Analysis of the negative sequence interactive impact of traction power supply system on the urban power grid

Lin Xu¹, Wei Wei¹, Chang Liu¹, Lei Ai²*, Dan Jin¹, Xueyuan Liu¹ and Hua Yang¹
¹ Electric Power Research Institute of State Grid Sichuan Electric Power Company, Chengdu, Sichuan, 610041, China
² School of Electrical Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 611756, China
*Corresponding author’s e-mail: al51522@my.swjtu.edu.cn

Abstract. The high-speed railway adopts single-phase power supply, which is asymmetric load for the three-phase power grid. Its high power and fluctuation characteristics will cause the negative sequence voltage problem of urban power grid. With the rapid development of high-speed railway in recent years, this problem is becoming more and more serious. Therefore, it is urgent to analyse the negative sequence of the urban power grid caused by TPSS (Traction Power Supply System). Usually, the mathematical and simulation model of TPSS is established to analyse the power quality of TPSS. However, the modelling process is usually simplified, and the load of TPSS has randomness and volatility, which makes the simulation results deviate from the actual results. Therefore, based on the measured data of TPSS loads and the method of dynamic power flow calculation, considering the factors of station number, common phase of traction transformer and train marshal, the negative sequence influence of TPSS on the whole urban power grid under different conditions is analysed in this paper. Finally, the feasibility of alternation commutation phase to weaken negative sequence voltage is verified.

1. Introduction

Different from Germany and other countries with independent power plants, China's TPSSs are directly connected to the urban power grid [1]. As a typical high power, asymmetric load, high-speed train will bring serious harmonic, negative sequence and other power quality problems to urban power grid. Moreover, with the development of long-distance, large-scale and intensive high-speed railways in China, the negative sequence problem brought by it to urban power grid is becoming more and more serious. The unbalance of negative sequence voltage will reduce the utilization efficiency of transformer, increase the system loss, overheat the motor and cause other damages [2].

The simplified three-phase power flow program is used in [3] to analyse the voltage unbalance of TPSS. Meanwhile, compared with the approximate formula of voltage unbalance, the power flow calculation can simulate the more real power grid. The negative sequence contribution factor is proposed in [4], which is applied to analyse the negative sequence problem caused by TPSS. The power factor of TPSS is analysed by using dynamic three-phase power flow calculation in [5]. Because the active power of TPSS fluctuates violently, dynamic power flow calculation can better analyse the influence of TPSS load change on the negative sequence of urban power grid. Therefore, this method is also suitable for the negative sequence analysis of TPSS.
In addition, the extant method mostly uses accurate mathematical model for power quality analysis of TPSS [6]. But the type and number of the train are complex, as well as the connection of traction transformer and the power supply way of the system. Moreover, in the modelling, some simplifications are usually carried out, which make the result deviate from the reality. However, the measured data is the actual operation of the TPSS, including the train type, line conditions, weather, geographical environment and other factors which are ignored by mathematical modelling.

A large number of researchers on power quality of TPSS simply equate the power grid to Thevenin circuit, which can only analyse the influence of TPSS on the common coupling point. Therefore, this paper analyses the measured data of TPSS to find out the typical load characteristics. Applying dynamic power flow calculation, this paper studies the negative sequence interaction mechanism of IEEE 30 bus system under the access of various TPSS load characteristics, and verifies the feasibility of TSS (Traction Substation) alternation commutation phase to weaken the negative sequence of urban power grid.

2. Load characteristics of TSS

China's high-speed trains are generally 8-marshals or 16-marshals. Taking CRH380A as example, the rated traction power of 8-marshals is 9.6MW, while 16-marshals 19.6MW. There are many types of high-speed trains in China and the rated power of different types of trains is also different. In addition, the train usually has many working conditions such as starting, uniform speed running, coasting and braking, which makes the power fluctuation of high-speed train is very severe [7]. Generally, the power of 8-marshals is between 6 and 12MW, while that of 16-marshals is between 14 and 24MW (ignoring braking). Figure 1 shows the load active power curve of two traction substations in 12 hours. It can be seen from the figure that the load of TPSS fluctuates greatly with strong randomness. Among them, TPSS in b) is the hub substation, which has a higher traffic density and a higher probability of multiple vehicles running at the same time [8].

![Figure 1. The load active power curve of two TSSs](image)

Figure 2 is the partial active power load curve of the above ordinary TSS, in which the traction transformer with V/x connection is adopted and the common phase is C. Taking Figure 2.a as example, between 0 and 10 minutes, phase A and C have load. What’s more, the sum of the active power of them is between 16 and 20MW, while phase B is 0. It can be seen that there is a 16-marshals train in
the $\alpha$ power supply arm. After 10 minutes, the three-phase power is 0, it can be inferred that the train stops at the station. And then the phase B and C have load, while phase A is 0, which illustrates that the train has entered the $\beta$ power supply arm. For convenience, $\alpha(8+16)$ represents an 8-marshals train and a 16-marshals train on $\alpha$ power supply arm. Other curves can be interpreted similarly.

Figure 2. The partial active power load curve of the ordinary TSS

Figure 3 shows the partial active power load curve of the above hub TSS. The traction transformer supplying power to the tested line also adopts V/x connection mode. But the common phase is B phase. As depicted in Figure 3, More trains are running on the line at the same time, which means the load power is higher and the voltage unbalance of urban power grid is more serious.

Figure 3. The partial active power load curve of the hub TSS
3. Negative sequence influence of single TSS on urban power grid

Voltage unbalance is usually expressed by negative-sequence voltage unbalance factor (NF)

\[ NF = \frac{U_2}{U_1} \times 100\% \]  

(1)

Where, \( U_2 \) is negative sequence voltage and \( U_1 \) is positive sequence voltage.

IEEE 30 bus system is used to simulate the urban power grid. Newton-Raphson power flow calculation method is used in the analysis.

Node 6 is selected as the access node of TSS. The traction loads in a)–b) in Figure 2 and b) in Figure 3 are considered in the power flow calculation as three typical conditions (named as case 1.1, case 1.2 and case 1.3). The NF curves are shown in Figure 4. Without considering the unbalance caused by other loads, comparing Figure 2 and Figure 4, it can be found out that the change trend of NF is almost the same as the absolute value of active power.

The 95% probability maximum and maximum values of NF in three cases are shown in Table 1. By comparing case 1.1 with case 1.2, it can be found that when there are trains on both power supply arms, the three-phase load power is more balanced, making the NF on the grid is smaller. Compared with 1.1 and 1.3, when the number of trains on single power supply arm increases, the NF of power grid also increases rapidly.

![Figure 4. The NF curve of case 1.1~1.3](image)

| Train distribution | NF 95% probability maximum | NF maximum |
|--------------------|-----------------------------|------------|
| case 1.1 α(16)→β(16) | 0.60% | 0.64% |
| case 1.2 α(8)+β(16) | 0.45% | 0.58% |
| Case 1.3 β(16+16+16) | 1.20% | 1.31% |

4. Negative sequence influence of multiple TSSs on urban power grid

4.1. Negative sequence influence of two TSSs on urban power grid

Three cases (case 2.1, case 2.2 and case 2.3) are designed as shown in Table 2. In case 2.1, the two TSSs are ordinary TSS. And the common phase of traction transformer is C. In addition, the loads correspond to d) and E) in Figure 2 respectively. In case 2.2, the TSS is the same as case 2.1. But the load corresponds to d) and F) in Figure 2 respectively. In case 2.3, TSS1 is the hub station with
common phase B, while TSS 2 is the common station with common phase C. The loads correspond to c) in Figure 3 and f) in Figure 2 respectively. The NF curve of node 6 and node 21 is shown in Figure 5.

![Figure 5. The NF curve of case 2.1~2.3](image)

It can be seen from Figure 5 that in case 2.2, the NF curve of TSS2 has a bulge at 2 minutes, which is due to the regenerative braking of the train in TSS1, resulting in the aggravation of three-phase power unbalance. Therefore, the NF curve of each node of the system is affected by the two TSSs.

The NF curves of whole system is showed in Figure 6. Due to the electrical distance between Node 6 and 2 is 0.19Z_B and that of Node 6 and 7 is 0.09Z_B (Z_B is the reference impedance), Node 2 is less affected by the negative sequence of node 6.

![Figure 6. The NF curves of whole system in case 2.2](image)

According to Table 2, comparing case 2.1 and case 1.1, if there is a train running on the same arm of TSS1 and TSS2, it will deteriorate the unbalance of three-phase power, making the increase of NF of the whole system. Similarly, by comparing case 2.2 and case 1.1, it can be seen that when there is a train running on another arm of TSS2, the three-phase power is more balanced and the NF of the
whole system is reduced due to the fact that the phase A and C of TSS1 have load, while the phase B and C of TSS2 have load. Comparing case 2.3 and case 1.2, when the common phase of two TSSs is different and the trains are running on the same arm at the same time, the NF of whole system will decrease.

Table 2. The 95% probability maximum and maximum of NF in case 2.1~2.3

|      | TSS1 (Node 6)  | TSS2 (Node 21) | NF(Node 6/Node 21) |
|------|----------------|----------------|--------------------|
| case 2.1 | α(16)          | α(16)          | 0.97%/1.54%        |
| case 2.2 | α(16)          | β(16)          | 0.53%/1.13%        |
| case 2.3 | α(16+16)       | α(16)          | 0.81%/1.10%        |

4.2. Negative sequence influence of three TSSs
Case 3.1 is set as a single station experiment and case 3.2 is set as an alternation commutation phase experiment. The load in case 3.1 is the same as that in Figure 2.a). However, the hub TSS is connected to the 21th node. In case 3.2, the common phase of TSS1, TSS2 and TSS3 is phase A, B and C respectively. Their loads are shown in Figure 2.d), Figure 3.a) and Figure 2.f) respectively. It is noted that due to the change of common phase, phase A in Figure 2.f) is exchanged with phase C. The NF curve of each TSS is shown in Figure 7.

![NF curves](image)

Figure 7. The NF curve of case 3.1~3.2

The NF of each TSS is recorded in Table 3. Compared with case 3.1 and 3.2, due to the phase A and C of TSS1 have load, the phase B and C of TSS2 have load and the phase A and B of TSS3 have load, the three-phase load is relatively balanced. What’s more the NF of TSS2 is reduced by 0.42%, which solves the problem that the NF of TSS2 in case 3.1 do not satisfy the national standard. Similarly, compared with case 3.2 and case 2.1, the NF of TSS1 also decreased by 0.58%. Alternation commutation phase can alleviate the harmonic problem of TPSS.

Table 3. The 95% probability maximum and maximum of NF in case 3.1~3.2

|      | Train distribution | 95% probability maximum | maximum |
|------|--------------------|-------------------------|---------|
| case 3.1 | TSS2(Node 21)      | β(16+16)                | 1.49%   | 1.53%   |
|        | TSS1(Node 6)       | α(16)                   | 0.39%   | 0.60%   |
| case 3.2 | TSS2(Node 21)      | β(16+16)                | 1.07%   | 1.12%   |
|        | TSS3(Node 10)      | α(16)                   | 0.78%   | 0.85%   |
5. Conclusions
Based on a large number of case studies, the following conclusions are gained:

1) Each traction substation can be regarded as a three-phase unbalanced load, and its unbalance will spread and decrease with the increase of electrical distance;
2) In the case of single TSS, the variation law of NF is almost the same as that of active power. In the case of multiple TSSs, it can be regarded as the superposition of NF influence of each TSS;
3) The increase of trains with the same power supply arm in TSS will aggravate the three-phase power unbalance of the system and worsen the negative sequence problem of urban power grid. In contrast, the increase of trains on the other power supply arm will weaken the three-phase unbalance of the system and improve the negative sequence problem of urban power grid;
4) The negative sequence of multiple TSSs will be affected by the common phase of traction transformer, the power supply arm of the train and other factors. The problem of negative sequence in urban power grid can be greatly improved by using alternate commutation phase between multiple TSSs.

Acknowledgments
The study is supported by the science and technology project of State Grid Sichuan Electric Power Company of China (Research on the Interaction Mechanism and Comprehensive Prevention Technology of the Power Quality of Urban Distribution Network with Mass Rail Transit Load, 52199719001D).

References
[1] Shen M.S., Zhou F.Y. (2019) Current Status and Trend for Development of Railway Traction Power Supply Technologies at Home and Abroad. Electric Railway, 1-7.
[2] Zhang D.H., Zhang Z.X., Wang W.A., Yang Y.L. (2016) Negative Sequence Current Optimizing Control Based on Railway Static Power Conditioner in V/v Traction Power Supply System. IEEE Transactions on Power Electronics, 31: 200-212
[3] Kuo H.Y., Chen T.S. (1998). Rigorous Evaluation of the Voltage Unbalance Due to High-Speed Railway Demands. IEEE Transactions on Vehicular Technology, 47: 1385-1389.
[4] Chen S.L., Li R.J., His P.H. (2004). Traction System Unbalance Problem -- Analysis Methodologies. J IEEE Transactions on Power Delivery, 19: 1877-1883.
[5] Wang K., Hu H.T., He Zheng Z., He Z.Y., Chen L.H. (2018) Study on Power Factor Behavior in High-Speed Railways Considering Train Timetable. IEEE Transactions on Transportation Electrification, 4: 220-231.
[6] Hu H.T., He Z.Y., Wang. K., Ma X.L., Gao S.B. (2016) Power-Quality Impact Assessment for High-Speed Railway Associated With High-Speed Trains Using Train Timetable—Part II: Verifications, Estimations and Applications. IEEE Transactions on Power Delivery, 31:1482-1492.
[7] Wang B., Gao S.B., Huang W., Jiang X.F., Qiu Z.C. (2014). Analysis on Harmonic Transmission Characteristics of Traction Power Supply System During Regenerative Braking of High Speed Train. Power System Technology, 38: 489-494.
[8] Hou W.Y. (2016) Researches on Harmonics of Hub Traction Power Supply System. Electric Railway, 7-13.