the converter stations always consume reactive power, VSC-HVDC is able to supply reactive power to the grid independent of its active power transmission.

Figure 6 B) shows an example that VSC-HVDC stabilizes the ac voltage as the ac loads are continuously changed. The connected VSC-HVDC initially consumes reactive power to maintain the ac voltage since the ac transmission line generates reactive power as it is lightly loaded. When the added load is equal to the “natural load”, the ac transmission line neither generates nor consumes reactive power. As the connected loads are further increased, VSC-HVDC starts to generate reactive power to support the ac system. Figure 6 A) shows the “P-V curve”, which describes the voltage/power relationship. By continuous reactive power support from VSC-HVDC, the voltage stability margin is improved.

An interesting feature of VSC-HVDC is that its reactive power support capability is actually maximized when the grid voltage is low, on contrary to conventional shunt compensation. This feature makes VSC-HVDC particularly useful in preventing voltage collapse caused by progressive voltage depression.
Figure 6 Voltage stability improvements by VSC-HVDC. A) The improved voltage stability margin by continuous reactive power support from VSC-HVDC. B) VSC-HVDC stabilizes ac voltage as the ac loads are continuously changed but keeps active power transmission constant. Curves from up to down: 1. Active power on one ac line (MW). 2. Reactive power support from VSC-HVDC (MVAR) (according to VSC-HVDC convention, “minus” means reactive power generation and “plus” means reactive power consumption). 3. Voltage on the converter bus (pu). 4. Active power output from VSC-HVDC (MW).

6. CONCLUSIONS

Several interesting features of VSC-HVDC have shown to be very useful in improving the transfer capability and reliability of power systems.

The examples used in the paper are demonstrated by a VSC-HVDC model implemented in PSS/E [5]. The model is developed and supported by ABB HVDC section. The model keeps all the major features of the real VSC-HVDC system and is suitable for various power system electro-mechanical transient studies.

7. REFERENCES