Harmonic voltage excess problem test and analysis in UHV and EHV grid particular operation mode

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Abstract. The test and analysis of the power quality of some 1000kV UHV transmission lines and 500kV EHV transmission lines is carried out. It is found that there is harmonic voltage excess problems when the power supply of the UHV and EHV voltage line is single-ended or single-loop, the problem basically disappeared after the operation mode change, different operating conditions, the harmonic current has not been greatly affected, indicating that the harmonic voltage changes mainly caused by the system harmonic impedance. With the analysis of MATLAB Simulink system model, it can be seen that there are specific harmonic voltage excess in the system under the specific operating mode, which results in serious distortion of the specific harmonic voltage. Since such phenomena are found in 500kV and 1000kV systems, it is suggested that the test evaluation work should be done under the typical mode of operation in 500kV, 1000kV Planning and construction process to prevent the occurrence of serious distortion and the regional harmonic current monitoring and suppression work should be done.

1. Introduction
As of June 2017, China has built six UHV AC projects and seven UHV DC projects. UHV DC project is usually connected to 500kV power grid or hierarchically connected to 500kV and 1000kV power grid. UHV projects achieve a greater range allocation optimization of resources, warrant the efficient development and utilization of energy and promote sustainable economic and social development. As a whole network hub substation, UHV substation power supply quality directly affect the quality of the entire region of the pros and cons. At present, the research of power quality of UHV transmission project is mainly concentrated in the low frequency resonance of UHV DC transmission system[1], Non-characteristic harmonic analysis[2], the influence of UHV DC on AC power system background harmonic[3], non-characteristic harmonic in UHVDC system[4], harmonic of ±800kV ultra high voltage direct current transmission system[5], Harmonic Suppression Method for UHVDC Transmission Systems[6], harmonic instability for ±800kV UHVDC system[7] and Harmonic characteristics under AC and DC hybrid[8].

In this paper, through the testing of one UHV AC project and one UHV DC project, it is found that there are specific frequency circuit resonance in UHV and EHV AC transmission line under special operation mode. The harmonic current flows through the resonant circuit, resulting in harmonic voltage amplification, Which leads to the occurrence of more serious distortion of the voltage.
2. UHV and EHVAC harmonic voltage test

2.1. 1000kV UHV AC harmonic voltage test

A UHV AC transmission project includes A, B, C, D, E a total of five 1000kV substations, 736 km overhead 1000kV double-circuit transmission lines, a 5 km cross-river GIL project which is under construction. A-B-C segment has been put into operation, the system wiring diagram is shown in figure 1. Power quality test of B station and C station in different operating mode is carried out in system testing process and the high harmonic voltage is found.

![Figure 1. the 1000kV system wiring diagram.](image)

When A, B and C is connected by single-circuit transmission line, measured voltage THD (Total Harmonic Distortion) in B station and C station 1000kV was significantly increased, and the C station measured 5th harmonic current is significantly increased. At that time, the transmitted power is about 400MW. The related curves are shown below. Because the data in C substation is limited, the start time of figure 4 is different from figure 2. In figure 3 and figure 4, the succedent test data is also shown.

![Figure 2. The voltage THD measured in B substation with single-circuit transmission line operating.](image)
Figure 3. The 5th harmonic current measured in C substation with single-circuit transmission line operating.

Figure 4. The voltage THD measured in C substation with single-circuit transmission line operating.

2.2. 500kV EHV AC harmonic voltage test
A UHV DC transmission project transmits 10000MW power across 1620 km. The receiving-end converter station hierarchically connected to 500kV and 1000kV power grid. The receiving-end converter station 500kV segment power grid wiring diagram is shown in the figure 5, the transmitted power by the DC is allocated by 6-circuit 500kV transmission line (4-circuit put into operation, 2-
circuit to be built) to three 500kV substation (H, I, and J). The background power quality test is carried out in the converter station in the red ellipses label position as shown in figure 6 under different operating mode. The voltage THD of A, B and C phase is 9.661%, 8.266%, 7.469% when the 5K24 supplied alone and the 5K23 was uncharged, the THD is 3.832%, 3.900%, 4.780% when the 5K24 supplied alone and the 5K23 is charged, the THD is 1.502%, 1.455%, 1.181% when H and I substation supplied together, the test curves is shown in figure 7 and figure 8.

Figure 5. The receiving-end converter station 500kV segment power grid wiring diagram.
Figure 6. The voltage THD measured in K substation when 5k24 supplied. (Recessed part is 5k23 was charged).

Figure 7. The 5\textsuperscript{th} harmonic current measured in K substation when 5k24 supplied.
3. Test result theoretical analysis

According to the GB/T 14549-93 "Quality of electric energy supply Harmonic in public supply network" [9]110kV public power grid voltage THD limit is 2%, 220kV public grid refer to 110kV utility network, 500kV and 1000kV grid voltage THD limit is not specified yet. However, according to the standard, with the voltage class increasing, the public power grid THD limit gradually reduced, so 500kV and 1000kV public grid voltage THD of more than 2% can be identified is very high Level. The voltage harmonic was found out on the AC bus-bar in the substation. From the point of view of the test point, the power system can be equivalent to a circuit shown in figure 9. In the circuit, all the plant and harmonic source can be simplified to a fundamental AC source and harmonic AC source, the impedance of power system can be equivalent to $Z_{eq}$[10]. The voltage harmonic monitored is from the harmonic AC source and the $Z_{eq}$. To different frequency, the harmonic AC source and $Z_{eq}$ are different. because the generator, the transformer, the transmission line, and the load are different. The frequency scanning is need to determine the $Z_{eq}$ in different frequency. The harmonic AC source is difficult to determine because of the equivalent way integrated many kinds of harmonic AC source and connection path. All the harmonic AC source make out the harmonic monitored through harmonic flow related to $Z_{eq}$.

![Figure 8](image_url)

**Figure 8.** the voltage THD measured in K substation when H and I supplied together.

![Figure 9](image_url)

**Figure 9.** the equivalent diagram of power system in test result theoretical analysis.
4. Test result simulation analysis
To find out the reason of high voltage THD, simulation analysis of the harmonic voltage phenomenon of the above test is carried out.

4.1. 1000kV UHV AC voltage harmonic analysis
As the scale of the grid UHV transmission line connected is very large, it is difficult to realize the details of the power grid in the simulation software. In this paper, the simulation method in the literature[3] is adopted, The short-circuit impedance of the 500 kV bus is used as the equivalent impedance of the external network, it can be obtained through power flow calculation. The MATLAB simulation software is used to scan the harmonic impedance of the relevant measuring points at different frequencies, and analyse harmonic impedance in different operation of the substation with different connection mode. The equivalent impedance of the external network is shown in table 1. The simulation model is shown in figure 10.

| Table 1. UHV location grid equivalent parameters. |
|-----------------------------------------------|
| Zero sequence admittance (p.u.) | Positive sequence admittance (p.u.) | Negative sequence admittance (p.u.) | Current injection(kA) |
| A | 4.5447+j(-367.7453) | 4.3252+j(-291.27) | 4.3252+j(-291.27) | 16.0175 |
| B | 4.6243+j(-80.0705) | 2.0424+j(-78.725) | 2.0424+j(-78.725) | 4.3302 |
| C | 3.3617+j(-108.8605) | 2.1303+j(-77.878) | 2.1303+j(-77.878) | 4.2838 |

| Zero sequence admittance (p.u.) | Positive sequence admittance (p.u.) | Negative sequence admittance (p.u.) | Voltage(kV) |
|--------------------------------|-----------------------------------|-----------------------------------|-------------|
| A-B | 0.0002+j 0.0067 | 0.0001+j 0.0021 | 0.0001+j 0.0021 | 1050 |
| A-C | 128.7167 +j 329.7713 | 0.1583+j 2.1473 | 0.1583+j 2.1473 | 1050 |
| B-C | 0.0001+j 0.0054 | 0.0000+j 0.0017 | 0.0000+j 0.0017 | 1050 |

Figure 10. 1000kV UHV AC voltage harmonic analysis simulation model.
The impedance-frequency characteristics of the equivalent system are scanned and analysed, and the results are shown in Figure 11 and Figure 12.

Figure 10 shows the impedance-frequency characteristic curve of the single-circuit operation mode. It can be seen that there is a peak near 228 Hz in the 1000 kV transmission system with single-circuit. Since the 5th harmonic (250 Hz) is the dominant harmonic component in the grid, with the fifth harmonic current injected from the load side of the grid, and due to the peak impedance close to the
single-circuit operation mode, the resulting 5th harmonic voltage amplitude is also larger, resulting in 5th harmonic voltage distortion rate is higher.

**Figure 11.** Impedance - frequency characteristic curve of single-circuit loop.

Figure 12 shows the impedance-frequency characteristic curve of the double-circuit operation mode. It can be seen that the impedance of the 1000kV transmission system in the double-circuit operation mode has a peak near 165 Hz. The 5th harmonic impedance(250 Hz) deviates from the peak frequency, resulting in a reduction in the 5th harmonic voltage distortion rate.

**Figure 12.** Impedance - frequency characteristic curve of double-circuit loop.
Figure 13. 5<sup>th</sup> voltage harmonic (black) and current harmonic (green) measured in K station.

The analysis of the measured 5<sup>th</sup> harmonic current in figure 13 shows that the 5<sup>th</sup> harmonic current in the system topology is also changed, but the 5<sup>th</sup> harmonic voltage is mainly caused by single-circuit operation mode when the harmonic impedance is too large, because the harmonic voltage reduce more than harmonic current.

4.2. 500kV EHV AC harmonic voltage analysis

The equivalent impedance of the external network is shown in table 2. The simulation model is shown in figure 14.  

| Zero sequence admittance (p.u.) | Positive sequence admittance (p.u.) | Negative sequence admittance (p.u.) | Current injection(kA) |
|-------------------------------|-----------------------------------|-----------------------------------|----------------------|
| K | 0+j(-212.7660) | 0+j(0) | 0+j(0) | 0 |
| H | 23.5746+j(-281.4910) | 13.5210+j(-285.3716) | 13.5210+j(-285.3716) | 31.4176 |
| I | 11.0944+j(-54.0974) | 4.9292+j(-112.9696) | 4.9292+j(-112.9696) | 12.4353 |
| Voltage(kV) | | | | |
| K-H | 0.0021+j 0.0083 | 0.0002+j 0.0033 | 0.0002+j 0.0033 | 525 |
| K-I | 0.0042+j0.0167 | 0.0003+j0.0067 | 0.0003+j0.0067 | 525 |
| H-I | 3.5105+j 5.47 | 0.0079+j 0.0938 | 0.0079+j 0.0938 | 525 |
The harmonic impedance of different operating states is simulated. The results are shown in the figure 15 and figure 16.

**Figure 15.** Impedance - frequency characteristic curve of H substation supplied.

**Figure 16.** Impedance - frequency characteristic curve of H and I substation supplied.

It can be seen from the figure, when there are 5$^{th}$ harmonic current in the system, due to single-circuit power supply system 5$^{th}$ harmonic impedance there is a certain harmonic voltage excess phenomenon, will produce a larger harmonic voltage.
5. Conclusions
In the analysis of single-circuit operation, single-circuit power supply and other special operating mode in 500kV EHV and 1000kV UHV grid, there is a certain degree of harmonic voltage excession risk. When the system with the frequency of the same harmonic current, will produce a larger harmonic voltage, Part of the node's harmonic voltage is excessive, power planning should take into account the impact of this.

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