DC Resonance Analysis of a Hybrid HVDC System

Qinan Li, Mats Andersson

***Abstract*—To ensure stable operation of a hybrid HVDC system, it is necessary to analyze the DC resonance characteristics. In this paper, an example ±500kV/3000MW bipolar hybrid HVDC system is used. Both passive impedance models and active impedance models are used to analyze the DC resonance characteristics. The different factors that will have impact on DC impedance-frequency characteristics are studied, such as AC system short circuit ratio (SCR), length of transmission line, control strategies applied for rectifier station and inverter station. In addition, a SLG (single line to ground) fault is applied at the rectifier AC grid, to check for potential second order resonance issues. All simulations are performed in PSCAD/EMTDC, and the results show that the current design of Hybrid HVDC system is able to effectively avoid lower order DC resonance issues.**

***Index Terms*—DC Resonance, Hybrid HVDC, Impedance-frequency Characteristics.**

I. Introduction

A hybrid HVDC system was proposed in [1] where LCC is used at the rectifier station, and MMC-based VSC is used at the inverter station. Diode valves are placed between the MMC converter and the DC pole line, to add DC fault clearing capability. This hybrid system is considered an effective solution to realize long distance power delivery in China, as well as to upgrade existing LCC-based HVDC systems to VSC-based HVDC systems [2].

Concerning this hybrid HVDC system, a lot of research studies have been done recently. The DC line fault transient process is analyzed and an index of critical transmission power ensuring transient stability is also proposed in [3]; A calculation method and the complete process of harmonic current at the DC side are proposed in [4]; An analytical method for the calculation of dc-loop impedance is presented in [5]. A new control method is proposed to eliminate the DC resonance by dynamically adjusting the total number of inserted sub-modules of the MMC, without changing the current and voltage on the AC side [6]. In [7], a steady state mathematical model and coordination control for rectifier station and inverter station are proposed. Moreover, a coordination control strategy for fault conditions is also proposed. So far, the though analysis of on how system parameters and control modes will influence DC resonance characteristics in hybrid HVDC systems has not been reported according to the author’s literature survey. The previous studies on DC resonance issues mainly focus on LCC-based HVDC systems [8],[12],[13].

The DC resonance frequency is influenced by transmission line, smoothing reactor (including both rectifier station and inverter station), DC filters, converter transformer, and equivalent impedance of AC system as well as AC filters. As a consequence, there are several natural resonance frequencies [13] determined both by the parameter of each device in the DC system, and also by the operation mode.

According to the frequency transformation relationship between AC side and DC side of a LCC converter, a voltage with a frequency of $\omega_{dc} = \omega_m \pm \omega_{fund}$ will be generated on the DC side, when a voltage disturbance with frequency of ω_m is present on the AC side. ω_{fund} refers to the angular frequency of the AC voltage fundamental component; Similarly, currents with frequencies of $\omega_{ac} = \left|\omega_d \pm \omega_{fund}\right|$ will be generated at the AC side, when a current disturbance with a frequency of ω_d is present on the DC side [16].

As for MMC-based voltage source converter, if only the fundamental component is considered, a current with a frequency of $\omega_{dc} = \omega_m \pm \omega_{fund}$ will be generated at DC side, when a current disturbance with frequency of ω_m is present on the AC side; voltages with frequencies of $\omega_{ac} = \left|\omega_d \pm \omega_{fund}\right|$ will be generated at the AC side, when a voltage disturbance with frequency of ω_d is present on the DC side.

That is to say, AC side and DC side interact with each other, and disturbances or short circuit faults at AC side will introduce corresponding oscillations at DC side. If the oscillation frequencies are around fundamental or second harmonic, such a disturbance between AC and DC side will generate severe overvoltage, and consequently threaten the safe operation of DC equipment in the HVDC system [8],[9],[10].

In this paper, an example ±500kV/3000MW bipolar hybrid HVDC system is used. Both passive impedance models and active impedance models are used to analyze the DC resonance characteristics. The different factors that will have impact on DC impedance-frequency characteristics are studied, such as AC system short circuit ratio (SCR) , length of transmission line, control strategies applied for rectifier

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station and inverter station. In addition, a SLG (single line to ground) fault is applied at the rectifier AC grid, to check for potential second order resonance issues. All simulations are performed in PSCAD/EMTDC, and the results show that the current design of Hybrid HVDC system is able to effectively avoid lower order DC resonance issues.

II. General Structure and Bipolar HVDC System

General structure of the studied ±500kV/3000MW bipolar hybrid HVDC system is shown in Fig.1. Each rectifier pole includes a 12-pulse LCC converter (two 6-pulse converters in series connection), with its neutral point connected to earth through an electrode line. For each inverter pole, a MMC converter is used. To clear DC line faults, a diode valve is placed between the MMC converter and the DC pole line.

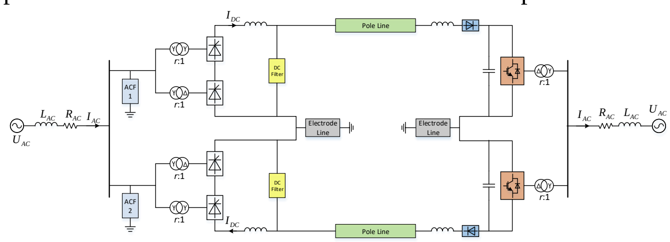

Fig.1 General structure of the studied ±500kV/3000MW bipolar hybrid HVDC system

ACF1，ACF2 are the installed AC filters at the rectifier AC bus. The length of the pole transmission line is 1000km, and other key parameters of the main circuit of the studied hybrid HVDC system are listed in Table 1.

Table 1 Key main circuit parameters in the studied system

Item	Rectifier Station	Inverter Station
AC System SCR	5	5
AC Bus Voltage/kV	525	525
Short-circuit voltage of converter transformer uk/%	16.4	15
Capacity of converter transformer/MVA	892.5	1700
Voltage ratio of converter transformer /（kV/kV）	525/210.4	525/332.3
Type of AC filters	3*DT11/13 3*DT24/36 4*SC + HP3	---
Capacity of AC filters /MVA	1640	0
Rated delivery power/MW	3000	3000
Smoothing reactor/mH	290	10
Type of DC filters	1*DT 12/24 1*DT 12/36	---
Converter	12-pulse LCC	MMC（Half bridge）

III. DC Impedance Model of Hybrid HVDC System

To carry out the measurement and calculation of DC impedance, related DC system modelling is required. Generally speaking, impedance models of a DC system are categorized into 2 types: passive impedance model and active impedance model [8]. For the passive impedance model, the converter is simplified as a linear equivalent circuit under one of the steady state operation points regardless of its switching process. Meanwhile the AC voltage sources are replaced by short circuits. However, the frequency transformation between AC and DC side of the converter is not considered with the passive impedance model. In addition, the damping provided by converter control system is also not taken into account.

As for the active impedance model, the switching actions of all the converters are considered and they are in operation with their related closed loop control system. Similar to a common electromagnetic transient simulation model, both the frequency transformation and the damping provided by converter control system are considered with active impedance model. How to build the related passive and active impedance models will be described in the following sections.

A. *Passive Impedance Model*

All the passive components of hybrid HVDC system such as AC/DC filters, transmission lines (including electrode lines) and smoothing reactors are included. The LCC and MMC converters are represented by equivalent linear passive circuits, as shown in Fig.2. AC voltage sources are short circuited, and Vh is the harmonic voltage injecting source which is used to measure the DC impedance. The detailed calculation method for DC impedance is introduced in the next sub-section.

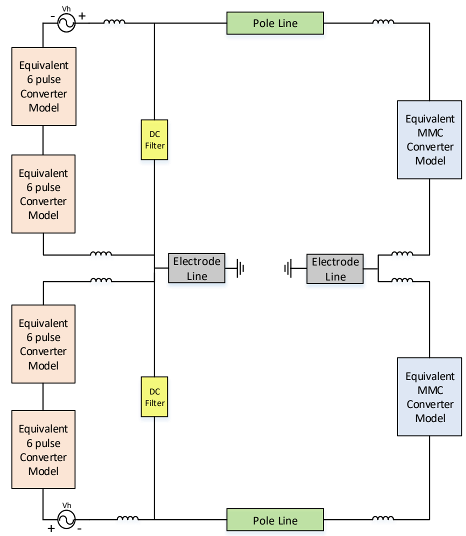

Fig.2 Passive impedance model of the studied hybrid HVDC system

1) *LCC Equivalent Model*

Each 6-pulse LCC converter could be represented by two 3-pulse models, and the equivalent inductance L_{3p} [8] is calculated according to the following equation:

$$L_{3p} = \frac{1}{2}[1.5 \cdot \frac{\mu}{60} + 2 \cdot (1 - \frac{\mu}{60})] \cdot L_c \quad (1)$$

where Lc is the commutation inductance. If AC system impedance and AC filters are not considered, the value of Lc is the same as the leakage inductance referred to the valve side of the converter transformer. μ is the overlap angle, expressed in electrical degrees. When AC system impedance and AC filters are taken into account, the above equation needs to be modified. AC system impedance and AC filters are “transformed” onto the valve side, and the modified equivalent model of a 6-pulse converter is shown in Fig.3.

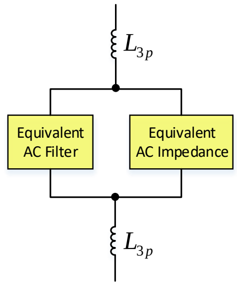

Fig.3 6-pulse converter equivalent model considering AC system impedance and AC filters

Equivalent AC Filter and equivalent AC system impedance are connected in parallel, and then connected in series with L3p. A detailed derivation can be found in [13].

2) MMC DC Impedance Model

The DC impedance model of MMC is represented by a passive branch with resistor, inductor and capacitor connected in series. The DC side impedance is expressed as [14],[15]:

$$Z_{dc}^{MMC}(f)=\frac{2}{3}R_0+j(\frac{4\pi fL_0}{3}-\frac{N}{12\pi fC_0}) \tag{2}$$

where R_0 refers to the equivalent resistance of each arm of MMC, and L_0 denotes the arm inductance and C_0 is the capacitance of each sub-module. N is the number of sub-module in each arm. In the analysis of this paper, the equivalent resistance of each arm R_0 is neglected. The detailed values of arm inductor and sub-module capacitors are listed in Table 1.

B. Active Impedance Model

Actually, an active impedance model is an electromagnetic transient model including both main circuit and complete control system, which is built according to Fig.1. An active impedance model is thus able to represent the impact of control system as well as non-linear converter characteristics, so that an accurate impedance-frequency characteristics could be obtained.

C. Calculation Method of DC impedance [11],[12],[14]

1) Harmonic voltage injection [11]

A harmonic voltage source using a sequence of cosine waves, is inserted at the LCC converter DC side. The detailed expression of the injected voltage source V_h is shown below:

$$V_h=\sum_{n=1}^{N_{\max}}A_m\cos(2\pi f_n t+\varphi_n) \tag{3}$$

where $f_n=n,\ \varphi_n=\frac{\pi}{180}n^2$. N_{max} is the maximum frequency and A_m refers to the amplitude of cosine waves with different frequencies. In the following analysis, A_m is selected as 0.1% of the rated DC line voltage and N_{max}=250.

2) Perform FFT calculation after time domain simulation

Time domain simulations of the passive/active impedance models in PSCAD/EMTDC are performed, while monitoring the DC current I_h, the DC voltage across DC filter and so on. When the hybrid HVDC system is in steady state, record the related data and then apply FFT analysis to obtain the corresponding voltage phasor and current phasor. DC impedance seen from the DC side of rectifier or inverter is calculated as:

$$Z_{dc}(f)=\frac{\dot{V}_h(f)}{\dot{I}_h(f)} \tag{4}$$

IV. Simulation Study

A. Frequency Domain Simulation Study

1) SCR Level of AC System

The hybrid HVDC system is in bipolar operation, and all the AC filters at the rectifier station are switched on. The rectifier station uses constant DC power control, while the inverter station is using constant DC voltage control. SCR of AC system for rectifier station and inverter station are shown in Table 2.

Table 2 SCR of AC system for rectifier station and inverter station

SCR of AC system	Case1	Case2	Case3	Case4	Case5
Rectifier station	5	2.5	5	2.5	1000(infinite)
Inverter station	5	2.5	2.5	5	1000(infinite)

The related DC impedance-frequency characteristics are shown in Fig.4. "SCR:rec" refers to the SCR level at rectifier station and "SCR:inv" refers to the SCR level at inverter station.

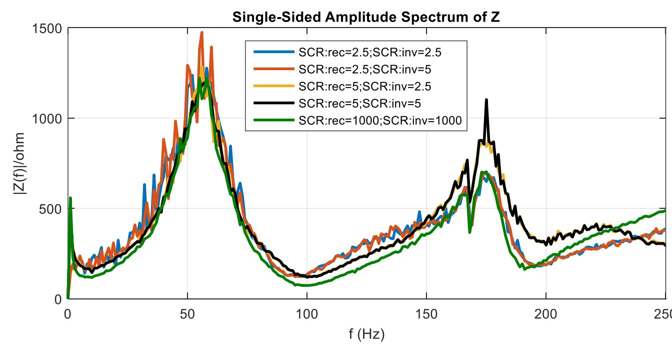

Fig.4 DC impedance-frequency characteristics with different SCR level

From Fig.4, it is clear that the obtained impedance-frequency characteristics are mainly affected by SCR level at rectifier station when the harmonic voltage source is close to the DC terminal of 12-pulse converter. The SCR level at inverter station has less impact on the impedance-frequency characteristics. The detailed resonance frequencies and related impedance with different SCR levels at rectifier station are listed in Table 3.

Table 3 Resonance frequencies and related impedance with different SCR level

SCR level at rectifier station	fs1(Hz)	Zs1(Ohm)	fs2(Hz)	Zs2(Ohm)
2.5	95	122.4	196	181.4
5	100	118.5	200	296.6
1000	99	73.4	191	162

It is clear that the resonance frequency doesn't change too much but the impedance at resonance frequency decrease with higher SCR level at rectifier station.

2) Comparison of passive impedance model and active impedance model

The hybrid HVDC system is in bipolar operation with SCR level of 5 at both rectifier and inverter station, and all the AC

filters are switched on. For active impedance model, constant firing angle control (15 deg) and constant power control (rated power) are utilized respectively. The corresponding DC impedance-frequency characteristics are shown in Fig.5.

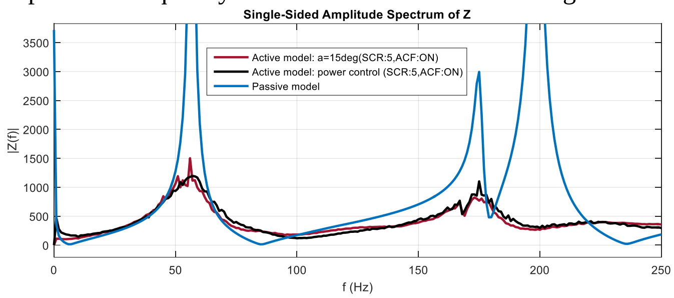

Fig.5 DC impedance-frequency characteristics with passive and active impedance model

For the active impedance model, similar impedance-frequency characteristics are obtained with constant firing angle mode and constant power control mode, where certain damping is observed at series resonant frequencies (120 Ω at 100Hz and 316 Ω at 198Hz); However, for the passive impedance model, the impedance at series resonant frequencies is close to 0 Ω since the additional damping effects are not considered.

3) Control Mode and Delivered Power Level

The control strategies for LCC and MMC are listed in Table 4.

Table 4 Control strategies applied for LCC and MMC converter

Control mode	LCC	AC filter	MMC
1. MP_VC	Udref_Rec=1.0 p.u	DT 11/13 +DT 24/36	Porder =145MW, Uac=525kV
2. MP_CV	Porder = 0.1 p.u	DT 11/13 +DT 24/36	Udref=250kV, Uac=525kV
3. FP_VC	Udref_Rec=1.0p.u	All switched on	Porder =1390MW, Uac=525kV
4. FP_CV	Porder = 1.0 p.u	All switched on	Udref=250kV, Uac=525kV

In Table 4, FP means Full Power operation and MP means Minimum Power operation with a power order of 10%. CV denotes that constant DC power (constant current) control is used by the LCC and constant DC voltage control is used by the MMC. As for VC, it means that the LCC uses constant DC voltage control mode and the MMC uses constant DC power control.

At full power operation, the reactive power consumption of LCC is also large so that all the AC filters including double-tuned filters, shunt capacitors as well as high-pass filters are switched on; For the case of minimum power operation, the reactive power consumption of LCC is lower so only the double-tuned filters are required. Fig.6 demonstrates the related impedance-frequency characteristics with different control modes listed in Table 4.

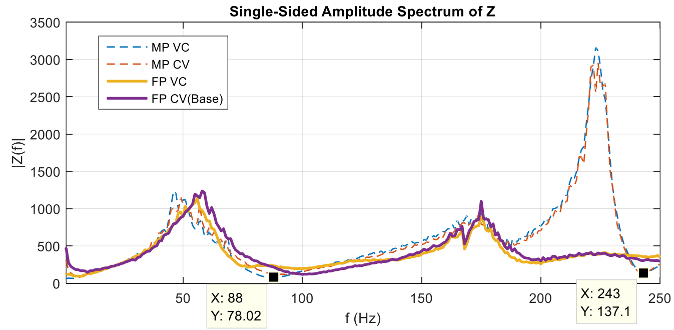

Fig.6 DC impedance-frequency characteristics with different control modes of LCC and MMC

From Fig.6 it can be seen that the impedance-frequency characteristics with the two different control strategies (CV and VC), are almost the same when the delivered power is identical. The differences in impedance-frequency characteristics mainly are in the frequency range of 180Hz~250Hz, and originates from different AC filter configurations. In addition, the first series resonant frequency is around 88Hz for MP operation while the first series resonant frequency is around 100Hz for FP operation.

4) Length of Transmission Line

The hybrid HVDC system is in bipolar operation and only the length of transmission line varied, while the rest of the parameters remain unchanged. The obtained DC impedance-frequency characteristics are shown in Fig.7.

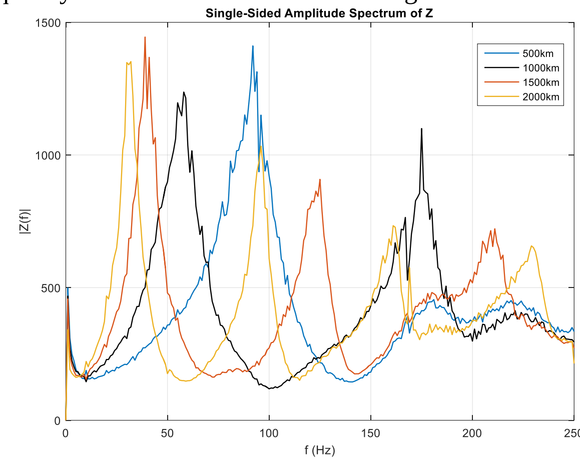

Fig.7 DC impedance-frequency characteristics with different length of transmission line

Detailed data of resonant frequencies and impedances are listed in Table 5. fs1 is the first series resonant frequency and Zs1 is the related impedance at this frequency; fs2 is the second series resonant frequency and Zs2 is the related impedance at this frequency.

Table 5 Resonance frequencies and related impedance with different length of transmission line

Length of Transmission line（km）	fs1(Hz)	Zs1(Ohm)	fs2(Hz)	Zs2(Ohm)
500	138	148.3	---	---
1000（rated value）	100	118.5	198	316.1
1500	73	162.7	143	175.2
2000	58	149.4	116	165.8

It is clear that the DC resonant frequencies will be lower, with increasing transmission line length. The value of Zs1 at frequency of fs1 doesn't change too much and the impedance is in the range of 110Ω ~165Ω.

B. *Time Domain Simulation Study*

According to the above simulation results, the first series resonant frequency in the DC system is around 100Hz and the impedance at this frequency is about 120 Ω, when the hybrid HVDC system is in bipolar operation. So there is a potential second order resonance in the DC system. In the PSCAD/EMTDC simulation model, a SLG fault is applied to the rectifier AC grid. A SLG fault generates negative sequence voltage at the AC side, and consequently a second harmonic oscillation will be introduced to the DC side. Therefore, this is a good and practical way to check for potential DC resonance issues.

At t=3s, a solid SLG fault is applied to phase A in the rectifier AC grid, and is cleared 100ms later. The rectifier system response to this fault is shown in 错误!未找到引用源。. UD_S1P1_kV shows the voltage across the DC filters and Id_SIP1 refers to the direct current in the pole line. Udc_12p is the voltage across the 12-pulse group inside the smoothing reactor. Iconv_S1P1 is primary phase current of transformer and Econv_S1P1 refers to the primary phase voltage.

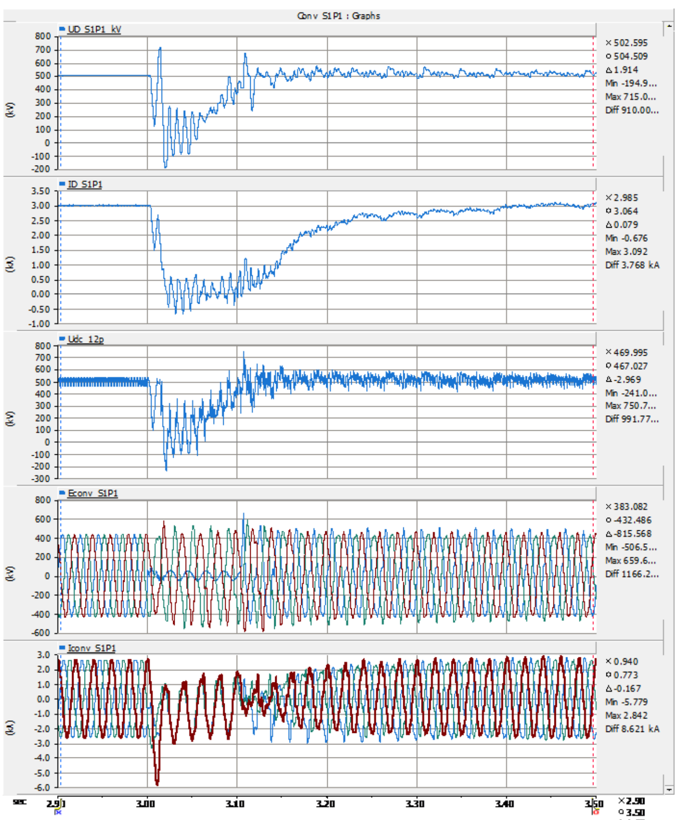

Fig.8 Rectifier system response to SLG AC fault

From the top graph in 错误!未找到引用源。, obvious 2nd order voltage is observed in the DC filter voltage following a SLG fault. The maximum 2nd order harmonic overvoltage on pole line is up to 715kV (1.43 p.u). After 3.05s, 2nd order harmonic voltage is damped significantly due to damping provided by the control system. Even though there is a potential 2nd order oscillation, the oscillation decays in a relative short time. Consequently it is not necessary to take extra actions to attenuate the potential DC resonance.

V. CONCLUSION

In this paper, the DC resonance characteristics are analyzed in an example ±500kV/3000MW bipolar hybrid HVDC system. The different factors that will have impact on DC impedance-frequency characteristics are studied, such as AC system short circuit ratio (SCR), length of transmission line, control strategies applied for rectifier station and inverter station. The main conclusions are:

1) DC resonance frequency doesn't change too much but the impedance at resonance frequency decrease with higher SCR level of AC system;

2) DC resonant frequencies will be lower with increasing transmission line length. The impedance amplitude at the first resonant frequency doesn't change too much.

3) There is no significant difference on the impedance-frequency characteristics with CV control and VC control mode;

4) The difference of impedance-frequency characteristics with minimum power operation and rated power operation mainly exists in the frequency range of 180Hz~250Hz. Such difference results from different configurations of AC filters.

5) Simulation results from PSCAD/EMTDC show that the 2nd order resonant overvoltage on DC line decays quickly. Consequently it is not necessary to take extra actions to attenuate the potential DC resonance.

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