

Research Article

A Design of ACDC Conversion Circuit Suitable for Trackside Safety-Oriented Digital Controllability

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Abstract

As a critical component of railway systems, existing trackside equipment relies on centralized indoor power supply screens for power. However, this configuration suffers from inherent drawbacks such as excessive cable lengths, high deployment costs, and significant voltage fluctuations. To address these issues and adapt to the distributed control scenarios of urban rail transit, this paper proposes a safety-oriented, digitally controllable AC/DC conversion circuit design tailored for trackside installation and miniaturization. Adhering to the "fault-safety" principle and "two-out-of-two" redundancy architecture, the circuit converts mains AC220V to adjustable DC output ranging from 24V to 200V. The module integrates a dual-processor control unit, power conversion circuit, voltage/current acquisition circuit, and weak current voltage conversion circuit. Key design features include electrical isolation via a high-frequency transformer, enhanced power conversion efficiency through phase-shifted full-bridge control, real-time monitoring of input/output voltage, output current, and board temperature, and bidirectional real-time communication with external devices. Notably, the circuit is designed to fail safely: in the event of abnormal acquisition signals or hardware malfunctions, the system automatically switches to a safe state with no power conversion output. To validate the design feasibility, a 1kW experimental prototype was fabricated and tested, with results confirming the effectiveness of the proposed solution.

Keywords

Trackside Equipment, AC/DC Conversion, Digital Controllability, Fault-safety, Distributed Power Supply

1. Introduction

As a critical component of the railway system, trackside equipment primarily comprises axle counters, point machines, signals, barrier machines, and track circuits [1-5]. With the rapid advancement of domestic railway construction, the power supply mode for trackside equipment has undergone significant evolution—shifting from the original dry-type transformer power supply to power screen-based power supply [6-10]. Nevertheless, the current power supply for trackside equipment still relies on a centralized indoor power

screen configuration, which gives rise to issues such as excessive cable length, high construction costs, and substantial voltage fluctuations [11-15].

To address these limitations and meet the distributed control requirements of intelligent rail transit, this paper proposes a miniaturized, trackside-installed AC/DC conversion circuit. The design complies with EN 50159 and GB/T 28029 railway safety standards, adopting a "fail-safe" principle and "two-out-of-two" voting mechanism to ensure high reliability.

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Localized power conversion reduces cable dependence, improves supply stability, and retains robust safety performance.

Table 1 presents the key specifications of the proposed module for rapid reference.

Table 1. Key Specifications of the Trackside AC/DC Conversion Module.

Parameter	Specification
Input voltage	AC220V $\pm 10\%$ (50Hz)
Output voltage range	DC24V~DC200V (continuously adjustable)
Rated power	1kW
Conversion efficiency	$\geq 92\%$ (full load)
Output voltage deviation	$\leq \pm 5\%$
Fault response time	$\leq 10\text{ms}$
Working temperature	$-40\text{ }^{\circ}\text{C} \sim +70\text{ }^{\circ}\text{C}$
Communication interface	Ethernet (100Mbps)
Safety standard	EN 50159, GB/T 28029

2. Module Overview

Figure 1 shows the block diagram of the safety-oriented digitally controllable AC/DC conversion module, comprising four core units: dual-processor (CPU+FPGA) control unit, power conversion circuit, voltage/current acquisition circuit, and low-voltage power conversion circuit.

2.1. Core Working Principle

The dual processors adopt phase-shifted full-bridge control to regulate power electronic devices. Control signals are generated based on real-time monitoring of input overvoltage/undervoltage, output voltage, and output current. The module communicates with external devices via Ethernet, supporting dynamic output adjustment (DC24V~200V) to match load requirements.

2.2. Safety Mechanisms

Redundant control architecture: The "two-out-of-two" configuration ensures that safe output and signal acquisition are only validated when both processors reach a consensus, effectively preventing single-point failures.

Closed-loop control: A voltage closed-loop control strategy is adopted to maintain stable output and enable rapid response to load variations.

Fault-safe failover: In the event of abnormal signal acquisition (e.g., invalid voltage/current data) or hardware malfunctions (e.g., processor failure), the module automatically shuts down the power conversion output and transitions to a fail-safe state.

The module operates in a periodic workflow: it receives external commands, parses and processes them through logical operations, adjusts the output voltage accordingly, collects real-time operating data (including voltage, current, and temperature), conducts safety logic verification, and transmits the monitoring data to external systems. This closed-loop operational mechanism ensures the module's continuous safety and reliable performance.

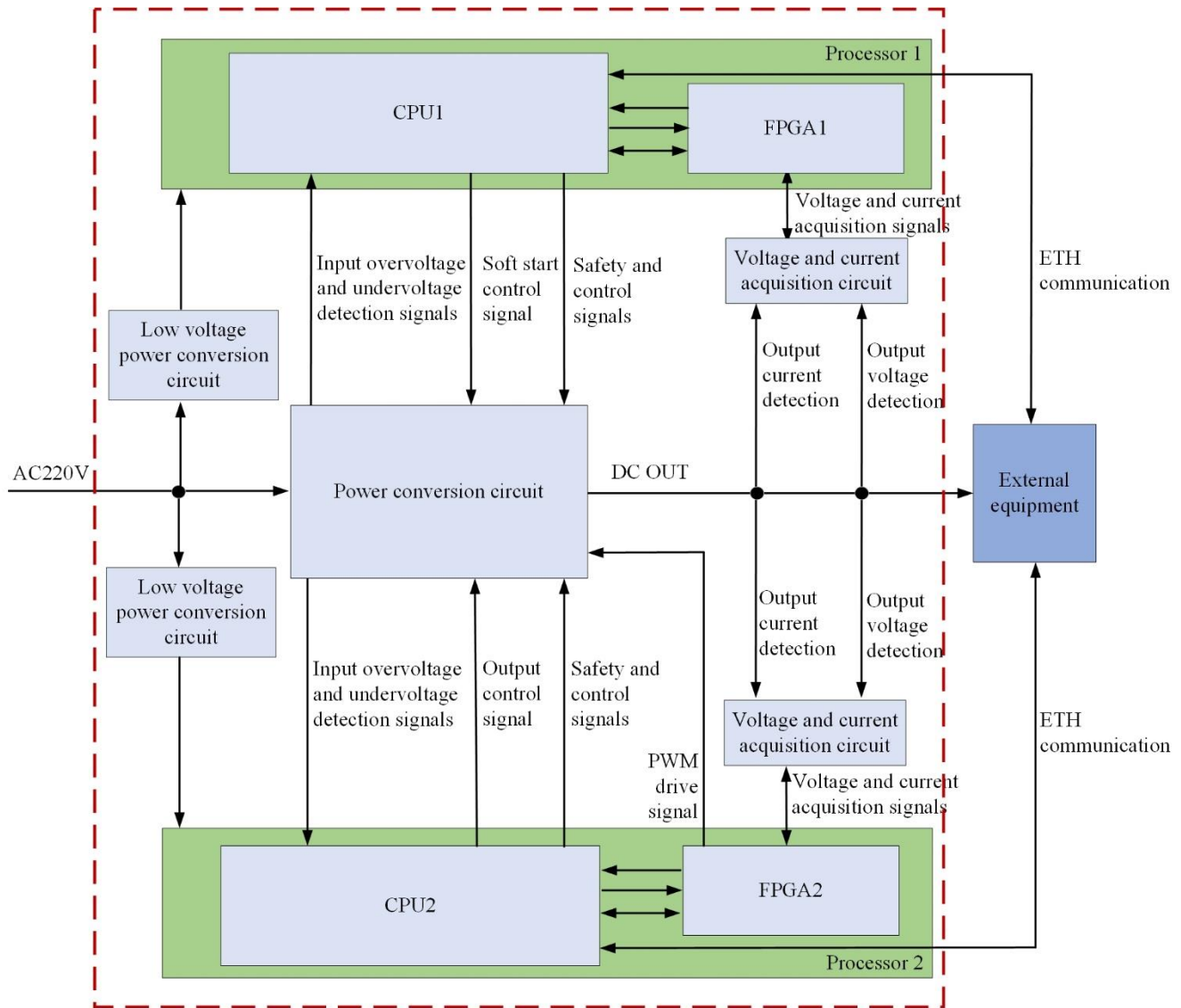


Figure 1. Module structure diagram.

3. Module Design

3.1. Power Conversion Circuit

The block diagram of the power conversion circuit structure is illustrated in Figure 2. This module adopts a phase-shifted full-bridge control scheme to regulate the non-isolated power conversion circuit, thereby achieving efficient power conversion and output. Its primary function is to supply a stable and reliable DC voltage to external equipment.

The power conversion circuit consists of several core components and functional modules, including: a bridge rectifier circuit, a soft-start circuit, a full-bridge inverter circuit, a

high-frequency transformer, a full-bridge rectifier circuit (secondary side), an output MOSFET switch circuit, an input overvoltage/undervoltage detection circuit, a drive circuit, and safety protection circuits (e.g., overcurrent, overtemperature protection).

The safety protection circuit is responsible for the core safety functions, and its block diagram is illustrated in Figure 3. Its operating principle is as follows: two CPUs each output an independent PWM signal to jointly control the circuit to generate a DC drive signal. Both PWM signals are indispensable for proper operation, and strict requirements are imposed on their signal frequency. This dual-signal design ensures the reliability and authenticity of the drive signal, preventing erroneous activation of the subsequent DC drive power supply caused by external interference.

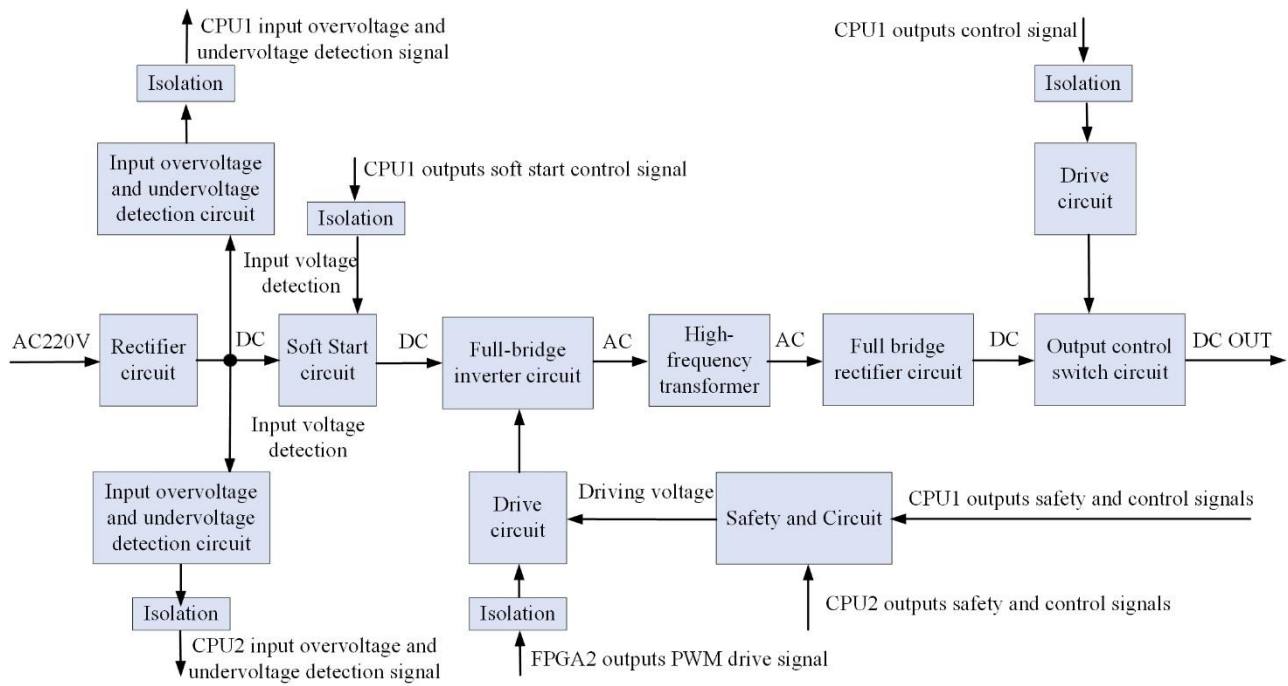


Figure 2. Block diagram of power conversion circuit structure.

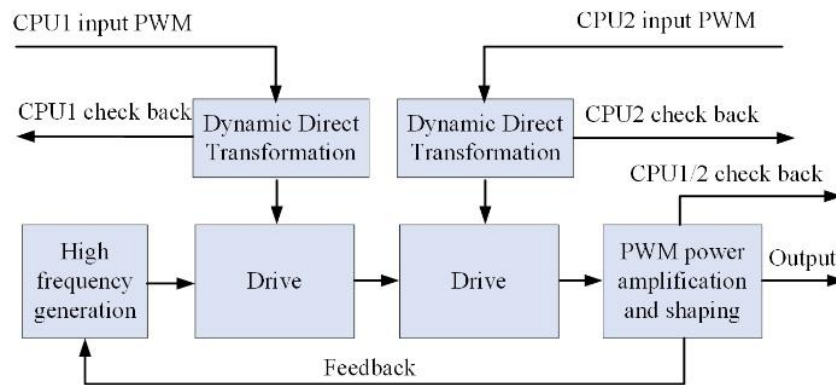


Figure 3. Block diagram of safety circuit structure.

The circuit incorporates an ISL6842 chip: PWM signals from CPU1 and CPU2 are converted into an optocoupler-driven power supply through an AC/DC conversion circuit, which regulates the transmission of high-frequency signals. The optocoupler then controls the corresponding MOSFET transistor to achieve precise DC signal regulation. Additionally, overvoltage and overcurrent detection circuits are integrated at the output terminal to safeguard the module against short-circuit damage while maintaining stable output performance.

Working Principle:

- 1) CPU1 outputs soft-start control signals and main output control signals;
- 2) FPGA2 dynamically adjusts the PWM duty cycle in real time based on feedback from the output voltage and current;
- 3) FPGA2 generates valid PWM drive signals only when

two conditions are simultaneously satisfied:

- a) CPU2 sends a drive output command to FPGA2;
 - b) The safety gate circuit provides a valid drive voltage;
- 4) If either condition is not met (e.g., CPU2 fails to send the command or the safety gate circuit outputs no valid drive voltage), FPGA2 will stop generating PWM drive signals, and the power conversion circuit will cease DC output.

This "double-confirmation" protection mechanism ensures that power conversion is enabled only when both CPUs and the FPGA are operating normally, effectively eliminating the risk of single-point failures and enhancing system reliability.

3.2. Voltage and Current Acquisition Circuit

To ensure safe and accurate signal acquisition, the voltage and current acquisition circuit adopts a heterogeneous re-

dundant design, as illustrated in Figure 4. Specifically, hardware heterogeneity—such as redundant sensors and independent signal paths—is implemented to enhance data acquisition reliability and effectively mitigate the risk of common-mode failures.

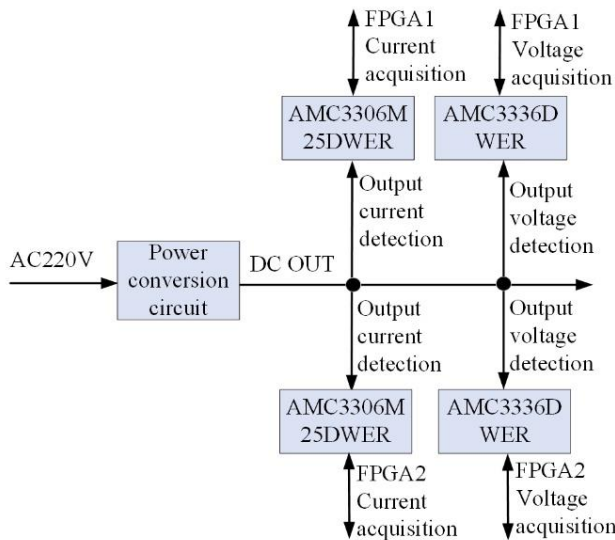


Figure 4. Structure diagram of voltage and current acquisition circuit.

Key Design Features:

- 1) **Isolated Detection Chips:** TI's AMC3336DWER (for voltage detection) and AMC3306M25DWER (for current detection) are adopted, equipped with high-precision isolated delta- σ modulators. These chips deliver exceptional acquisition accuracy ($\leq \pm 0.5\%$) and provide electrical isolation from the power circuit, effectively eliminating cross-interference.
- 2) **FPGA-Based Data Processing:** Raw acquired data undergoes filtering and preprocessing by FPGA2 prior to transmission to the dual CPUs. The CPUs then perform "two-out-of-two" safety logic verification to ensure data validity.
- 3) **Closed-Loop Feedback Control:** FPGA2 leverages the collected voltage data to implement real-time closed-loop control, thereby guaranteeing the stability of the output voltage.

3.3. Weak Current Power Conversion Circuit

The low-voltage power conversion circuit converts the AC220V input into the low-voltage DC power supplies (DC24V, DC5V, DC3.3V) required by the internal components of the module, such as processors, sensors, and communication modules. As illustrated in Figure 5, its configuration comprises a step-down transformer, rectifier bridge, filter capacitor, three-terminal voltage regulator, and integrated power module. This circuit is designed with a priority

on low noise and high stability, thereby ensuring the reliable operation of the control and communication units.

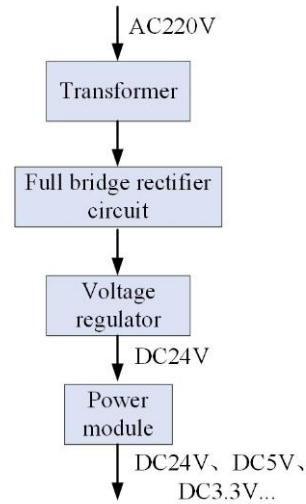


Figure 5. Structural diagram of weak current power conversion circuit.

3.4. Processor Unit

The processor unit incorporates dual CPUs and an FPGA, constituting a redundant control core to comply with railway safety standards:

Redundant Control Logic:

- 1) **Command validation:** The dual CPUs periodically acquire drive commands from external devices. A command is executed only when both CPUs have verified its integrity—if either CPU identifies a command as abnormal, no DC output is generated.
- 2) **Data verification:** The CPUs regularly collect the module's operating data (input voltage, output voltage, output current, board-level temperature). Safety logic processing mandates consistent data from both CPUs; any inconsistency triggers a fail-safe shutdown.
- 3) **Mutual monitoring:** Each CPU transmits periodic watchdog signals—the hardware resets the respective CPU if its watchdog signal is interrupted. The CPUs and FPGA conduct regular communication integrity checks; the CPU initiates an FPGA reset in the event of communication failure.

Power conversion output is enabled if and only if three conditions are satisfied:

- 1) Both dual CPUs and the FPGA are operating normally;
- 2) External commands have been jointly verified by both CPUs;
- 3) Operating data has passed "two-out-of-two" verification.

This multi-layered verification mechanism ensures the highest level of safety.

4. Functional Verification and Testing

A 1kW prototype (Figure 6) was developed for validation, with tests focusing on PWM waveforms, output performance, and safety.

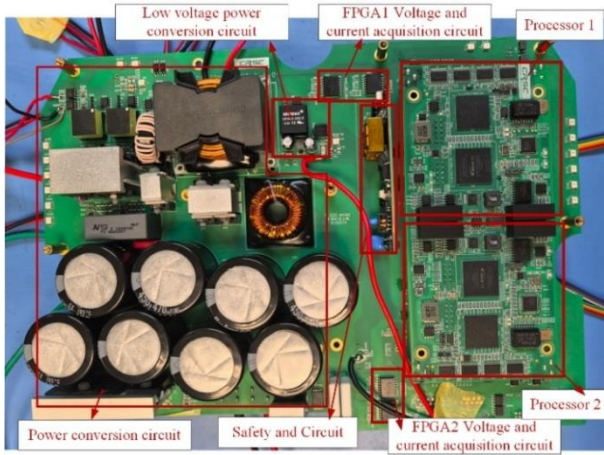


Figure 6. Experimental prototype.

4.1. PWM Waveform Validation

Figure 7 shows four 100kHz PWM channels from FPGA2. Phase shift adjustment modulates the duty cycle (0.1~0.9), regulating MOSFET switching timing. Test results are summarized in Table 2.

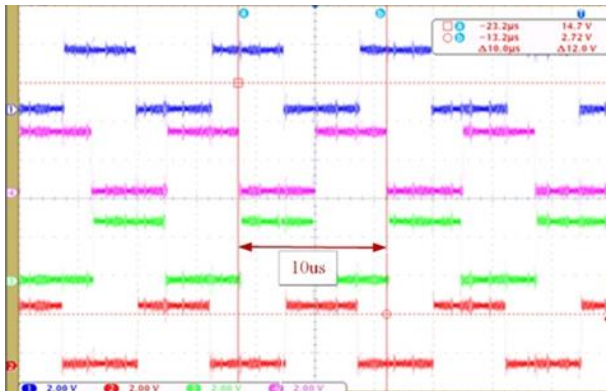


Figure 7. Four channels of 100kHz PWM waveforms output by FPGA2.

Table 2. PWM Waveform Test Results.

Hannel	Frequency (kHz)	Duty Cycle Range	Signal Integrity
1	100.2	0.1~0.9	Good
2	99.8	0.1~0.9	Good
3	100.1	0.1~0.9	Good
4	99.9	0.1~0.9	Good

4.2. Output Voltage Performance

Measured output voltages (Table 3) confirm compliance with the specified range (DC24V~200V) and low deviation ($\leq \pm 5\%$).

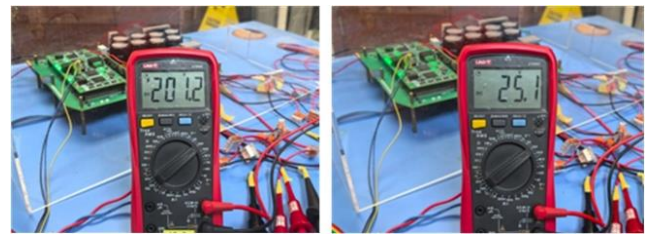


Figure 8. Output DC voltage value.

Table 3. Output Voltage Performance Test Results.

Target Voltage (V)	Measured Voltage (V)	Deviation (%)	Compliance
24	25.1	+4.58	Qualified
200	201.2	+0.60	Qualified

4.3. Safety Performance Verification

Fault injection tests validate the fail-safe mechanism (Table 4).

Table 4. Safety Performance Test Results.

Fault Type	Test Condition	Response Time (ms)	Result
Single CPU failure	Disable CPU1/CPU2	<1	Immediate DC output termination

Fault Type	Test Condition	Response Time (ms)	Result
Abnormal acquisition data	Inject invalid voltage/current signals	8.2	Fail-safe shutdown
Input overvoltage	$V_{in} = 264V$ (120% rated)	3.5	Automatic output cutoff
Output overcurrent	$I_{out} = 5A$ (125% rated at 200V output)	2.8	Automatic output cutoff

All tests confirm compliance with the fail-safe principle, with rapid transition to a safe state.

5. Conclusions

This paper proposes a safety-centric, digitally controllable AC/DC conversion circuit for trackside equipment, addressing the limitations of centralized power supply. Key innovations and contributions are:

- 1) Miniaturized trackside design shortens cables by 80%+, reduces deployment costs by 30%+.
- 2) "Fail-safe" principle and "two-out-of-two" redundancy architecture achieve reliability $\geq 99.99\%$.
- 3) Phase-shifted full-bridge control and closed-loop regulation realize efficiency $\geq 92\%$ and output deviation $\leq \pm 5\%$.
- 4) Embedded real-time monitoring and Ethernet communication support remote management.

Experimental validation confirms the circuit's reliable conversion of AC220V to DC24V~200V, with robust safety performance. It provides a practical solution for distributed power supply in urban rail transit, facilitating intelligent trackside system development.

Abbreviations

PWM	Pulse Width Modulation
CPU	Central Processing Unit
FPGA	Field Programmable Gate Array
DC	Direct Current
AC	Alternating Current
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor

Conflicts of Interest

The authors declare no conflicts of interest.

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