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Discussion on Technical Solutions for Train Stopping at Overlap Section of Metro Flexible Catenary Systems

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Abstract: **Urban metro systems rely on flexible catenary systems, yet train stops at overlap sections pose safety risks, as highlighted by the 2022 Shanghai Metro Line 11 accident, where a stalled train caused catenary wire breakage due to kiloampere-level through-currents. This study evaluates five safety technical solutions—section insulator, load switch cabinet, de-energized section insulated overlap, anti-fusing device system, and encapsulated partial insulation—to address such risks. Through comparative analysis of safety performance, implementation complexity, cost, system compatibility, pantograph-catenary interaction, technical maturity, and maintenance, the encapsulated partial insulation solution emerges as optimal. By employing PTFE-modified U-shaped insulation sleeves on non-working contact wire supports, it physically blocks cross-currents without altering existing overlap mechanics or compromising pantograph-catenary dynamics. This approach demonstrates superior safety by eliminating transition zone arcing and overheating, lower implementation costs compared to structural modifications, and high compatibility with existing systems. Its self-lubricating PTFE reduces maintenance demands, aligning with digital monitoring trends. While PTFE's long-term durability in metro-specific conditions requires validation, its technical maturity in other fields and innovative design position it as a transformative solution for enhancing system reliability, reducing costs, and improving passenger safety. This research provides a critical framework for metro operators and policymakers to adopt optimal safety measures, with future work recommended on accelerated aging tests and pilot deployments to standardize global implementation.**

Keywords: **Metro flexible catenary systems, Overlap Section, Technical Solutions, PTFE.**

I. INTRODUCTION

Urban metro systems serve as critical infrastructure for modern cities, with flexible catenary systems playing a pivotal role in ensuring reliable power supply for trains (Fan, 2018). However, safety incidents during train operations, particularly those involving train stops at overlap sections of flexible catenary systems, have raised significant concerns. These overlap sections, designed to manage electrical transitions between different power segments, become potential hazard zones when trains stop unexpectedly, as evidenced by the catenary wire breakage incident on Shanghai Metro Line 11 in November 2022. This accident, triggered by a train stalling in an insulated overlap section during peak hours, resulted in prolonged service disruptions and highlighted the urgent need for effective safety technical solutions.

The root cause of such incidents lies in the formation of kiloampere-level through-currents when a train stops in the overlap section's transition zone without lowering the pantograph, leading to overheating and wire failure due to transition resistance. Despite the existence of no-stopping zones at overlap sections, the risk of such accidents persists, necessitating a reliable technical solution that can eliminate these safety hazards without compromising operational efficiency.

This study aims to evaluate and compare various safety technical solutions for train stopping at overlap sections of metro flexible catenary systems, with a focus on identifying the most effective and feasible approach. The research is significant as it addresses a pressing safety issue in metro operations, with implications for enhancing system reliability, reducing maintenance costs, and improving passenger safety. By providing a comprehensive analysis of available solutions, this study seeks to inform decision-making processes for metro operators and policymakers, facilitating the adoption of optimal safety measures.

The study begins by analysing the accident on Shanghai Metro Line 11 to understand the underlying causes and consequences of train stops at overlap sections. Subsequently, it reviews five technical solutions: section insulator, load switch cabinet, de-energized section insulated overlap, anti-fusing device system, and encapsulated partial insulation. Each solution is evaluated based on its safety performance, implementation complexity and cost, system compatibility, pantograph-catenary performance, technical maturity, and maintenance requirements.

Through a comparative analysis, the study reveals that while each solution offers certain advantages, the encapsulated partial insulation solution stands out due to its superior safety performance, lower implementation cost, high system compatibility, minimal impact on pantograph-catenary performance, and ease of maintenance. This solution employs PTFE-modified U-shaped insulation sleeves on the non-working branch of overlap sections, forming an insulation barrier that eliminates the risk of cross-current. Its innovative design, coupled with the self-lubricating properties of PTFE, makes it a promising candidate for enhancing safety in metro flexible catenary systems.

II. ACCIDENT ANALYSIS

On November 11, 2022, during peak hours, a catenary wire breakage occurred on Shanghai Metro Line 11 when Train 1120 stalled in an insulated overlap section. The incident began when Train 1110 was boarding passengers at Jiading Xincheng Station, forcing Train 1120 to stop 100 meters outside the station. Restart attempts caused abnormal pantograph-catenary contact, triggering a power trip that led to wire sagging. Inspection revealed four contact wires with melting characteristics, disrupting service for over two hours (Wang, 2023).

The accident's root cause was the train stopping in the overlap section's transition zone without lowering the pantograph. The carbon strip bridged two contact wires, allowing kiloampere-level through-current from other trains to flow. Poor contact created transition resistance, influenced by contact pressure and surface contaminants. Per Joule's law ($Q=I^2Rt$), this combination of high current and resistance caused overheating and wire failure (Wang et al., 2025).

While no-stopping zones exist at overlap sections, risks remain. Over-restriction would increase pantograph operations, raising failure risks and reducing efficiency during peak hours. A reliable technical solution is urgently needed to eliminate these safety hazards in flexible catenary systems (Sun, 2024).

III. TECHNICAL SOLUTIONS

A. Section Insulator Solution

Following an incident, the section insulator solution requires operational management adjustments and signal system software modifications to confine trains to designated parking areas, consequently resulting in an increased minimum operating interval between trains. According to the standard of China's TB/T 3036-2016, section insulators are applicable for train speeds ≤120 km/h. However, it remains uncommon on Chinese elevated lines. These devices use insulated runners to isolate power sections, preventing short-circuiting when trains stop. The pantograph contacts only one live conductor, eliminating current transfer risks.

There are two advantages for this solution: (1) Component replacement without full line shutdown; (2) Compact vertical design. Meanwhile, there are four disadvantages: (1) "Hard spots" increase wear, requiring frequent power-off maintenance; (2) Transition-zone arcing damages conductive surfaces; (3) Junction vulnerability to carbon deposit-induced flashover and weather-related insulation loss; (4) not suitable for installation in curved track sections.

B. Load Switch Cabinet Solution

The load switch cabinet dynamically reconfigures power supply topology to prevent contact wire melting. When a train stops at an insulated overlap section, the load switch creates equipotential connection between working and non-working branches, eliminating potential differences. The core mechanism of this solution utilizes low-resistance cabinet cables to bypass current, excluding the pantograph strip from the main current path. In addition, this solution can integrate video monitoring and remote operation for intelligent centralized control (Liao, 2025).

There are two advantages for the solution: (1) no structural modifications required; (2) reduced manual intervention with remote control. Meanwhile, there are three disadvantages: (1) reporting and remote switch closure procedures may cause emergency response delay; (2) Installation constraints exist for elevated sections due to bridge clearance; (3) High retrofit costs requiring service suspension; (3) It requires a complex support system to implement this solution and cannot guarantee their operational reliability.

C. De-energized Section Insulated Overlap Solution

The de-energized section insulated overlap prevents simultaneous pantograph contact with two contact wires of different potentials. The neutral section, isolated by insulating components and kept de-energized, breaks potential short-circuit paths. During operation, the pantograph transitions smoothly from one energized contact wire through the neutral section to another, without sustained short-circuiting. When stopped, no current path forms between working and non-working branches, eliminating melting risks. Current practice in passenger-dedicated railways features three consecutive insulated overlaps creating three breaks and two neutral sections, preventing simultaneous short-circuiting across all breaks regardless of dual-pantograph spacing (Liu et al., 2017).

There are two advantages for this solution: (1) hard-point wear eliminated from rigid insulators; (2) neutral section reliably interrupting current paths. Meanwhile, there are four disadvantages: (1) complex maintenance requiring precision adjustments; (2) space constraint in tight areas like turnouts; (3) arcing hazards during energized-to-de-energized transitions; (4) limited metro application.

D. Anti-Fusing Device System Solution

The anti-fusing device employs a current diversion mechanism for core protection. When a train stops within an insulated overlap section, the system utilizes sensors for real-time position/speed monitoring. Then, it activates trackside contactors to establish low-impedance bypass cables. And the system diverts through-current from the primary "working branch→pantograph→non-working branch" path. In the end, it reduces current density below safety thresholds to prevent overheating.

There are three advantages for this solution: (1) minimal infrastructure modification, only installation trackside; (2) integrated arc suppression and fuse protection; (3) millisecond-level response time. Meanwhile, there are two disadvantages: (1) sensor accuracy dependency for proper bypass timing; (2) unproven long-term reliability in metro applications.

E. Encapsulated Partial Insulation Solution

The encapsulated partial insulation solution employs polytetrafluoroethylene (PTFE)-modified U-shaped insulation sleeves on the non-working branch of flexible catenary system overlap sections. Specifically, the U-shaped insulating material is designed to encapsulate a specific area of the non-working support of the contact wire, forming an insulation barrier. When the pantograph carbon strip slides over this area, the insulating material blocks the current path between the working and non-working supports, eliminating the risk of "cross-current". Meanwhile, the arc extinguishing device rapidly reduces the arc when the carbon strip enters the insulated area.

There are two advantages for this solution: (1) retaining the standard overlap section configuration; (2) lower implementation cost compared to signalling modifications. The disadvantages of this solution are: (1) regular monitoring of insulation thickness being required, increasing maintenance complexity; (2) limited metro application experience for modified PTFE.

IV. SOLUTION COMPARISON AND RECOMMENDATION

Based on the analysis of technical solutions in the previous section, a comprehensive comparison is conducted here from six aspects, which are safety, implementation complexity and cost, system compatibility, pantograph-catenary performance, technical maturity, and maintenance. The comparative summary is seen in Table 1. While all solutions address fusing risks at insulated overlap sections, the encapsulated partial insulation approach offers distinct advantages.

In the aspect of safety, the encapsulated partial insulation solution forms a physical barrier by encapsulating the non-working support contact wire with PTFE-modified material, eliminating kiloampere-level cross-current risks between working and non-working supports. Unlike section insulators—which suffer from hard-point arcing at slide-wire connections—or load switch cabinets with contact resistance heating hazards in bypass cables, it ensures zero current conduction through material insulation. Its arc extinguisher rapidly suppresses transition zone arcs, preventing high-temperature contact wire erosion—a critical safety improvement over de-energized sections, where sustained arcing occurs during train passage.

In the aspect of implementation and cost, the encapsulated partial insulation solution only requires the installation of U-shaped insulating sleeves on the non-working support contact wire of existing overlap sections, without necessitating adjustments to the catenary suspension structure or the addition of trackside equipment. In contrast, the load switch cabinet solution requires bridge clearance modifications, the de-energized section solution increases civil engineering costs by over 20%, and the section insulator solution necessitates replacing the entire slide structure. The encapsulated solution offers lower implementation difficulty and optimal overall cost.

In the aspect of system compatibility, retaining existing overlap section mechanics and electrical segmentation, the encapsulated partial insulation solution requires no SCADA logic changes or power supply zone adjustments. Unlike anti-fusing systems (requiring new sensor networks), de-energized sections (catenary phase reconfiguration), or load switch cabinets (substation protection modifications), it minimizes disruption—ideal for retrofitting existing lines.

In the aspect of pantograph-catenary performance, the encapsulated partial insulation solution only covers the transition zone of the non-working support, preserving the full conductivity of the working support and avoiding the increased pantograph off-line rate caused by the insulating slide in the section insulator solution. Moreover, it does not alter the catenary tension compensation mechanism, suspension elasticity, or dynamic uplift, ensuring no negative impact on train current collection quality. In contrast, the rigid structure introduced by the section insulator solution alters the uniformity of catenary elasticity, potentially triggering pantograph-catenary vibrations during high-speed passage.

In the aspect of maintenance, the encapsulated partial insulation solution outperforms alternatives with quarterly laser scans for insulation thickness or RFID wear tags for digital monitoring. Its self-lubricating PTFE reduces carbon slide wear checks, aligning with condition-based maintenance trends. In contrast, load switch cabinets need remote operation monitoring and cable diagnostics; section insulators suffer high wear rates and weather-induced flashovers; de-energized sections demand complex, time-consuming conductor height and insulator adjustments.

Although PTFE, used in the encapsulated partial insulation solution, exhibits characteristics such as high-temperature resistance and low friction coefficients, and is widely applied in cable insulation and other fields with high technical maturity, its engineering practice in the metro sector remains unexplored when fabricated into a U-shaped structure to encapsulate contact wires and coordinate with arc extinguishing devices. Critical data, such as performance degradation under extreme operating conditions, are lacking and require validation through accelerated aging tests and small-scale pilot projects. This represents an innovative design in the field of metro catenary systems.

TABLE I: PERFORMANCE MATRIX

Characteristic	**Encapsulated Partial Insulation**	**Section Insulator**	**Load Switch Cabinet**	**De-energized Section Insulated Overlap**	**Anti-Fusing Device System**
Safety	High	Medium	Medium	Low	Medium
Implementation & Cost	Low	High	High	High	High
System Compatibility	High	Low	Low	Low	Low
Pantograph Performance	High	Low	N/A	N/A	N/A
Maintenance	Low	High	Medium	High	Medium
Technical Maturity	Low	High	High	High	High

V. CONCLUSION

This study systematically evaluates safety technical solutions for train stops at overlap sections in metro flexible catenary systems, addressing a critical gap in mitigating risks such as through-current-induced wire failures. Through comparative analysis of five solutions—section insulator, load switch cabinet, de-energized section insulated overlap, anti-fusing device system, and encapsulated partial insulation—the encapsulated partial insulation approach emerges as the most effective and feasible option. This solution leverages PTFE-modified U-shaped insulation sleeves to create a physical barrier on non-working contact wire supports, eliminating cross-current risks without altering existing overlap section mechanics or compromising pantograph-catenary interaction. Its advantages include superior safety performance, minimal implementation complexity, cost-effectiveness, high system compatibility, and alignment with modern maintenance practices such as digital monitoring. Unlike alternatives requiring structural modifications or introducing new failure modes, this solution preserves operational efficiency while providing robust protection against overheating and wire breakage. Despite the need for validation of PTFE's long-term durability under metro-specific conditions, its technical maturity in other fields and self-lubricating properties position it as a transformative innovation. For metro operators and policymakers, adopting this solution offers a balanced pathway to enhancing system reliability, reducing maintenance costs, and improving passenger safety. Future research should focus on accelerated aging tests and pilot deployments to refine design parameters and establish industry-wide standards, ensuring scalable implementation across global metro networks.

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