An evaluation method of power quality about electrified railways connected to power grid based on PSCAD/EMTDC

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Abstract. The existing modeling process of power quality about electrified railways connected to power grid is complicated and the simulation scene is incomplete, so this paper puts forward a novel evaluation method of power quality based on PSCAD/ETMDC. Firstly, a model of power quality about electrified railways connected to power grid is established, which is based on testing report or measured data. The equivalent model of electrified locomotive contains power characteristic and harmonic characteristic, which are substituted by load and harmonic source. Secondly, in order to make evaluation more complete, an analysis scheme has been put forward. The scheme uses a combination of three-dimensions of electrified locomotive, which contains types, working conditions and quantity. At last, Shenmao Railway is taken as example to evaluate the power quality at different scenes, and the result shows electrified railways connected to power grid have significant effect on power quality.

1. Introduction
With the rapid development of electrified railways, their influence on power quality attracts more and more attention. Electrified railways produce a lot of harmonic and negative sequence current, which may causes serious negative impact if they connect to power grid. Therefore, it has scientific significance and practical application value to carry out detailed modeling research and comprehensive analysis [1].

At present, the researches on electrified railways connected to power grid mostly focus on modeling analysis, such as connection mode of traction transformer [2-4] and the internal characteristics of electrified locomotive [4-6]. They also focus on the power quality evaluation of the influence of traction station driving single locomotive load [6-7]. However, there are still some shortages as follows:

(1) So far, the simulation model of electrified railways mainly considers the connection structures of electronic circuit and the control strategies corresponding to each type of the locomotive [4-6]. However, it is hard to be generalized because the complexity and diversity of locomotive structures and strategies causes the modeling process too complicated.

(2) The simulation scene of power quality evaluation is not comprehensive enough. In practical operation, there are possibilities that each power supply section (up and down) may have various combinations of types, working conditions, quantity of locomotive. But most literatures [6-7]...
considered only an evaluation of single locomotive connected to power grid.

Aiming at the problems above, this paper proposes a simulation and evaluation method of power quality about electrified railways connected to power grid based on PSCAD/EMTDC (Power Systems Computer Aided Design). Firstly, a model is established, including the V/v type traction transformer, the electrified locomotive, which can make effective use of the factory testing report and measured data. Secondly, in order to improve the comprehensiveness of evaluation, a comprehensive evaluation scene is put forward, which takes three-dimensions of locomotive into consideration, including types, working conditions and quantity. Last but not least, in order to evaluate the influence on power quality of electrified railways connected to power grid, Shenmao Railway is taken as example to simulate in the comprehensive evaluation scenes.

2. Simulation model of electrified railway connected to power grid

In this paper, the model of electrified railways connected to grid is built in PSCAD/EMTDC, focusing on two main parts, the traction transformer and the electrified locomotive.

2.1. V/v Type Traction Transformer

At present, most of high-speed railways in China adopt the V/v type transformer, which has advantages of simple structure and high-capacity-utilization. From the consideration on the structure, this transformer is formed by two single-phase traction transformers, which are connected into an open triangle. Its primary winding is accessed to AB phase and BC phase. And the outlet terminals of secondary winding, connected to two traction bus groups, supply energy to power supply sections through feeder lines.

According to the structure characteristics of three-phase V/v connected traction transformer above, two single-phase two-winding transformers in transformer component library of PSCAD can be used for simulation. The wiring diagram is shown in Figure 1.

2.2. Electrified locomotive

Electrified locomotive is the main load of traction power supply system for electrified railway. What’s more, it is the main source of harmonics and negative sequences. Harmonics cause the voltage distortion. And negative sequence current causes the three-phase unbalance. Therefore, a simulation model should fully reflect its power characteristic and harmonic characteristic.

Aiming at the situation that the present modeling method is complex and most of the electrified locomotives have detailed factory testing reports, an equivalent model of electrified locomotive is put forward. It reflects power characteristic and harmonic characteristic, substituted by load and harmonic source. This model is based on factory testing reports or measured data, which can simplify the modeling process. As a result, it can be widely used and suitable for engineering applications. Firstly, harmonic current data and its corresponding power data of electrified locomotive in different working conditions should be obtained from factory testing reports or actual measured data. Secondly, a harmonic signal generator component should be built in PSCAD, which can produce harmonic signal. Harmonic current data should be inputted to this component. As a result, harmonic current of locomotive, as the harmonic source, is injected onto power supply sections and power data in corresponding conditions are injected as the load too.
3. Simulation scenes setting analysis

In practical application, each power supply section (up and down) may take several combinations of locomotive, including different types, working conditions and quantity. This scheme synthetically considers three-dimensions of electrified locomotive, including types, working conditions and quantity. All possible scenes are taken into consideration, which makes up defects of incomplete analysis in existing literatures. Taking Shenmao Railway as example, the combinations of electrified locomotive are as follow:

(1) Types. In China, at present stage, the mainly passenger train is motor train unit (CRH type locomotive), with a small amount of SS9 type locomotives. And the mainly freight train is HXD3 type locomotive. Therefore, electrified locomotives are divided into three types, including CRH, SS9, and HXD3.

(2) Working conditions. 5 typical conditions of locomotive are taken as representatives to simulate, including starting condition, high-power-condition, medium-power-condition, low-power-condition, and braking condition. They cover all possible power range of electrified locomotive.

(3) Quantity. Traction substation not taking locomotive or each power supply section taking different amount of locomotives are all taken into consideration. A2B1 represents that up power supply section takes 2 locomotives and down power supply section takes 1 locomotive. Considering the capacity of traction transformer and practical application plan in the example, the extreme combination is set to be A2B2. There are 6 kinds of combination totally. In addition, according to provisions of train operation, it is impossible that 2 locomotives driven by the same supply section are both in starting condition or braking condition. Therefore, the limit combination of locomotive in starting and braking conditions is set to be A1B1.

4. Example analysis

Electrified railways has some characteristics, such as asymmetry, nonlinearity and volatility. It causes some power quality problems, including voltage deviation, harmonic and negative sequence, so it is necessary to make a detailed simulation and evaluation analysis about electrified railways connected to power grid.

The traction station connects to 110kV substation through a outlet line, whose length is 5.65km. The traction station uses an 110/27.5kV three-phase V/v transformer, whose capacity is (16+16) MVA. And the traction power supply system connects to two power supply sections (up and down). The schematic diagram of traction station connected to power grid is shown in Figure 2.

![Figure 2. Schematic diagram of a traction substation of Guangdong Province connected to power grid](image)

4.1. Voltage Deviation

The higher power of electrified railway is, the greater voltage deviation is. Therefore, in this paper, among high-power condition, middle-power condition and low-power condition, only high-power condition is taken for analysis. In this section, three kinds of electrified locomotives in starting
condition, high-power condition and braking condition are taken as examples for analysis. In different simulation scenarios, the voltage deviation in 110kV side of 110kV substation is shown in Table 1.

According to the simulation results shown in Table 1: ① when electrified locomotives are in starting condition or high-power condition, it absorbs power from power grid, so that the voltage deviation in 110kV bus of substation is negative, and the voltage of grid connection point drops. ② when they are in braking condition, it delivers power to the grid, so that the voltage deviation is positive, and the voltage of grid connection point is increased.

To sum up, in this case, the voltage deviation of grid connection point in a variety of scenes is not more than 10% of the nominal voltage, which conforms to the national standard.

### Table 1. Voltage deviation of multiple simulation scenes

| Type  | Combination | Starting condition | High-power condition | Braking condition |
|-------|-------------|--------------------|----------------------|-------------------|
| SS9   | A0B0        | 0.50%              | 0.50%                | 0.50%             |
|       | A1B0        | -1.50%             | -0.81%               | 1.18%             |
|       | A1B1        | -1.94%             | -0.98%               | 1.18%             |
|       | A2B0        |                    | -2.28%               |                   |
|       | A2B1        |                    | -2.34%               |                   |
|       | A2B2        |                    | -2.70%               |                   |
| CRH   | A0B0        | 0.50%              | 0.50%                | 0.50%             |
|       | A1B0        | -1.26%             | -0.65%               | 1.08%             |
|       | A1B1        | -1.30%             | -0.67%               | 1.08%             |
|       | A2B0        |                    | -1.94%               |                   |
|       | A2B1        |                    | -1.97%               |                   |
|       | A2B2        |                    | -2.02%               |                   |
| HXD3  | A0B0        | 0.50%              | 0.50%                | 0.50%             |
|       | A1B0        | -1.72%             | -1.03%               | 1.25%             |
|       | A1B1        | -1.79%             | -1.06%               | 1.25%             |
|       | A2B0        |                    | -2.77%               |                   |
|       | A2B1        |                    | -2.84%               |                   |
|       | A2B2        |                    | -2.92%               |                   |

### Table 2. Unbalance of three-phase voltage of multiple simulation scenes

| Type  | Combination | Starting condition | High-power condition | Braking condition |
|-------|-------------|--------------------|----------------------|-------------------|
| SS9   | A0B0        | 0.01%              | 0.01%                | 0.01%             |
|       | A1B0        | 1.28%              | 0.85%                | 0.45%             |
|       | A1B1        | 1.40%              | 0.89%                | 0.76%             |
|       | A2B0        |                    |                      |                   |
|       | A2B1        |                    |                      |                   |
|       | A2B2        |                    |                      |                   |
| CRH   | A0B0        | 0.01%              | 0.01%                | 0.01%             |
|       | A1B0        | 1.44%              | 0.96%                | 0.52%             |
|       | A1B1        | 1.50%              | 0.99%                | 0.87%             |
|       | A2B0        |                    |                      |                   |
|       | A2B1        |                    |                      |                   |
|       | A2B2        |                    |                      |                   |
| HXD3  | A0B0        | 0.01%              | 0.01%                | 0.01%             |
|       | A1B0        | 1.77%              | 1.26%                | 0.67%             |
|       | A1B1        | 1.85%              | 1.30%                | 1.14%             |
|       | A2B0        |                    |                      |                   |
|       | A2B1        |                    |                      |                   |
|       | A2B2        |                    |                      |                   |

4.2. Three-Phase Voltage Unbalance

The unbalance of single-phase power supply connecting to electrified railways can bring negative sequence current to power grid, which is easy to cause the unbalance of three-phase voltage at PPC. National standard stipulates that the unbalance of three-phase voltage at the PPC caused by load should be less than 1.3%.

In this section, three kinds of electrified locomotives in starting condition, high-power condition and braking condition are taken as examples for analysis. In different simulation scenarios, the three-phase voltage unbalance in 110kV side of 110kV substation is shown in Table 2.

According to the results shown in Table 2. ① when the traction station drives the same quantity of electrified locomotives, among 3 typical working conditions, electrified locomotives in starting condition cause the maximum three-phase voltage unbalance, while high power condition ranks 2nd and braking condition ranks the 3rd. ② when the traction station drives the same combination and working condition of locomotives, the three-phase voltage unbalance caused by HXD3 is the maximum, which caused by CRH ranks 2nd and by SS9 ranks the 3rd.

To sum up, the three-phase voltage unbalance caused by electrified locomotives is easy to exceed the national standard, so it is necessary to take certain restrictive measures or compensatory measures.

4.3. Harmonic

Harmonic current caused by electrified locomotive can be injected at PPC of power grid. It is easy to cause voltage distortion of PPC, so harmonic caused by electrified locomotive should be limited.
4.3.1. Harmonic Voltage. Since the processes of starting condition and braking condition are short and the combinations of them are simple, in this section, only SS9 in high, medium and low-power conditions are taken as examples to evaluate voltage distortion. In different simulation scenarios, the voltage distortion of 110kV substation 110kV side caused by SS9 is shown in Figure 3.

![Figure 3. Simulation results of total voltage distortion caused by SS9 locomotive in different conditions](image)

The simulation results show that: when traction substation drives SS9 in high-power condition, only in the combination of A1B0, the total harmonic voltage distortion rate is less than 2%. On the other hand, in middle-power or low-power conditions, only in the combination of A1B0, A1B1 and A2B0, the total harmonic voltage distortion rates are less than the national standard limit.

Results proves that the harmonics caused by SS9 are easy to cause the total harmonic voltage distortions of 110kV substation 110kV side greater than national standard limitation, so it is necessary to take certain restrictive measures or compensatory measures.

4.3.2. Harmonic Current. SS9 locomotive in high-power condition causes the highest rate of harmonic voltage distortion, so SS9 in high-power condition is taken as an example to simulate the influence of harmonic current. The simulation results are shown in Table 3.

According to the Table 3, the 3rd harmonic current values caused by all combinations of SS9 in high-power condition exceed the limitation in Table 3. The 5th harmonic current values exceed the limitation as well, except A1B0. The 7th and 9th harmonic current values exceed the limitation as well, with A1B0, A1B1 and A2B0 exception. The 11th and over harmonic currents are all within the standard limitation.

In summary, the SS9 may cause a problem that 3rd, 5th, 7th, 9th harmonic current values exceed the limitation of national standard, so it is necessary to take restrictive measures or compensatory measures.
Table 3. Simulation results of harmonic current caused by SS9 locomotive in high power condition

| Number of Harmonic Current | A1B0 | A1B1 | A2B0 | A2B1 | A2B2 Allowable Harmonic Current (A) | Number of Harmonic Current | A1B0 | A1B1 | A2B0 | A2B1 | A2B2 Allowable Harmonic Current (A) |
|---------------------------|------|------|------|------|-------------------------------------|---------------------------|------|------|------|------|-------------------------------------|
| 2                         | 0    | 0    | 0.01 | 0.01 | 0.02                                | 8.9                       | 14   | 0    | 0    | 0    | 0                                   |
| 3                         | 10.62| 21.15| 19.9 | 29.88| 38.53                               | 7.1                       | 15   | 0.03 | 0.03 | 0.06 | 0.03                                |
| 4                         | 0    | 0    | 0.01 | 0.01 | 0.01                                | 4.5                       | 16   | 0    | 0    | 0    | 0                                   |
| 5                         | 4.82 | 9.27 | 8.67 | 12.64| 15.9                                | 7.1                       | 17   | 0.03 | 0.01 | 0.06 | 0.02                                |
| 6                         | 0    | 0    | 0    | 0.01 | 0.01                                | 3                         | 18   | 0    | 0    | 0    | 0                                   |
| 7                         | 2.47 | 4.66 | 4.26 | 6.17 | 7.58                                | 5.1                       | 19   | 0.02 | 0.02 | 0.04 | 0.01                                |
| 8                         | 0    | 0    | 0    | 0    | 0.01                                | 2.2                       | 20   | 0    | 0    | 0    | 0                                   |
| 9                         | 1.12 | 2.17 | 1.85 | 2.75 | 3.37                                | 2.4                       | 21   | 0.02 | 0.03 | 0.04 | 0.02                                |
| 10                        | 0    | 0    | 0    | 0    | 0.01                                | 1.8                       | 22   | 0    | 0    | 0    | 0                                   |
| 11                        | 0.68 | 1.25 | 1.09 | 1.57 | 1.87                                | 3.2                       | 23   | 0.01 | 0.01 | 0.03 | 0.03                                |
| 12                        | 0    | 0    | 0    | 0    | 0.01                                | 1.5                       | 24   | 0    | 0    | 0    | 0                                   |
| 13                        | 0.02 | 0.02 | 0.03 | 0.02 | 0.04                                | 2.8                       | 25   | 0    | 0.01 | 0.01 | 0.01                                |

5. Conclusion
(1) In this paper, an equivalent model of the electrified locomotive is proposed, whose power characteristic and harmonic characteristic are substituted by load and harmonic source. This model is based on testing reports or measured data, which uses load and harmonic source as equivalent substitution of electrified locomotive. It is easy to generalize and its modeling process is simple, which is suitable for engineering application.

(2) This paper puts forward a detailed and comprehensive evaluation scheme, taking Shenmao Railway as example. This scheme contains three dimensions of electrified locomotive for analysis, including types, working conditions and quantity, which can get a more completed evaluation result.

(3) The power quality problems on the 110kV side of the Shenmao Railway Traction Station are evaluated, including voltage deviation, three-phase voltage unbalance, and harmonics. The results shows that three-phase voltage unbalance and harmonics caused by Shenmao Railway are serious, it must take some restrictive measures or compensatory measures.

References
[1] Bai Jianhai. Electric railway affecting the governance of the harmonic and three-phase unbalanced[D]. Beijing: North China Electric Power University, 2013.
[2] Liu Ying. Research on effect evaluation and governance of the power quality in electrified railways accessed to the power grid[D]. Jinan: Shandong University, 2014.
[3] Liu Jinxin, Ge Qiongxuan, Wang Xiaoxin, et al. Traction-system research for high-speed maglev based on double-end supply[J]. Advanced Technology of Electrical Engineering and Energy, 2015, 34(6): 16-21,44.
[4] Liu Yu. Simulation analysis of electrified railway traction network[D].Jinan: Shandong University, 2007.
[5] Yu Danping. Simulation and influence research on electrified railway traction power supply system[D].Hangzhou: Zhejiang University,2011.
[6] Zhou Sheng. Load modeling and analysis of high-speed railway traction load[D]. Hangzhou: Zhejiang University, 2011.
[7] Zhang Junjie, Xiao Xiangning, Yin Zhongdong, et al. Simulation model of SS6B electrical locomotive based on PSCAD/EMTDC[J]. Electric Drive for Locomotives, 2008, (6): 27-29.