Control and Protection of Hybrid LCC-VSC HVDC Transmission System based on VDCOL Strategy

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Abstract: The combination of line combined converter LCC and voltage source converter VSC technology provides the benefits of both techniques by constituting a hybrid LCC-VSC HVDC system. In this paper to discover the potential and the performances of this system a control design is adopted for both converter considering the protection by using Voltage dependent current order limiter (VDCOL). This technique used to decrease the current reference of LCC HVDC converter station when the voltage at that station is depressed during disturbances. Different case studies are proposed starting with normal operation, DC current variation, reactive power variation, and finally system operation under AC and DC faults. The responses of the system during faults demonstrate the tracking performance and also its ability to protect the stations and limit the references during AC and DC faults. The control strategy is examined by simulations using Matlab/Simulink software.

Keywords: high voltage direct current (HVDC); line commutated converter (LCC); voltage source converter (VSC); Voltage dependent current order control (VDCOL)

1. Introduction

Industrialization and population growth are the primary factors for the steady increase in electrical energy consumption. In addition, more and more electricity is produced far from urban areas and therefore has to travel long distances. Thus, in order to have a balance between production and consumption, the complexity of the electrical networks increases regularly and is accompanied by strong constraints related to the stability of the networks [1]. In addition to this, there are problems related to the liberalization of the electricity market, which creates various operating scenarios. These factors therefore also require systems to operate as close to their limits as possible while ensuring maximum safety. In addition, the quality of electrical power has become a major concern for consumers and suppliers. Therefore, rigorous criteria for the development and operation of networks are required.

High-voltage direct current (HVDC) technology, which has been used for more than 70 years [2], is suitable for transmitting large amounts of energy over long distances with minimal losses. In 1954, the first commercial HVDC link, with a capacity of 20 MW/±100 kV, was installed between Sweden and the island of Gotland. Since then, the cumulative capacity of HVDC transmission installed around the world has steadily increased [3], and recently a huge increase in volume is in progress [4]. To date, most of the HVDC systems installed worldwide are of the LCC (Line-Commutated Converter) type and use thyristor valves.

LCCs are the oldest technology for HVDC links. The converters use thyristors. The thyristor-based HVDC line commutated converter (LCC) is used for bulk power transfer [5] (more than several GW) over long distances due to its mature, efficient, reliable, and cost-effective technology. However, LCC-HVDC technology has some inherent problems, such as switching failure [6], difficulty in connecting weak AC systems [7], interconnection problems with renewable energy sources such as turbine-generator shafts [8] that are subject to high stresses during faults such as through fire, misfire, short circuit through the inverter station, flashover, and a three-phase short circuit in the AC system, which can result in severe damage to the entire system [9] and the need to reverse the polarity of the DC voltage during power flow reversal.

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These obstacles make this technology difficult to implement on large-scale DC networks. HVDC based on a voltage source converter (VSC) [10] is a more current technology that offers greater operational flexibility, such as separate control of active and reactive power and black start capabilities [11-12]. VSCs, but in the other hand, have larger switching losses and construction costs than LCCs.

Overall, LCC-HVDC leads VSC-HVDC in terms of maturity and cost efficiency, but VSC-HVDC offers greater operational flexibility and the capacity to operate in extremely weak systems. LCC-HVDC, on the other hand, lacks islanded operation and voltage support, necessitating synchronous sources and huge bulk reactive power compensation devices on the ac side.

Hybrid HVDC using LCCs and VSCs has been proposed as a promising alternative solution [13] that incorporates the benefits of both converter topologies: lower power losses and costs, as well as greater control flexibility. Furthermore, by replacing one of the terminals with VSC, the hybrid LCC-VSC HVDC [14-15] concept can be used to improve an existing LCC-HVDC connection. The LCC-HVDC and VSC-HVDC systems can also be linked to create a new hybrid network. The control approach and operation method of the LCC and VSC are, however, completely different.

Many research works have dealt with hybrid systems [16-18] and have proposed many contributions including control laws in order to improve their performances also the possibility of integrating renewable energy sources and offshore parks to constitute multi-terminal systems [19] using LCC and VSC structures together, without forgetting the evaluation and control of these systems during the different probable faults on the networks as well as their protection systems.

In this paper the hybrid LCC-VSC HVDC system employs one converter using LCC technology as the rectifier while the other converter uses VSC technology as the inverter, the two stations are interconnected via a DC cable. The control modes of the rectifier and the inverter are realized and implemented by a PI control to guarantee good performance and ensure the stability and reliability of the system. The first part of this paper will be devoted to the structure of the hybrid system by detailing the topology used for the LCC station and the topology for the VSC station and secondly the proposed controls for each station using the VDCOL strategy and finally for the rest of the paper a simulation of the hybrid LCC-VSC HVDC system under different cases including normal operation, DC current variation, reactive power variation and with the presence of the AC and DC default.

2. Structure of hybrid HVDC systems:

Figure 1 shows the basic structure of a point-to-point hybrid HVDC. The rectifier station is the conventional LCC based on two 12 pulse rectifier. The inverter station is VSC converter which utilizes the three-level neutral point clamped (NPC).

![Figure 1. Hybrid LCC-VSC transmission system](image)

A. Structure of LCC

The major component of an LCC is the six-pulse bridge (Graetz bridge) consisting of six controlled thyristor switches or valves. To operate the converter at the desired nominal voltage, the thyristors are usually connected in series to create a suitable thyristor switch. The
disadvantage of the six-pulse bridge is that considerable harmonics of the AC current and DC voltage are produced because of the phase change at every 60°. To overcome this problem, two six-pulse bridges are connected in series to form a twelve-pulse bridge. In this way, each of the two six-pulse bridges is connected to a DC rail, whose phase change at every 30° helps to eliminate some of the harmonics.

\[
V_{DC} = B \frac{2\sqrt{2}}{\pi} V_s \cos \alpha - B \frac{3}{\pi} X_c I_{DC}
\]  

Figure 2. 12-pulse rectifier

Where \(V_{DC}\), \(I_{DC}\) are respectively the output voltage and current of the converter, \(\alpha\) the firing angle, \(V_s\) are the RMS (Root Mean square) AC voltages of the primary and secondary side of the converter. \(X_c\) is the converter transformer reactance. The parameter \(B\) is one (\(B = 1\)) for six-pulse HVDC systems and \(B\) equals two (\(B = 2\)) for twelve-pulse units.

B. Structure of VSC:

The second generation of HVDCs uses VSC technology. The main difference with VSCs is that other components are used instead of thyristors. Most of the time, IGBTs are used in combination with antiparallel diodes, but GTO thyristors can also be used. These components offer a new freedom: their activation and deactivation can be controlled, which was not possible with thyristors, whose activation was only controlled. This additional freedom offers new possibilities to the user, such as independent control of active and reactive power. As the name indicates, a VSC link acts as a voltage source. This means that the voltage on its link never changes polarity, and remains fixed at a reference value.

VSC topologies are developing to increase the power transferred, and they are classified into three types, namely; two-level converter, three-level converter, modular multi-level converter (MMC). The three-level VSC topology, shown in figure 3, is called Neutral Point Clamped converter (NPC).

Each phase of the VSC can switch to three different voltage levels, specifically; the positive DC terminal, the negative DC terminal and the midpoint. The three-level NPC converter minimizes harmonics to bring the output signal closer to the reference. In addition, the three-level NPC allows for a lower switching loss than a two-level VSC technology. This topology can be extended to more voltage levels, resulting in reduced harmonics and lower switching losses. However, increasing the number of levels using the NPC topology becomes more complicated and requires cooling equipment for the converter devices.
3. Control strategy of hybrid LCC-VSC HVDC system

Figure 1 represents an LCC-VSC HVDC grid, with LCC acting as rectifier and VSC acting as inverter. The advantages of hybrid structure in terms of technical maturity, high power rating, low manufacturing cost, and reduced power losses are all utilized in this architecture. Without forgetting its capacity to reduce the danger of commutation failure. [17-21] investigated the operation, control, and protection of LCC/VSC hybrid DC networks [22].

The rectifier based on LCC structure ensures constant dc current control combined with minimum firing angle control and voltage dependent current order limiter (VDCOL) [23]. During normal operation, the rectifier converter is under the constant dc current control. During a fault, VDCOL try to reduce the dc current order in accordance with dc voltage drop, thus the fault current progressively decreases to a new dc current order as shown in figure 4.

The inverter based on VSC structure ensures direct voltage control, including inner loop current control and outer loop voltage control. The inner loop current controller regulates the amplitude and phase of AC current. The outer loop voltage controller includes an active power class control and a reactive power class control, which are chose as the constant dc voltage control and the constant reactive power control respectively in this paper.

![Figure 4, characteristic of VDCOL control](image)

A. LCC control system

We describe below the control method of the LCC, the basic schematic of the rectifier is shown in figure 5.

We applying Kirchhoff theorem we have:

\[ V_{dcr} = V_{dor \cdot \cos \alpha - R_{cr}I_{dc}} \]  \hspace{1cm} (2)

With:

\[ R_{cr} = \frac{3X_{cr}}{\pi} \]
\[ V_{dor} = \frac{3\sqrt{2}}{\pi} V_{eff} \]
\[ \alpha: \text{ Firing angle} \]
\[ V_{eff}: \text{ RMS value of the voltage between phases} \]
\[ X_{cr}: \text{ Rectifier switching reactance} \]

Figure 5. Schematic of LCC rectifier

The current \( I_{dc} \) in the DC line is given by the expression:
\[ I_{dc} = \frac{V_{dcr} - V_{dci}}{R_{dc}} \] (3)

Where \( R_{dc} \) and \( V_{dci} \) is the total resistance of the DC cable and DC output voltage at the VSC converter. According to (2) and (3) the parameters in the denominator being constant, the only way to modify the current \( I_{dc} \) is to control the angle \( \alpha \) because the voltages \( V_{dcr} \) and \( V_{dci} \) are exposed to unpredictable fluctuations on the AC side.

The current controller is shown in Figure 6. The measured DC current \( I_{dc} \) of the system compared with the current reference \( I_{dc-ref} \). The output of the PI controller is the firing angle. This angle limited in the range \([\alpha_{min}, \alpha_{max}]\) is used to generate the rectifier firing pulses.

B. VSC Control system

For any VSC-HVDC system, the control objectives are to compensate for disturbances and ensure good transient and performance. The vector control method is the most widely used control approach in power system applications. This control technique has a cascade control structure. It is composed of two loops: the internal current control loops and the external control loops and the external control loops. Figure 7 shows the structure of the station based on VSC converter.
Applying Kirchhoff’s laws we find:
\[ L \frac{di_{ij}}{dt} + R_{ij} = u_{gj} - u_{mj} \]  
(4)
The system (4) can be written as:
\[ u_{gabc} = R_{i} i_{gabc} + L \frac{di_{gabc}}{dt} \]  
(5)

Applying the park transformation we find the state representation of the station:
\[
\begin{align*}
\frac{d\dot{i}_d}{dt} &= \omega_i i_q - R_{id} + \frac{(u_{qd} - u_{md})}{L} \\
\frac{d\dot{i}_q}{dt} &= -\omega_i i_d - R_{i} + \frac{(u_{q} - u_{mq})}{L}
\end{align*}
\]  
(6)

### B.1 Outer loop control

The outer control loop can control several variables; the current \( i_d \) can regulate the DC bus voltage or the active power while the current \( i_q \) can regulate the reactive power or the AC voltage

#### Power control:
Active and reactive power can be controlled independently. They are used to generate the reference currents of the internal loops. The dq reference frame is selected that the d-axis is synchronized to the AC source voltage. This results in \( u_q = 0 \).

\[
\begin{align*}
P_{dq} &= \frac{3}{2} \cdot (u_d i_d + u_q i_q) = \frac{3}{2} \cdot (u_d i_d) \\
Q_{dq} &= \frac{3}{2} \cdot (u_q i_d - u_d i_q) = -\frac{3}{2} \cdot (u_d i_q)
\end{align*}
\]  
(7, 8)

Figure 9 shows the structure of the power control loops. PI correctors are used to regulate the dynamic responses of the power loops.

#### DC Voltage Control:
The DC voltage control loop is required to control the DC bus voltage by ensuring the balance between the power injected to the DC network and the power absorbed by the AC network. The structure of the controlled system is shown in Figure 1.12. The output of the control loop provides the reference input for the forward current.

#### AC voltage control:
This control loop is particularly designed for VSC converters connected to a weak AC network, which is sensitive to interactions between AC and DC because of its high impedance compared to the rated DC power. Moreover, any disturbance on the DC or AC side of the converter can induce AC voltage instability (e.g. voltage drop, overvoltage, etc.). To avoid these problems, an AC voltage control loop can ensure the regulation of the low AC voltage of the network at fixed amplitude.

### B.2 Inner loop control

The internal control is responsible for generating the reference signal for the voltage Vdq-ref. This reference is provided in the dq0 frame. It must be translated into the abc frame to inform the PWM which controls the IGBT gates. Figure 8 shows the control scheme of inner current loop.
Figure 9 describes completely the control structure of the VSC station; we can see the outer and inner control loops as well as the controlled variables. As mentioned before, the VSC station of the Hybrid LCC-VSC system controls the DC voltage and the reactive power.

3. Simulation Analysis and Results

In order to test and verify the validity of the hybrid LCC-VSC HVDC system and to see its different performances, a simulation was performed using Matlab/Simulink software.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCC Station</td>
<td></td>
</tr>
<tr>
<td>Rated power</td>
<td>200 MVA</td>
</tr>
<tr>
<td>AC side voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>230 kV</td>
</tr>
<tr>
<td>DC Current</td>
<td>1kA</td>
</tr>
<tr>
<td>AC reactance and resistor</td>
<td>R=30Ω ; L= 48,86 Mh</td>
</tr>
<tr>
<td>AC filters</td>
<td>4*150 Mvar</td>
</tr>
<tr>
<td>DC Link capacitors</td>
<td>C1=80μF ; C2=80μF</td>
</tr>
<tr>
<td>LCC</td>
<td>two 12-pulse</td>
</tr>
</tbody>
</table>
To demonstrate the effectiveness of the system structure three scenarios were established:
1. Normal operating conditions
2. Tracking performance (DC current reference variation, reactive power variation)
3. Performance during AC and DC faults. Other faults such as misfire, firethrough on VSC converters are the subject of several studies [24-25].

A. Steady-state:
During normal operation of the Hybrid LCC-VSC HVDC system, the converter station based on LCC technology (rectifier) operates in current control mode ($i_{dc\_ref}=1kA=1p.u$) and the other station based on VSC technology (Inverter) operates in DC volt control mode ($V_{dc\_ref}=220kV=1p.u$). Figure 10 shows the behaviour of the system.
B. Performances in Tracking

B.1. Current reference Change:

To test the performance of the rectifier LCC side current controller, a decrease of 0.5 applied to the current reference during the interval [0.8s 1s] is applied as shown in figure 11 (a). The figure shows the active powers of the two stations, the DC voltage is properly controlled and remains stable with acceptable oscillations during the duration of the change in the current reference, note also that the firing angle has increased because it is determined by the current regulator.

B.2. Reactive Power change:
At t=1s the reactive power of the VSC station is decreased from 0 p.u to -0.5 p.u, figure 12 shows the responses of the hybrid LCC-VSC HVDC system, we notice that the DC voltage and current remain constant during the change of reactive power with small oscillations. The change of the reactive power has no impact on the LCC station, which guarantees more reliability.

C. Performances under AC and DC faults
C.1. AC fault
AC faults are very common in electrical networks and cause many problems and failures, hence the need to correct them quickly. Figure 13 shows the global behavior of the hybrid LCC-VSC HVDC system following a fault in the AC network on the LCC side. A line break on phase
1 during 200 ms causes power oscillations as shown in figure 13, DC voltage returns to its reference value after a phase of oscillations. The integrator of the dc current controller will be reset to 0 to clearing AC fault and to increase the firing angle at $t=1\,\text{s}$ to return to normal operation.
C.2. DC Fault

At t=1s a line to line fault in DC side as shown in the following figure.

This fault results a rise in DC current, the DC voltage drops to zero at the rectifier. This DC voltage drop is detected by the voltage dependent current limiter (VDCOL) which reduces the reference current to 0.3 pu at the rectifier as shown in figure 15 (a), which shows the great importance of the VDCOL in limiting the reference current in case of a fault and therefore protecting the electronic switches. The active power of both LCC and VSC stations tends towards 0 during the fault detection it should also be noted that the firing angle is increased to keep the DC current constant.
Figure 13. Circuit of Hybrid LCC-VSC system under DC Fault

(a).

(b).

(c).

(d).
5. Results Analysis

The figures 10-15 show the evolution of the different variables of the system, the transient regime starts from 0 until about 10ms, then the system stabilizes until a disturbance occurs, observing the simulation results it should be noted that the transient regime of the system is related to the chosen parameters of the controller and also to the parameters of the VDCOL block. The VDCOL function has only one relationship between the input DC voltage and the current order of the VDCOL. Since a drop below 0.3 p.u of the DC voltage automatically leads to the modification of the transient aspect as can be seen in figures 10 to 15, it should also be noted that the reference current ramp starts only after 10ms, so the choice of the VDCOL parameters is crucial and must be well chosen. The choice of the VDCOL parameters is the subject of several research studies [25-26] the transient regime can be improved by modifying the reference current ramp and by adapting the VDCOL function as studied in [27-28] with a suitable delay.
Under the conditions of disturbance such as the variation of the reference current Fig 11 we can see at $t=80\text{ms}$ that the current decreases from 0 p.u to the value of 0.5 p.u which directly causes the increase of 80 degree of the firing angle to ensure the continuation of the current reference point. Fig 13-15 shows the variables of the system following AC and DC defaults here the VDCOL block must intervene and set a new current step, at fault application the DC current quickly increases above 1 p.u and the DC voltage falls to zero at the rectifier. This DC voltage drop is seen by the Voltage Dependent Current Order Limiter (VDCOL) which reduces the reference current to 0.3 p.u at the rectifier reached during 10 ms, a direct current then still flows during the default and at the same time protects the converters as studied in [29-31]. The dynamic response proposed by the control presents overshoots and oscillations compared to non-linear controls [32-34] which offers the consideration of the system parameters and giver smoother responses.

6. Conclusion

This article studied a hybrid HVDC transmission system that used an LCC as a rectifier and a VSC converter as the inverter station, respectively. Verification and validation of the performance of the hybrid LCC-VSC system using widely established HVDC operating standards is conducted by analytical selection of system parameters and consideration of various system operating situations. The results from a LCC-VSC hybrid HVDC system show that the proposed hybrid HVDC system can operates under various conditions and includes the protection of the converters, using the (VDCOL) Voltage Dependent Current Order Limit, this notion is used to detect a probable fault or a disturbance by reducing the reference current, The recovery after a DC line fault is problematic and especially for VSC-HVDC transmission system for this reason, hybrid systems remain a possible solution to avoid over voltages and over currents during dc line fault.

As future work many elements can be approached and will be of great importance as the elaboration of advanced control techniques, the extension of the system to a multi-terminal configuration by integrating renewable energy sources.

7. References


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