Analysis of Demand Factor for High Speed Railway Power Transmission Line from Load Measurement Data

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Abstract. With the rapid construction of high-speed railway in China and other developing countries, as well as the continuous expansion of its distance and scale, the load of power transmission line along the railway is increased accordingly. However, the existing design standards for power transmission line of high speed railway cannot specify the demand factor for the electrical load supplied by power transmission line, and there is no unified calculation method for the demand factor, resulting in a large difference between the theoretical value and the actual value of transformer capacity and cable section selected for engineering project, which takes huge additional energy penalty from the utility companies. To address the problems and formulate a more accurate selection standard for the load demand factor of high-speed railway power transmission line (HSR-PTL), the demand factor is calculated from the data measured on several typical high-speed railway operating in China. Firstly, the load model of HSR-PTL is proposed. According to the function and characteristics of the several kinds of load in HSR-PTL, each load is classified for load demand modelling. By measuring the load of several typical operating HSR-PTL, based on the proposed model, the value of the required coefficient of each load type based on the measured data is proposed. The calculated demand factor can be applied as an applicable reference for the design of high-speed railway power system.

1. Introduction
In recent decades, high speed trains (HSTs) are widely operating in high speed railways (HSRs) all over the world, especially in China [1]. With the operation of Hefei-Fuzhou, Harbin-Qiqihar, Chengdu-Chongqing high speed railway (HSR) in China, as of January 2016, the mileage of operating HSR in China exceeded 19,000 kilometres, accounting for more than 60% of the world's total mileage. With the planning and completion of more and longer high-speed railways in the future, it is important to guarantee the safe and stable operation of HSR.

Railway power systems can be divided into two types according to their functions. One is the system used to supply power to railway stations, and other living facilities along the railway. The other is the system used to supply power to the traction locomotives. This paper mainly analyses the first type: high speed railway power through line (HSR-PTL). As an important part of railway power system, HSR-PTL is mainly applied to supply power for communication, signal, tunnel lighting and other railway power loads, which is an important part to guarantee the safe and punctual operation of HST system [2].

With the connection of wireless network equipment, the load capacity of the HSR-PTL increases greatly. For example, the capacity of the public wireless network equipment of Hangzhou-Huangshan HSR reaches 50% of the railway load capacity on the HSR-PTL[3]. Therefore, the definition of the demand factor (DF) directly determines the power supply scheme, such as the capacity of voltage transformers, the section of the electric cable and power supply distance, which directly affects the project investment in construction stage and the power loss in operation stage [4][5].
Since there is no unified method for demand factor calculation\[6\], the theoretical values of transformer capacity and cable section are quite different from the value in the actual project\[7\]. If the transformer capacity is too large, the equipment will be under loaded, resulting in the waste of construction investment. Elsewise, it will lead to overload operation, resulting in overheating, insulation damage and increase of power loss, which will affect the safe operation of cables and other electrical equipment, and even cause fire accidents in serious cases\[8\]\[9\].

With the great evolutionary in power level of HSR-PTL, it becomes very important to identify the load patterns and estimate the electricity demand so that HSR-PTL energy resource planning can be well performed to meet the system peak demand in a very effective manner\[10\].

For the HSR-PTL electrical system, a detailed model of the AC 2×25 kV High Speed/High Capacity (HS/HC) railway lines is proposed in \[11\] to dynamically analyses the HSR-PTL systems. Based on the model, \[12\] analyses the constructive solutions that can influence the operating behaviour of the system. However, the analysis mainly focusses on the modelling analysis of HSR-PTL. There is little in the literature regarding load demand estimation problem for the power supply system of high-speed railway.

To address the problem, in this paper, a large number of measurements are conducted on the operating conditions of various loads in the HSR-PTL, and theoretical analysis is calculated based on the demand factor model from the design capacity and actual operating conditions of different kinds of loads according to the measurement data. Then the corresponding theoretical demand factors of each load in HSR-PTL are calculated. The calculated value can be applicable as the reference value for electric design of HSR-PTLs.

2. Load Classification of HSR-PTL

The simplified power systems for the ships are shown in Fig. 1, which depict selected main power loads in different location. Railway power loads in HSR-PTL mainly includes two types according to its location: one is the load in stations, such as control centre equipment and the lightnings in the railway station, the other is referred to as the load between stations. The load between stations can be classified as: signal equipment load in signal relay station and signal building, communication equipment load in wireless communication base station and optical fibre repeater station, public network equipment load, tunnel lighting load, etc.

The power loads of the HSR-PTL, especially the loads between stations are closely related to the traffic density of the railway, of which the communication facilities, signal facilities, and the lighting of the tunnel are influenced most. The number of trains in the section and the load status of each train change at any time, and the communication and signal loads between stations will also constantly changing. The load of the HSR-PTL presents a state of frequent fluctuations. When the traffic density of the section becomes higher, the signal equipment operates more frequently. When more passengers of each train use mobile phones at the same time, the power consumption of the main equipment of the communication base station covered by the public network along the line will be greater. For example, in the case of holidays or the resumption of operation after a railway failure, there will be close tracking of trains, and at this time, various loads of the power link will appear load peaks.

Since the load in stations can be considered constant and the tunnel lightning load is only activated when the railway line is out of service for maintenance. The power load of signal relay station, public network coverage equipment and communication equipment is the most important part for power fluctuation. Based on the field load data of several railways, such as Wuhan-Yichang high speed railway, Hefei-Wuhan high speed railway, Beijing-Shijiazhuang-Wuhan high speed railway, Wuhan-Guangzhou high speed railway, a detailed theoretical value analysis on the load demand factor of the HSR-PTL is proposed in this paper.
3. Demand factor Modelling for Different Kinds of load

The load in operation is not a constant value, but a variable value with time. Since electrical equipment will not operate at the same time and not all equipment can reach its rated capacity. In addition, the operating term of each equipment is also different, including long-term, short-term and repeated short-term and even short-term impact load. In the process of electric power system design, if the selected value is larger than the operating capacity, the transformer and the power line will be under loaded, resulting in waste of investment and non-ferrous metals. Otherwise, it will lead to overload operation, resulting in overheating, insulation damage, line loss increase, and then affect the conductor, cable or electrical equipment. Therefore, the load calculation can only be close to the actual situation. In order to avoid this kind of situation, the total load used in the design should be an assumed load, that is, the calculated power[9].

Since different equipment of HSR-PTL are used at different operating conditions, the power demands and usage periods are discontinuous. This time diversity in their power demand is taken into account by assigning a factor to each load equipment based on the heritage data on the operating railway. The demand factor also known by other names such as duty factor or load factor is defined as the calculated power over a period of time as a fraction of the peak or rated power of the equipment. Thus, the demand factor represents to what extent a specific load contributes to the total load on the generator, which aggregately powers all the connected loads. For a time-varying load, the power $p(t)$ expressed in kW over any specific operating period $T$, e.g., departure, operating, can be calculated as:

$$ k_{DFi,j} = \frac{Average\ power\ load}{Peak\ power\ load} = \frac{\int_{t_1}^{T_2} P_{i,j}(t) \, dt}{P_{rate} (T_2 - T_1)} $$ (1)
Where $k_{DFi,j}$ is the demand factor of load category $i$ during operating condition $j$, $P_{ij}(t)$ is the time-varying power (kW) of load category $i$ during operating condition $j$.

Since electrical equipment will not operate at the same time and not all equipment can reach its rated capacity and the operating term of each equipment will be different, including long-term, short-term and short-term impact load. The calculated power should be proposed for deriving the combined contribution to the transformer capacity requirement. That is, the rated power and the demand factor should be considered, which means time diversity in power demand. Therefore, the calculated power for single equipment and all equipment in that operating condition can be calculated as:

$$P_{cal} = P_{rate} \times k_{DF} \quad (2)$$

$$S_{cal} = \sum_{i=1}^{N} P_{rate_i} \times k_{DF} \quad (3)$$

In this paper, the field power measurements of several kinds of power loads in HSR-PTL are applied to determine load demand factors by (1). Based on the demand factor derived for the test load, the total load factor can be determined by (3) accordingly.

4. Test Results and Discussion

Three typical high-speed railway systems in operation (Wuhan-Yichang, Wuhan-Guangzhou, Wuhan-Kowloon high speed railway system) are used for the study. Several kinds of load in HSR-PTL are studied, the transformers with typical loads as shown in Fig. 1, are selected for field measurement, including the communication base station, fibre optic repeater and public network equipment. Fig. 2 shows the records for filed measurement. Fluke 1650 power quality monitor is applied. Based on the power log software, a monitoring platform can be built, which can realize the data acquisition and control of power quality instruments.

4.1. Analysis for Communication Base Station

The load operation data measured at each communication base station measurement point of different lines are shown in Table 1. $P_{ra}, P_{max}, P_{min}, P_{av}$ and $P_{jx}$ represent the designed capacity of load power, the maximum load power, the minimum load power, the average load power, the average power per 30 minutes within a year. Power factor is expressed as $\cos \varphi$. The ratio of maximum load power and minimum load power to rated power indicate the range of the load rate. And the ratio of $P_{jx}$ to $P_{rated}$ can be considered as demand factor.
Table 1 Load characteristics and demand factor analysis of communication base station

| Sampling point                     | $P_{\text{rated}}$/kW | $P_{\text{max}}$/kW | $P_{\text{min}}$/kW | $P_{\text{av}}$/kW | $\cos \phi$ | $P_{0.5}$/P | $P_{\text{max}}$/P | $P_{0.5}$/P |
|------------------------------------|------------------------|----------------------|----------------------|---------------------|-------------|--------------|-----------------|-------------|
| Wuhan-Yichang Railway 045          | 10                     | 3.59                 | 2.69                 | 2.85                | 0.8         | 3.54         | 0.33            | 0.45        |
| Railway Communication Station      |                        |                      |                      |                     |             |              |                 |             |
| Wuhan-Guangzhou Railway K1348-613  | 10                     | 4.01                 | 2.48                 | 3.06                | 0.8         | 3.94         | 0.31            | 0.50        |
| Communication Station              |                        |                      |                      |                     |             |              |                 |             |
| Wuhan-Kowloon Railway 25-1         | 10                     | 3.90                 | 1.69                 | 2.36                | 0.8         | 3.80         | 0.21            | 0.49        |
| Communication Station              |                        |                      |                      |                     |             |              |                 |             |

The design capacity of communication base station 045 of Wuhan-Yichang line is 10KVA, the maximum load power is 3.59kW, the minimum load power is 2.69kW, and the average load power is 2.85kw. In addition, the calculated power can be regarded as the average power per 30 minutes within a year based on the regression of measured data, which can be calculated according to (1). The calculated power is 3.54kW. Combining with the measurement of Wuhan-Guangzhou railway and Wuhan-Kowloon railway, the demand factor can be calculated as 0.347.

4.2. Analysis for Fibre Optic Repeater

The load operation data measured at each fibre optic repeater measurement point of different lines are shown in Table 2.

Table 2 Load characteristics and demand factor analysis of fibre optic repeater

| Sampling point                      | $P_{\text{rated}}$/kVA | $P_{\text{max}}$/kW | $P_{\text{min}}$/kW | $P_{\text{av}}$/kW | $\cos \phi$ | $P_{0.5}$/P | $P_{\text{max}}$/P | $P_{0.5}$/P |
|-------------------------------------|-------------------------|----------------------|----------------------|---------------------|-------------|--------------|-----------------|-------------|
| Wuhan-Kowloon Railway 24-1          | 3                       | 0.29                 | 0.25                 | 0.26                | 0.8         | 0.29         | 0.1             | 0.12        |
| Fibre Repeater                      |                         |                      |                      |                     |             |              |                 |             |
| Beijing-Wuhan Railway 107-1          | 3                       | 0.31                 | 0.26                 | 0.29                | 0.8         | 0.31         | 0.11            | 0.13        |
| Fibre Repeater                      |                         |                      |                      |                     |             |              |                 |             |
| Wuhan-Kowloon Railway 25              | 3                       | 0.33                 | 0.21                 | 0.29                | 0.8         | 0.33         | 0.09            | 0.14        |
| Repeater                            |                         |                      |                      |                     |             |              |                 |             |

With the same analysis method, the demand factor of fibre optic repeater can be calculated as 0.13.

4.3. Analysis for Public Network Equipment

The load operation data measured at each public network equipment station of different lines are shown in Table 3.

Table 3 Load characteristics and demand factor analysis of public network equipment station

| Sampling point                      | $P_{\text{rated}}$/kVA | $P_{\text{max}}$/kW | $P_{\text{min}}$/kW | $P_{\text{av}}$/kW | $\cos \phi$ | $P_{0.5}$/P | $P_{\text{max}}$/P | $P_{0.5}$/P |
|-------------------------------------|-------------------------|----------------------|----------------------|---------------------|-------------|--------------|-----------------|-------------|
| Hefei-Fuzhou Railway K1583-185      | 8                       | 2.43                 | 1.64                 | 2.22                | 0.8         | 2.39         | 0.25            | 0.38        |
| Public Network                      |                         |                      |                      |                     |             |              |                 |             |
| K58-900 Public Network              | 4                       | 1.79                 | 0.53                 | 1.16                | 0.8         | 1.73         | 0.165           | 0.56        |
| Nanping-Longyan Railway K4-769       | 13                      | 2.91                 | 1.79                 | 2.53                | 0.8         | 2.85         | 0.17            | 0.28        |
| Public Network                      |                         |                      |                      |                     |             |              |                 |             |

With the analysis method in 4.2 and the weighted regression analysis, the demand factor of public network equipment station can be calculated as 0.29.

5. Conclusion

The use of load measurement data for the calculation of load demand factor is proposed in this paper. The demand factors are a function of the average power over a period of time, peak or rated power of the equipment, and operating condition. Based on theoretical analysis of measured data on various loads of HSR-PTL, the demand factors of communication base stations, repeater station loads, and public
network coverage loads were calculated in detail, and reasonable values of the demand factors of various loads were obtained. Based on the measured data and its analysis, the recommended value for demand factor of communication base station is 0.347. The recommended value of demand factor of communication base station is 0.13. And the recommended value of demand factor of public network equipment station is 0.29. The analysis results can be the technical reference for the planning and design of HSR-PTL as well as the transformer selection and its safe and economic operation.

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