Research on harmonic transfer between HVDC transmission and AC grid

Dongshan He¹, Jun Wen, Xiaohong Geng and Sichao Wang

School of Electrical & Electronic Engineering, North China Electric Power University, Beijing 102206, China.

¹ E-mail: 415254257@qq.com

Abstract. Due to the reverse distribution of China's economy and resources, HVDC transmission with great advantages in long-distance and large-capacity transmission has been greatly developed. At the same time, the diversity of harmonic sources in the AC power grid is increasing, such as new energy power generation, electrified railways, and electric vehicle charging piles. These all have led to the extensive use of high-power power electronic equipment. In addition, the interaction of harmonics between AC and DC systems may cause Harmonic amplification, harmonic cross-modulation, harmonic resonance and harmonic instability. These all threaten the stability of power grid. This paper first analyzes the harmonic characteristics of HVDC transmission, establishes the harmonic model of HVDC transmission, and analyzes the harmonic characteristics of various harmonic sources in AC system. On the basis of this, the transmission characteristics of the DC side harmonics to the AC side and the transmission characteristics of the AC side harmonics to the DC side are theoretically derived and analyzed, and derive the DC voltage characteristics corresponding to the AC positive sequence, negative sequence and zero sequence voltage. Then the harmonic transfer model of the AC and DC side is obtained.

1. Introduction

With the rapid development of China's economy, due to the uneven distribution of energy and load, HVDC transmission with great advantages in long-distance and large-capacity transmission has been greatly developed in China [1]. At the same time, the diversity of harmonic sources in the AC power grid is increasing, and the proportion of new energy sources such as wind power generation and photovoltaic power generation is becoming larger. The loads such as electrified railways and electric vehicle charging piles are also developing rapidly, resulting in a large number of high-power power electronic equipment in the AC grid. This is bound to bring serious harmonic pollution in the system, which will pose a great threat to the power supply reliability and security stability of the power grid.

The hazards of harmonics to the power grid mainly include: increasing the electrical stress of the equipment, causing additional heat, causing interference to the communication system, generating induced potential which will cause equipment damage and even casualties. In addition, the DC grid and the AC grid are coupled to each other through the inverter. And there is a dynamic harmonic interaction between the AC grid and the DC grid. This interaction depends on the operating conditions, network structure and load level of the AC side of the converter. When harmonics are transmitted between AC and DC systems, they may cause problems such as harmonic amplification, harmonic cross modulation, harmonic resonance, and harmonic instability. Therefore, it is very necessary to study the mutual transmission of harmonics between HVDC and AC grids [2-4].
Literature [5] analyzes the principle of harmonics generated by HVDC system and gives its characteristic harmonics. Literature [6-9] analysis harmonic sources such as wind power, photovoltaic power, electrified railways and electric vehicle charging pile. In literature [10], the influence of harmonics on HVDC transmission is analyzed, and the voltage-time area analysis method is proposed. This method can quantitatively analyze the influence of harmonics on commutation failure. Literature [11] mainly analyzes the stability of power system of AC/DC hybrid power grid and related problems of DC control. And this paper theoretically deduces and analyzes the transmission characteristics of harmonics between HVDC transmission and grid, basing on the harmonic analysis of HVDC transmission and various harmonic sources in power grid.

This paper first analyzes the harmonic characteristics of various harmonic sources in AC system and HVDC transmission. And the harmonic model of HVDC transmission is established. On the basis of this, the transmission characteristics of the DC side harmonics to the AC side and the transmission characteristics of the AC side harmonics to the DC side are theoretically derived and analyzed, and derive the DC voltage characteristics corresponding to the AC positive sequence, negative sequence and zero sequence voltage. Then the harmonic transfer model of the AC and DC side is obtained.

2. Harmonic characteristics of the AC grid
Harmonic sources in the AC grid are mainly divided into two categories: power supply harmonic sources and load harmonic sources. Among them, power harmonic sources include thermal power, hydropower, wind power and photovoltaic power generation. The load harmonic sources mainly include electrified traction stations and electric vehicle charging piles.

In the power supply harmonic sources, the thermal power unit and the hydropower unit use synchronous generators, and are connected to the power grid through distributed and short-distance windings, as well as the conversion connection mode, and the harmonics generated by them are negligible. On the contrary, the integration of new energy sources such as wind power and photovoltaic power generation has led to the application of a large number of non-linear power electronic components, and the harmonic problems generated are particularly serious.

2.1. Wind power generation
Wind power is mainly connected to 220kV of the AC grid [6]. The main reason for harmonic problems caused by grid-connected wind turbines is the characteristics of the wind turbine itself and the power electronic components in the associated auxiliary equipment. In fact, the former is almost negligible, and the latter is the most important cause of harmonic problems caused by wind power grid connection. Since the constant speed unit does not have power electronic components to participate in its operation process, its operation process does not cause harmonic current.

Figure 1 shows the wiring diagram of the wind power converter, which contains a large number of power electronics.

![Wind power converter wiring diagram](image)

Since the switching frequency of the converter is unfixed, the PWM switching converter and filter can minimize the harmonic distortion. However, if the switching frequency of the power electronic device is just within the range of generating harmonics, serious harmonic problems will occur. The magnitude of the harmonic current is substantially linear with the output power, that is, related to the magnitude of the wind speed. The degree of harmonic interference depends on the design of the
converter and the condition of its filtering device, and is also related to the short-circuit capacity of the grid. The inverter with the new technology generates a few low-frequency harmonic, but it will also generate a certain high-frequency harmonic component, which is easy to remove due to its high frequency.

2.2. Photovoltaic power generation
Similar to wind power generation, power electronics are also important in photovoltaic grid-connected power generation systems. Similarly, the most fundamental cause of harmonic problems in photovoltaic power generation is the non-linear power electronic devices in photovoltaic power generation. At the same time, harmonics in photovoltaic power generation systems still have their unique problems [7].

(1) Disadvantages of the control method: regardless of the application of the control method, there are the following problems: the delay problem, that is, the presence of harmonics and the rapid change of the waveform cannot be detected in time, and the algorithm delay problem existing in the feedback loop itself; and the accuracy problem, that is, due to the use of digital discretization, higher accuracy and requires more sensitive devices are required. However it is now difficult to meet the requirements. The control principle using PWM itself generates a large amount of higher harmonics and DC components.

(2) DC side voltage stability problem: the stable input of the DC side voltage has a great influence on the output waveform of the inverter.

2.3. Electrified railways
The electrified railways used in China's heavy-duty railways are mainly AC-DC electric locomotives [8]. The AC-DC electric locomotive first converts the three-phase electric energy of the power system into two single-phase electric energy supply arms through a three-phase-two-phase traction transformer, and then transmits the electric energy through the direct power supply or the direct supply to the traction network with the return power supply mode. For the train, the train drives the DC motor to rotate through AC-DC conversion. This type of train has nonlinear, mobile and high-power load characteristics, and will inject a large amount of harmonics and negative sequence current through the traction network and the traction transformer network. The AC-DC electric locomotive mainly produces low-order harmonics of 3, 5, and 7 order.

Owing to the appliance of Single-Phase Pulse Width Modulation (PWM) Technology, the 3 and 5 order harmonics are reduced in AC-DC-AC electric locomotive, while the higher harmonic content near the switching frequency increases.

2.4. Electric vehicle charging pile
Most electric vehicles use AC charging piles to charge, and it has become a new kind of harmonic source [9]. The equivalent model of three-phase bridge rectifier charging pile is shown in Figure 2. In practice, a three-phase bridge type rectifying charging pile is commonly used, and the equivalent model of the three-phase bridge type rectifying charging pile is essentially a 6-pulse rectifying circuit.

The harmonic currents $i_a$, $i_b$ and $i_c$, generated by the model are analyzed by Fourier series method, and the law of harmonics is obtained. Electric vehicle charging pile inject harmonics of $6k\pm 1 \ (k=1, 2, 3, \ldots)$ orders, that is, 5, 7, 11, 13, 17, 19 and so on, into the grid. The valid value of each harmonic is inversely proportional to the harmonic order.

![Figure 2](image-url)  
**Figure 2.** Equivalent model of three-phase bridge rectifier charging pile.
3. Harmonic characteristics of HVDC transmission

Typical HVDC transmission uses a 12-pulse converter, which consists of a 6-pulse converter with a star-connected winding and a 6-pulse converter with a triangular-connected winding in series on the DC side [12]. The schematic diagram is shown in Figure 3. The normal operation mode of the 12-pulse rectifier is that in the repetition period of 30°, the four converter valves and the five converter valves are alternately turned on. The 12p converts the convert bus voltage \( u_b \) to 12-pulse DC voltage \( u_d \), the DC current \( i_d \) to AC current \( i_s \) as well.

![Figure 3. Principle diagram of 12-pulse converter.](image)

Decompose \( u_d \) and \( i_s \) with Fourier series to obtain the general conclusion of 12-pulse converter harmonics:

(1) The order of characteristic harmonics contained in the DC voltage \( u_d \) is \( h=12k \) \((k=1, 2, 3, ...)\), wherein the effective value of the \( h \)-order characteristic harmonic voltage \( U_{d,h}(\alpha, \mu) \) is

\[
U_{d,h}(\alpha, \mu) = \frac{U_{do}}{\sqrt{2}} \sqrt{C_1^2 + C_2^2 - 2C_1C_2 \cos(2\alpha + \mu)}
\]

(1)

Where \( \alpha \) is the trigger angle of the converter; \( \mu \) is the commutation angle of the converter; and the harmonic voltage coefficient \( C_1 \) and \( C_2 \) is

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

(2)

The ideal no-load direct voltage \( U_{do} \) is

\[
U_{do} = \frac{3\sqrt{2}}{\pi} E \approx 1.35E
\]

(3)

Where \( E \) is the effective value of the AC voltage

(2) The order of characteristic harmonics contained in the AC phase current is \( h=12k+1 \) \((k=1, 2, 3, ...)\), that is, containing 11, 13, 23, 25... order characteristic harmonics, where the effective value of the \( h \)-order characteristic harmonic current \( I_{h}(\alpha, \mu) \) is

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

(4)

The coefficient of harmonic current \( S_1 \) and \( S_2 \) is

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

(5)

The effective value of the fundamental current at no load \( I_{h,0}(\alpha, 0) \) is
\[
I_d(\alpha,0) = \frac{\sqrt{6}}{\pi} I_d \approx 0.78I_d
\] (6)

It can be seen from equations (2) and (5) that the harmonics injected on both sides of the AC and DC generated by the 12-pulse converter have the following characteristics:

1) As the number of harmonics increases, the value of each characteristic harmonic decreases. Therefore, low-order harmonics are the most harmful.

2) The increase of the firing angle \(\alpha\), the AC voltage \(E\) and the DC current average \(I_d\) will increase the amount of harmonic injection to varying degrees, and the reduction of the commutation angle \(\mu\) will also increase the harmonics. The voltage level of HVDC transmission is high and the transmission power is large. Therefore, the harmonics generated by HVDC are large, and a parallel AC filter and a DC filter are usually required to make the harmonics injected to AC/DC systems reach the standard.

4. Harmonic transfer model between HVDC transmission and AC grid

4.1. Transfer characteristics of harmonics from the AC side to the DC side

A typical 12-pulse HVDC system is shown in Figure 4.

![12 pulse HVDC system schematic](image)

**Figure 4.** 12 pulse HVDC system schematic.

When the fundamental frequencies of the AC systems at both ends are the same, and the three-phase electromotive force and parameters of the AC system are symmetric, the harmonic characteristics of the HVDC are basically as follows: When the order of harmonic currents flowing into the AC system is \(n=kp\pm 1\), the number of harmonic currents flowing through the DC line is \(n=kp\), where \(p\) is the number of pulses of the inverter, and \(k\) is a positive integer. The order of harmonics represented by the above two equations is called the characteristic harmonic order of the AC/DC system. However, if the three phase electromotive forces or parameters are asymmetric, in the case where the three phase electromotive forces of the AC system contains harmonics, and the fundamental frequencies of the AC systems on both sides are different, the characteristics of the harmonics generated by the HVDC transmission system will become very complicated.

Considering the general situation, set the AC bus voltage \(U_a\), \(U_b\) and \(U_c\) of the converter station to:

\[
\begin{align*}
U_a &= \sum_{m=1}^{\infty} U_{am} \cos(\omega_m t + \alpha_{am}) \\
U_b &= \sum_{m=1}^{\infty} U_{bm} \cos(\omega_m t + \alpha_{bm}) \\
U_c &= \sum_{m=1}^{\infty} U_{cm} \cos(\omega_m t + \alpha_{cm})
\end{align*}
\] (7)

In the formula, \(\omega_m\) is an arbitrary value, which means it is not limited to an integral multiple of the AC system rated angular frequency; \(U_{am}\), \(U_{bm}\), \(U_{cm}\) and \(\alpha_{am}\), \(\alpha_{bm}\), \(\alpha_{cm}\) are the phase voltage amplitudes and angle of A, B and C Phases.

In the actual operation, the AC system cannot achieve the three-phase symmetry under ideal conditions. For the sake of generality, the three-phase voltage can be expressed in the form of symmetrical components as follows:
After the Fourier decomposition and the inverter commutation are changed by the equation (8), the DC voltage when the AC system is disturbed can be obtained.

After the Fourier decomposition of the equation (8) and the commutation change of the converter, the DC voltage when the AC system with disturbance can be given:

\[
U_d = \sum_{m=1}^{\infty} \sum_{n=1}^{N} \sum_{s=1}^{\infty} \frac{A_d m}{2} \left[ 1 + 2 \cos \left( \frac{2(n-s)\pi}{3} \right) \right] \cos \left[ \left( \omega_m - n\omega_0 \right) t + \alpha_m \right] + \sum_{m=1}^{\infty} \sum_{n=1}^{N} \sum_{s=1}^{\infty} \frac{A_d m}{2} \left[ 1 - 2 \cos \left( \frac{2(n-s)\pi}{3} \right) \right] \cos \left[ \left( \omega_m - n\omega_0 \right) t + \alpha_m \right] \]

(9)

The DC voltage characteristics corresponding to the AC positive sequence, negative sequence and zero sequence voltage are as follows.

It can be seen from equation (9) that for the zero-sequence voltage, when \( S=0 \), substituting the correlation coefficient, \( U_d=0 \) is obtained, that means the zero-sequence voltage disturbance on the AC side does not flow through the inverter and thus has no effect on the DC component.

The response of the AC side positive and negative sequence voltage disturbances on the DC side-- \( U_d^+ \) and \( U_d^- \), can also be obtained.

\[
U_d^+ = \sum_{m=1}^{\infty} \sum_{n=1}^{N} \sum_{s=1}^{\infty} \frac{A_d m}{2} \left[ 1 + 2 \cos \left( \frac{2(n-s)\pi}{3} \right) \right] \cos \left[ \left( \omega_m + (6k-1)\omega \right) t + \alpha_m \right] + \sum_{m=1}^{\infty} \sum_{n=1}^{N} \sum_{s=1}^{\infty} \frac{A_d m}{2} \left[ 1 - 2 \cos \left( \frac{2(n-s)\pi}{3} \right) \right] \cos \left[ \left( \omega_m + (6k+1)\omega \right) t + \alpha_m \right]
\]

(10)

It can be seen from equation (10) that for the positive sequence disturbance of the angular frequency \( \omega_m \), the DC response components of \( \omega_m + (6k-1)\omega \) and \( \omega_m - (6k+1)\omega \) will be generated on the DC side; also for the negative sequence perturbation of the angular frequency \( \omega_m \), the DC response components of \( \omega_m + (6k+1)\omega \) and \( \omega_m - (6k-1)\omega \) will be generated on the DC side.

In summary, the theoretical study shows that for the positive \( m \)-order harmonic on the AC side, after flowing through the inverter, the \((m-1)\)-order dominant harmonic of is generated on the DC side, and its content varies linearly with the positive \( m \)-order harmonic content on the AC side. After the negative \( m \)-order harmonic on the AC side flows through the inverter, the \((m+1)\)-order dominant harmonic is generated on the DC side, and its content changes linearly with the negative \( m \)-order harmonic content of the AC side.

4.2. Transfer characteristics of harmonics from the DC side to the AC side

A small AC signal is superimposed on the direct current, and the signal generates a harmonic current characteristic on the alternating current side to introduce the transfer characteristic of the harmonic from direct current to alternating current. Therefore, set the small signal as \( I_d \) set, and its expression is

\[
I_d = I_{dm} \cos (\omega_d t + \varphi_d)
\]

(11)

Where \( I_{dm} \) is the amplitude of the small signal on the DC side; \( \omega_d \) is the angular frequency of the small signal on the DC side; and \( \varphi_d \) is the corresponding initial phase angle.

The Fourier transformation of corresponding switch function makes the expressions of three phases current of AC side. The dominant uncharacteristic harmonics are only analyzed, thus the first item of the Fourier expansion needs to be focused on, which is
\[
\begin{align*}
    i_a &\approx I_{an} \cos (\omega_d t + \varphi_d) A_0 \cos (\omega t) \\
    i_b &\approx I_{be} \cos (\omega_d t + \varphi_d) A_0 \cos \left( \omega t - \frac{2\pi}{3} \right) \\
    i_c &\approx I_{ce} \cos (\omega_d t + \varphi_d) A_0 \cos \left( \omega t + \frac{2\pi}{3} \right)
\end{align*}
\]  
\quad (12)

Expand \( i_a \) to get
\[
i_a = \frac{2\sqrt{3} \sin \frac{\mu}{\pi}}{n \mu} I_{an} \left[ \cos \left( (\omega_1 + \omega) t + \varphi_a \right) + \cos \left( (\omega_1 - \omega) t + \varphi_a \right) \right]
\quad (13)
\]

It’s concluded from formula (10) to (12) that the small signal of the DC side which is \( i_d \) produces two sets of dominant uncharacteristic harmonics, one of which has a positive phase sequence in angular frequency of \( \omega_d + \omega \), and the other of which has a negative phase sequence in angular frequency of \( \omega_d - \omega \).

Above all, the harmonics of DC side produces 2 sets of harmonics in the AC side which are positive sequence harmonic in one increased order and negative sequence harmonic in one decreased order, and their contents change linearly by injected harmonic content from DC side.

5. Conclusions
This paper focuses on the harmonic interaction between AC and DC systems. Firstly, the harmonic characteristics of various harmonic sources, such as new energy power generation, electrified railways, and electric vehicle charging piles, in the AC system are analyzed. And the harmonic source model is obtained. Secondly, the harmonic characteristics of HVDC transmission is analyzed, and the harmonic model was established. Finally, on the basis of this, the transmission characteristics of the DC side harmonics to the AC side and the transmission characteristics of the AC side harmonics to the DC side are theoretically derived and analyzed, and derive the DC voltage characteristics corresponding to the AC positive sequence, negative sequence and zero sequence voltage. Then the harmonic transfer model of the AC and DC side is obtained.

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