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A power-quality monitoring and assessment system for high-speed railways based on train-network-data center integration

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Abstract In recent years, with the rapid development of high-speed railways (HSRs), power interruptions or disturbances in traction power supply systems have become increasingly dangerous. However, it is often impossible to detect these faults immediately through single-point monitoring or collecting data after accidents. To coordinate the power quality data of both traction power supply systems (TPSSs) and high-speed trains (HSTs), a monitoring and assessing system is proposed to access the power quality issues on HSRs. By integrating train monitoring, traction substation monitoring and data center, this monitoring system not only realizes the real-time monitoring of operational behaviors for both TPSSs and HSTs, but also conducts a comprehensive assessment of operational quality for train-network systems. Based on a large number of monitoring data, the field measurements show that this real-time monitoring system is effective for monitoring and evaluating a traction-network system.

Keywords High-speed railway · Traction power supply system · Power quality monitoring · Data center

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1 Introduction

In recent years, high-speed railways (HSRs) have become a prevalent transportation system due to its excellent advantages in safety, environmental friendliness, comfort, and timeliness. By the middle of 2020, the total mileage of electrified railways in China has exceeded 141,400 km, of which the total mileage of HSRs reached 36,000 km [1]. The traction load of an HSR exhibits high power, density, nonlinearity, asymmetry and randomness, which presents a series of power quality problems (e.g., harmonics, negative sequence and imbalance) and excessive energy consumption.

Therefore, higher requirements are necessary for power supply safety and energy savings. To achieve the goal of comprehensive monitoring and assessment, a power quality and energy monitoring and assessment system for high-speed railways should be implemented.

Recent studies concerning power quality monitoring and analysis have mainly focused on power systems [2–8]. Zhang et al. [2] discussed the research status and development trend for the overall architecture of a power quality monitoring system in detail, including the power quality monitoring communication system and the software system of the monitoring center. The networks used for power system monitoring mainly include supervisory control and data acquisition (SCADA) systems, phasor measurement unit (PMU) systems, advanced metering infrastructure (AMI) systems and power quality monitoring systems. Among them, SCADA systems provide fundamental steady-state data. A PMU system provides multipoint fundamental synchronous phasor data. An AMI system provides steady-state data for measurement. A power quality monitoring system provides both steady-state and transient data, especially transient waveform data [3–5]. A type of surveillance equipment for power quality based on digital signal processing was designed, which also adopted controller area network bus communication to transfer the analyzed result to a data center [6]. Dabbs and Sabin [7] designed a power quality monitoring device based on power quality data interchange format in extensible markup language. A virtual instrument environment with a new network server architecture for a database and server systems was developed to process power quality measurements and GPS signals [8].

Several works have also developed various power quality monitoring systems for electrified railways. A preventive opportunistic maintenance method for traction power supply systems based on equipment reliability was introduced [9]. Zhang [10] developed a hardware system capable of collecting and analyzing power quality in a traction network in real-time based on digital signal processing. An HSR energy and power quality management system was proposed, which realized system-level consumption management and optimization for high-speed railways in [11, 12]. A kind of data collection system for electric railway traction load characteristics of electrified railways was introduced to realize the functions of data communication, data judgment, data display, data processing, harmonic analysis, file storage and network transmission [13]. Ji [14] designed an online monitoring and analysis system for the voltage quality of a traction network.

However, the traction load characteristics of HSRs are different from those in a power system, which is mainly manifested in the following aspects [11–14]:

(1) Due to high speed of the moving trains, it is difficult to coordinate the power quality data of both traction power supply systems (TPSSs) and high-speed trains (HSTs), resulting in the inability to conduct a comprehensive analysis of the data.
(2) A high-speed railway spans a large geo-graphic space, and a high-speed railway line often runs through multiple regions which causes a dynamic change in the power supply interval.
(3) A traction load is characterized by random fluctuations, high power usage, high-speed mobility, etc. It is difficult to extract the combined indices of the traction-network system (TNS) and HSTs.

Moreover, the interaction between a traction network and an HST is a dynamic coupling process, of which the electric behavior is complicated [15]. Single-point monitoring cannot monitor the power quality of the entire TPSS and capture events caused by power quality in a timely manner. Meanwhile, the monitoring efficiency of most terminals is low, and a unified analysis report format cannot be produced. It costs considerable manual work to sort out related reports and data after a test. As a result, a large amount of monitoring data have not been effectively utilized, and few studies on power quality data management strategies result in a lack of robust data [16].

In summary, although there is a national standard for power system [17–19], a unified standard for the communication and data processing of monitoring equipment is not available for HSRs. Therefore, there is an urgent need to develop a monitoring system for the traction network and high-speed trains with the effective use of data.

This paper is organized as follows: In Sect. 2, the railway monitoring and assessment system is structured as four layers: the data collection layer, data transmission layer, data analysis layer and data visualization layer. The data collection layer is introduced in Sect. 3, which explains the hardware working principle and data collection process. Section 4 presents the data transmission process of the RMAS. Section 5 uses a field measurement study to verify the effectiveness of the system. Finally, Sect. 6 presents the conclusions.

2 System description

This work builds an integration monitoring system of traction substations and moving trains and builds a comprehensive assessment system with multiple power quality and energy indices to evaluate the operational performance of a train-network system.

Figure 1 illustrates the overall structure of the railway monitoring and assessment system, which is a complex system integrating hardware configurations and software development. As Fig. 2 shows, the system contains four layers, namely, the data collection layer, data communication layer, data analysis layer, and data visualization layer.

(1) Data collection layer includes a voltage sensor, current sensor, radar, inertial navigation, the BeiDou Navigation Satellite System (BDS) or the GPS and monitoring units, which implements the synchronous collection and data fusion of multiple data sources (both electric quantity and nonelectrical data quantity) from high-speed trains and traction substations.
(2) Data communication layer realizes the transmission of monitoring results and oscilloscope records from trains and substations to the data center by developing corresponding communication programs. The communication layer defines the main channel for data communication.
(3) Data analysis layer implements data pre-processing and data mining. Comprehensive evaluation of the traction network can be realized in terms of power quality, energy and fault detection.

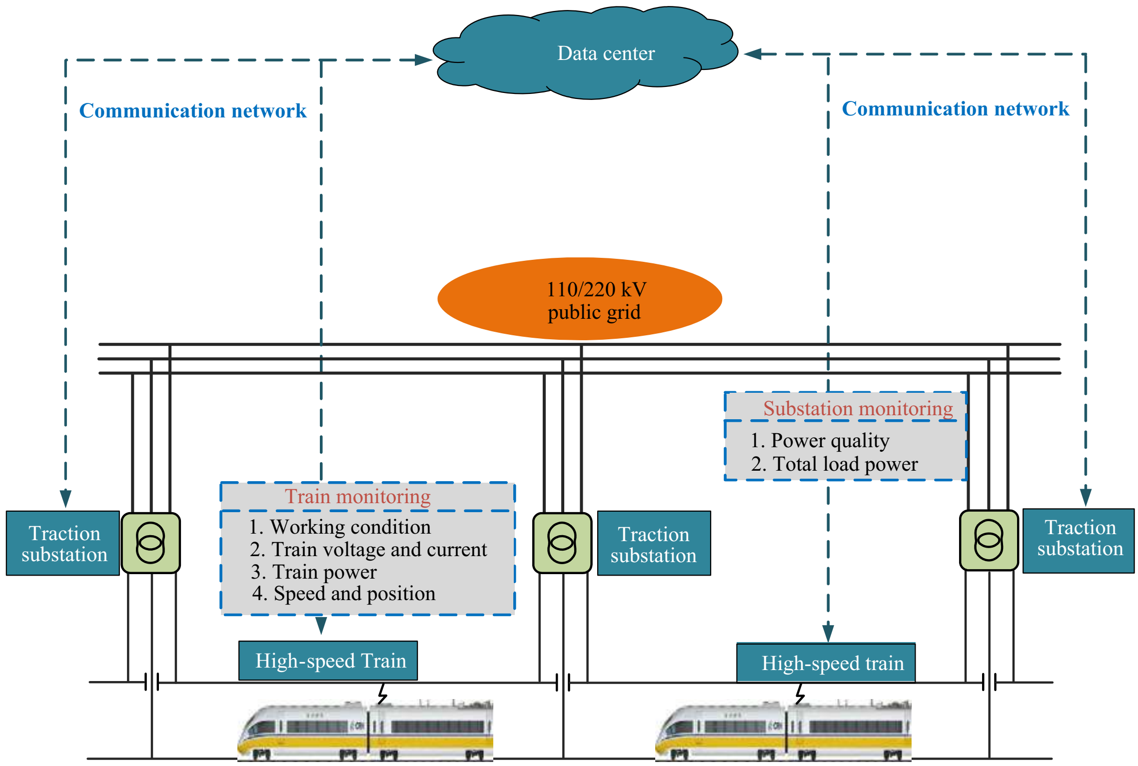


Fig. 1 Overall structure of the railway monitoring and assessment system

(4) Data visualization layer realizes the display of data by data communication and establishes a local Apache server. Its main function is to realize the online monitoring of data and statistics for related indices.

3 Data collection layer

The data collection layer mainly implements the synchronous data acquisition and data fusion from each measured point, including monitoring units and various sensors. The function of the sensors is to realize the transformation of the signal to facilitate the data collection by monitoring units, including voltage sensors, current sensors, radar, inertial measurement units, the BeiDou Navigation Satellite System or GPS.

For the collection of electrical data, voltage and current sensors can convert the high-voltage and large current signals of measuring points from the high-speed train and traction power supply system into small signals that can be measured by monitoring units. To improve the accuracy of data collection, high-accuracy sensors should be selected.

Speed sensors can measure the real-time speed of a train and then calculate the mileage. With the use of various sensors, this system can not only measure the electrical information (voltage and current) of the train-network system but also monitor the running speed, trajectory and mileage of the HST.

In addition to these sensors, monitoring units are also required to realize real-time data processing and data fusion. In IEC61000-4-30, three levels (A, S, and B) of measurement methods are classified according to power instruments [20].

The monitoring unit receives the small current or voltage signal corresponding to the measured electrical signal from the sensors at each measuring point, converts these signals into a voltage signal with an appropriate amplitude through the conditioning circuit, and then performs analog-to-digital conversion through a high-speed multichannel parallel acquisition card. Finally, the signal is transferred to the central processing unit for calculation, display, storage and communication.

The monitoring unit uses GPS for timing and positioning with functions such as conditional recording, local data storage, and data communication. It can be flexibly configured on software and hardware to match various sensors on site. Its monitoring of energy consumption complies with the EN50463 (IEC62888) standard, and the calculation methods of various indicators are in accordance with the relevant international measurement standards. The main module composition is shown in Fig. 3.

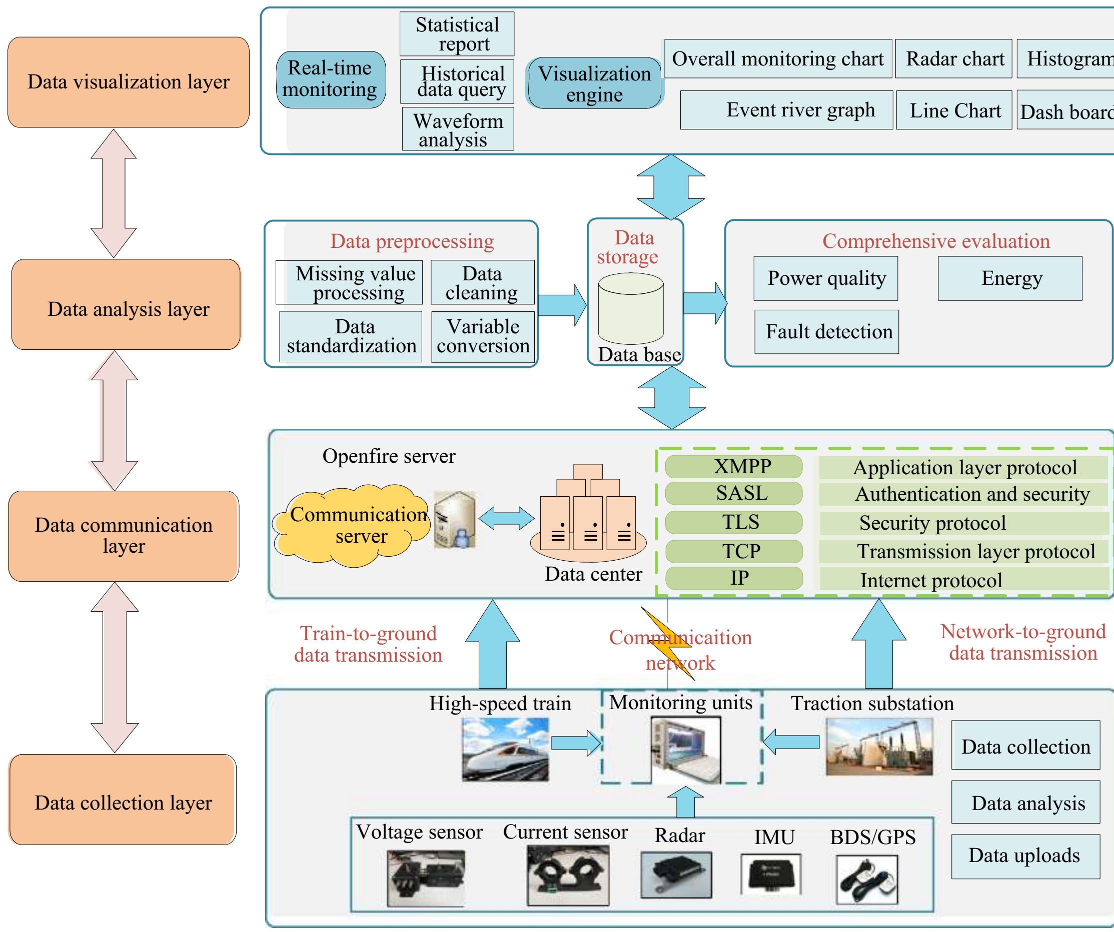


Fig. 2 Framework of the railway monitoring and assessment system

4 Data communication layer

In power system substations, the IEC 61850 standard is a commonly used communication protocol that divides the substation into a process layer, a bay layer and a station control layer to realize information sharing and interoperability between intelligent electrical equipment and ensure the seamless connection between systems and the consistency of each interface [20–22].

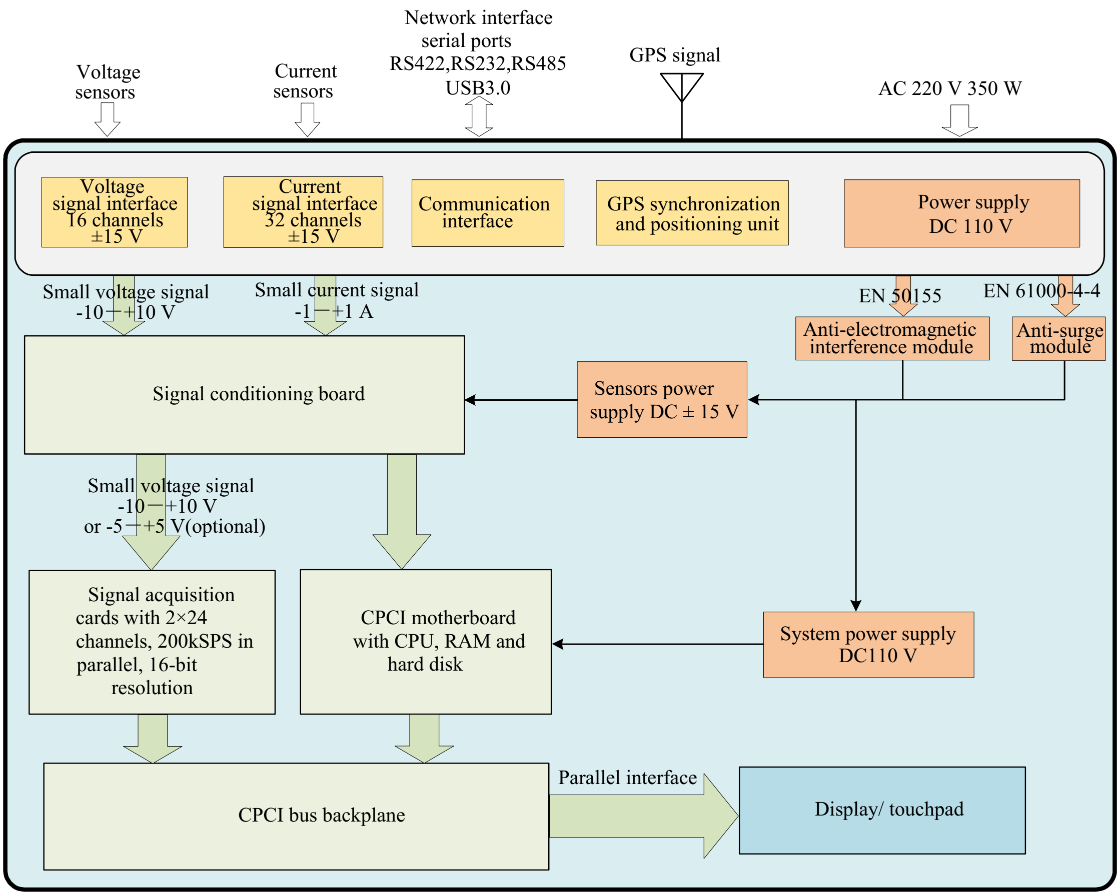
However, IEC 61850 is only suitable for fixed substation monitoring and cannot handle the data transmission of mobile trains well. For mobile communication on high-speed trains, poor communication quality caused by various factors (such as high-speed movement, signal dead zones, and wireless interference) should also be considered. Therefore, it is necessary to build a real-time communication network for this system to realize synchronous data transmission over a wide area.

To achieve remote data transmission, we need to deploy a data center on a cloud server so that the data center can be accessed by directly accessing the fixed IP of the cloud server, as shown in Fig. 4. Since the solution deploys all databases and web servers in the cloud, the development process is relatively simple, and the amount of data processing is relatively small. However, higher requirements are placed on the bandwidth and capacity of the cloud server since all the data are aggregated on the cloud server.

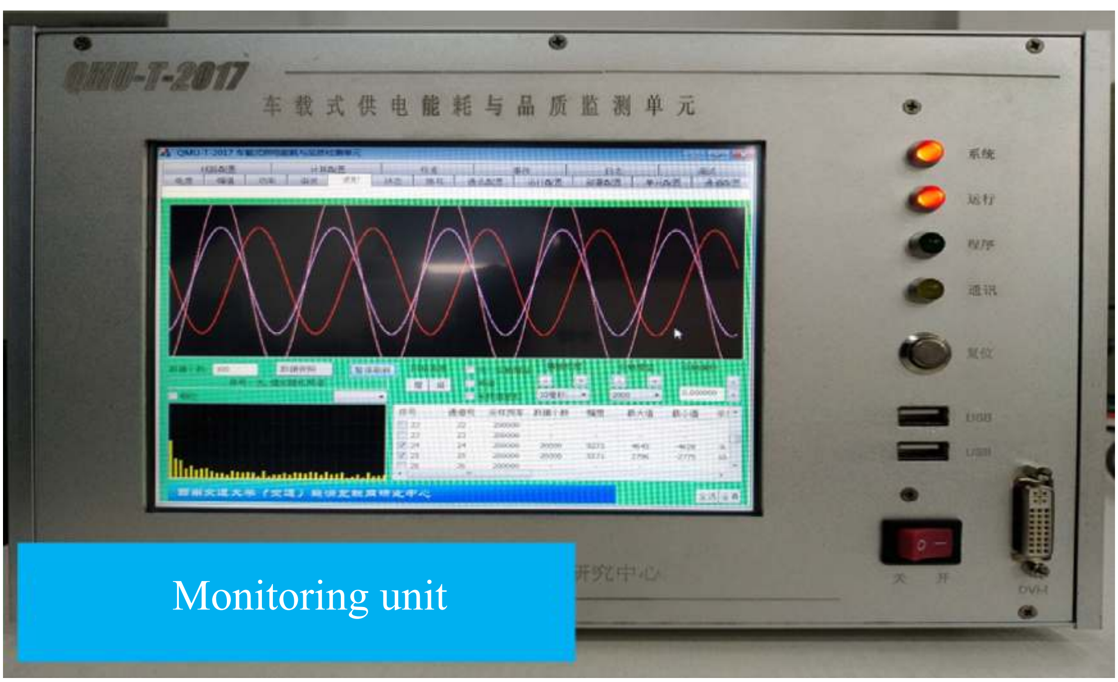
This work improves the above communication method. We design a communication protocol based on the structure of a client/server (C/S), and its core feature is message transmission based on the extensible messaging and presence protocol (XMPP) and openfire server. Its communication network topology is shown in Fig. 5.

In this improved communication network, the information transfer between two clients is based on the communication server as a transit station. In other words, to realize the transmission from the monitoring unit to the data center, it is necessary to establish a connection with the communication server first, then send the message to the communication server, and the server will forward the data.

This improved communication architecture has the following advantages.



(a) Hardware block diagram of the monitoring unit



(b) Device of the monitoring unit

Fig. 3 Monitoring unit system

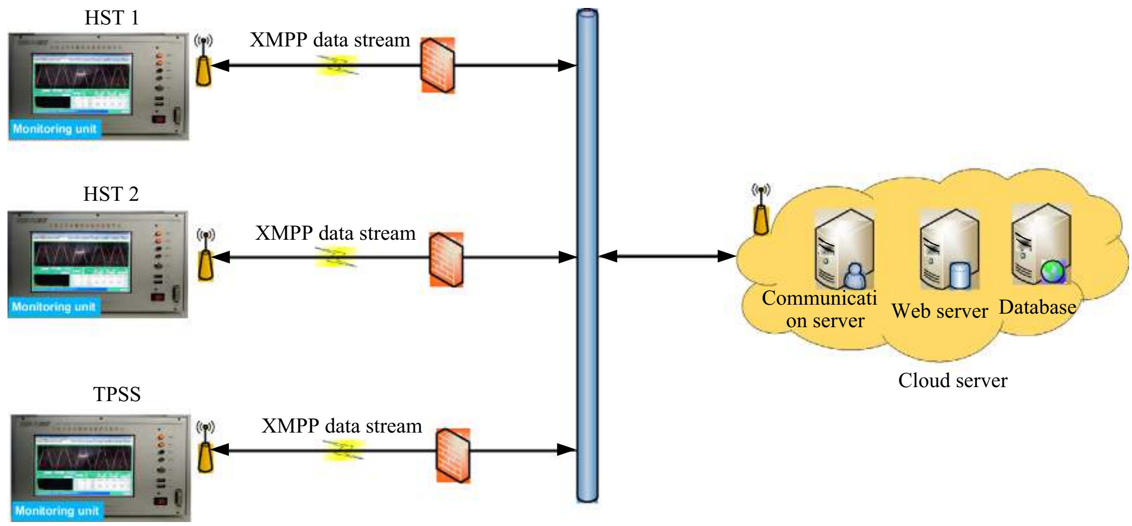


Fig. 4 Communication mode of data center deployed on cloud server

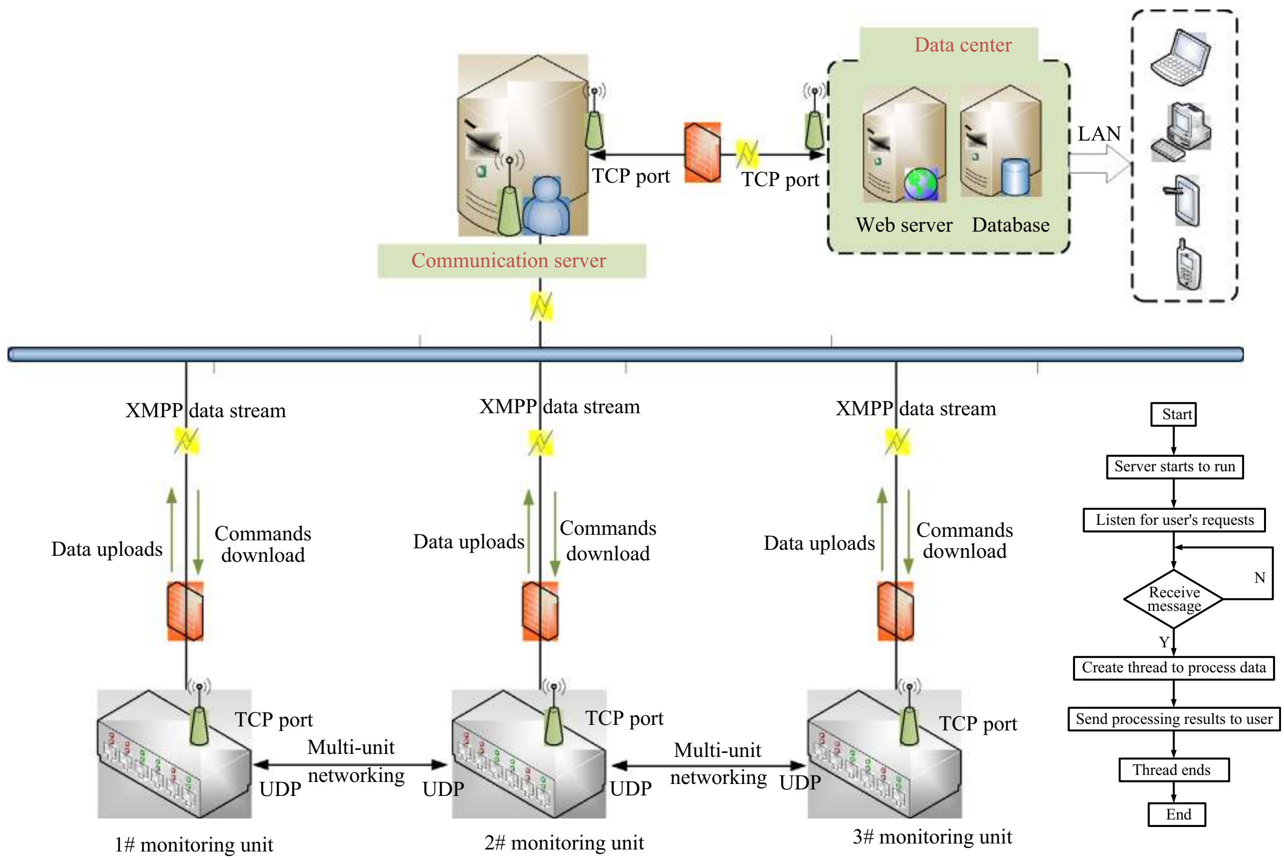


Fig. 5 The communication architecture of the railway monitoring and assessment system

(1) It avoids massive storage of data in the cloud and reduces the risk of data leakage.
(2) The capacity requirements of the cloud server are not strict because the cloud server does not save data and is only responsible for transferring data.
(3) Because the data center is deployed locally, the development costs can be controlled.

In this communication method, each monitoring unit and data center are regarded as an individual. The data are transmitted to the cloud server from monitoring units to the cloud server, but the cloud server does not save the data and functions as a transfer station. After obtaining the data from the cloud server, the data are stored in the database and then published through the Apache server. The data center can support a variety of terminals connected to the Internet as well as LAN devices.

The principle of instant communication is based on the transmission control protocol (TCP) and user datagram protocol (UDP). Both are communication transmission protocols built on lower-layer IP protocols. The former divides and packs the data in the form of a data stream and then establishes a virtual circuit between the two machines to carry out continuous and bidirectional data transmission, which strictly guarantees the correctness of the data transmission. The latter, in the form of datagrams, does not require the arrival sequence of the split data, so its reliability of data transmission is lower than the TCP. Therefore, to ensure the accurate and error-free transmission of data, the TCP is used for long-distance communication between trains (substations) and data centers. The UDP is suitable for multiple unit networking, thus enabling the measurement module to use measurement data at more points, and it also enables data statistics to cover more comprehensive data.

Each logged-in monitoring unit needs to establish a stable TCP connection with the communication server. All messages and data sent from the monitoring unit to the data center must pass through the communication server. The communication server described here is based on Openfire secondary development program, which can realize the parallel processing of file transmission and text communication. Among them, the real-time monitoring results are transmitted in the form of instant messages, wave recorder data, and configuration information that can be transmitted in the form of files.

Considering the reduction of pressure on the communication server and the capacity of the data center, as shown in Fig. 6, for the data with a small amount of monitoring results and status information, the method of uninterrupted transmission is used, and for the recording file, the method of transmission after inquiry is used. This method can improve the overall transmission efficiency of the system.

The communications between the data center and monitoring units comply with the EN50463-4 standard. The main performance indices of the data center are listed as follows.

(1) Ethernet communication rate $\geq$ 100 Mbps.
(2) Maximum number of simultaneous online monitoring units $\geq$ 64.
(3) Historical data retrieval time $\leq$ 10 s.

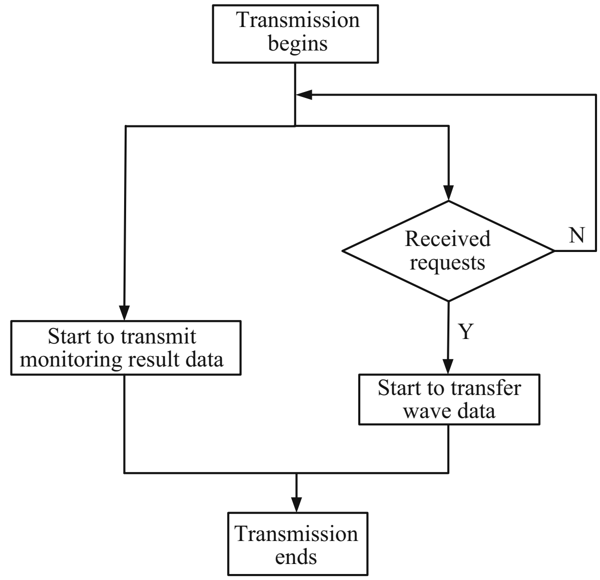


Fig. 6 Data transmission strategy

(4) Man–machine operation response delay time: $\leq$ 3 s.
(5) Mean time between failure: 15,000 h.

5 Data analysis layer

In the railway monitoring and assessment system, the voltage, frequency or current deviation that affects the normal operation of a TPSS should be monitored and recorded. In addition to collecting real-time waveform data of voltage and current according to demand, the monitoring units also need to record relevant statistical indices. Each power quality problem involves many feature quantities, and there are often many monitoring points in the entire monitoring system. The recorded data include both real-time and historical data; so the data are undoubtedly extremely large.

The information collected by the data center comes from different monitoring units. Due to transmission delays and differences in different monitoring units, these data often appear as incomplete and inconsistent dirty data, and subsequent data processing and visualization cannot be carried out. Although the data accuracy can be improved through a higher-resolution sensing device [23] and better detection algorithms [24], it cannot fundamentally solve the errors caused by differences. To ensure rapid and real-time data transmission and to achieve the integrity and unity of data from different monitoring units, it is necessary to preprocess the data before transmission.

Reasonably layering and standardizing the monitored data are necessary methods to increase the data processing

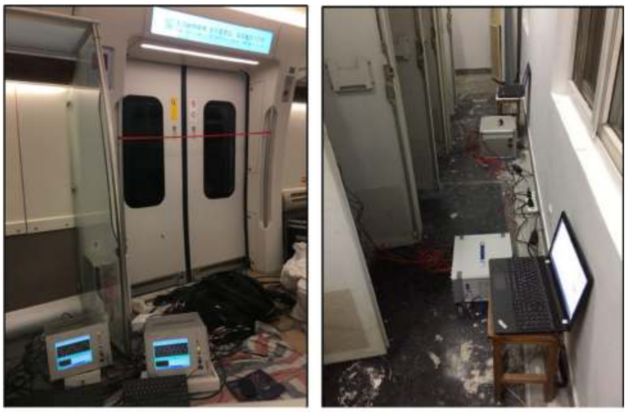
Table 1 System index hierarchy

Power quality indices	1. Power supply safety: (1) Voltage amplitude/deviation; (2) Voltage fluctuation; (3) Flicker; (4) Negative sequence voltage/unbalance; (5) Zero-sequence voltage/unbalance; (6) Negative sequence current; (7) Over-voltage identification; (8) Under-voltage identification; (9) Voltage swell identification; (10) Voltage sag identification; (11) Short-term interrupt identification; (12) Traction transformer secondary voltage; (13) No-load voltage/load voltage of traction network; (14) Primary current amplitude/proportion of traction transformer; (15) Current amplitude/proportion of primary side of traction transformer; (16) Current amplitude/proportion of secondary side of traction transformer; (17) Feeder current amplitude/proportion; (18) Traction network voltage loss; (19) Rail current. 2. Train-Network interaction: (1) Power system frequency deviation; (2) Power system harmonic voltage content rate/background harmonic voltage content rate/THD; (3) Power system interharmonic voltage content rate (4) Traction network harmonic voltage content rate/background harmonic voltage content rate/THD (5) DC bias of traction transformer; (6) Harmonic magnification; (7) Harmonic impedance distribution; (8) Resonance risk indicators; (9) Low-frequency fluctuation identification for network voltage; (10) Harmonic resonance identification; (11) Harmonic instability identification.
Energy indices	1. Energy supply: (1) Active power/electricity of traction substation; (2) Reactive power/electricity of traction substation; (3) Apparent power of traction substation; (4) Power factor of traction substation; 2. Energy consumption: (1) Total energy consumption of train; (2) Traction subsystem energy consumption and its proportion of trains. (3) Air conditioning subsystem energy consumption and its proportion of trains, (4) Auxiliary subsystem energy consumption and its proportion of trains. Among them, energy consumption includes power and electricity. 3. Energy loss: (1) No-load loss of traction transformer; (2) Load loss of traction transformer; (3) Capacity utilization of traction transformer; (4) No-load loss of traction network; (5) Load loss of traction network. 4. Energy storage: (1) Reverse active power/active power of traction substation; (2) Regenerative energy and energy returning mode of train; (3) Utilization rate of regenerative energy of trains on the same power arm; (4) Proportion of regenerative energy returned to the grid by trains. 5. Transfer efficiency of energy: (1) Traction transformer transfer efficiency; (2) Traction network transfer efficiency; (3) On-Train transformer transfer efficiency; (4) Converter transfer efficiency.
Fault detection	(1) High-resistance grounding fault identification of traction network; (2) Short-circuit fault identification of traction network; (3) Duration of failure; (6) Incidence of catenary failures; (7) Failure rate of traction transformer; (8) Mean time to repair.

rate and realize real-time data transmission. To evaluate the operational quality of the train-network system more comprehensively, it is necessary to classify the monitoring indicators in detail. The evaluation indicators of the train-network system operation quality index should include the following:

(1) The indices must be able to reflect the structure, characteristics, and operating conditions of the train-network system.
(2) The indices should and can be calculated from the historical data collected by monitoring units.
(3) The indices can reasonably predict and evaluate the potential failure of a TNS.

In view of the above three points, an evaluation index system for a TNS can be established. The monitoring unit receives the recording data of the voltage and current sensors from each measuring point and obtains the corresponding indices through the existing relevant standard algorithm. Table 1 divides the indices into three different types: power quality indices, energy indices and fault detection. The power quality indices mainly include power supply safety and train-network interaction; and energy indices include energy supply, energy consumption, energy loss, energy storage, and energy transferring efficiency.



(a) Train monitoring **(b)** Substation monitoring

Fig. 7 Monitoring platform connected to the train and substation

6 Application example

To evaluate the power quality and energy consumption of a high-speed railway line in China, as shown in Fig. 7, traction substations and moving trains were tested. Monitoring units were deployed on the substations and trains to collect the high-frequency voltage and current data of each

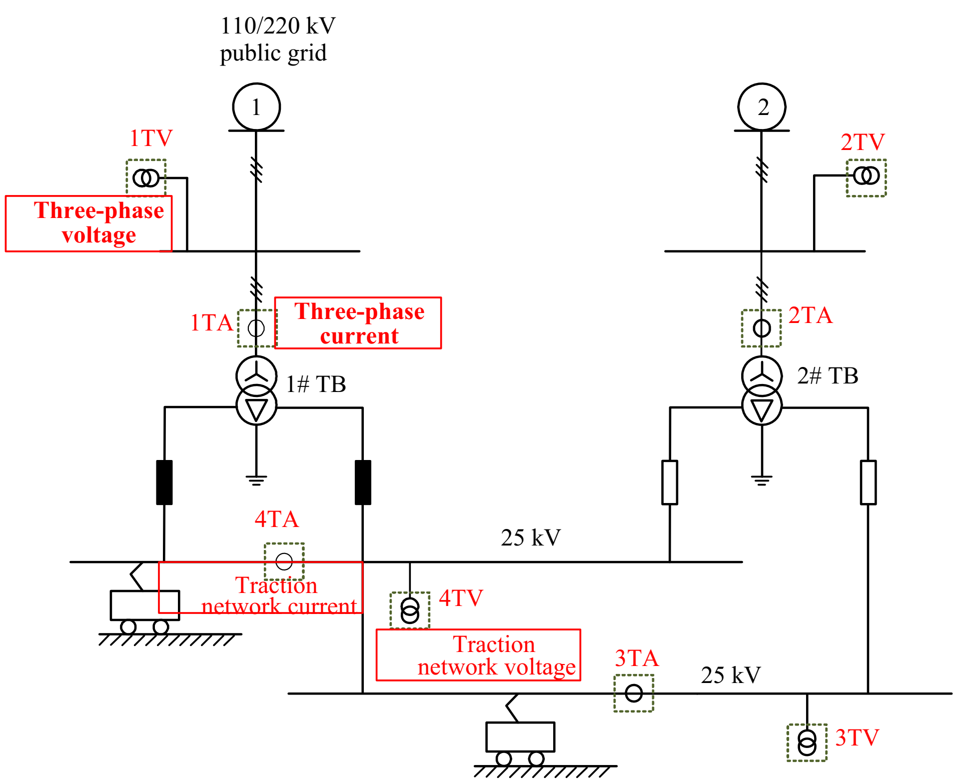


Fig. 8 Schematic diagram of measured points at substation

measuring point. The confirmation of measuring points needs to be based on the specific situation of the monitoring task, mainly on-site investigation, supplemented by design drawings and other description files, and the location and electrical characteristics of the measured electrical quantity need to be confirmed.

A schematic diagram of the measured points of the substation is shown in Fig. 8, and the measured electrical quantities are shown in Table 2. The three-phase voltage and current were mainly tested on the grid side. The traction side mainly tested the feeder voltage and current.

The dynamic changes in the three-phase voltage are shown in Fig. 9. The all-day statistical results of the traction network bus voltage harmonic spectrum are shown in Fig. 10. It can be seen in figures that the harmonic spectra with higher harmonic content of the three-phase voltage are the 5th, 11th, 13, 47th, 77th, 95th, and 97th harmonics, and the 13th harmonic has the highest content. The 13th harmonic voltage content rate of phase A is 1.024%, which is close to the 1.6% specified in the harmonic standard.

In terms of energy consumption, the active power and power factor of phase A are shown in Figs. 11 and 12. Figure 12 represents the change of phase-A power factor monitored by traction substation with 24 h. When there is no train running at night, the power factor is basically maintained at 0, but when there are more trains running during the day, the fluctuation of the power factor is also relatively large.

At the same time, at the remote data center, the monitoring results and energy consumption statistics can be observed in real time, as shown in Fig. 11.

Table 2 Electrical quantity measured for substation

Electrical quantity	220 kV	27.5 kV
Voltage	U_A, U_B, U_C	U_{T1}, U_{F1}, U_{T2}, U_{F2}
Current	I_A, I_B, I_C	I_{T1}, I_{F1}, I_{T2}, I_{F2}

Note: Subscripts T and F stand for catenary and positive feeder, respectively

7 Conclusions

Different from the monitoring system of the power grid company, the monitoring system of the traction power system should not be limited to monitoring the traction power supply system [23–25] but should combine the TPSS and HST to analyze power quality issues and

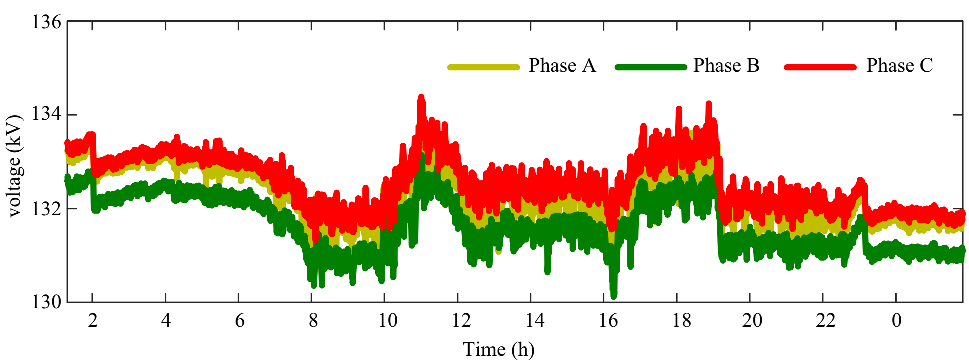


Fig. 9 Dynamic changes in the three-phase voltage

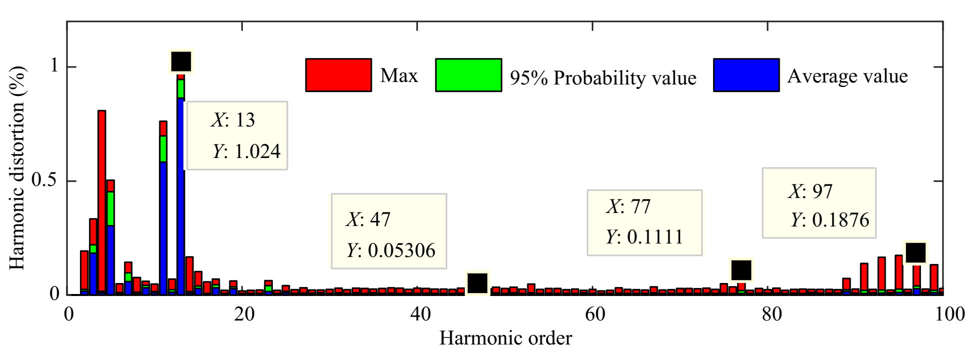


Fig. 10 Bus voltage harmonic spectrum of the traction network

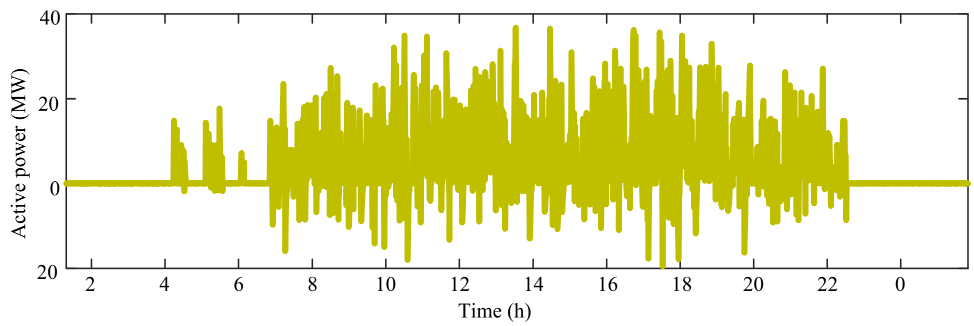


Fig. 11 Active power of phase A

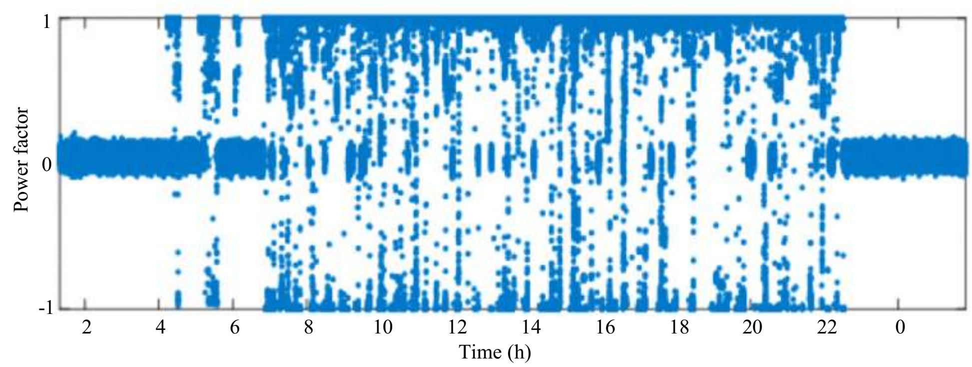


Fig. 12 Power factor of phase A

formulate power-quality monitoring system standards for high-speed rail traction power supply systems as soon as possible.

Our ultimate goal is to build an index library based on measured data to achieve a comprehensive evaluation of TPSS operations. As the technology of big data and artificial intelligence advances, its application in the service performance of TPSSs, electrical coupling performances of train-networks, and health diagnosis of traction systems will be strengthened.

With this system, it is possible to study the power transmission efficiency of each electrical link. We can explore ways to improve the power utilization rate of the system, and realize the overall energy consumption improvement of the train-network system. At the same time, combined with TPSS and HST power quality monitoring data, the integrated management and evaluation of the power quality of train-network system can be realized, thereby realizing the optimization and improvement of power quality.

It is also possible to study the changing laws and influencing factors of the impedance/damping of train-network system with parameters changing. We achieve a good match of train-network system.

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