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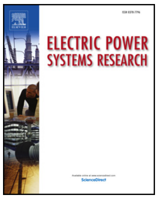

Analysis and mitigation of low-frequency resonance in a long-distance UHVDC ± 1100 kV system

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ABSTRACT

Low-frequency resonance may seriously threaten the stable operation of a long-distance ultra-high-voltage-direct-current (UHVDC) system. In this paper, the impedance model of long-distance UHVDC systems was analyzed for various disturbances. For different disturbances, the positions of voltage sources in the simulated DC loop are different. Taking the first ± 1100-kV DC power transmission project with a length of 2688 km as an example, the frequency characteristics of the DC-loop impedance were studied using the PSCAD/EMTDC simulation platform. The effects of various operating modes and the firing angle of the converters on impedance–frequency characteristics of the DC loop were discussed. The effect of the length of DC transmission lines on the DC-loop resonant frequency was studied. The distance is the most important factor determining the system low-frequency resonance. Faults in an AC grid, such as phase-to-phase short-circuit and single-phase faults, are shown to produce 50-Hz positive sequence harmonics on the AC side and 100-Hz disturbances in the DC loop. Two methods of mitigating low-frequency resonance were proposed and the effects simulated. Installation of the blocking filter in the neutral bus of the converter station can reduce the amplitude of the resonance overvoltage.

1. Introduction

Disturbances in AC/DC networks may generate harmonic currents and voltages in a DC power system [1–4]. When DC system resonance occurs, the DC-side harmonic current will increase to several times its normal value and affect the normal operation of or even damage the converter, capacitors, reactors and other components. Serious distortion of the DC voltage leads to difficulties in the operation of the HVDC transmission system, and even blocks the system and threatens stable operation of the power grid [5–7].

Induced current from AC lines in the same corridor can produce 50-Hz disturbances in the DC loop. Faults of converters can produce both 50- and 100-Hz disturbances. The AC and DC transmission systems interface with each other. When there is an nth-order harmonic current in the DC loop, a positive sequence voltage of $(n + 1)$th-order and negative sequence voltage of $(n - 1)$th-order will be induced in the AC loop [8,9]. Faults in the AC grid, such as a phase-to-phase short circuit and single-phase earthed fault, can produce 50-Hz positive sequence disturbances on the AC side and 100-Hz positive sequence disturbances in the DC loop. The oscillation overvoltage level resulting from these disturbances is determined by the amplitude of disturbances and the impedance of the DC loop. It has been pointed out that series resonance may occur when the impedance of the DC loop is insufficient at frequencies neighboring 50 and 100 Hz [8–10].

A model of the impedance of a UHVDC system based on a test signal has been proposed for time-domain simulation [11,12], and the loop impedance or resonant overvoltage has been calculated. However, the cited studies were based on ± 500-kV or ± 800-kV systems. The Zhundong–Wannan ± 1100-kV system is a new UHVDC project in China, belonging to the highest voltage class in the world. Both ends of the project have two 12-pulse converters in series and the length of the transmission line is 2688 km, which is the greatest length among UHVDC projects worldwide. Owing to the length of the transmission line and complexity of the structures, the impedance-frequency characteristics of the DC loop of the Zhundong–Wannan system are special.

The present study investigated the low-frequency resonance characteristics of the Zhundong to Wannan ± 1100-kV DC transmission project, considering different operation modes and conditions.

2. Analysis of the resonance phenomenon

The intervention of an HVDC transmission system weakens damping

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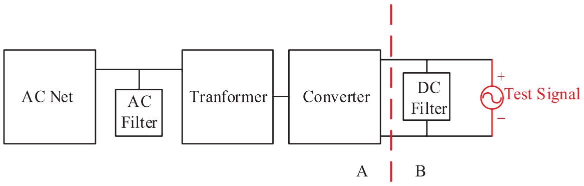

Fig. 1. Definition of the impedance of a converter station.

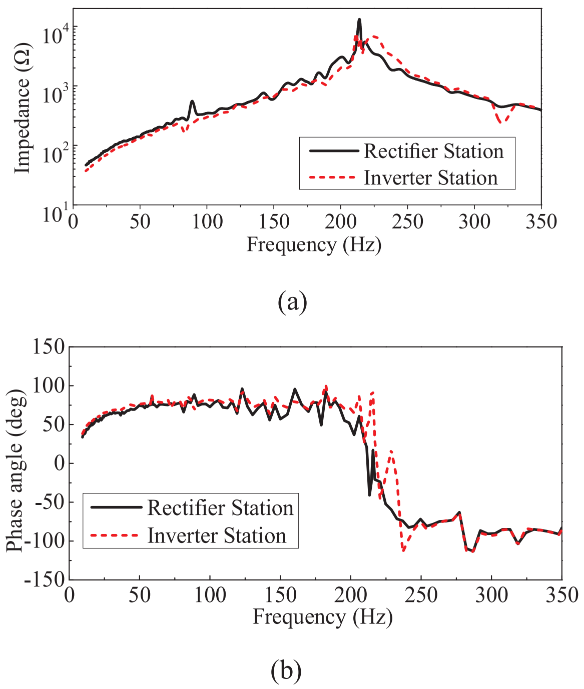

Fig. 2. Frequency characteristics of station impedance between 0 and 350 Hz: (a) impedance, (b) phase angle.

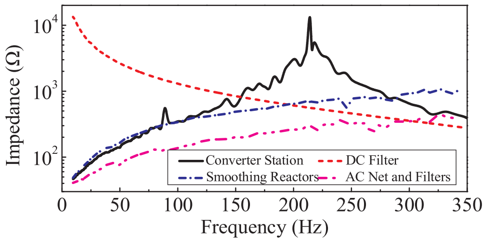

Fig. 3. Frequency characteristics of impedance at 0–350 Hz.

of the power grid and threatens the stable operation of the system. Farmer proposed a frequency scanning method based on approximately linear analysis in 1979 [13]. A test point is first selected and a small harmonic voltage source $U(f) = U(2\pi ft + \varphi_f)$ is injected, where f is determined according to the frequency range to be studied, U is the voltage amplitude, which is usually 0.1% of the rated voltage, and φ_f is the phase angle. To damage the linearized conditions of the DC system, the phase angle φ_f should be different for different frequency of the harmonic voltage [14]. Then, in the steady-state period, the voltage u and current i are extracted at the same time and the impedance at frequency f is calculated through Fourier analysis. Finally, an impedance–frequency characteristic curve of the DC transmission system is drawn. For a real DC transmission system, when the minimum of the impedance–frequency curve is less than 100 Ω, there is series resonance and the minimum point represents the resonant frequency.

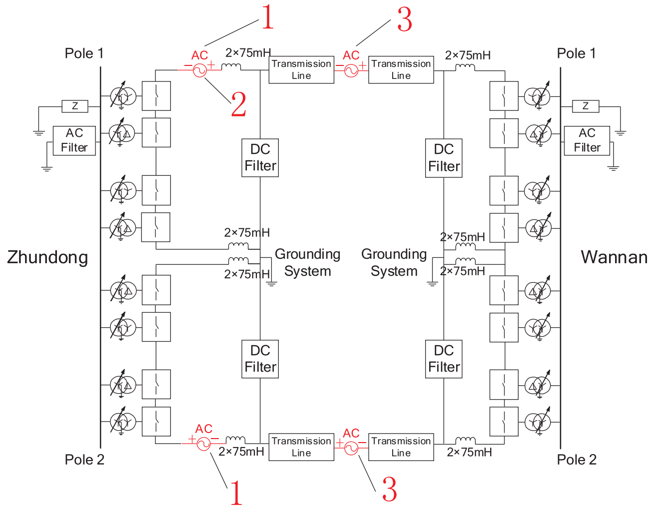

Fig. 4. Simulating sources for resonance in different situations. Labels 1–3 respectively show the fault locations of a fault of the AC grid, fault of a converter and induced current.

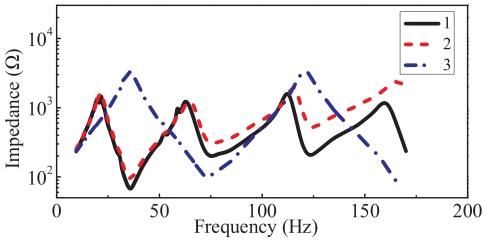

Fig. 5. Effects of various source points on the frequency characteristics of DC-loop impedance.

2.1. *Equivalent simulation model*

To reflect low-frequency harmonic characteristics at 5–200 Hz, according to the principle of signal analysis, the duration of the simulation should be longer than 0.4 s. The accuracy of the model improves as the simulation time increases at low frequencies. At the same time, owing to the presence of switching elements and nonlinear elements, the simulation step should not be too large, to ensure accurate calculation. Therefore, the quantity of simulation data is large and the calculation process is long. An equivalent model should be used to improve the computational efficiency of the model. It is better to find the important parameters affecting low-frequency characteristics and their influence rules, and to then propose estimation formulas for application in other systems. The discussion of the model in this paper mainly focuses on this purpose.

In this paper, the transient characteristics of switch operation at high frequency are not important and the thyristor can be described as an ideal switch, the use of the model greatly improves the simulation efficiency and reduces the simulation time.

2.2. *Impedance of a converter station*

A DC transmission system usually comprises AC lines, AC filters, transformers, converters, smoothing reactors, DC filters (DCFs) and DC lines. For impedance analysis of the DC loop, the DC system can be divided into three parts: a rectifier station, inverter station and DC transmission lines.

The converter station should be studied first to obtain the resonance characteristics of the whole DC transmission system. The equivalent impedance of a rectifier station can be obtained as the open-circuit voltage divided by the short-circuit current, as illustrated in Fig. 1. The