Postprint of a Novel Neutral Section Passing Coordination Strategy for Hybrid Power EMUs

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Abstract

This paper introduces the currently mainstream neutral-section passing schemes, discusses the control strategies for grid-side converters in hybrid electric multiple unit power systems and the overview of power battery systems, and proposes a novel neutral-section passing scheme based on hybrid electric multiple units (under three operating conditions). The adoption of this scheme enables trains to maintain traction power when passing through dead zones without speed loss, while auxiliary units remain normally online. Finally, the scientific validity and feasibility of the aforementioned theory are verified based on waveforms from actual experiments.

Full Text

The New Strategy of Passing Neutral Section Based on Hybrid Electric Multiple Units

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Abstract

This paper introduces the current mainstream schemes for passing neutral sections and discusses the control strategies for the grid-side converter and power battery system in hybrid electric multiple units (EMUs). A novel neutral-section-passing strategy based on hybrid EMUs is proposed for three operational conditions. Using this strategy, the train can maintain traction power and speed without loss while keeping auxiliary units online when passing through dead zones. Finally, the scientific validity and feasibility of the proposed theory are verified through actual test waveforms.

Keywords: Hybrid EMU, neutral section passing strategy, grid-side converter, traction and braking conditions, dead zone

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1 Introduction

Conventional high-speed EMUs exclusively use the 25 kV AC traction network as their power supply, requiring catenary installation along the entire route. However, the grid-side converter of an EMU is a single-phase high-power electronic conversion device. Drawing power from only one phase of the grid would inevitably cause load imbalance in the power system. To maintain three-phase load balance and ensure safe operation of electrical equipment, electric locomotives must adopt a segmented phase-changing power supply scheme, switching phases at regular intervals. Meanwhile, to maintain stable contact between the pantograph and catenary, mechanical connection must be preserved between different phase supply arms, while electrical isolation is required. A dead zone is therefore established between the two supply arms to prevent inter-phase short circuits—this is the origin of neutral sections [1].

Currently, there are two mainstream neutral-section-passing schemes worldwide. The first is the on-board automatic neutral-section-passing scheme, widely adopted in European countries. This scheme relies primarily on on-board equipment for automatic operation, with trains coasting or micro-braking through dead zones. However, when the dead zone is long or on uphill sections, the train experiences significant speed reduction, impacting railway operational efficiency [2]. The second is the ground automatic neutral-section-passing scheme, which offers the advantage of short power interruption time and minimal speed reduction during neutral-section passage, currently implemented in Japan' s Shinkansen. Its drawbacks include high cost and large volume of switching equipment; additionally, the physical switching speed of vacuum circuit breakers is slow, preventing precise control of opening/closing timing. The opening process generates overvoltage impulses, while the closing process can cause magnetizing inrush current in the train' s main transformer [3-4].

The novel neutral-section-passing strategy proposed in this paper for hybrid EMUs enables trains to maintain adequate traction power without speed loss while keeping auxiliary units online, allowing rapid and smooth passage through dead zones.

2 Hybrid EMU Power System Configuration

The hybrid EMU is China' s first multiple unit designed specifically for intercity passenger service with multiple power sources. This train type breaks the limitation of relying solely on catenary power supply, expanding operational range and enabling cross-line operation from mainline to branch lines and from electrified to non-electrified railways.

Figure 1 [Figure 1: see original paper] illustrates the structure of the traction drive system for the hybrid EMU. When operating in non-electrified sections, the train draws power from the battery or diesel power pack; in electrified sections, it draws power from the catenary while simultaneously charging the power battery.

2.1 Grid-Side Converter in Catenary Mode

The grid-side converter of the hybrid EMU employs an improved decoupling control method based on the dq rotating coordinate frame, enabling independent control of active and reactive power and effectively handling grid voltage fluctuations [5-6]. This method essentially converts time-varying AC quantities into DC quantities for control, utilizing a fast virtual axis calculation unit to reduce control delay in the current control inner loop, thereby improving system dynamic performance [7-8].

The d-axis is defined as the active power axis. The control system for the grid-side converter is designed and implemented based on three core equations and a control block diagram:

$$\begin{aligned} I_d &= I_\alpha \sin \omega t - I_\beta \cos \omega t \\ I_q &= I_\alpha \cos \omega t + I_\beta \sin \omega t \\ I_\alpha &= \frac{(E_\alpha - U_\alpha)}{sL} \end{aligned}$$

where E_d and E_q are the d- and q-components of grid voltage; U_d and U_q are the d- and q-components of input voltage; I_d and I_q are the d- and q-components of grid-side current; K_P and K_I are the proportional and integral coefficients of the current inner loop; L is the AC-side inductance; I_α is the actual axis current; and I_β is the virtual axis current. The corresponding control block diagram is shown in Figure 2 [Figure 2: see original paper], with the fast virtual axis calculation unit principle corresponding to Equation (3).

Figure 3 [Figure 3: see original paper] shows actual test waveforms of the EMU, which first accelerates with high-level traction force, then coasts, and finally applies seven-level electric braking. In catenary mode, the grid-side converter operates to provide power for the train. Throughout the entire load variation and high-power load switching process, the converter demonstrates excellent dynamic and static performance.

Figure 4 [Figure 4: see original paper] illustrates the high-level traction force acceleration process. During the entire motor load switching process, the grid-side converter maintains stable control of the input current with good sinusoidal waveform quality.

2.2 Power Battery in Non-Catenary Mode

The hybrid EMU employs lithium iron phosphate ($LiFePO_4$) batteries, currently a mature and widely used lithium battery material that is readily available, environmentally friendly, and free from memory effects during charge/discharge cycling. Additionally, these batteries offer high safety and will not explode even under severe impact [9-10]. A bidirectional DC-DC converter serves as the main control circuit for the power battery.

The charging control strategy incorporates both fast and slow charging modes. To maintain sufficient battery capacity for recovering regenerative braking energy, the charging cutoff SOC is set at 90%. Figure 5 [Figure 5: see original paper] shows actual test waveforms of the power battery charging control strategy.

The battery discharge power supply strategy is developed based on the classic dual closed-loop design [11]. Actual test waveforms of power battery discharge supplying the load are shown in Figure 6 [Figure 6: see original paper].

3 Neutral Section Passing Coordination Strategy

Railways are equipped with two signals: a pre-neutral-section signal and a neutral-section-completion signal, as shown in Figure 7 [Figure 7: see original paper]. For convenience, let the pre-neutral-section signal be designated as Signal 1 and the neutral-section-completion signal as Signal 2, with ΔU as the set value. The following discusses the neutral-section-passing coordination strategy under three operational conditions.

3.1 Traction Neutral Section Passing Strategy

The coordination logic diagram for trains passing neutral sections in traction state is shown in Figure 8 [Figure 8: see original paper]. Before entering the neutral section, the grid-side converter supplies power to the train. Upon receiving Signal 1, if the train is in traction or coasting state, traction force should be gradually reduced, the grid-side converter set to "rectification-only" mode, and the current DC voltage value U_{dc} recorded. Simultaneously, the DC-DC system controls the power battery to release energy, maintaining the intermediate DC link voltage at $U_{dc} + \Delta U$.

Considering potential hardware differences in A-D sampling units among multiple systems, a ΔU offset is configured in the DC voltage control command value. This command redundancy prevents mutual interference among multiple voltage loops and achieves smooth transition between power supply systems. During this process, all train loads can be smoothly transferred from the grid-side converter system to the power battery system. After receiving Signal 1 or forced separation of the train’ s main circuit breaker, the grid-side converter stops operating, and the power battery supplies power to the train. Upon receiving Signal 2, the power battery is set to “discharge-only” mode, maintaining the intermediate DC link voltage at $U_{dc} - \Delta U$. The grid-side converter then starts, controlling DC voltage to the target value U_{dc}, after which the power battery output naturally ceases.

This strategy enables smooth load handover between the grid-side converter and power battery systems, meaning on-board auxiliary equipment requires no power interruption during traction neutral-section passage, and train speed can be maintained or increased as needed.

3.2 Braking Neutral Section Passing Strategy

The coordination logic diagram for trains passing neutral sections in braking state is shown in Figure 9 [Figure 9: see original paper]. If the train is in braking state, the grid-side converter absorbs braking energy and feeds it back to the catenary. Upon receiving Signal 1, considering the battery’ s power absorption capacity, the actual braking force from traction motors should be appropriately reduced, and the grid-side converter set to “inversion-only” mode, recording the current DC voltage value U_{dc}. Simultaneously, the DC-DC system controls the power battery to absorb braking energy, maintaining the intermediate DC link voltage at $U_{dc} - \Delta U$. During this process, all train loads can also be smoothly transferred from the grid-side converter system to the power battery system.

After confirming receipt of Signal 1 or forced separation of the main circuit breaker, the grid-side converter stops operating, and the power battery maintains the intermediate DC link voltage. Upon receiving Signal 2, the power battery is set to “charge-only” mode, maintaining the intermediate DC link voltage at $U_{dc} + \Delta U$. The grid-side converter then starts, controlling DC voltage to the target value U_{dc}, after which the power battery stops charging.

With this braking neutral-section-passing strategy, seamless switching between grid-side converter and power battery operation can also be achieved during braking passage through dead zones, maintaining normal operation of on-board auxiliary equipment while recovering excess braking energy into the power battery.

3.3 Neutral Section Passing Strategy Under Battery System Offline Conditions

In complex operating conditions, battery system offline may occur due to unexpected circumstances [12]. When the battery system is offline (due to faults, communication interruption, extreme low temperature, etc., preventing normal battery performance), the neutral-section-passing strategy configuration for hybrid EMUs is similar to the on-board automatic neutral-section-passing scheme.

Before entering the neutral section, the grid-side converter draws power from the 25 kV catenary to supply the train, with DC voltage stabilized at U_{dc}. Upon receiving Signal 1, the EMU switches to regenerative braking state. When the main circuit breaker is forced open, the grid-side converter stops operating, relying on the train' s regenerative braking energy to maintain intermediate DC link voltage, with some on-board equipment temporarily going offline. After the EMU leaves the dead zone, the main circuit breaker automatically closes, then the grid-side converter pre-charges and restarts to supply power to the EMU. Its startup process is smooth with good dynamic and static characteristics. Subsequently, the battery group is engaged as a load with total power of approximately 120 kW.

4 Experimental Research and Analysis

The feasibility of the novel neutral-section-passing strategy was experimentally verified on the hybrid EMU ground traction chain test platform. The traction neutral-section-passing strategy verification test is described as an example.

The experiment selected one grid-side converter and two battery groups. One battery group was set to "charge-only" mode, equivalent to part of the train' s load; the other battery group coordinated with the grid-side converter for seamless load handover during neutral-section passage, alternately assuming power supply responsibilities.

Actual power test waveforms are shown in Figure 10 [Figure 10: see original paper]. Test analysis proceeds as follows: First, the grid-side converter established stable DC voltage after grid connection. Before entering the neutral section, DC voltage was stabilized at 1650 V, with the grid-side converter supplying the load.

Upon receiving Signal 1, the DC voltage command for the power battery group was adjusted to 1680 V, and the battery began discharging to output power. Simultaneously, the grid-side converter blocked its "inversion" function, and the grid-side input current dropped to zero, meaning the battery system assumed the load and supplied energy to the train in the dead zone. The entire switching process produced minimal load impact, with stable DC voltage control. After the train received Signal 2, the battery command voltage was reduced to 1620 V, and the grid-side converter started. Once the grid-side converter raised the actual DC voltage above 1620 V, the battery stopped discharging, and the grid-side converter assumed the load to begin power supply.

Therefore, by coordinating the operation of the grid-side converter and power battery, the hybrid EMU successfully passed the neutral section with load. Additionally, the actual traction force delivered by motors during neutral-section passage should consider the maximum available power the battery group can currently provide.

5 Conclusion

Based on an overview of the grid-side converter and power battery control systems for hybrid EMUs, this paper proposes a novel neutral-section-passing coordination strategy for this train type, presenting targeted design solutions for three operational conditions. The scientific validity and feasibility of this new strategy are verified through actual experiments. Compared with conventional neutral-section-passing schemes, this approach eliminates the need for complex ground switching equipment and reduces driver workload. Applying this strategy ensures the train retains adequate power without speed loss when passing neutral sections, while maintaining auxiliary equipment online. This not only enhances the cross-line operation capability and applicability range of EMU trains but also improves railway operational efficiency.

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Note: Figure translations are in progress. See original paper for figures.