

Research and application of diagnosis methods and devices for urban rail traction systems

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Abstract

Purpose – With the deepening integration of rail transit systems—encompassing urban rail, regional railways, trunk lines and medium-low capacity transportation—the four-network integration imposes higher demands on operation and maintenance systems regarding cross-modal coordination, full-element interconnectivity and dynamic responsiveness.

Design/methodology/approach – This paper, based on policy directives and engineering practices, analyzes the operational maintenance characteristics of urban rail traction systems from perspectives including device interconnectivity and fault data mining. A non-intrusive high-frequency diagnostic device independent of vehicle control is proposed, informed by practical onboard operation experience. This innovation significantly enhances diagnostic accuracy for components requiring high sampling frequency, while integrating “Flash” storage with far greater capacity than conventional control chips.

Findings – This article will systematically introduces the key points and diagnostic methods for typical faults in urban rail traction systems. Through rational diagnostic algorithms combined with high-precision, high-storage diagnostic instrumentation, the overall safety and reliability of urban rail traction systems have been improved. The proposed non-intrusive high-frequency diagnostic solution has been validated across multiple rail lines.

Originality/value – This paper introduces an innovative non-intrusive diagnostic device with a dual-channel design for multi-system compatibility and a high-speed acquisition architecture enabling 400 kHz sampling. Its originality stems from the independent, high-fidelity capture of microsecond-level transient faults like IGBT shoot-through and pantograph arcing; Validated in operational environments, this approach provides a significant leap in diagnostic precision, directly enhancing traction system availability and operational safety by enabling precise fault localization and intelligent, adaptive protection strategies.

Keywords VVVF converters, High-frequency data acquisition, Edge storage, Fault pattern mining

Paper type Research article

1. Introduction

With the rapid development of China’s rail transit industry, 58 cities in the country have initiated rail transit operations, with a total mileage exceeding 12,000 kilometers and 361 routes. The increase in mileage has surpassed 8%, in the same time, a total mileage of 5,800 kilometers is under construction. According to [China Urban Rail Transit Association \(2025\)](#), during the year 2024, the passenger volume exceeded 30 billion trips, as the total mileage and the passenger



volume steadily increase, the number of vehicles in operation within urban rail systems is also on the rise, posing greater challenges to the reliability and safety of traction system components.

1.1 Literature review

The fault diagnosis function of urban rail traction systems has always been a top priority in the field of rail transit and other industry projects. Due to the complexity of maintenance and repair processes and the lack of effective early warning methods, there is a high demand for the accuracy and real-time capability of fault diagnosis (Wang, 2017). In the past several years, the development and application of advanced maintenance technologies, particularly for traction systems, are crucial for reducing costs and ensuring the safe and reliable operation (Xu *et al.*, 2021). Furthermore, an intelligent PHM-based operation and maintenance system for urban rail transit vehicles is designed and validated through testing, improving maintenance safety and economy while enabling intelligent fault diagnosis and health management (Nie, Shi, & Dai, 2022). In addition, Wang and Li (2023), explore the large language models (LLM) to revolute the rail transit PHM system, analyzing the cons and pros of the LLM in the PHM field. Wang and Yao (2023), proposed a PHM technique in nuclear electrical system, using data analysis and processing method to locate the main fault types, significantly enhancing the safety and maintenance efficiency through the implementation of the predictive model.

With the development of the artificial intelligence algorithm, big data and cloud computing, the Digital-Twin model has become a cutting-edge method in rail transit traction system, it typically constructs a virtual mirror of the traction system, combining real-time data and simulation technology to provide dynamic, proactive and high-precision technical support for the diagnosis and early warning of urban rail traction system (Xin, Pei, & Wang, 2023), especially in defection area, by using LLMs, Ferdousi (2025) achieves high accuracy in visual defect inspection. As an emerging technology, achieving precise localization of abnormal data, real-time prediction of equipment lifespan and fault scenario simulation using actual vehicle data will offer effective technical methods for optimizing traction system control strategies and enabling accurate fault diagnosis (Song, Zhang, Ye, Zhang, & Zou, 2023). In addition, Zhang, Du, Zhang, and Wang (2021) explore the application of digital twin technology in rail vehicle health management by proposing a management architecture, outlining key modules and analyzing its workflow for fault prediction and maintenance decision-making. The high-voltage transient diagnosis is another challenge in traction system, as Sun, Qiu, and Gao (2019) have introduced a non-stop, sensor-efficient method for online IGBT voltage drop measurement using switching and voltage signals, enabling real-time fault detection and health monitoring for urban rail traction systems, which is highly relied on high-speed data recording device.

1.2 Requirements for the new diagnostic system architecture

In order to increase the system suitability, the traction system should support multi-system compatibility. Under different power supply modes, such as DC-750 V power shoe and DC-1,500 V pantograph, the fault characteristics vary significantly. To meet the demands of the new diagnostic system, the traction system requires additional diagnostic logic and device for components beyond the converter, an online health monitoring framework for traction motors using dynamically updated temperature signals is proposed, reducing prediction errors by 5–12% compared to traditional offline models and adapting effectively to real-time data streams (Dong *et al.*, 2022). Within the entire traction system, in addition to diagnostics related to the inverter circuit, it is also necessary to perform diagnostics on associated devices such as motors, braking resistors and high-speed circuit breakers. Meanwhile, standalone components and devices have totally difference interfaces, which make the system difficult to modify or reuse. In order to enhance the reusability, Shen (2024) proposed a new method to create a unified framework with universal interface. Furthermore, Nanjing Metro Line 4 has designed and implemented a new PHM framework in practice with new data collection and processing architecture, provides an application case for other urban rail transit maintenance projects.

1.3 Real-time hardware data recording requirement

Traditional fault data recording relies on controllers and dynamic data transmission (e.g. Controller area network (CAN) bus, Ethernet, multifunction vehicle bus (MVB), etc.). However, data loss or distortion may occur in the following scenarios:

High-voltage transient interference: electromagnetic pulses generated during insulate-gate bipolar transistor (IGBT) short-circuit events in converters may cause communication controller failure. In practice, IGBT module drivers share a common $\pm 24\text{V}$ power supply with controllers, using an isolate DC-DC converter chip to achieve the core function. A failure occurs on the driver board's power circuit, would propagates back to the main controller, causing a brownout or complete reset of the controller, which would also ending up with loss of critical fault data, due to the controller's RAMs and register's sudden power loss.

Instantaneous control power interruption: during pantograph flashover or power supply switching, the control system may experience brief power loss, resulting in erroneous and unreliable recorded data. The past research mainly focuses on the arc spectrum distribution (Yu & Su, 2020), the origin of the lightning flashover (Cao *et al.*, 2021), or the electromagnetic characteristic of catenary contact loss (Yang *et al.*, 2023).

High-frequency data signals: the interrupt cycle of existing controllers operates at the kHz level, leading to severe distortion in recorded data for pulse signals and high-frequency grid voltage resonance, which are at the hundred-microsecond level, making accurate fault condition judgment impossible (Jiang, 2019). Tang, Zhou, Guo and Zhuo (2024) designed a monitoring system for rail transit with Internet of Things, which sample rate is up to 2 kHz and use embedded GPS for real-time tracking, performs a significant effect in the area of crucial vibration acceleration data collecting.

2. Urban rail traction systems components characteristic

2.1 Composition of urban rail traction systems

Urban rail traction systems are generally referred to as variable voltage variable frequency (VVVF) inverters, which are devices capable of varying both voltage and frequency in electrical control and regulation. They are primarily used to adjust the voltage and frequency of AC electric motors to control motor speed and torque. Urban rail traction inverters typically consist of several main components:

- (1) Parallel motors: driven by inverter IGBTs, motors are the main power source in urban rail transit, responsible for converting electrical energy into mechanical torques.
- (2) Inverter power IGBTs: activated based on control signals, it converts the intermediate DC current into variable-frequency AC current. The inverter provides adjustable voltage and frequency to drive the motor as needed.
- (3) Intermediate DC circuit: used for energy storage and smoothing input current waveforms. The intermediate circuit is typically composed of parallel-connected support capacitors and series-connected reactance.
- (4) Control unit: responsible for logic processing of the entire inverter system and control of the inverter power module. The control unit typically includes multiple microprocessors or digital signal processors and, in addition to control, it also handles communication with the onboard network system and fault diagnosis work.

2.2 Application characteristics of urban rail traction systems

- (1) High efficiency and energy savings: through variable frequency control and energy feedback technology, urban rail traction systems can achieve efficient energy utilization and recovery. In actual operation, under the direct current power supply

mode, all trains draw power from the same DC power supply arm. Different vehicles can utilize the energy from electric braking, effectively reducing energy consumption and emissions in line operation.

- (2) Higher brake control requirements: urban rail operations often involve frequent starts and stops between stations, with less continuous running in high-power zones. Considering passenger riding experience and brake longevity, urban rail traction motors may employ techniques like electric braking to reduce impact and decrease the frequency of mechanical braking usage.
- (3) Quick traction response and good acceleration performance: urban rail systems frequently start and stop with small distances between vehicles. To ensure precise timing during operations and maintain high efficiency, there are higher demands for the dynamic traction performance of the motors.
- (4) Fewer sensors with high control requirements: urban rail traction systems have limited space available due to their small size. Additionally, urban rail traction motors often lack active cooling and temperature sensors, posing a certain challenge for motor control.

3. Urban rail traction system diagnosis and challenges

3.1 Complexity and diversity of urban rail traction system diagnosis

The basic structure of the urban rail traction inverter is shown in Figure 1, and its diagnostic methods, as categorized in dashed boxes 1–4 in the figure, can be divided into the following:

3.1.1 Pantograph-catenary anomaly diagnosis in traction systems. A multiple-unit train on a newly built line in Tianjin experiences pantograph arcing with the overhead catenary when operating in reverse direction (i.e. running downward on an upward track or running upward on a downward track). This arcing occurs under both traction and braking conditions. During braking, where energy is regenerated back to the power grid, the under-voltage condition does not cause significant impact. However, under traction conditions, the higher power demand leads to faults such as under-voltage alarms, resulting in traction system shutdown.

To address this operational scenario, the controller must be able to recognize the voltage and current waveforms characteristic of arcing to initiate appropriate protective measures, the core technical methods may include below:

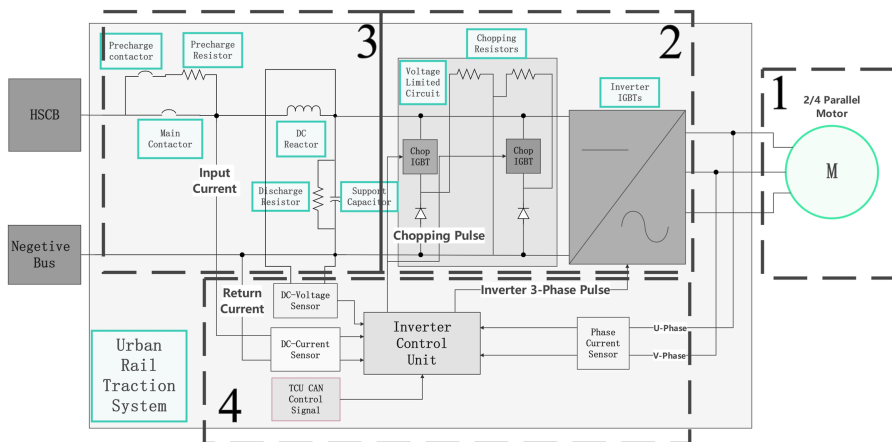


Figure 1. Metro traction system basic architecture. Source: Authors' own work

- (1) **High-Fidelity Data Acquisition:** The system must be equipped with independent high-frequency data recorders (as outlined in [Section 1.3](#)) to capture transient waveform characteristics of arcing (e.g. microsecond-level voltage dips, high-frequency oscillations) with a sampling rate far exceeding that of standard controllers. This is essential to avoid data aliasing and loss caused by electromagnetic interference or power interruptions.
- (2) **Intelligent Waveform Recognition Algorithms:** The controller must employ advanced algorithms (e.g. neural networks, as mentioned in [Section 1.1](#)) to analyze the acquired data in real-time. This enables precise differentiation between arcing patterns and waveforms from normal operations or other fault conditions (e.g. short circuits).
- (3) **Adaptive Protection Strategies:** During traction mode, the system should implement a graded response. Instead of an immediate shutdown, initial actions may include a motor torque reduction to attempt maintaining operation through the faulty section. A full system halt is only executed if the anomaly persists or worsens; During Braking mode, the chopping resistor should put into operation immediately, to absorb the motor energy in order to avoid DC link overload.
- (4) **Leveraging Digital Twin Technology:** Digital Twin models (as described in [Section 1.1](#)) can be utilized to simulate fault scenarios, refine recognition algorithms, optimize protection parameters and potentially enable predictive maintenance by analyzing trends from historical operational data.

3.1.2 Chopping and inverter module faults.

- (1) **Direct bypass fault:** this type of fault is often severe and can result in module explosion if triggered due to control failure or abnormal driving. Therefore, the diagnosis of such faults requires a high sampling rate, typically on a nanosecond scale, to detect direct bypass. Once direct bypass is detected, pulse blocking operations are immediately initiated to prevent harm to the module.
- (2) In practice, to avoid unexpected high voltage when blocking PWM pulse due to the back electromotive force generated by DC reactor, as shown as in [Figure 1](#).
- (3) **Module overheating and cooling system faults:** the temperature of the modules inside the inverter is estimated based on the specific air temperature inside the cabinet, and there is a temperature difference from the actual junction temperature. Determining the protection range involves temperature rise, line tests and environmental temperature and is closely related to operational experience. The inverter's internal cooling relies mainly on forced air cooling, which is greatly influenced by ambient temperature and airflow. Designing protection values faces significant challenges, as it needs to adapt to various operating environments.

3.1.3 Contactor and DC main circuit faults. The diagnosis of contactor faults primarily aims to identify control feedback anomalies, abnormal closing times and excessive switching. This diagnosis is mainly intended to protect the service life of temperature-sensitive components in the main circuit, such as pre-charge resistors and resonant inductors. Frequent contactor actions can potentially cause permanent damage to these electrical components, thereby affecting the performance of the entire traction system.

4. Urban rail traction diagnostic device

4.1 Characteristics of urban rail traction system diagnostic devices

To overcome the main controller fails in some extreme operating conditions (e.g. crashes, loses power, or suffers from software exceptions) and becomes incapable of recording data, an independent data recorder is indispensable to provides critical support. Its key advantages are:

- (1) Independence and reliability of data recording: the diagnostic device features its own power supply management, dedicated processor and storage. Its operation is completely independent of the main controller's status. Even if the main controller crashes, the recorder continues to function. It continues to capture critical parameters to guaranteed data preservation (such as system status, DC voltage, AC output current, etc.) during and after the controller's failure. This provides the only data source for analyzing why the controller failed and how the system behaved afterward.
- (2) High-Fidelity and resilience: as previously mentioned, these independent units typically boast higher sampling rates and superior immunity to electromagnetic interference (EMI). In scenarios where a controller might crash due to high-voltage transients (e.g. an IGBT short-circuit), the independent recorder can withstand the interference and accurately capture the exact waveform of the fault event, as opposed to recording distorted data or stopping altogether.
- (3) Enhanced post-event analysis and accountability: "Black Box" functionality: like an aircraft's flight recorder, it preserves the most complete and authentic data from the most severe failures. This provides an indisputable data trail for engineers to perform root cause analysis (RCA), pinpointing whether the failure was due to the controller's own flaws or external extreme conditions (e.g. a massive surge current).
- (4) Supports system optimization: analyzing data from these extreme events allows for improvements in the controller's hardware and software design, enhancing its robustness and preventing future similar failures.
- (5) In summary, the paramount advantage of an independent diagnostic unit during controller failure is its "survivability." It ensures that the system's "final moments" are captured completely and accurately under the most severe fault conditions, transforming an unexplainable crash into a diagnosable and optimizable engineering event.

Therefore, independent storage devices are crucial in practical operation. Higher sampling frequencies and power-off protection ensure normal data storage. Additionally, large-capacity storage, far exceeding the internal memory of controllers, enables diagnostics for long-duration faults such as motor shaft breakage and IGBT open-circuit failures.

4.2 Architecture of urban rail traction system diagnostic device

In response to the precision and real-time requirements for motor fault diagnosis, a high-frequency data sampling and recording device with a sampling frequency as high as microseconds is proposed as [Figure 2](#). This device effectively assists in fault analysis, ultimately reducing the difficulty of frontline maintenance personnel's work, preventing accidents and improving component availability.

The conceptual diagram of the diagnostic device is shown in [Figure 2](#).

Analog data from sensors is digitized and continuously streamed via high-speed low-voltage differential signaling (LVDS) links into the RAM of the independent diagnostic device. This design provides high noise immunity, ensuring clean data capture even in electrically noisy environments, as pantograph arcing, fulfilling the need for a reliable independent data recorder.

The signal path from RAM to FLASH is the core of the "black box" functionality. The RAM acts as a continuous buffer. Upon a predefined trigger (e.g. a voltage dip characteristic of arcing), a critical window of data is automatically transferred from the RAM to the FLASH memory. Since FLASH is non-volatile, this data is permanently saved, even if a main controller fails or power is lost, ensuring that vital fault waveforms are never lost.

Moreover, the inverter control unit (ICU) has high-speed access to both the real-time data stream (RAM) and the recorded fault events (FLASH). Here, advanced algorithms (like neural networks) can analyze the data to identify fault patterns (like arcing) in real-time and initiate appropriate protective actions, such as a graded power reduction.

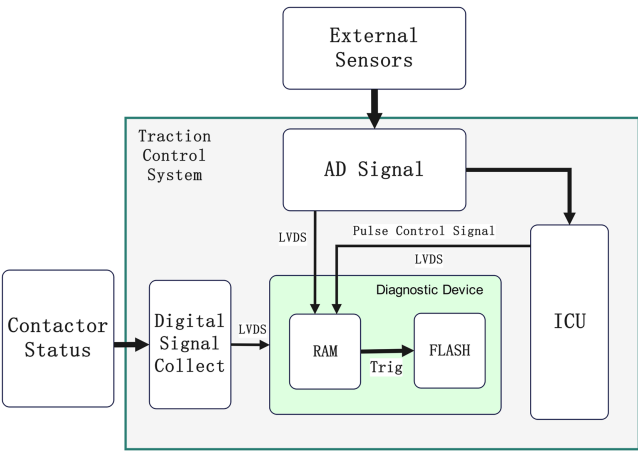


Figure 2. Metro fault diagnosis device architecture. Source: Authors’ own work

4.3 Data storage capability of the diagnostic device

Considering the high acquisition frequency required for pulse diagnosis and the need for long-term data storage, the diagnostic device’s data acquisition frequency is set in an adjustable mode. When a fault is triggered, it uses the highest frequency for storage. Under normal conditions, data can be stored slightly higher than the control board’s frequency for subsequent fault analysis.

In terms of storage hardware, fast storage devices such as random access memory (RAM) and non-volatile storage devices like FLASH or hard drives are used for data recording. The operation modes are designed as follows:

- (1) Data cache: RAM serves as a data buffer, storing all received data sequentially from the starting address. When RAM is full, it continues to overwrite from the beginning address until all RAM addresses are refreshed in a continuous loop.
- (2) Triggered recording: when pre-defined trigger conditions (fault triggers, manual triggers, etc.) occur, data is recorded for a pre-set duration, ranging from seconds to tens of seconds. It records data before and after the trigger until the recording duration ends.
- (3) Recording storage: after RAM’s storage operation stops, the data in RAM is read and written to non-volatile storage. In the diagnostic device, RAM’s read/write operations require high bandwidth and should be supported by a capable processor. It is advisable to use a co-processor or other dedicated hardware to avoid significant resource consumption by the main processor.

From practical application, based on the set storage resolution and the vehicle maintenance cycle, non-volatile storage should be able to continuously store data for at least two weeks. When exceeding the maximum storage capacity, newly generated records should overwrite the earliest records.

In the initial design, for easy configuration of recording duration, trigger conditions, etc., the format of the storage files should be easy to understand and analyze. This can be achieved by modifying a fixed configuration file for storage mode selection and the configuration file can be changed directly by logging in through FTP. The configuration file should include at least: configured sampling frequency, modifiable maintenance network IP address, ability to configure the board for trigger storage mode and continuous acquisition storage mode and the ability to allocate storage space flexibly by configuring the exclusion of any channel storage. For example, only store 1 channel out of N analog channels and only store 2 pairs out of M

pulse pairs, in which “N” and “M” are integers and far less than the total data have achieved by Railway Sciences the diagnose device.

Furthermore, when data storage is full, it can automatically start overwriting from the earliest data. Data storage can also utilize specific compression methods for fast local downloading via FTP.

5. Application of urban rail traction system diagnostic devices

5.1 Application of urban rail traction system diagnostic devices in operations

5.1.1 Pulse data analyze. Taking a Beijing line as an example, a train frequently reported a fault in one of its power module pins during operation. In the initial analysis, the cause of the fault could not be determined from the recorded fault data in the controller alone. The continuous module faults were causing the train to lose power, significantly affecting its operation. Furthermore, as this train was an older version and did not have a diagnostic device originally installed, a fixed device was temporarily added and a new version of control boards was installed to collect on-site operational data.

In practical applications, the minimum pulse turn-on time is on the order of 10 microseconds. Therefore, to capture complete pulse data, a sampling rate of at least 200 kHz is required. In the actual vehicle, the data recording performance of a pulse acquisition board with a 400 kHz sampling rate is shown in Figure 3 above. The figure completely records a pulse switching process of an asynchronous motor. From top to bottom, the six PWM signals for the three-phase motor currents are displayed, showing the transition from square-wave modulation to SHE3 (Selective Harmonic Elimination suppress 3-times Stator frequency, SHE3) modulation. The recorded data is distortion-free, with upper and lower switches maintaining symmetry. This provides reliable data support for fault analysis.

As shown in the data of Figure 4, this is a data graph of a traction inverter reporting a module fault during actual vehicle operation. The blue waveform represents the pulse control signal, while the red waveform shows the pulse feedback signal. The pulse data was captured at a sampling rate of 400 kHz. The anomaly in the feedback pulse is clearly visible, which explains the loss of traction capability encountered on-site and ultimately allowed for the fault to be pinpointed to the power module’s driver board.

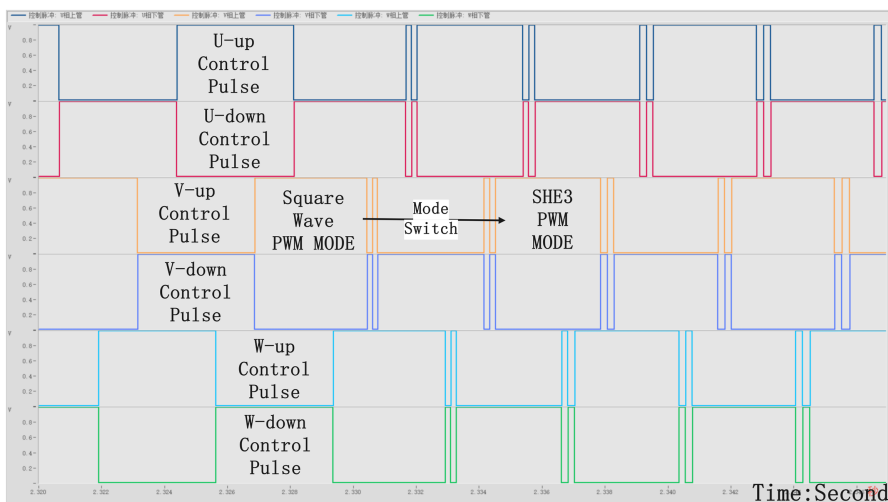


Figure 3. Pulse recording by fault diagnosis device. Source: Authors’ own work

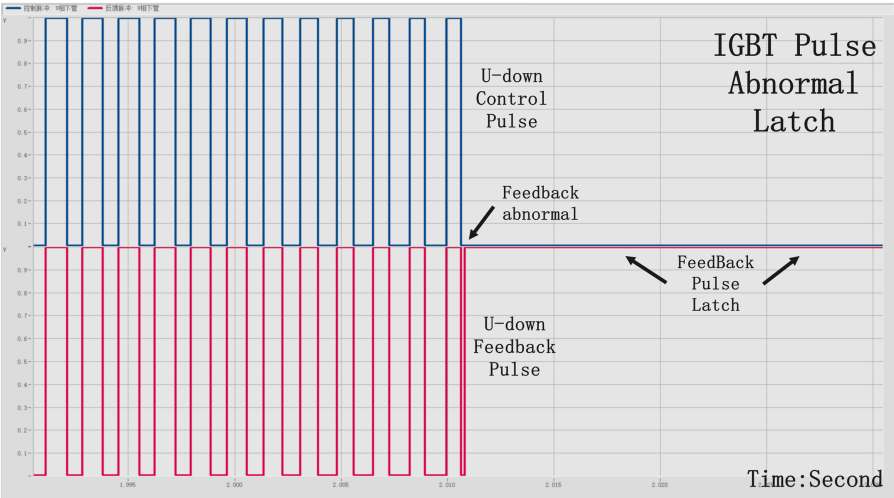


Figure 4. Pulse recording by fault diagnosis device. Source: Authors’ own work

5.1.2 *Diagnosis of pantograph-catenary arcing.* As described in Section 3.1, pantograph-catenary arcing events occurring in actual vehicle operation can lead to loss of traction capability, disrupting train service schedules. By analyzing vast amounts of data stored in the onboard diagnostic device, successful diagnosis was achieved by determining the rate of change of voltage and current, enabling timely identification based on arcing characteristics. The strategy of reducing the torque command was employed to mitigate the intermediate voltage drop, allowing the train to pass through the faulty section without triggering a system lockdown. The analyzed data is shown in the figure below:

The data in Figure 5 demonstrates that during the initial stage of the arc, the traction converter rapidly reduced the torque. This action maintained the intermediate voltage above

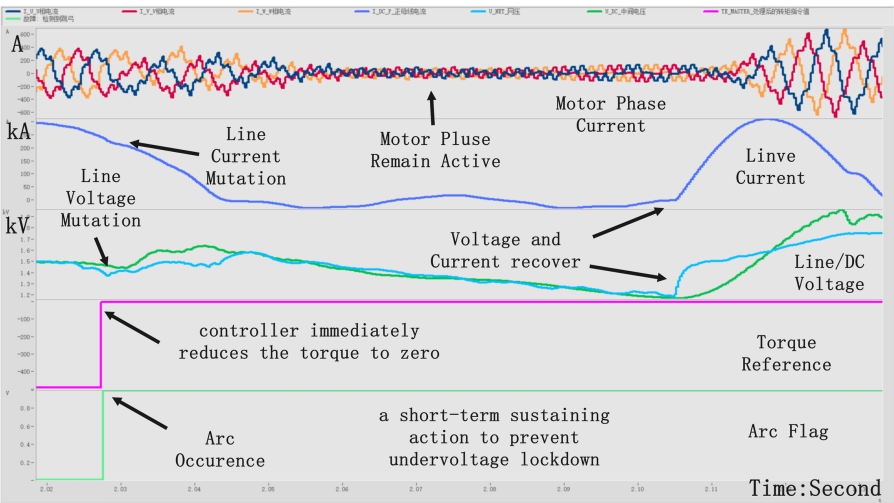


Figure 5. Diagnostic data under pantograph-catenary arcing conditions. Source: Authors’ own work

1,000 V, preventing an under-voltage fault from being reported. Simultaneously, the torque value was restored to its pre-arcing level within a short period. Railway Sciences

5.2 Necessity of retrofitting diagnostic devices in operations

- (1) **Fault Localization and Diagnosis:** Based on experience in actual operations, diagnostic devices for urban rail traction systems can help pinpoint the specific location and causes of system faults. They can provide higher sampling frequencies and longer data storage times, helping maintenance personnel quickly locate issues and take appropriate repair measures. This contributes to reducing various maintenance times and enhancing maintenance efficiency.
- (2) **Performance Optimization and Monitoring:** Urban rail diagnostic devices can monitor the performance parameters of the urban rail traction system in real-time, such as current, voltage and temperature. By continuously monitoring these parameters, the system's operational status and performance can be assessed. This allows for the timely detection of potential problems and adjustments to optimize the system for optimal performance.
- (3) **Safety and Reliability Enhancement:** Urban rail traction systems play a crucial role in daily transportation, carrying a large volume of passengers and operating for extended hours. Safety and reliability are of paramount importance. Traction system diagnostic devices can promptly detect potential safety hazards, improve system safety and enhance reliability through rapid fault localization features.

97

6. Conclusion and further development

Addressing pain points in today's urban rail transit traction systems, such as the use of the same train models on both new and old lines and tight maintenance schedules, the non-intrusive high-frequency diagnostic device and supporting methodology proposed in this paper have achieved the following results in validation across multiple lines:

- (1) **Enhanced Multi-System Compatibility:** Featuring an innovative dual-channel signal conditioning circuit, the system simultaneously supports both 750 V current collector shoe supply and 1,500 V pantograph supply, with automatic switching capability. During cross-network operation tests on the Tianjin Line 5 trial section, new trains successfully adapted to the power supply networks of both new and old lines. The system accurately identified intermediate voltage dips caused by contact network flashover (see [Figure 5](#)). Combined with a self-developed arcing characteristic library, it maintained pulse activation during brief contact network abnormalities, significantly improving traction system availability.
- (2) **Breakthrough in Diagnostic Precision for Core Components:** Leveraging 400 kHz sampling and ring RAM caching technology (cache depth ≥ 2 MB), the system enables the detection of microsecond-level anomalies in drive signals preceding IGBT shoot-through faults ([Figure 4](#)). On a newly built line in Beijing, it precisely pinpointed a fault involving abnormal pulse blockage caused by transient interference on a driver board.

Furthermore, there remains significant room for improvement in the diagnostic methods and devices for urban rail traction systems:

- (1) **Accuracy:** When dealing with complex faults, diagnostic algorithms relying solely on fixed thresholds face challenges in selecting appropriate values and accurately pinpointing faulty components. To enhance accuracy, developing advanced application algorithms is essential for achieving more precise fault location and diagnosis.

- (2) Fault Prediction and Health Management (PHM) Capability: Merely diagnosing faults after they occur does not reduce the overall fault rate. Developing fault prediction and health management capabilities is crucial. By monitoring system health, collecting and analyzing vast amounts of operational data, algorithms independent of the primary vehicle control logic can be designed to assess component degradation and failure risk. This can guide maintenance personnel and software developers in performing timely inspections and repairs, thereby reducing the failure rate.
- (3) Remote Big Data Systems: Urban rail traction systems operate for extended periods daily, generating massive volumes of data, including sensor readings, monitoring data and historical records. The storage capacity of onboard systems is orders of magnitude smaller than that of off-board servers. Efficiently managing and processing this data is vital for effective fault prediction and diagnosis. In the foreseeable future, more efficient data acquisition, storage and processing technologies, coupled with remote diagnostic platforms offering stronger real-time capabilities, will further reduce fault response times, making the diagnosis of urban rail traction systems more efficient and reliable.

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Further reading

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