Case analysis of power quality impact assessment and governance of electrified railway based on ETAP software

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Abstract. As the traction load of electrified railway belongs to high-power nonlinear single-phase load, it will bring power quality problems such as harmonics and three-phase unbalance to the power system after being connected to the power grid, which is not conducive to the safety and economic operation of the public power grid. Therefore, it is necessary to evaluate the impact of the electrified railway operation under different conditions on the power quality of the system substation. In this paper, combined with an electrified railway transformation project of the power grid, an ETAP-based simulation model for electrified railway access to the power grid is established, which can quickly assess the power quality impact of the system-side substation caused by the traction load, and provide corresponding treatment measures for the electrified railway connection system program. At the same time, it can provide a basis for the electrified railway connection system scheme and equipment configuration.

1. Introduction

With the continuous increase of non-linear and unbalanced loads of electrical equipment in the power system, a large amount of harmonics and negative sequence currents are generated, causing different levels of harmonic and negative sequence current pollution to the power grid. At present, the main influence on the power quality of the power grid mainly includes thyristor rectifier equipment, frequency conversion devices, electric arc furnace harmonic source devices, and the electrified railways with negative sequence effects. The problems of harmonics, three-phase voltage unbalance, and negative sequence caused by the unbalance and fluctuation of electrified railway loads are becoming more and more serious, so the power quality assessment of the traction station access system needs to be carried out[1-3].

At present, the modeling process of the impact of electrified railway access to the power grid on power quality is complex, and the simulation scenario is not comprehensive enough to be suitable for engineering applications[4-6]. In view of this situation, this paper proposes a power quality assessment method for electrified railway access system based on ETAP software. First, based on the factory test report data or measured data of the electric locomotive, this method builds an electric locomotive simulation model to simulate the power and harmonic. According to the traction station access system plan and the main wiring method in the station, models such as traction transformers, transmission
lines, and access to the power grid are built. Secondly, according to the combination of the locomotive operating conditions and the number of up-links and down-links, the impact on the power quality of the connected power grid is simulated and evaluated. Finally, in order to ensure that the national standard meets the power quality requirements of the traction station after the electrification, corresponding governance measures are formulated to provide a basis for system design and equipment selection.

2. Construction of a simulation model of an electrified railway

2.1. Operating characteristics of electrified railways

According to the way of the traction station accessing the power grid and the load data provided by the user, this project case is the capacity transformation of the transformer of the traction station, involving 3 traction stations (TSA, TSB, TSC). The scheme of the system connected to the traction station remains unchanged. The original line is LGJ-240 type conductor, which can meet the transmission requirements of the new capacity, and the power transmission line remains unchanged.

The main technical indicators of the power supply system of each traction station:

- The transformer installation capacity of the traction substation is:

| Installation capacity | Rated voltage | Rated current | Impedance voltage |
|-----------------------|---------------|---------------|-------------------|
| 2×40 MVA             | 220±2×2.5%/27.5kV | 181.8A/1454.5A | U=10.5%           |

- The minimum power and the short-term maximum power of the traction substation on low voltage side are 28800KW and 9600KW respectively.
- The locomotive adopts AC-DC-AC drive EMU. The proportion (%) of each harmonic content and fundamental wave is shown in Table 2.

2.2. Model building

The calculation software used in this article is the "ETAP Power System Analysis and Calculation Application Software" developed by the American OTI software company. The modules used are: harmonic analysis module, power flow calculation module, unbalance analysis module[7-9].

3. Harmonic analysis of traction station access system

3.1. Harmonic Allowance Calculation

When the minimum short-circuit capacity of the public connection point of the power grid is different from the reference short-circuit capacity, the allowable value of harmonic current should be converted according to formula (1):

\[ I_h = \frac{S_{11}}{S_{12}} I_{hp} \]  

Where: \( S_{11} \) - minimum short-circuit capacity of the common connection point; \( S_{12} \) - reference short-circuit capacity, MVA, 220kV reference short-circuit capacity is 2000MVA; \( I_{hp} \) - allowable value of the
h-th harmonic current, \( A; I_h \) - the allowable value of the h-th harmonic current when the short-circuit capacity is \( S_{i1}, A \).

The short-circuit capacity corresponding to the large and small operation modes of the system stations connected to each traction station is shown in Table 3.

### Table 3. 220kV bus short-circuit capacity of the system.

| Traction station | System station     | Large load mode MVA | Small load mode MVA |
|------------------|--------------------|---------------------|--------------------|
| TSA              | System substation A(STA) | 7562               | 6349               |
| TSB              | System substation B(STB)  | 4870               | 2033               |
| TSC              | System substation C(STC)   | 9269               | 6394               |

Calculate the allowable value of the 220kV bus harmonic current of each connected system side when the grid is operated with a small load. The allowable value of the hth harmonic current of the i-th user at the common connection point is:

\[
I_{hi} = I_h \left( \frac{S_i}{S_f} \right)^{\alpha}
\]  

(2)

Where: \( I_h \) is the allowable value of the h-th harmonic current of the public connection point, \( A; S_i \) is the power consumption agreement capacity of the i-th user, MVA; \( S_f \) is the power supply equipment capacity of the public connection point, MVA; \( \alpha \) is the phase superposition coefficient, according to Table 4 value.

### Table 4. Phase superposition factor.

| \( h \) | 3 | 5 | 7 | 11 | 13 | 9, >13, even |
|--------|---|---|---|----|----|-------------|
| \( \alpha \) | 1.1 | 1.2 | 1.4 | 1.8 | 1.9 | 2.0 |

The capacity \( S_t \) of the power supply equipment of the system substations A, B and C is 220MVA, 280MVA and 450MVA respectively, and the load power agreement capacity of the three traction stations is 40MVA. Calculate the allowable value of harmonic current of each traction station:

### Table 5. Allowable value of harmonic current of traction station A.

| Harmonic order | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------------|---|---|---|---|---|---|---|---|
| Harmonic current A | 16.2 | 6.5 | 8.1 | 7.4 | 5.4 | 6.4 | 4.1 | 4.3 |
| Harmonic order | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Harmonic current A | 3.2 | 5.3 | 2.7 | 4.8 | 2.3 | 2.6 | 2.0 | 3.2 |
| Harmonic order | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Harmonic current A | 1.8 | 3.4 | 1.6 | 1.9 | 1.5 | 2.8 | 1.4 | 1.8 |

### Table 6. Allowable value of harmonic current of traction station B.

| Harmonic order | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------------|---|---|---|---|---|---|---|---|
| Harmonic current A | 4.7 | 1.7 | 2.3 | 2.0 | 1.6 | 1.8 | 1.2 | 1.2 |
| Harmonic order | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Harmonic current A | 0.9 | 1.5 | 0.8 | 1.4 | 0.7 | 0.7 | 0.6 | 1.1 |
| Harmonic order | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Harmonic current A | 0.5 | 1.0 | 0.5 | 0.5 | 0.4 | 0.8 | 0.4 | 0.7 |

### Table 7. Allowable value of harmonic current of traction station C.

| Harmonic order | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------------|---|---|---|---|---|---|---|---|
| Harmonic current A | 38.8 | 12.1 | 19.4 | 14.4 | 12.9 | 13.4 | 9.7 | 10.3 |
| Harmonic order | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Harmonic current A | 7.8 | 12.2 | 6.5 | 11.3 | 5.5 | 6.1 | 4.8 | 9.0 |
| Harmonic order | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Harmonic current A | 4.2 | 8.1 | 3.9 | 4.5 | 3.6 | 6.8 | 3.2 | 6.1 |
The allowable value of harmonic voltage distortion rate (phase voltage) of 220kV public network is shown in Table 8:

| Nominal voltage of power grid kV | Voltage total harmonic distortion rate % | Each harmonic voltage content rate % | Odd | Even |
|----------------------------------|-----------------------------------------|-------------------------------------|-----|------|
| 220                              | 2.0                                     | 1.6                                 | 0.8 |      |

### 3.2. Harmonic current and voltage analysis

In the light load operation mode of the power grid, with the traction transformer under close operation, the harmonic currents injected into the system by each traction substation are shown in figures 1-3. The harmonic voltage content rate and total harmonic distortion rate of the 220kV side of the system station caused by each traction substation are shown in figure 4.

After the traction station were expanded and transformed, the 23 and 25 times harmonic current of injection system B of traction station B exceeds the standard under the tight operation mode, and the harmonic voltage content and total voltage distortion rate of the system caused by each traction station meet the requirements of the national standard limit.

### 3.3. Harmonic current and harmonic voltage analysis considering background harmonics

Since the background harmonics include the harmonics caused by the original traction train before the traction station was reformed, this report calculates the harmonic current distribution of the newly added 50% traction station power based on the original background harmonic test data. The harmonic currents injected into the system and harmonic voltage content rate are shown in the figures 5-8:
Figure 5. Harmonic current and its allowable value of TSA injected into STA.

Figure 6. Harmonic current and its allowable value of TSB injected into the STB.

Figure 7. Harmonic current and its allowable value of TSC injected into the STC.

Figure 8. Each harmonic and total voltage content rate of traction station and system substation.

Considering the background harmonic data and the harmonic characteristics of the newly added load capacity, and comparing the calculation results of the harmonic voltage content rate and total distortion rate of the traction station, during close operation, the 23rd and 25th harmonic currents of the TSB injected into the STB allowable value, the harmonic voltage content rate and total distortion rate of the system station caused by each traction station meet the requirements of the national standard limit.

4. Negative sequence current analysis

In this paper, when calculating the negative sequence current flowing into a certain power plant, the load of the traction station adopts the short-term maximum load. The negative sequence current calculation results are shown in Table 9.

| Monitoring point | Unit capacity MW | Grid operation mode | $I_2/I_N$ % | $I_2/I_N$ allowance % |
|------------------|------------------|---------------------|-------------|----------------------|
| A Power Plant G1 | 300.00           | Light load          | 1.44        | 8.0                  |
| B Power Plant G1 | 660.00           | Light load          | 0.80        | 6.4                  |

After the three traction stations were put into operation, the negative sequence current injected into the G1 generator of the A power plant due to the three-phase imbalance was 61.01 A, and the negative sequence current injected into the G1 generator of the B power plant was 67.85 A, accounting for power generation. The ratio of the rated current of the machine meets the limit of the national standard on the negative sequence current of the rotating electrical machine.

5. Three-phase voltage unbalance analysis

The unbalance degree of different load levels of the traction station under the light load mode of the power grid is shown in Table 10.
Table 10. Three-phase unbalance analysis of power grid with small load level

| Traction substation | Connection point | Power MW | Short-circuit capacity MVA | Three-phase unbalance | allowance |
|---------------------|------------------|----------|---------------------------|-----------------------|-----------|
| TSA                 | STA              | Normal   | 9.6                       | 6349.0               | 0.17%     | 1.3%      |
|                     |                  | Short time | 28.8                    | 6349.0               | 0.54%     | 2.6%      |
| TSB                 | STB              | Normal   | 9.6                       | 2033.0               | 0.52%     | 1.3%      |
|                     |                  | Short time | 28.8                    | 2033.0               | 1.63%     | 2.6%      |
| TSC                 | STC              | Normal   | 9.6                       | 6394.0               | 0.17%     | 1.3%      |
|                     |                  | Short time | 28.8                    | 6394.0               | 0.51%     | 2.6%      |

Under the small load mode of the power grid and the normal and short-term maximum power of the traction substation, the three-phase voltage unbalance of the 220kV bus in the substation meets the requirements of the national standard limits.

6. Conclusion

This paper proposes an ETAP-based power quality assessment method for electrified railways connected to the grid based on the prediction and assessment of power quality of electrified railways. The modeling process is simple, highly popularized, and suitable for engineering applications. Taking an electrified railway upgrade and transformation line as an example, this paper calculates the impact on the power quality of the power grid after the transformation, including the harmonic analysis, negative sequence current, three-phase voltage imbalance simulation analysis. Then the variation characteristics of the main power quality indexes in the actual operation of the line are obtained, which provides a basis for the scheme design and equipment selection of the access system. At the same time, it can provide some reference for power quality management of nonlinear load access network with large capacity and frequency conversion control.

References

[1] HUANG Zhicheng, CHU Hongbo. Analysis and Suppression of Three-Phase Voltage Unbalance of Electrified Railway[J]. Electrical & Energy Management Technology, 2017(09):74-77.
[2] NA Guang-yu, Wang Jun. The Power Supply System of Electrified Railway and It's Impact on the Power System[J]. Northeast Electric Power Technology, 2011, 32(11):13-18.
[3] CHEN Weirong, JIANG Tian, DAI Chaohua, YUAN Shuang. Probabilistic Load Flow of Power System with Traction Power Load of Electrified Railways[J]. Proceedings of the CSEE, 2019, 39(23):6899-6907+7103.
[4] OUYANG Sen, LIANG Wei-bin. An evaluation method of power quality about electrified railways connected to power grid based on PSCAD /EMTDC[J]. Advanced Technology of Electrical Engineering and Energy, 2016, 35(12):52-58.
[5] DING Fanfan, ZHANG Dahai, LIU Hui, HE Jinghan. Evaluation and Forecast of Electrified Railway Influence on Wind Farm[J]. Electric Power Construction, 2018, 39(01):119-124.
[6] CHANG Shuai, GUO Kunli, WANG Jianbo, ZHAO Huiming. The influence of electrified railway harmonics on regional power grid[J]. Journal of Xi’an Polytechnic University, 2016, 30(03):327-332.
[7] LIU Jia, LIN Tao, XIAN Xing, GONG Qing, WU Fuzhang. Power Quality of Electrified Railways. Research of Effects on Power System Relay Protection by Power Quality of Electrified Railways[J]. Electrical & Energy Management Technology, 2016(20):32-37.
[8] ZHANG Ce, LIU Li, WANG Da, YIN Bo, ZHAO Wen-jing. Influence of Electrified Railway on Power Network Harmonic and Analysis of Restraining Measures[J]. Journal of Shenyang Institute of Engineering (Natural Science), 2018, 14(01):50-55.
[9] LI Xiaobo, WANG Chonglin. Harmonic analysis based on ETAP for Shanghai-Nanjing Intercity Railroad[J]. Electric Power Automation Equipment, 2011, 31(06):108-111+121.