Review of Frequency Support Control Strategies for Asynchronous AC Systems Connected Through VSC-HVDC

Pan-dian LUO¹, Zhi-chang YUAN²*, Chao SHENG¹, Liang-he ZHU¹ and Fen-yan YANG¹

¹Electric Power Research Institute of Guangdong Power Grid Co., Ltd, Guangdong, China
²Department of Electrical Engineering, Tsinghua University, Beijing, China

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Abstract. The ability of fast power response of VSC-HVDC can provide frequency support control for asynchronous AC systems connected through VSC-HVDC, which improves the stability of power system by sharing of the spinning reserves among non-synchronous AC areas. Methods that have been proposed to enable VSC-HVDC systems to provide frequency support, including methods base on remote communication, methods based on DC voltage droop, methods based on droop control and methods with virtual synchronous generator characteristic, are reviewed. The performance and application trends of frequency support control of VSC-HVDC are analyzed.

Introduction

Compared with the traditional LCC-HVDC (Line-Commutated Converter based HVDC), VSC-HVDC (Voltage Source Converter based HVDC) has advantages including strong controllability, fast response, decoupled active and reactive output, etc. Moreover, it is not limited by the AC power short circuit capacity, suitable for sending power to the passive system, and is capable of forming a DC grid, thus becoming a major topic in the field of electrical engineering [1-7]. The application of this technology have also been widely recognized in the applications of asynchronous interconnection of the AC girds. The main applications scenarios of VSC-HVDC include [8-10]: connection of onshore or offshore wind power farm, feeding island power, long distance power transmission, load center power supply, and asynchronous interconnection of AC grids.

Existing VSC-HVDC projects applied to asynchronous interconnection of the AC grids usually focus on the function of asynchronous isolation. They are operated at preset reference powers, limiting the impact of AC faults to its own area, and preventing the impact on the opposite AC grid. However, when the power transmitted in DC line occupies a large proportion of the capacity of the receiving-end AC grid, the VSC- HVDC station should have the ability to support the AC grid during faults. The ability is based on the fast and precise adjustment of active and reactive power of VSC. By exerting this predominant advantage, the safety and stability of the entire interconnected system would be enhanced, and the fault transfer between AC systems would be avoided.

The frequency support control for asynchronous AC systems connected through VSC-HVDC is one of the means to achieve the above objectives. Nevertheless, it is still in the stage of theoretical research. Researchers have carried out a lot of studies on this problem from different perspectives and proposed many technical methods. The main contributions of this paper are as follows. First, a detailed discussion of the research status in this field is presented. Then, a comparison of the application characteristics and control performance of various methods are made. Finally, applications and trends of frequency support control of VSC-HVDC are analyzed.

Structure of AC Systems Connected by VSC-HVDC

The structure of AC systems connected by VSC-HVDC is shown in Fig. 1 which can be divided into double-terminal and multi-terminal systems according to the number of converter stations. Due to VSC’s capability of DC voltage control, the power flow in the DC power network can be controlled.
This advantage contributes to the formation of multi-terminal DC power network and provides a more flexible way for the interconnection of asynchronous AC systems.

![Figure 1. Structure of AC systems connected by VSC-HVDC. (a) Double-terminal structure. (b) Multi-terminal structure.](image)

Typically, the control system of a VSC shown in Fig.2 presents a cascaded structure [11]. The innermost is a current controller which is implemented in the synchronously rotating dq-frame, controls the phase and amplitude output of the VSC. The inner current reference is calculated by outer loop. Normally, the d-axis current reference is determined by the active power or DC voltage, and the q-axis current reference is determined by the reactive power or the AC side voltage. In steady state, ideal zero steady-state error can be acquired. Currently, this control structure has been widely used in the field about variable frequency speed control, stationary synchronous compensator (STATCOM), wind power converter and so on.

![Figure 2. Inner current control loop of VSC-HVDC.](image)

**Frequency Support Control Strategies**

**Principle of Frequency Control Based on VSC-HVDC.** Normally, the VSC station takes its transmission power as its direct control target and the control characteristics do not change when the voltage and frequency fluctuations occur in AC grid, so as to achieve asynchronous interconnection of different AC grids. When VSC-HVDC is required to participate in AC system frequency control, the basic principle is to add an additional control loop on the active power controller [12,13], as shown in Figure 3. Similar to the generator speed control system [14], the outer loop create an additional power increment by detecting the frequency deviation of the AC grid through a proportional or PI controller, and the power increment is injected into the AC grid to regulate frequency.

![Figure 3. Outer loop with frequency regulation of VSC-HVDC.](image)

In double-terminal VSC-HVDC system, master-slave control is usually used, that is, one terminal operates in fixed DC voltage and reactive power control mode \( \text{VdcQ} \), and the other terminal operates in active and reactive power control mode \( \text{PQ} \). If the VSC in PQ control adopts the frequency regulation controller mentioned above, the frequency control problem of the power grid can be effectively solved. For example, when the frequency of the AC power network drops, the VSC automatically increases the output power to regulate frequency. The power changes in the DC system automatically transferred to the constant voltage station, then this station absorbs corresponding power from this side AC system. Consequently, the frequency support between two asynchronous interconnection AC power networks is achieved. However, the frequency regulation controller cannot
be added in a VSC which adopts VdcQ control, because this kind VSC cannot control the output power directly.

Moreover, for the multi-terminal VSC-HVDC system using master-slave control, each terminal only responds to the frequency fluctuation of the AC system connected with it and each terminal is independent of each other. Therefore, the frequency regulation capacity of the whole system cannot be fully utilized.

**Communication-based Frequency Support Control.** In order to solve the problems mentioned in the previous section, a variety of control methods have been proposed by scholars both in China and abroad to enable automatic frequency support between asynchronous interconnected partitions. A simple method is to transmit frequency information of each area to each converter station by means of communication, and add frequency regulation control [15-18] to the outer loop of the converter station, as shown in figure 4. Different from the method in the previous section, the frequency regulation control integrates frequency deviation information of all interconnected areas, which can respond to the frequency fluctuation in any area. Thus, this method can make full use of the spare capacity of the whole system.

The method based on communication is clear in principle, simple in structure and easy in parameter setting [19]. However, the main drawback is that the control system is highly dependent on the communication. When the scale of asynchronous interconnected AC power grid is large, or the geographic distance between VSCs is far away, communication delay or interruption will cause serious influence on control performance. In addition, the investment cost of telecommunication also restricts the practicability of this method.

**Master-slave Frequency Support Control Based on DC Voltage.** In order to get rid of the restrictions brought by communication between VSCs, Scholars have put forward many different schemes. Although these methods have different characteristics in form and control performance, the basic idea is to take the DC voltage as the medium to transmit the frequency change of each asynchronous interconnected area. In essence, the weak communication signal is replaced by the strong DC voltage signal. According to the different form, these methods can be divided into: master-slave frequency control method based on DC voltage, droop control based frequency control method, and virtual synchronous machine based frequency control method.

The control structure of the frequency fluctuation signal transmitted by DC voltage is shown in Figure 5 [21-24]. Basic principle is introduced combining the system shown in Fig. 1(a). It is assumed that VSC1 is a slave station in PQ control and VSC2 is a master station in VdcQ control. The frequencies of the AC systems on both sides are recorded as f1 and f2 respectively, and the DC voltages on both DC sides are recorded as Udc1 and Udc2 respectively. Fig. 5 (a) is an improved constant power controller that introduces the f1-P1 slope characteristic (slope as α1). The active power P1 is appropriately raised or dropped according to the value of the f1, so as to influence and control the frequency of the AC1. For a double-terminal system, the P2 is equal to the P1, which means that the AC2 participates in the frequency tuning of the AC1 via flexible DC lines. Due to the VSC2 cannot control the power directly, the f2-Udc2 slope characteristic (slope as α2) is introduced in order to let the DC voltage follow the frequency change in AC2, as shown in Fig. 5 (b). At the same time, the Udc1-P1 slope characteristic (slope as β) is introduced into the fixed active power controller VSC1. The purpose is to change the power of VSC1 according to Udc1. Thus, when the f2 changes, it will affect the DC voltage value, and eventually indirectly change the transmission power of VSC1, that is, AC1 participates in the frequency adjustment of AC2 through the flexible DC line. In order to avoid the
sensitive dynamic response of the controller, the dead zone is set at the action value of the frequency and voltage, as shown in Figure 5(c).

\[ f_1, f_{h1}, f_{l1}, P_{max}, P_{min}, U_{dc1}, U_{dc2}, \Delta f_1, \alpha, \beta, U_{dcref}, P_{ref}, P_{max}, P_{min}, U_{max}, U_{min}, K_f, K_D, \]

Figure 5. Frequency support control based on DC voltage drop of VSC-HVDC stations. (a) PQ controller with frequency regulation. (b) VdcQ controller with frequency regulation. (c) Characteristic of controller.

**Frequency Support Control Based on Droop Control.** Due to no communication, simple control structure, good scalability and other advantages in droop control, it is therefore more suitable for multi-terminal flexible DC system [24]. The conventional droop control is shown in Fig. 6. The reference current \( i_{\text{dref}} \) in the inner current control loop is determined by the DC voltage and transmission power, as shown in Eq. (1):

\[ i_{\text{dref}} = (k_p + k_i/s)[(U_{\text{dcref}} - U_{dc}) + K_f(P_{\text{ref}} - P)] \]  

(1)

With the proportional integral controller, the DC voltages with the variation of output power in steady state are shown in Fig. 6 (a), in which the rated operating point is \( (P_{\text{ref}}, U_{dc}) \). When the injected power in the DC-link increases or decreases, the DC voltage automatically droops according to the linearity of slope \( K_D \).

\[ U_{dc} = K_D P_{\text{ref}} + U_{dc0} \]

Figure 6. Droop control of multi-terminal VSC-HVDC. (a) Characteristic of droop control. (b) Structure of droop controller.

The voltage-power droop control cannot respond to the frequency fluctuations in AC system. In order to achieve this function, the literature [25] proposed to add a frequency outer loop into the droop control, as shown in Fig. 7 (a). In order to prevent the frequent changes in reference power cause by minor frequency fluctuation, the dead zone is set in the frequency - power droop characteristic [26], as shown in Fig. 7 (b). The reference power changes only when the frequency is below the lower limit \( f_l \) or exceeds the upper limit \( f_h \), and the slope is \( K_f \). The similar control effect can be obtained under the strategy proposed in [27], which regulates power according to the square of voltage.

\[ P_{\text{ref}} = K_f (f_{h1} - f) \]

Figure 7. Droop control with frequency regulation loop of multi-terminal VSC-HVDC. (a) Controller structure. (b) Characteristic of power-frequency droop control.
By applying the droop control as shown in Fig. 7 in each converter station, the frequency changes over the dead zone in any AC area will cause the variation of output power in converter station, thereby directly adjusting the AC grid frequency. Meanwhile, under the voltage-power droop characteristic, the DC voltage can be adjusted, and transferred to other interconnected stations. These converter stations change the output power according to the change of DC voltage together, thus realizing the interconnected AC system supporting the AC system with frequency disturbance, and reducing the frequency deviation caused by the power shortage. From the above working principle, the droop control also uses the DC voltage as a media to transmit the frequency fluctuations to the interconnected asynchronous system.

**Frequency Support Control Based on Virtual Synchronous Generator Characteristics.** The major advantage of the VSC is the fast dynamic response of its outputs. However, as becoming more and more popular in the grid, VSC’s problem of lack of inertia and damping has become increasingly prominent, especially in recent years [28-30]. Aiming at the problems, researchers proposed the concept of virtual synchronous generator (VSG), whose structure is shown in Fig. 8 (a). The basic mechanism of VSG is to simulate the model of synchronous generator and its characteristics, such as active power adjustment and reactive voltage adjustment. With this simulation, the grid-connected inverter can act like a traditional synchronous generator in the operating mechanism and external characteristics. Synchronous generator emulation control (SGEC) can be seen as another form of the VSG technology [30], whose structure shown in Fig. 8 (b). The main difference between SGEC and VSG is that the latter method directly control the voltage amplitude and frequency (phase) of the VSC. Comparatively, the inner loop control structure of SGEC is similar to that of the decoupled current control shown in Fig. 2. The only difference is that in SGEC, voltage phase angle used in calculating the three-phase reference voltage is calculated by the moment of inertia of an analog synchronous generator, so that the output characteristics of the voltage source converter have some inertia.

As the basis of VSG technology is to simulate the operating characteristics of synchronous generators, so it naturally owns the ability to participate in the frequency control of the AC grid [31-33]. As shown in Fig. 8 (a), the frequency-active power droop control module can not only automatically respond to the frequency variation of the AC grid, but also correct the reference value of active power of the converter and adjust the grid frequency by increasing or decreasing the output power. However, the VSG-category control methods typically use master-slave control, which requires a master station (usually connected to an AC grid with large capacity) to control the DC voltage at the reference value, providing an operating foundation for the slave stations. Similar to the traditional master-slave control method, the master station cannot respond to the frequency fluctuation of the connected AC system, which is its shortcoming.

![Figure 8. Control structure of virtual synchronous generator for VSC-HVDC. (a) Structure of VSG. (b) Structure of SGEC.](image-url)

In order to solve this problem, a voltage square -power droop control method for VSG is proposed in [33]. Its structure is shown in Fig. 9. An outer loop controller with the characteristics of square of voltage-power droop is added to the active power reference value. The main function of this outer loop is to transmit the variation of active power to the DC voltage. The variation is then transmitted through the DC lines to all the connected VSC stations, triggering the whole system to participate in frequency adjustment using their reserve power capacity. With the method shown in Fig. 9, each VSC...
station is operated in the voltage square-power droop control method, without assigning master station and slave stations, thus solving the problem mentioned above.

![Control structure of virtual synchronous generator with DC voltage droop for VSC-HVDC.](image)

**Comparison of Frequency Support Control Methods of VSC-HVDC**

The existing frequency support control methods have similar effects in terms of frequency adjustment capability. The main features and differences can be summarized in the following areas, as shown in Table 2:

1. The communication-based frequency support control method performs excellent in terms of frequency regulation capability, and its greatest advantage is DC voltage can be maintained at the rated value, while the other methods require a DC voltage as a medium for transmitting the frequency fluctuation signal. Therefore, the DC voltage is usually deviated from the rated value, which is not conducive to the stability of flexible DC system operation. When the DC voltage is deviated from the rated value, it may cause DC protection action.

2. From the controller structure, the control method based on the characteristics of virtual synchronous machine is relatively complex, and the parameter setting is difficult, while the other methods are relatively simple.

3. From the scalability, under dropping control and virtual synchronizer characteristic with additional frequency adjustment, the control strategies in respective converters are the same, and there is no division between the master station and slave station. Thus, its number of ends can be easily extended.

4. Communication-based master-slave control is the only method needs the communication between stations, which leads to the increase of cost and reduction of reliability. Therefore, this approach is more suitable for back-to-back applications. The remaining three methods do not rely on communication, thus they have better engineering practicality.

<table>
<thead>
<tr>
<th>Method</th>
<th>Communication</th>
<th>DC voltage</th>
<th>Controller structure</th>
<th>Extensibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication-based master-slave control</td>
<td>Yes</td>
<td>Constant</td>
<td>Simple</td>
<td>limited</td>
</tr>
<tr>
<td>Voltage-based master-slave control</td>
<td>No</td>
<td>Variable</td>
<td>Simple</td>
<td>limited</td>
</tr>
<tr>
<td>Additional frequency regulation-based droop control</td>
<td>No</td>
<td>Variable</td>
<td>Simple</td>
<td>Flexible</td>
</tr>
<tr>
<td>Virtual synchronous generator-based control</td>
<td>No</td>
<td>Variable</td>
<td>Complicated</td>
<td>Flexible</td>
</tr>
</tbody>
</table>

**Summary**

To improve the security and stability of interconnected systems, the frequency support control between asynchronously interconnected systems based on the fast and accurate power control capability of VSC stations is an effective way. This paper reviews state of art on this issue and compares the performance of different control methods. Additional frequency regulation based droop control method has the advantages of simple control structure, flexibly extending terminals, and the independence of communication, which makes it suitable for engineering application. However, the DC voltage deviates from rated value under frequency disturbances in AC grids. Which should be solved in the further research. In addition, when multi-terminal VSC-HVDC is applied to connect AC
systems asynchronously, it remains a problem to optimize the frequency controller's parameters according to the reserve capacity and generator characteristics in different AC systems, so as to obtain the best frequency support.

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References


