Review of oscillations in VSC-HVDC systems caused by control interactions

Congqi Yin\textsuperscript{1}, Xiaorong Xie\textsuperscript{2}, Shukai Xu\textsuperscript{2}, Changyue Zou\textsuperscript{2}

\textsuperscript{1}State Key Lab of Power Systems (Department of Electrical Engineering), Tsinghua University, Haidian District, Beijing, People's Republic of China

\textsuperscript{2}State Key Laboratory of HVDC, Electric Power Research Institute, China Southern Power Grid, Huangu District, Guangzhou 510080, People's Republic of China

E-mail: xiegx@tsinghua.edu.cn

Abstract: Owing to the fast control response and distinct characteristics of the voltage source converter (VSC), various types of oscillation incidents related to the VSC-HVDC systems have been observed around the world. However, the causes of such oscillations are complex due to the interactions among the components of the transmission system and the various control methods of the converter station, and yet not systematically comprehended and summarised. Therefore, this study reviews several typical VSC-HVDC oscillation incidents and focuses on the root causes of the oscillation phenomenon. The analysis indicates that oscillations in the VSC-HVDC system can occur either in subsynchronous frequency range or in high-frequency range, up to 1.2 kHz. The modelling methods, including the conventional detailed model, equivalent detailed model, and average equivalent model, are also affecting the accuracy of describing the oscillations. The control methods, including adding active control scheme, passive filter at oscillation frequency, and temporary power plant disconnections, are also discussed. The advantages and drawbacks of these modelling methods, analysis methods, and control methods are summarised based on the various system conditions. The end, the future research perspectives and key challenges are provided for further research.

1 Introduction

The voltage source converter (VSC)-HVDC system has been considered as one of the most popular candidates of the future transmission system \cite{1}. Benefiting from the highly developed power electronic converters, the VSC-HVDC system is one of the most suitable system topologies for long distance, large capacity, and interconnected power transmission. Recently, there is a new kind of oscillation, which is caused by the interactions between the converter and the grid, observed in several VSC-HVDC systems around the world. The complicated root cause of this oscillation has drawn attentions from researchers from various organisations. The impedance characteristics of the power electronic converters can be affected by the control schemes, grid operation conditions, the controller parameters, etc. When the converter shows capacitive impedance or negative resistance at the oscillation frequency range, the resonant circuit formed by the inductive device and the capacitive converter will amplify the resonant harmonics exist in the system. Based on the initial research, this kind of interactions between the converters and other devices is considered as the primary cause of such oscillations in VSC-HVDC systems.

In this paper, the oscillation events observed around the world are provided along with the initial analysis. Also then, the major analysis methods are also categorised and investigated based on their advantages and disadvantages. At last, the potential challenges regarding this oscillation are predicted for further research reference.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Frequency range, Hz & Name & Converter topology & Rated voltage, kV/power, MVA \\
\hline
20–30 & Nanhai VSC-HVDC in Shanghai & 48-level MMC & 30/18 \\
20–30 & Nanao VSC-HVDC in Guangdong & 200-level MMC\textsuperscript{a} & 160/200 \\
23.6–25.2 & Xiamen VSC-HVDC in Fujian & 216-level MMC\textsuperscript{a} & 320/1000 \\
250–350 & North Sea VSC-HVDC in German & two-level PWM converter & 110/400 \\
over 1000 & Zhoushan VSC-HVDC in Zhejiang & 200-level MMC\textsuperscript{a} & 200/400 \\
1200 & Luxi VSC-HVDC in Yunnan & VSC/LCC\textsuperscript{b} & 350/1000 \\
\hline
\end{tabular}
\caption{Oscillations observed around the world}
\end{table}

2 Oscillation incidents in the VSC-HVDC system

As shown in Table 1, the oscillations observed around the world are listed based on their frequency ranges. The system configurations and rated powers are given as well. Based on the initial research, the oscillations can be categorised into two parts: the sustained oscillations exist at the subsynchronous frequency range, and the diverge oscillations caused by negative resistance of the converter showing at the medium- or high-frequency range. However, the oscillation can happen from subsynchronous frequency range to high-frequency range despite the converter topologies, rated power etc.

2.1 Oscillations in the range of subsynchronous frequency

The Nanhai VSC-HVDC in Shanghai is the first VSC-HVDC transmission system connecting the off-shore wind farm and the on-shore grid. It is also the first VSC-HVDC system observing the oscillations caused by the interactions between the converter and grid in 2011 \cite{2}. It employs the 48-level modular multilevel converter (MMC) as its converter topology. At the early testing stage, there are several voltage/current oscillations observed when the transmitted power has changed. Later in 2014, during the grid...
connection test of Nanao VSC-HVDC in Nanao Island in Guangdong, there were 20–30 Hz subsynchronous oscillations observed when gradually increasing the output power [3]. The next year, current oscillation at 23.6 Hz was observed when the output power of the Xiamen VSC-HVDC was at 100 MW, while there was 25.2 Hz current oscillation observed when the output power is 500 MW [4].

Once the power transmitted through the converter has changed, the power imbalance between the input and output of the converter may cause voltage/current ripples at both sides of the converter. The chance of the oscillation will increase dramatically if the converter shows negative resistance when there is active power flowing into the dc transmission lines from the converter controlling the dc voltage [5]. On the other hand, it is mentioned that the interactions between the grids and the wind turbine or the controller of the DFIG can potentially generate ~10 Hz harmonics [6]. If the system happens to lack damping around the harmonic frequency, the oscillation risk rises.

By further investigating the following control methods for the oscillations in the range of subsynchronous frequency, the results have shown that most of the VSC-HVDC chooses the additional damping controller as the primary oscillation control method. The additional damping controller can increase the damping of the system around the oscillation frequency range, thus suppressing the oscillation voltage/current. However, the additional damping controller requires extra control loop in the VSC-HVDC system, and the virtual damping effect can also reduce the efficiency of the overall system.

### 2.2 Oscillations in the range of medium frequency

The North Sea HVDC system uses the HVDC Light technology provided by ABB. In 2013 [7], when the off-shore wind power was transmitted through the VSC-HVDC system, there were 250–350 Hz current oscillations observed and the oscillating current can be as high as 40% of the fundamental current.

In [8], Buchhagen et al. derived the grid impedance according to the North sea system configurations, and then estimated the system stability by comparing the impedance intersections of the generation unit and the grid. According to the Nyquist criteria, both intersections have phase margins <180°; thus, there are very slight chance of oscillations of the VSC-HVDC system. However, the oscillation incident happened in 2013 and caused the wind farm closing down over 10 months.

In that case, the North Sea wind farm VSC-HVDC system lacks the precise impedance model of related devices, such as the subsea cable, for stability analysis. Therefore, Song and Breitholtz [9] suggested a new cable modelling method, which consists of two series-connected blocks, one representing the electrical characteristic affected by the cable length and the other representing the impedance variations along with the frequency changes. The time-based simulation results have proved that this modelling method is more accurate than the conventional pi model at medium-frequency range.

### 2.3 Oscillations in the range of high frequency

In 2016, there was high-frequency components observed in Zhourshan five-terminal VSC-HVDC system when one of the terminals has switched from the grid-connected mode to islanded mode. The next year, the 1.2 kHz current oscillation was observed in the Luxi VSC-HVDC system when one of the terminals was connected to the ac grid solely through weak grid.

The Luxi VSC-HVDC system was the first HVDC system interconnecting both conventional line commutated converter (LCC)-HVDC and VSC-HVDC in parallel. However, the VSC-HVDC control unit was the primary cause of the high-frequency oscillation. During the incident, at first, the conventional LCC-VSC system drop out due to the line faults, the VSC-HVDC unit was operating solely from that moment. Also then, the system configuration has been changed as shown in Fig. 1. The LCC-HVDC transmission lines from Mawo to the Luxi substation, Wuping to Baise, and Yongan to Baise were disconnected. Then the oscillation was observed and, finally, the VSC-HVDC unit was dropped out as well. The oscillation is caused because of the high-frequency oscillation model in the MMC when it connects the grid through long distance or weak grid [10].

In order to estimate the stability of the Luxi VSC-HVDC system, the simplified HVDC control unit and the equivalent grid impedance model based on the system configuration shown in Fig. 1 has been constructed. The oscillation started at 3 s when there was a disturbance inserted to simulate the drop out of the LCC-VSC system as shown in Fig. 2. It can be seen the high-frequency components existing in the voltage when the disturbance was inserted. Therefore, once there are harmonics or disturbance around the resonant frequency inserted into the system, it will cause oscillations. Also because of the poor overload ability of the power electric converter, the system is at risk of triggering the protection when the oscillation happens. However, the impedance characteristic can be significantly different when the impacts of the control loops, such as PLL control loop, outer/inner control loop etc., are considered.

Not only the frequency range of this oscillation is different from the subsynchronous oscillations, but also the fundamental cause of such oscillation is different. It is believed that the high-frequency oscillation was generated by the voltage forward control loop. The delay of the control loop was typically set around 650 μs, which corresponds to over 1.5 kHz harmonics. Therefore, the voltage forward control loop can be one of the root causes of the high-frequency oscillations in the Luxi VSC-HVDC system. In this case, Changyue et al. [11] have suggested a dynamic performance optimisation approach for the VSC-HVDC system with delays. This approach provided a phase compensation method for related control loop – the optimised control loop model has more smooth response regarding the various faults, or the impulse current component caused by the system operation changes.

### 3 Modelling and control method

#### 3.1 Derivation of the impedance model

The low harmonic and good reliability under various operating conditions have made the MMC-based VSC-HVDC system one of the most popular candidates in renewable energy networks. The modelling of the VSC-HVDC system can be divided into three...
parts, the generation unit, the HVDC control unit, and the equivalent grid model.

As the generation unit, the wind energy networks are commonly connected to the VSC-HVDC system for on-shore or off-shore energy transmission. The wind energy networks often consist of hundreds and thousands of generators; it is difficult to derive the impedance model for each of them. Therefore, Amin and Molinas [12] provided a new modelling method, it replaces the wind farm by using an aggregated full rated equivalent model. In this case, the wind turbine and the converter can be combined and modelled as an ideal current source with the equivalent RLC circuit. To further describe the dynamics of the generation unit, the relationships between the system stability and the number of the wind generators connected to the VSC-HVDC system are investigated [13]. Kunjumuhammed divided the wind farm into four different parts, and then connected them to the VSC-HVDC system in sequence to observe the oscillation modes. The results indicated that the oscillation risk will increase when transmission capacity is increased.

The modelling of the HVDC control unit is based on the converter types. The derivations of the traditional two- or three-level VSC models are much simpler than the modelling of MMC, because they have fewer number of submodules. The derivations for two- or three-level converters have very little difference since the simple structure. In contrast, because there are a large number of submodules in the MMC model, this will significantly increase the derivation and calculation difficulty. Therefore, the modelling of the MMC is focusing on the accuracy of the model while reducing the calculation difficulty.

Based on the equivalent approach for the insulated gate bipolar transistors and diodes, the modelling methods for MMC can be categorised as: the conventional detailed model, the equivalent detailed model, and the simplified model. In [14], Beddar et al. have compared the accuracy and the calculation difficulty of these three modelling methods by investigating the tolerances of the voltage and current when they are at various conditions, such as steady state, ac short-circuit fault, and dc ground fault conditions. The conventional detailed model has the most accurate results but slowest in speed; thus, it is not suitable for large and complex HVDC system. On the other hand, both equivalent detailed model and simplified model can accurately describe the electric characteristics of the MMC in various conditions. Although the equivalent detailed model is slower than the simplified model, it can provide more accurate results regarding the submodule behaviours than the simplified model; therefore, it is preferred in MMC-based HVDC system.

It is necessary to make some assumptions to simplify the derivation when derive the model of MMC. However, with inappropriate assumption, the derived model may not be as accurate as required for oscillation analysis. Therefore, Lyu et al. [15] further investigated the impact of the circulating current suppression control loop on the oscillation based on the present impedance model of MMC. By inserting small voltage/current signals into both ac and dc side of the converter, it also validated that the PLL control loop, outer control loop, and submodule parameters can have great impact to the impedance characteristics of the converter.

The modelling of the equivalent grid model requires the detailed configuration of the interconnected system. Under normal circumstances, it is difficult to obtain the detailed parameters from the manufacturer. Therefore, it is applicable to pay more attentions to the modelling of the transmission lines in order to stay as close as the practical system characteristics. Sometimes, the oscillation happens at fault conditions, whereas one of the terminals is disconnected, it is also important to obtain the system configuration when the oscillation was observed.

3.2 System stability analysis approach

The appropriate stability analysis approach can spot the oscillation frequency, amplitude, and other related information. Based on the fundamental theories of the analysis methods for the oscillations in the VSC-HVDC system, the major stability analysis methods can be categorised into the following aspects: eigenvalue approach, frequency scanning approach, time-domain simulation approach, and impedance model approach.

Fig. 3 illustrates the information against the speed of these analysis approaches. The eigenvalue approach can provide the most detailed information regarding the oscillations. However, it is nearly impossible to derive the detailed model when the scale of the system is large and the system parameters are not provided by the manufacturer, when the capacity and structure of the system have increased, the dimensions of the results will also increase drastically, causing significant calculation difficulty. The time domain simulation approach is suitable for both complex and simply system under various conditions. However, it can only provide the time-varying results, but not the oscillation information, such as oscillation frequency or the device causing the oscillation. Therefore, this approach can be used as an auxiliary approach to investigate the behaviours of each device while the system is running. The frequency scanning approach is efficient to find out the unstable frequency area by deriving the impedance model of the targeted system. It is fast and efficient against complex system. However, the analysis results can be distorted by the fundamental harmonics and high-frequency components; thus, it is preferred when the accuracy of a complex system is not strict.

The impedance model approach investigates the system stability based on the Nyquist or behaviours Nyquist analysis method. Compared to the other analysis approaches, the impedance model approach is more accurate in analysing the characteristics of the oscillations in either complex or simply systems, and providing most of the information regarding the oscillation frequency, the most related devices or control loops etc.

The cause of the oscillation varies depending on the system configurations. Amin and Molinas [12] have derived the interconnection model of the wind farm and the grid in order to analyse the system stability when there are power variations at the generation unit side. According to the Nyquist analysis, when the output power of the generation unit has increased, the system is vulnerable to harmonics. D’Arco et al. [16] have investigated the impacts of the cut-off actions of one of the terminals in the system and the dynamic interactions among the devices; it helps to understand the high-frequency oscillations caused by the impedance characteristics of the control loops and the grids. Lyu et al. derived the small signal models of HVDC substation, converter controller, and the dc transmission line, and also provided the optimisation approach for the control parameters according to the system stability criteria [17]. If the HVDC system is interconnected with ac transmission system, or through off-shore weak grid, the new approach is required to estimate the stability of the interconnected system was introduced [18].

4 HVDC system oscillation control approach

4.1 Optimisation of the converter parameters

The fundamental cause of the oscillation in the HVDC system is the under-damped converter impedance at the oscillation frequency. Therefore, by optimising the impedance of the converter or adding compensators to the control loops where there are delays or poor dynamics can improve the interactions among the devices and lower the risk of oscillations. If the MMC is used as the converter topology, it is also necessary to avoid the resonance
frequency area of the resonant circuit formed by the arm inductor and the capacitors in submodules [19].

However, if there are several converters in the same system, they may be coupled, thus increasing the optimisation difficulty. In that case, once there are potential oscillations observed, cutting off the wind turbine or modifying the power transmitted can be a temporary way to stabilise the system by avoiding the resonant operating area. However, this can only be a short-term oscillation control approach for its high cost and power losses.

4.2 Additional damping controller

In the case of the high optimisation cost, it is also practical to improve the damping of the system by adding additional damping controller. However, the additional damping controller is facing the problems, such as poor dynamic performance, low robustness etc. Therefore, a damping controller was designed to be used in multi-terminal HVDC system, which is focusing on improving the overall performance of the converter in various operating conditions [20]. A virtual harmonic resistance controller was also provided to improve the system stability, especially around the oscillation frequency [21]. However, the damping controller still under risk of having interactions with other devices in the system, causing oscillations.

4.3 Additional filter device

The additional filter device can be divided into two kinds: the blocking filter and the parallel filter. The blocking filter is connected in series with the system, it is designed to pass the signals at the fundamental frequency and block the resonant currents at the oscillation frequency [22]. However, it requires a large room in a power plant and has low efficiency since the maintenance fee is high. Therefore, it is suitable for emergency oscillation control method instead of being used as a regular control method. The parallel filter consists of several RLC filters connected in parallel with the grid [23]. The advantage of this filter is that it can be designed to have several resonant points corresponding to the oscillation frequencies if there are more than one existing in the system. However, it suffers the same problems as the blocking filter, thus both filter approaches can be implemented as backup oscillation control method.

5 Future challenges of the oscillation problems

The researches regarding the oscillations in HVDC system now are still focusing on the individual converter, or a single system, it lacks the insights of the coupling effects of the interconnected system. The system stability analysis is still based on the conventional small signal linear model, the electric–magnetic transient model, and the simplified impedance model, which ignores the delays or other practical statuses existing in the system, such as PLL control loop, outer/inner control loop, and the PWM generator. On the other hand, the oscillation can happen at various frequencies, such as subsynchronous or medium/frequency range; therefore, the design of the converter should ensure the consistency of the impedance through a wide frequency range. Therefore, constructing the systematic broadband impedance model of the multi-terminal system can be one of the future challenges regarding the oscillations in the HVDC system.

6 Conclusion

The HVDC transmission system is one of the most promising power transmission topologies for large scale, large capacity, and multi-terminal system, ensuring that the stable and robust operation is one of the most concerned challenges in future. This paper reported the typical oscillation incidents observed around the world and provided with the initial research results. Then the analysis methods, modelling approaches, and the control of the oscillations are summarised and compared to provide reference for future researches regarding the oscillation in the VSC-HVDC system.

7 Acknowledgment

This research work of oscillation in VSC-HVDC system was supported by the project of ‘The research of the impacts on the main devices regarding the harmonic mechanism and suppression control in AC/DC interconnected power system’ (ZBJKJXM201700065), financed by China Southern Power Grid.

8 References

[1] Alyami, H., Mohammad, Y.: ‘Review and development of MMC employed in VSC-HVDC systems’. 2017 IEEE 30th Canadian Conf. on Electrical and Computer Engineering (CCECE), Windsor, ON, 2017, pp. 1–6
[2] Yuefeng, Y., Jie, Y., Zhiyun, H., et al.: ‘Research on control and protection system for Shanjun-Nanhai MMC VSC-HVDC demonstration project’. 10th IET Int. Conf. on AC and DC Power Transmission (ACDC 2012), Birmingham, 2012, pp. 1–6
[3] Gao, X., Deng, M., Wang, K.: ‘Characteristics and performance of Xiamen VSC-HVDC transmission demonstration project’. 2016 IEEE Int. Conf. on High Voltage Engineering and Application (ICHVE), Chengdu, 2016, pp. 1–4
[4] Yang, L., Li, Y., Li, L.: ‘Stability analysis of a string of average power loss for modular multilevel converter’, IEEE Trans. Ind. Electron., 2017, 66, pp. 1–6
[5] Pinares, G., Bongiorno, M.: ‘Modeling and analysis of VSC-based HVDC systems for DC network stability studies’, IEEE Trans. Power Deliv., 2016, 31, (2), pp. 848–856
[6] Mei, F., Bal, B.: ‘Modal analysis of grid-connected doubly fed induction generators’, IEEE Trans. Power Deliv., 2015, 30, (4), pp. 1898–907
[7] Bodin, A.: ‘HVDC light® – a preferable power transmission system for renewable energies’. Proc. of the 2011 3rd Int. Youth Conf. on Energetics (IYCE), Leiria, 2011, pp. 1–4
[8] Buchhagen, C., Rauscher, C., Menze, A., et al.: ‘BorWin1 – first experiences with harmonic interactions in converter dominated grids’. Int. ETG Congress 2015; Die Energiewende – Blueprints for the new energy age, Bonn, Germany, 2015, pp. 245–248
[9] Song, Y., Breitholtz, C.: ‘Nyquist stability analysis of an AC-grid connected VSC-HVDC system using a distributed parameter DC cable model’, IEEE Trans. Power Deliv., 2016, 31, (4), pp. 1560–1565
[10] Saad, H., Fillion, Y., Deschanvres, S., et al.: ‘On resonances and harmonics in HVDC-MM plant station connected to AC grid’, IEEE Trans. Power Deliv., 2017, 32, (3), pp. 1452–1459
[11] Changyue, Z., Juan, C., Shukai, X., et al.: ‘Dynamic performance optimization of VSC-HVDC considering its long delay’, Power System Technol., 2017, 41, (10), pp. 3216–3222
[12] Amin, M., Molinas, M.: ‘Understanding the origin of oscillatory phenomena observed between wind farms and HVDC systems’, IEEE J. Emerging Sel. Topics Power Electron., 2017, 5, (1), pp. 378–392
[13] Kanjuhammuird, I., Pal, B.C., Gupta, R.: ‘Stability analysis of a PMSC-based large offshore wind farm connected to a VSC-HVDC’, IEEE Trans. Energy Convers., 2017, 32, (3), pp. 1166–1176
[14] Beddard, A., Barnes, M., Preece, R.: ‘Comparison of detailed modeling techniques for DC-MMC employed on VSC-HVDC schemes’, IEEE Trans. Power Deliv., 2015, 30, (2), pp. 579–589
[15] Lyu, J., Cai, X., Molinas, M.: ‘Impedance modeling of modular multilevel converters’, IEC-CON, 2016, 3 (1), pp. 898–907
[16] Mei, F., Pal, B.: ‘Modal analysis of grid-connected doubly fed induction generators’, IEEE Trans. Power Deliv., 2016, 31, (4), pp. 1898–907
[17] Beddard, A., Barnes, M., Preece, R.: ‘Comparison of detailed modeling techniques for DC-MMC employed on VSC-HVDC schemes’, IEEE Trans. Power Deliv., 2015, 30, (2), pp. 579–589
[18] Lyu, J., Cai, X., Molinas, M.: ‘Optimal design of controller parameters for improving the stability of MMC-HVDC for wind farm integration’, IEEE J. Emerging Sel. Topics Power Electron., 2018, 6, (1), pp. 40–53
[19] Ding, H., Fan, S., Zhou, I.Z., et al.: ‘Parameter selection of the stability of VSC-HVDC converters’, IET Int. Conf. on AC and DC Power Transmission, Birmingham, 2015, pp. 1–6
[20] Zygmanski, M., Grzesik, B., Nalepa, R.: ‘Capacitance and inductance selection of the modular multilevel converter’. 15th European Conf. on Power Electronics and Applications (EPE), Lille, France, 2013, pp. 1–10
[21] Dong, X., Wang, X., Yang, Y.: ‘Suppression of sub-synchronous oscillation caused by HVDC using supplementary excitation damping controller’. 2014 17th Int. Conf. on Electrical Machines and Systems (ICEMS), Hangzhou, 2014, pp. 2431–2434
[22] Liu, Y., Raza, A., Rouzbeh, K., et al.: ‘Dynamic resonance analysis and oscillation damping of multiterminal DC grids’, IEEE Access., 2017, 5, pp. 16974–16984
[23] Ren, S., Wang, S., Zhu, Y., et al.: ‘A blocking filter design method of effective suppression of three forms of SSR’. 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conf. (APPEEC), Xi’an, 2016, pp. 599–603
[24] Wang, S., Xu, Z., Wang, S.: ‘New findings on bypass damping filter in increasing subsynchronous resonance damping of series compensated system’, IET Gener. Transm. Distrib., 2015, 9, (13), pp. 1718–1726