Research on harmonic cooperative suppression strategy of hybrid parallel DC transmission system

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Abstract. Hybrid parallel DC transmission system has both flexible control characteristics of MMC-HVDC and large capacity transmission capacity of LCC-HVDC, which has good economy and practicability. However, the connection of hybrid parallel DC transmission system will bring a series of harmonic problems, so harmonic suppression measures must be taken. This paper firstly introduces the generation mechanism and basic characteristics of LCC-HVDC characteristic and non-characteristic harmonics. Then the causes of MMC-HVDC circulation are analysed. Finally, based on the parallel connection of LCC-HVDC and MMC-HVDC in the same AC bus, a harmonic co-suppression strategy of hybrid parallel DC transmission system is proposed and the simulation verification is carried out. The results show that the strategy can use MMC-HVDC to assist in absorbing the harmonics generated by LCC-HVDC.

1. Introduction

High voltage direct current (HVDC) transmission technology can be divided into line commutated converter HVDC (LCC-HVDC) and voltage source converter HVDC (VSC-HVDC). LCC-HVDC is suitable for large-scale long-distance transmission. VSC-HVDC has the advantages of flexible operation and small area of converter station [1]. Hybrid parallel DC (HPDC) system integrates the advantages of LCC-HVDC and VSC-HVDC. As is shown in Figure 1, HPDC system adopts LCC-HVDC and modular multilevel converter HVDC (MMC-HVDC) parallel structure connected to the same bus.

LCC-HVDC outputs a lot of harmonics to the grid. Measures must be taken to deal with harmonic problems, otherwise the power quality will be reduced and even the safe and stable operation of the power system will be endangered. For HPDC system, the particularity of structure makes it showing different harmonic characteristics. The harmonic exchange between converter and AC system is the interaction of LCC-HVDC and MMC-HVDC. In view of the good controllability of MMC-HVDC, MMC-HVDC can be used to absorb the harmonics generated by LCC-HVDC on the same bus. At this time, in addition to normal power transmission, MMC-HVDC also provides some active power filter (APF) functions, which can reduce the harmonics injected into AC system by HPDC system. Based on the analysis of HPDC system harmonic characteristics, MMC-HVDC is used to suppress harmonics combined with the unique topology of HPDC system and the active harmonic principle of MMC-HVDC. In this paper, the generation mechanism and basic characteristics of LCC-HVDC and MMC-HVDC harmonics are analysed firstly. And then a harmonic cooperative suppression strategy of HPDC system using MMC-HVDC to assist in absorbing the harmonics generated by LCC-HVDC is proposed. Finally, a simulation model is built in PSCAD / EMTDC software to verify the harmonic...
compensation control strategy proposed. The results show that the harmonic coordination control strategy can effectively improve the power quality of HPDC system, which is conducive to the safe and stable operation of the system.

2. Harmonic characteristics of LCC-HVDC and MMC-HVDC analysis

2.1. Harmonic characteristics of LCC-HVDC

2.1.1. AC and DC characteristic harmonic. The characteristics of LCC-HVDC determine that it will still produce harmonics even under perfect working conditions [2]. The frequency and content of characteristic harmonics show certain regularity. Under ideal condition the line current at valve side of three-phase 6 pulse converter bridge transformer only contains \(6k\pm1\) (k is the natural number) harmonic except for the fundamental current. LCC-HVDC adopts 12 pulse converter structure, which is connected in series at DC side by two 6 pulse converters and in parallel at AC side through converter transformer. In normal operation, the current at AC side of 12 pulse converter is

\[
i_{A12} = \frac{2\sqrt{3}}{\pi} I_p (\cos \theta - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t - \cdots) \tag{1}
\]

The characteristic harmonic times contained in the phase current \(i_A\) of the AC side are \(h=12\ k\pm1\) times, and the effective value of the \(h\)-th characteristic harmonic current is

\[
I_{A12}(\alpha, \mu) = \frac{i_{A12}(\alpha, 0) \sqrt{S_1^2 + S_2^2 - 2S_1S_2 \cos(2\alpha + \mu)}}{h \cdot \cos \alpha - \cos(\alpha + \mu)} \tag{2}
\]

In Formula (2) the harmonic current coefficient is

\[
S_1 = \frac{\sin((h+1)\frac{\mu}{2})}{h+1}, \quad S_2 = \frac{\sin((h-1)\frac{\mu}{2})}{h-1} \tag{3}
\]

The number of characteristic harmonics in the rectifier voltage \(u_{dc}\) of the converter is \(h=12k\), and the effective value of the \(h\)-th characteristic harmonic voltage is

\[
U_{nh}(\alpha, \mu) = \frac{U_{dc}}{\sqrt{2}} \sqrt{C_1^2 + C_2^2 - 2C_1C_2 \cos(2\alpha + \mu)} \tag{4}
\]

In Formula (4) the harmonic voltage coefficient is

\[
C_1 = \frac{\cos((h+1)\frac{\mu}{2})}{h+1}, \quad C_2 = \frac{\cos((h-1)\frac{\mu}{2})}{h-1} \tag{5}
\]

2.1.2. AC and DC non-characteristic harmonic. When 12 pulse converter works, it will inject harmonics into both AC and DC system. All other frequency components except characteristic

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**Figure 1.** Structure diagram of hybrid parallel DC transmission system.
harmonics are non-characteristic harmonics \[3\]. The most important reason for the generation of non-characteristic harmonics is that the triggering angle \(\alpha\) of each valve or the triggering time interval are not equal.

Taking a 6-pulse converter as an example, it is assumed that the odd valve of the upper half bridge is triggered \(\Delta \alpha\) in advance, while the even valve of the lower half bridge is delayed \(\Delta \alpha\) in advance.

When the commutation process is not considered, the ratio of \(n\)-th even harmonic to fundamental wave is

\[
\frac{I_{(n)}}{I_{(0)}} = \frac{2 \sin n(\Delta \alpha)}{2 \cos n(\Delta \alpha)} = \frac{n \Delta \alpha - \frac{1}{6} (n \Delta \alpha)^3 + \frac{1}{120} (n \Delta \alpha)^5 + \ldots}{n[1 - \frac{1}{2} (n \Delta \alpha)^2 + \frac{1}{24} (n \Delta \alpha)^4 + \ldots]} = (\Delta \alpha)[1 + \frac{1}{3} (n \Delta \alpha)^3 + \frac{2}{15} (n \Delta \alpha)^5 + \ldots] = \Delta \alpha \tag{6}
\]

Similarly, the ratio of odd harmonics to fundamental waves is

\[
\frac{I_{(2n+1)}}{I_{(0)}} = \frac{\sin[k \pi \cos 1.5 k(\Delta \alpha) \pm \cos k \pi \sin 1.5 k(\Delta \alpha)]}{3k \sin(\frac{\pi}{3} \pm \Delta \alpha / 2)} = \frac{\sin 1.5 k(\Delta \alpha)}{3k \left[ \frac{\sqrt{3}}{2} \cos \frac{\Delta \alpha}{2} \pm \frac{1}{2} \sin \frac{\Delta \alpha}{2} \right]} \tag{7}
\]

When \(a\) is very small, there is

\[
\frac{I_{(2n+1)}}{I_{(0)}} \approx \frac{1.5k(\Delta \alpha)}{3k \left( \frac{\sqrt{3}}{2} \right)} = \frac{\Delta \alpha}{0.557(\Delta \alpha)} = 0.557(\Delta \alpha) \tag{8}
\]

In the commutation process, the no-load DC voltage is equal to the average value of the two phase to the third phase line voltage. While in the non-commutation process, the no-load DC voltage is equal to the average value of the line voltage between the two conduction phases \[4\]. When the trigger angle is not equal to the interval, the non-characteristic harmonic in the rectifier voltage \(U_{d}(\alpha, \mu)\) of single bridge converter is

\[
U_{d}(\alpha, \mu) = \frac{1}{2} \left[ U_{d}(\alpha, 0) + U_{d}(\alpha, \mu, 0) \right] \tag{9}
\]

The unit value of non-characteristic harmonic vector in DC voltage is

\[
U_{d}(\Delta \alpha, \Delta \mu) = \frac{1}{2} \left[ U_{d}(\Delta \alpha, 0) + U_{d}(\Delta \alpha, \mu, 0) \right] \tag{10}
\]

The first term in Formula (10) refers to the non-characteristic harmonic vector caused by the difference of the commutation angle at the beginning of commutation. The second term refers to the non-characteristic harmonic vector caused by the difference of the commutation angle at the end of commutation. It can be proved that the two vectors are equal in size and the phase angle is equal to \(n \mu p\). Thus,

\[
U_{d(n)}(\Delta \alpha, \Delta \mu) = U_{d}(\Delta \alpha, 0) \cos \frac{n \mu p}{2} \tag{11}
\]

It can be seen from the Formula (11) that the non-characteristic harmonic of the converter with load will not exceed the non-characteristic harmonic without load, which is due to the increase of the current leading to the increase of the commutation angle \(\mu\). Therefore, when the converter is loaded, the distortion degree of the rectifier voltage curve caused by the unequal triggering angle is smaller than that caused by no-load.

### 2.2. Harmonic characteristics of MMC-HVDC

Because the output voltage and current of MMC-HVDC approach to sine wave, the harmonic content of MMC is very low when it works \[5\]. However, due to the structure characteristics and working principle of MMC, the energy of converter bridge arm fluctuates inevitably, which leads to the circulation between the bridge arms of each phase \[6\].
The energy exchange between the AC and DC of MMC is completed by charging and discharging the sub-module capacitance. The voltage of the sub-module capacitance can’t be completely constant in the working process. And it will inevitably fluctuate with the charging and discharging, which will introduce the AC component into the circulation. The AC component is mainly composed of negative order component of 2-fold frequency. It can be proved that in addition to the 2-fold frequency component there are all other even frequency AC components.

2.3. Harmonic characteristics of HPDC system
In the HPDC system, LCC-HVDC is a harmonic current source and MMC-HVDC is a harmonic voltage source [7]. However, the internal impedance of its equivalent voltage source is in the order of hundreds of ohms, which shows a high resistance characteristic compared with the equivalent impedance of the AC system where the bus is located, so it can also be equivalent to the form of harmonic current source by transformation. The wiring structure and harmonic current distribution at the AC bus of the HPDC transmission project are shown in Figure 2. In Figure 2, \(i_{hLCC}\) is the harmonic current injected into AC bus by LCC-HVDC. \(i_{hMMC}\) is the harmonic current injected into AC bus by MMC-HVDC. \(i_{hf}\) is the harmonic current absorbed by AC filter. \(i_{hs}\) is the harmonic current injected into AC system by bus.

Because the two converters are equivalent to harmonic current source, \(i_{hLCC}\) and \(i_{hMMC}\) can be directly superposed according to the circuit principle. The harmonic injected into the AC system by the HPDC system is equal to the sum of the harmonic injected by the two converters. The characteristic harmonic frequency of LCC-HVDC converter is \(12k \pm 1\) \((k = 1, 2, 3...\). The harmonic of MMC-HVDC converter is very small, but the circulation in MMC-HVDC will cause 2-fold frequency pulsation in AC current. Even if it is equipped with circulation suppression measures, the AC current harmonic of MMC-HVDC is still dominated by the second harmonic due to the circulation suppression effect. Therefore, the main harmonics of HPDC system include: 2, 11, 13, 23, 25 and so on.

![Figure 2. AC harmonic diagram of hybrid parallel DC system.](image)

3. Harmonic cooperative suppression of parallel hybrid DC transmission
Using power filter to absorb the harmonic current produced by the filter source nearby is an effective measure to suppress harmonic pollution. Passive filter is the most widely used means of harmonic suppression at present, which is characterized by less investment, high efficiency and reliable operation. However, the filter characteristics of passive filter are greatly affected by the system parameters. Harmonic amplification may even occur which leads to resonance. With the development of power electronic technology, the research direction of power system filter gradually turns to active filter [8]. In other words, a controllable power semiconductor device is used to inject a current with the same amplitude and opposite phase to the original harmonic current into the power grid so that the total harmonic current of the power supply is zero and the harmonic current can be compensated in real time. The control system of APF consists of harmonic detection and compensation [9]. The distorted part of the current and voltage in the power grid is detected by the detection circuit and then the corresponding compensation current component is generated by the control power circuit and injected into the power grid to reduce the harmonic. Referring to the filtering principle of shunt active
power filter [10-12], the harmonic compensation control strategy is designed for MMC-HVDC. The content of $i_{aG}$ and $i_{bG}$ is reduced by introducing the current component of equal amplitude and inverse phase to $i_{bLCC}$ in $i_{aMMC}$. The harmonic compensation control strategy of hybrid parallel DC system is shown in Figure 3.

The harmonic compensation control strategy of HPDC system consists of basic control strategy of MMC-HVDC, the harmonic detection unit and harmonic compensation unit. The basic control strategy of MMC-HVDC adopts the inner loop constant-current control and outer loop constant-DC voltage / constant-active power with constant-AC voltage / constant-reactive power, which is the basis of controlling the stable transmission of DC power by MMC-HVDC. The harmonic detection unit adopts the basic wave elimination method based on the instantaneous power theory to detect the harmonic current $i_{bLCC}$ generated by LCC-HVDC. The harmonic compensation unit constructs the compensation voltage reference value according to the harmonic current signal obtained from the harmonic detection unit, which is used to trigger the bridge arm module after superposing with the bridge arm voltage reference value given by MMC basic control strategy.

![Figure 3. Diagram of harmonic cooperative suppression strategy.](image)

![Figure 4. Structure diagram of MMC.](image)

![Figure 5. Diagram of the current path of AC harmonic in converter bridge arm.](image)
3.1. Basic control strategy of MMC-HVDC

Modular multilevel converter (MMC) is a new focused voltage source converter [13]. As is shown in Figure 4, MMC converter includes three parallel phase units a, b, c. Each phase unit is composed of two upper and lower bridge arms. Each bridge arm contains N sub-modules. By controlling the on and off of two full-controlled devices in the sub-module, the switching of each sub module capacitance on the bridge arm can be controlled. In normal operation, each sub-module is input and removed symmetrically and mutually according to the sinusoidal law, so as to keep the DC voltage constant and generate the AC voltage at the AC side [14]. The control law of MMC-HVDC in abc static coordinate system is

\[
e_k = u_k + \frac{1}{2} R_k i_k + \frac{1}{2} L_k \frac{di_k}{dt}
\]  

(12)

In Formula (12), \(u_k\) (\(k=a,b,c\)) represents the three-phase AC voltage of the converter port. \(i_k\) represents the three-phase AC current output by the converter. \(L_0\) and \(R_0\) are the reactance and internal resistance of each bridge arm respectively. \(e_k\) is the reference values of the bridge arm voltage required to obtain \(i_k\). All the above variables are AC time variables. In order to facilitate the controller design, Formula (12) is generally transformed into dq rotation coordinate system in frequency domain.

\[
\begin{align*}
e_d &= u_d + \frac{1}{2} (R_o + sL_o) i_d + \frac{1}{2} \omega L_o i_q \\
e_q &= u_q + \frac{1}{2} (R_o + sL_o) i_q - \frac{1}{2} \omega L_o i_d
\end{align*}
\]  

(13)

In Formula (13), \(i_d\) and \(i_q\) are the controlled variables. \(e_d\) and \(e_q\) are the control variables. \(u_d\) and \(u_q\) are the disturbances. \(\omega\) is the basic frequency rotation angular velocity.

The function of MMC basic control strategy is to form stable DC voltage and power, which is mainly aimed at the fundamental frequency component of AC current signal. The fundamental frequency component is transformed into DC signal through the above coordinate transformation and it can be tracked without difference with the PI unit. However, the harmonic component in the signal is still AC signal after transformation, so it shows periodic fluctuation of \(i_d\) and \(i_q\). When the harmonic compensation control strategy is put into operation, \(i_s\), \(i_h\) and \(i_c\) contain the harmonic current for compensation. In order to avoid the mutual interference between the basic control strategy and the harmonic compensation control strategy, the basic control strategy needs to carry out low-pass filtering on \(i_d\) and \(i_q\). Therefore, only the DC components \(i_{d1}\) and \(i_{q1}\) are kept as the controlled variables of the current inner loop. Accordingly, the voltage reference value of the basic frequency bridge arm is recorded as \(e_{k1}\).

3.2. Harmonic detection unit

In order to obtain the real-time harmonic current output signal of LCC-HVDC, the low-pass filter is applied to the \(i_{dLCC}\) after the abc-dq coordinate transformation in MMC-HVDC harmonic detection unit. The DC signals \(i_{d1}'\) and \(i_{q1}'\) are inversely transformed into the fundamental current signals of \(i_{dLCC}\). The harmonic current signal \(i_{h}\) can be obtained by the subtraction between the signal and the original signal.

3.3. Harmonic compensation unit

The current path of AC harmonic in converter bridge arm is shown in Figure 5. Because the reactance of the upper and lower bridge arms is equal, the harmonic current is distributed symmetrically in the upper and lower bridge arms.

In order to make the specified harmonic current of MMC-HVDC output being \(-i_{h}\), the bridge arm voltage reference value is modified to

\[
e_k = e_{k1} - \frac{1}{2} R_0 i_{h} - \frac{1}{2} L_0 \frac{di_{h}}{dt}
\]  

(14)
In Formula (14), \( e_{kh} \) are given by Formula (12). \( \frac{1}{2} R_{kh} j_{kh} + \frac{1}{2} L_{kh} \frac{d}{dt} i_{kh} \) is defined as the reference value of harmonic voltage \( e_{kh} \) needed to compensate the harmonic current \( i_{kh} \).

\[
e_{kh} = \frac{1}{2} R_{kh} j_{kh} + \frac{1}{2} L_{kh} \frac{d}{dt} i_{kh} \quad (15)
\]

Ignoring the internal resistance of the bridge arm, \( e_{kh} \) is approximately the derivative of \( i_{kh} \), which adopts the differential link in the controller.

4. Simulation verification
Based on PSCAD / EMTDC simulation platform, the HPDC system model is built and the HPDC harmonic cooperative suppression strategy proposed in this paper is simulated and verified. The model is shown in Figure 6.

In order to observe the effect of the HPDC harmonic coordinated control strategy, there is no AC filter at the AC bus. The harmonic coordinated control strategy starts when \( t = 2s \). The current waveform of rectifier station AC bus before and after the HPDC harmonic coordinated control strategy is put into operation is shown in Figure 7. In Figure 7, the current flowing from AC bus to AC system. \( i_{LCC} \) is the current flowing from LCC-HVDC to AC bus. \( i_{MMC} \) is the current flowing from MMC-HVDC to AC bus. It can be seen that \( i_{MMC} \) is basically a sinusoidal waveform before the harmonic coordinated control strategy is put into operation. After the harmonic compensation control strategy is put into operation, \( i_{MMC} \) starts to produce complementary distortion with \( i_{LCC} \) which reduces the distortion degree of \( i_s \). Figure 8 shows the content of each harmonic and total harmonic distortion rate of \( i_s \) before and after the harmonic compensation control strategy is put into operation.

![Simulation model of HPDC system.](image)

![Current waveform of rectifier station AC bus before and after harmonic coordinated control strategy is input.](image)
Figure 8. Content of each harmonic and total harmonic distortion rate of $i_s$ before and after the harmonic compensation control strategy is put into operation.

It can be seen from Figure 7 and Figure 8 that after the harmonic collaborative control strategy is put into operation, the higher harmonics of more than 25 times are not reduced or even increased due to the influence of harmonic detection means, switching frequency and other factors. However, the content of 11 times, 13 times and 23 times harmonics is greatly reduced. The total distortion rate of AC bus output current is significantly reduced. The above results show that the harmonic cooperative suppression strategy of HPDC system can effectively reduce the degree of harmonic exceeding standard and reduce the probability of LCC-HVDC outage. Therefore, the power quality and operation stability of HPDC system is improved.

5. Conclusions

In this paper, the harmonic characteristics and suppression strategy of HPDC system are studied. And harmonic coordinated control strategy of HPDC system is proposed. Based on PSCAD / EMTDC simulation platform, the HPDC system model is built and the proposed strategy is verified. The main conclusions of this paper are as follows:

1) LCC-HVDC has $12k$ DC characteristic harmonics and $12k \pm 1$ AC characteristic harmonics. MMC-HVDC has 2-fold negative sequence component of bridge arm circulation.

2) Because the equivalent impedance of LCC-HVDC and MMC-HVDC is much greater than that of AC power grid, the harmonic exchange between LCC-HVDC and MMC-HVDC in HPDC system is very few. The harmonic injected into the AC system by the HPDC system is equal to the sum of the harmonic injected by the two converters. LCC-HVDC is the main harmonic source of HPDC system because MMC-HVDC is a harmonic voltage source with high quality and high impedance so that the harmonics injected into AC bus are very few.
3) Based on the parallel connection of LCC-HVDC and MMC-HVDC on the same bus, a hybrid parallel DC harmonic suppression strategy is proposed. When the AC filter exits or is out of resonance, MMC-HVDC is used to assist in absorbing the harmonics generated by LCC-HVDC on the same bus without affecting the normal transmission power and the safe operation of MMC-HVDC. Simulation results show that the control strategy can effectively reduce the harmonic level on the AC bus and improve the power quality and operation stability of HPDC system.

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