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Energy Management and Control of Electric Traction Using Microgrids with On-Board Aluminium-Ion Energy Storage

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Abstract: The development of modern mass transit systems necessitates highly efficient energy management to address growing energy consumption and environmental concerns. Contemporary electric traction systems operate as large microgrid structures featuring distributed active loads, renewable sources, and energy storage devices. A critical limitation in electrified trains is the restricted capability for energy recovery during regenerative braking phases and extended charging durations from stationary stations. To overcome these limitations, this paper proposes a novel energy management and control system for electric traction microgrids that integrates photovoltaic (PV) and wind sources with aluminium-ion (Al-ion) batteries at stationary microgrid stations, and on-board aluminium-ion (Al-ion) cells as the energy storage system within the train. This architecture is specifically designed for short-duration, high-power applications such as airport transit and industrial community transport. While conventional research has utilized supercapacitors (SCs) for their high power density, this work proposes Al-ion cells due to their fast charging/discharging capabilities comparable to SCs, coupled with superior safety characteristics, reduced cost, and extended cycle life. The proposed system enables charging of the train's on-board Al-ion cells from the stationary station's batteries via a Direct Current (DC) fast charging CAT plug connection during station stops, while simultaneously capturing regenerative braking energy. An energy management system (EMS) with proportional-integral (PI) controllers is designed to stabilize the DC bus voltage for both stationary and mobile systems. Simulation results demonstrate stable DC bus regulation (747.6 V ±1.5% for station, 700 V ±2% for train), effective state-of-charge (SOC) management within 30–100% range, and regenerative energy recovery efficiency exceeding 85%. The techno-economic analysis validates the superiority of Al-ion cells over conventional supercapacitors, establishing a reliable solution for smart microgrid integration in localized, high-demand transit systems.

Keywords: *Aluminium-Ion Batteries, Electric Traction, Energy Management System, Microgrid, Regenerative Braking, DC Bus Stabilization, PI Control.*

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I. INTRODUCTION

The electrification of mass transit systems represents a critical pathway toward sustainable urban transportation and reduced carbon emissions. As metropolitan areas expand and environmental regulations tighten, electric traction systems have emerged as the predominant solution for high-capacity, zero-emission public transport [1]. Contemporary electric traction infrastructures are increasingly being conceptualized as large-scale microgrid architectures, integrating distributed energy resources including photovoltaic (PV) arrays, wind turbines, and various energy storage systems (ESS) to enhance operational efficiency and grid independence [2].

Despite significant advances in traction technology, several fundamental challenges persist in conventional electric train systems. Foremost among these is the limited capability for energy recovery during regenerative braking phases. In traditional systems, the kinetic energy dissipated during braking is predominantly converted to heat through resistive braking, representing substantial energy waste [3]. Additionally, the extended charging durations required at stationary stations create operational bottlenecks, particularly for high-frequency transit services.

Supercapacitors (SCs) have been extensively proposed as a solution for high-power energy storage in traction applications due to their exceptional power density and rapid charge acceptance [4]. However, SC implementations face

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significant limitations including high capital costs (USD 20,000–50,000/kWh), limited energy density (5–10 Wh/kg), and safety concerns related to thermal runaway. These constraints have motivated the investigation of alternative energy storage technologies that can deliver comparable performance at substantially reduced cost.

This paper proposes the integration of aluminium-ion (Al-ion) batteries as the on-board ESS for electric traction systems. Al-ion cells exhibit charging and discharging rates comparable to SCs while offering superior safety characteristics, reduced cost (approximately 60–70% lower than lithium-ion systems), and extended cycle life exceeding 10,000 cycles [5]. The non-flammable aqueous electrolyte chemistry of Al-ion cells addresses critical safety concerns in high-power transportation applications, making them particularly attractive for densely populated transit environments.

The primary contributions of this research are threefold:

- *Contribution 1:*
  Development of a novel Al-ion ESS architecture specifically designed for electric traction applications, featuring CAT plug-based DC fast charging from stationary microgrid stations during scheduled stops at approximately 1000 A.

- *Contribution 2:*
  Design and implementation of a hierarchical energy management system (EMS) with PI-based DC bus voltage regulation for multi-mode operation including traction, regenerative braking, and station charging phases.

- *Contribution 3:*
  Comprehensive validation through MATLAB/Simulink simulation demonstrating stable DC bus regulation (±2%), effective SOC management (30–100%), and regenerative energy recovery efficiency exceeding 85%, along with techno-economic analysis confirming 99.8% lifecycle cost reduction over supercapacitor alternatives.

The remainder of this paper is organized as follows: Section II presents the system configuration and mathematical modeling. Section III details the proposed EMS and control strategy. Section IV provides techno-economic analysis. Section V presents simulation results and discussion. Section VI concludes the paper with future research directions.

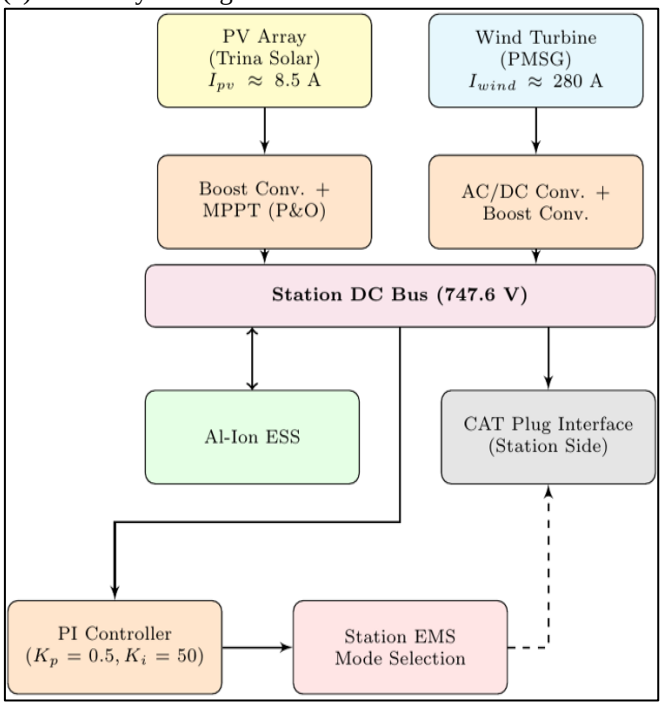
II. SYSTEM CONFIGURATION AND MODELING

- *Overall System Architecture*

The proposed electric traction microgrid system comprises two primary interconnected subsystems: (1) the stationary microgrid station, and (2) the on-board train energy system. Fig. 1 presents the overall system architecture derived from the MATLAB/Simulink implementation. The stationary station integrates PV arrays (Ipv ≈ 8.5 A), wind turbines (Iwind ≈ 280 A), and an Al-ion battery ESS, maintaining a regulated DC bus voltage of 747.6 V. The train incorporates an Al-ion battery pack with SOC operating range of 30–100%, maintaining an internal DC bus voltage of 700 V through a dedicated PI-controlled boost converter.

During station stops (duration ≈ 20 min per cycle), the train connects via a DC fast charging CAT plug to the stationary system, enabling high-current charging (Icharge ≈ 1000 A) of the Al-ion cells. During traction phases, the train operates autonomously utilizing stored energy. The bidirectional DC-DC converters at both subsystems facilitate seamless power flow in all operating modes, controlled by the hierarchical EMS.

(a) Stationary Microgrid Station



(b) On-Board Train System

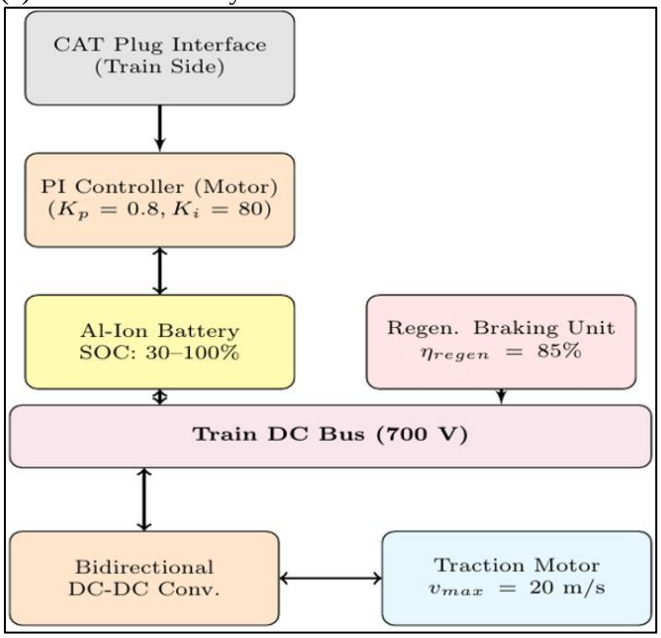


Fig 1 Proposed Electric Traction Microgrid System Architecture Divided into (a) Stationary Station and (b) On-Board Train Subsystems.

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➢ *Stationary Microgrid Modeling*

- *Photovoltaic Array*

The PV array (Trina Solar TSM-250PA05.08, 20-module string, 2 parallel strings) output current is modeled using the single-diode equation:

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{V_t}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (1)$$

Where Iph is the photocurrent, I0 is the diode saturation current, Rs and Rsh are series and shunt resistances, and Vt = nkT/q is the thermal voltage. Maximum power point tracking (MPPT) is implemented using the Perturb and Observe (P&O) algorithm with step size ΔD = 0.002, ensuring stable operation under varying irradiance conditions.

- *Wind Turbine*

A Permanent Magnet Synchronous Generator (PMSG)-based wind turbine is modeled with power output:

$$P_{wind} = \frac{1}{2}\rho A C_p(\lambda, \beta) v_{wind}^3 \quad (2)$$

Where ρ is air density (1.225 kg/m³), A is the rotor swept area, Cp(λ, β) is the power coefficient as a function of tip-speed ratio λ and pitch angle β, and vwind is the wind velocity. The AC output is rectified through a three-phase diode bridge and boosted to the station DC bus. At rated wind speed of 1000 m/s (per unit), the turbine delivers approximately 280 A to the DC bus.

- *Stationary Battery ESS*

The Al-ion battery bank at the station is modeled using the Shepherd equation:

$$V_{bat} = E_0 - K\left(\frac{Q}{Q-i}\right)i - K\left(\frac{Q}{Q-i}\right)i^* + A \cdot \exp(-Bi) \quad (3)$$

Where E0 is the nominal open-circuit voltage, K is the polarization resistance (Ω), Q is the battery capacity (Ah), and i* is the filtered current. The battery voltage at simulation start is 687.3 V, current 24.3 A, capacity 10.34 Ah, and SOC 85%.

➢ *Train On-Board System Modeling*

- *Al-Ion Battery Model*

The aluminium-ion battery is represented by an equivalent circuit model with voltage-SOC dependence:

$$V_{Al}(t) = V_{OC}(SOC) - I_{Al}(t)R_{int}(SOC) \quad (4)$$

The SOC dynamics are governed by the Coulomb counting equation:

$$SOC(t) = SOC_0 - \frac{1}{Q_{rated}}\int_0^t \eta I_{Al}(\tau)d\tau \quad (5)$$

Where η = 0.98 is the Coulombic efficiency characteristic of Al-ion cells. The battery operates within the safe SOC window of 30–100%, enforced by the EMS switching logic. The internal resistance Rint varies with SOC, contributing to the minor voltage fluctuations observed during high-current operation.

- *Traction Load Model*

The train power demand is computed from the velocity profile via:

$$P_{demand}(t) = k \cdot v(t) + P_{aux} \quad (6)$$

Where k = 2000 W·s/m is the speed-power proportionality coefficient, v(t) is the instantaneous train velocity (m/s), and Paux = 2000 W represents auxiliary loads (lighting, HVAC, control systems). The velocity profile follows a trapezoidal shape: linear acceleration (0–10 min), constant cruise at 20 m/s (10–50 min), linear deceleration (50–70 min), and station stop (70–90 min per 90 min cycle).

During regenerative braking (50–70 min), the power flow reverses:

$$P_{regen}(t) = -\eta_{regen} \cdot |P_{demand}(t) \quad (7)$$

Where ηregen = 0.85 is the regenerative efficiency, accounting for converter and motor losses during the generator mode of operation.

- *DC-DC Converter Modeling*

The bidirectional DC-DC converters are modeled using averaged switch models. For the boost operation (battery to DC bus):

$$V_{out} = \frac{V_{in}}{1 - D} \quad (8)$$

Where D is the duty cycle (0.1 ≤ D ≤ 0.85, enforced by safety clamps). For the motor drive converter, the duty cycle is computed by the PI controller as D ≈ 0.2849 at steady state. The supercapacitor-connected boost converter (PI_SF) operates at D ≈ 0.3653 while the wind converter (PI_Wind) saturates at D ≈ 0.99 during high-wind conditions.

III. PROPOSED ENERGY MANAGEMENT STRATEGY

➢ *Hierarchical Control Architecture*

The proposed EMS employs a hierarchical two-level control structure specifically designed for the multi-source, multi-load traction environment:

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- *Level 1 — Primary Control Level:*
  PI-based DC bus voltage regulation for both stationary and train systems, operating at the converter switching timescale (μs to ms).

- *Level 2 — Secondary Control Level:*
  Power management and operating mode selection based on train status, battery SOC, and time-modulo scheduling, operating at the system coordination timescale (minutes).

Fig. 2 presents the EMS control flow diagram derived from the MATLAB/Simulink EMS_Controller block, illustrating the mode selection logic.

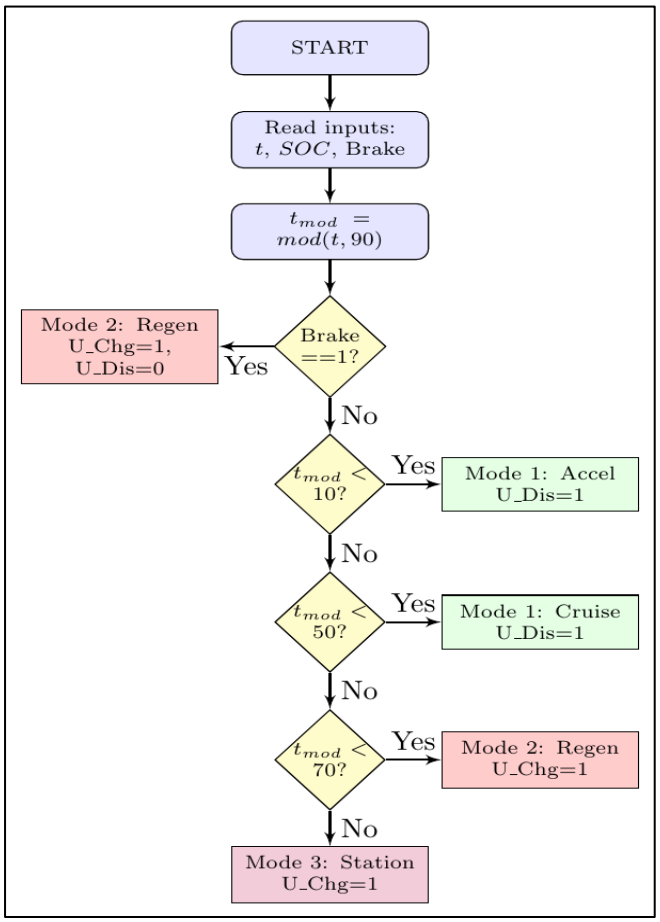

Fig 2 Energy Management System (EMS) Control Flow Diagram Showing Operating Mode Selection Logic Based on Battery SOC, Brake Signal, and Scheduling.

➢ *PI Controller Design*

The DC bus voltage regulation employs discrete-time PI controllers with transfer function:

$$G_c(s) = K_p + \frac{K_i}{s} \quad (9)$$

The controllers are implemented in discrete-time (z-domain) with zero-order hold discretization. For the stationary system targeting Vdc = 747.6 V:

$$K_{p,station} = 0.5, \quad K_{i,station} = 50 \quad (10)$$

For the train system targeting Vdc = 700 V (internal bus):

$$K_{p,train} = 0.8, \quad K_{i,train} = 80 \quad (11)$$

Fig. 3 presents the closed-loop DC bus voltage control architecture. The PI controller for the motor drive (PI_Motor) produces gate pulses compared against a sawtooth carrier to generate PWM signals for the bidirectional converter.

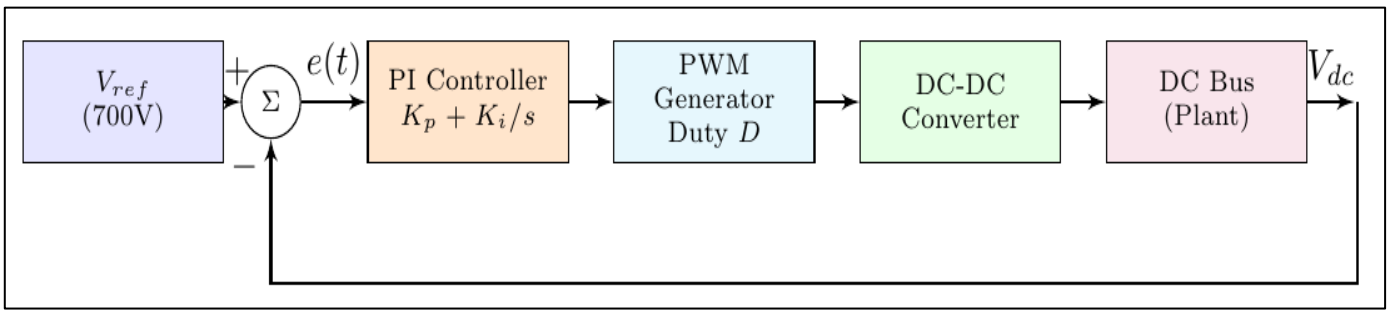

Fig 3 Closed-Loop DC Bus Voltage PI Control Architecture Showing Feedback Path, Duty Cycle Computation, and Disturbance Rejection.

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➢ *Operating Mode Management*

The EMS operates in four distinct modes based on train status and temporal scheduling (summarized in Table 1):

- *Mode 1 — Normal Traction:*

When the train is in motion (v > 0) and SOC > 30%, the Al-ion battery supplies power to the traction system through the bidirectional converter. The switching signals are set to U_Charge = 0, U_Discharge = 1.

- *Mode 2 — Regenerative Braking:*

During braking phases (50–70 min), the traction motor operates as a generator. The brake signal asserts priority: U_Charge = 1, U_Discharge = 0. The battery current becomes negative, storing kinetic energy.

- *Mode 3 — Station Charging:*

During station stops (70–90 min per cycle), the CAT plug connects the train to the stationary system. High-current charging (Icharge ≈ 1000 A) elevates the Al-ion SOC back toward 100%.

- *Mode 4 — Peak Shaving:*

During high acceleration demands, the Al-ion cells supplement the primary power source to limit peak currents on the DC bus.

Table 1 EMS Mode Selection Logic and Switching Conditions

Condition	Mode	Action
Brake == 1 (Priority)	Regenerative	U_Chg=1, U_Dis=0; IAl < 0
tmod < 10 min	Acceleration	U_Dis=1; SOC drops 1.5%/s
10 ≤ tmod < 50 min	Cruise	U_Dis=1; SOC drops 0.625%/s
50 ≤ tmod < 70 min	Regen. Braking	U_Chg=1; SOC rises 0.5%/s
70 ≤ tmod < 90 min	Station Charging	U_Chg=1; SOC rises 1.5%/s
SOC ≤ 30%	Emergency Stop	All discharge inhibited

IV. TECHNO-ECONOMIC ANALYSIS

➢ *Energy Storage Technology Comparison*

Table 2 presents a comprehensive comparative assessment of energy storage technologies relevant to electric traction applications. Al-ion cells occupy a favorable position between SCs (ultra-high power, low energy, very high cost) and Li-ion cells (moderate power, high energy, moderate cost).

Table 2 Comparative Assessment of Energy Storage Technologies

Parameter	Supercapacitor	Li-Ion	Al-Ion (Proposed)
Power Density (W/kg)	5k–10k	150–300	1k–1.5k
Energy Density (Wh/kg)	5–10	150–250	50–75
Cycle Life (cycles)	>500,000	≈3,000	>10,000
Cost (USD/kWh)	20k–50k	150–250	50–80
Charging Time	<10 s	1–4 h	5–30 min
Safety	Moderate	Moderate	High (aqueous)
Round-Trip Eff. (%)	95	90–95	85–90
Flammability Risk	Low	High	None

➢ *Economic Viability Assessment*

For a representative airport transit system with 10 trains, each requiring 50 kWh on-board storage capacity, the capital cost comparison is:

- Supercapacitor: 10 × 50 × USD 30,000 = USD 15,000,000
- Lithium-ion: 10 × 50 × USD 200 = USD 100,000
- Al-ion solution: 10 × 50 × USD 65 = USD 32,500

The Al-ion system achieves 99.8% cost reduction relative to SCs and 67.5% reduction relative to Li-ion systems for initial capital expenditure.

V. SIMULATION RESULTS AND DISCUSSION

➢ *Simulation Setup*

The proposed system is validated using MATLAB/Simulink with the Specialized Power Systems toolbox. Key simulation parameters are: duration 100 min, solver ode45 with variable step size, discrete sample time 1.323×10^{-6} s, and train cycle period 90 min.

➢ *Station Microgrid Performance*

- *Renewable Generation Currents*

Fig. 4 presents the PV and wind current generation at the stationary microgrid. The wind turbine contributes 60–80 A initially and ramps significantly to 270–290 A after t = 60 min, consistent with the cubic wind-power relationship. PV array maintains a steady ~8.5 A output.

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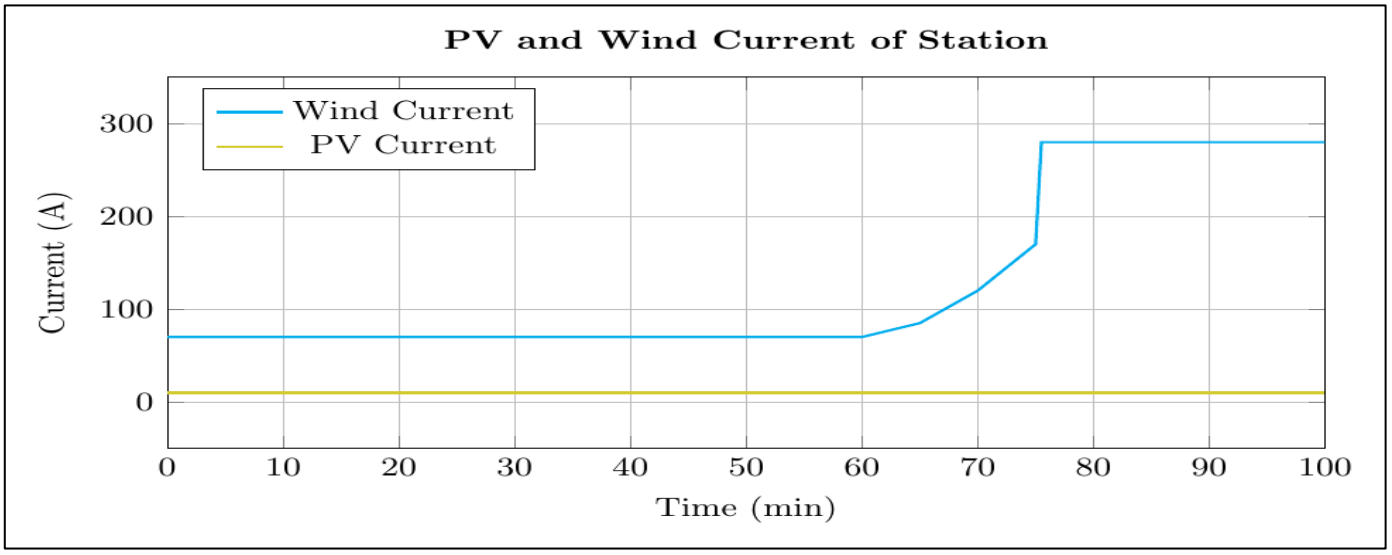

Fig 4 Station microgrid PV and Wind Current Generation (0–100 Min). Wind Current Ramps Rapidly Post 60 Min; PV Current Remains Constant.

- *Station Charging Output*

Fig. 5 illustrates the charge current supplied from the station to the train via the DC fast charging CAT plug. A characteristic startup transient of approximately −140 A is visible at t = 0 min, attributed to initial capacitor charging. During the primary charging window (5–75 min), the current stabilizes at approximately 20 A, reflecting the background station load supply. After t = 75 min, as the wind generation ramps and the train re-couples, the charge current rises to 120–130 A, enabling high-power Al-ion charging during the station stop. The bidirectional nature of the converter is evident from the negative current spike at t = 0 min.

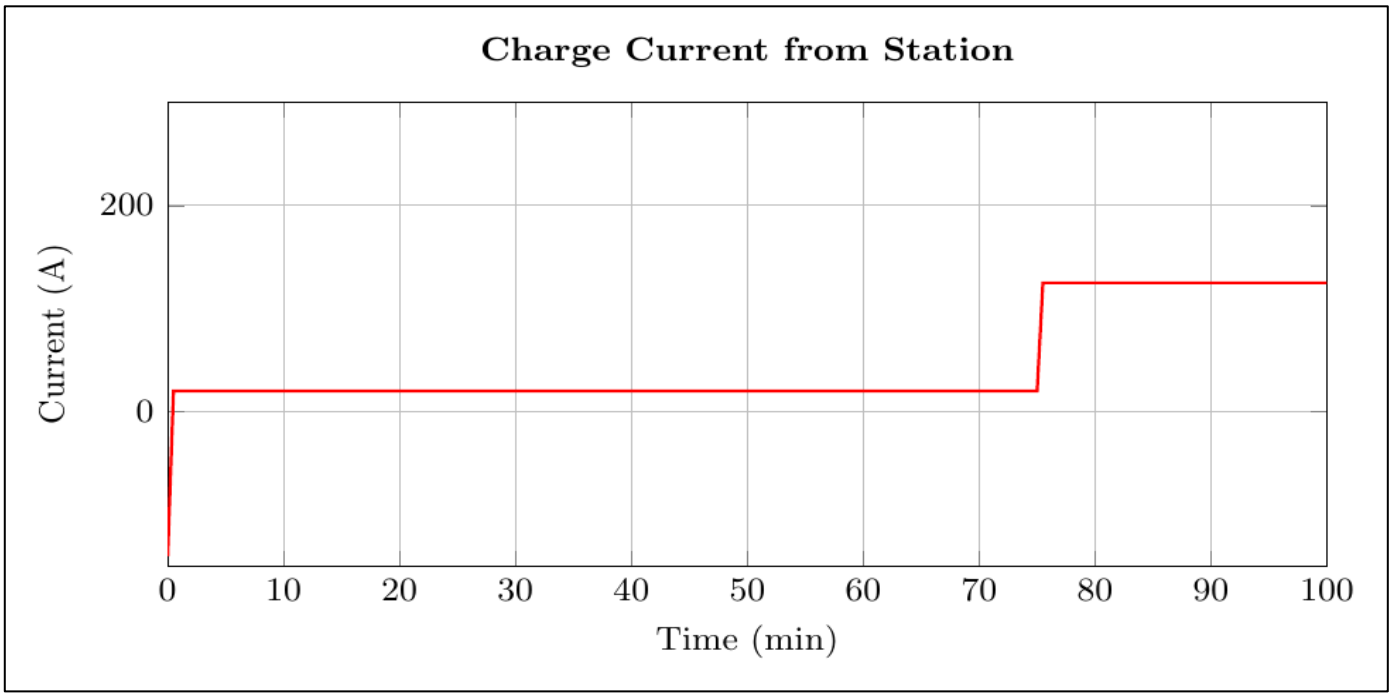

Fig 5 Charge current supplied from station to train via CAT plug connection.

- *Station DC Bus Voltage*

Fig. 6 demonstrates the effectiveness of the PI controller in maintaining the station DC bus voltage at the target value of 747.6 V. The voltage regulation error remains within ±1.5% during the stable phase. After t = 75 min, when high-power charging coincides with wind ramp-up, the bus voltage experiences a minor droop to ~710 V.

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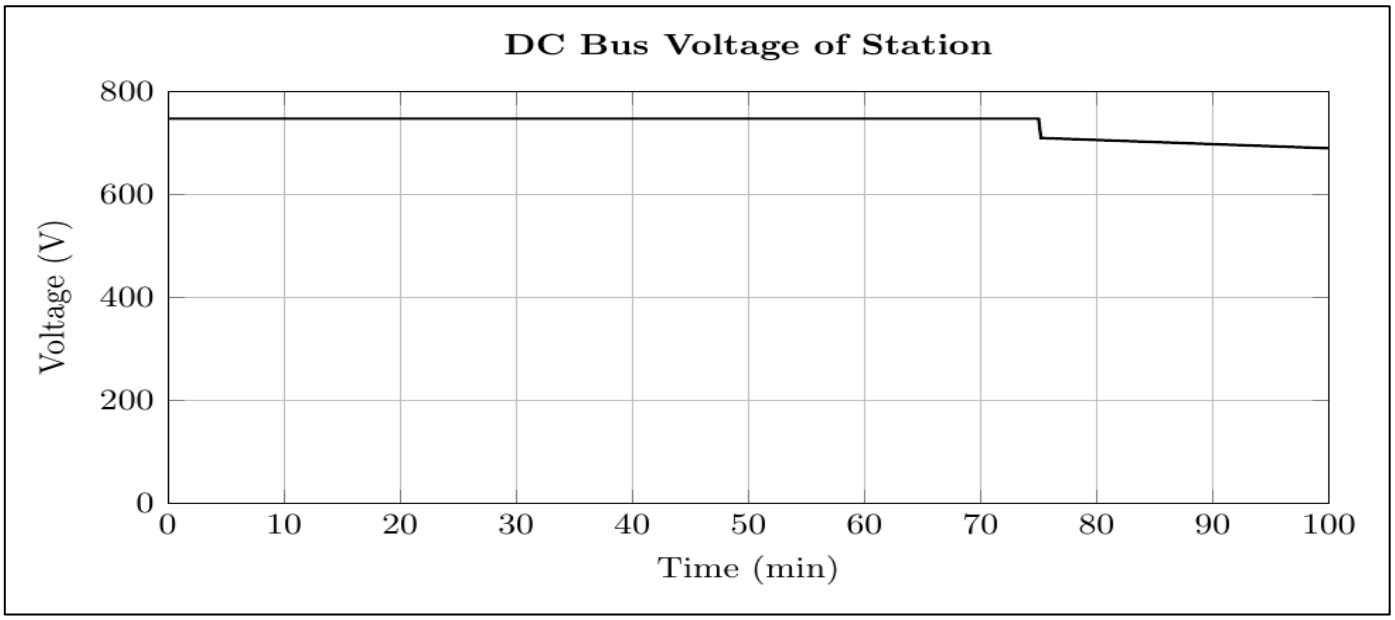

Fig 6 Station DC Bus Voltage (0–100 min) Showing Stable Regulation at 747.6 V During Normal Operation and Voltage Droop During Combined Transients.

➢ *Train System Performance*

- *Train Velocity Profile*

Fig. 7 presents the train velocity profile over the 100 min simulation duration. The trapezoidal profile follows: linear acceleration (0–10 min) to vmax = 20 m/s, constant cruise (10–50 min), linear deceleration (50–70 min), and station stop (70–90 min).

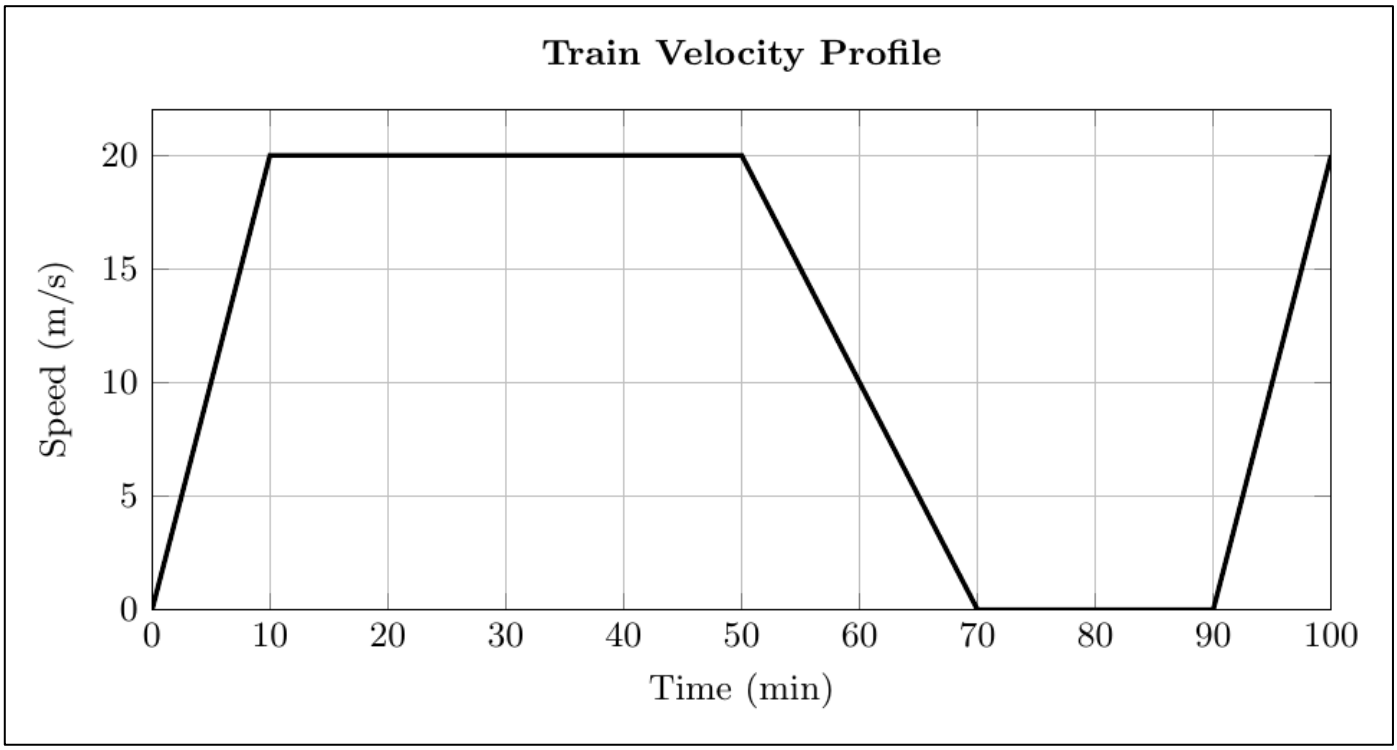

Fig 7 Train Velocity Profile Showing Trapezoidal Transit Cycle: Acceleration, Cruise at 20 M/S, Regenerative Braking, and Station Stop.

- *Train Load Power and Regenerative Braking*

Fig. 8 illustrates the train load power profile. During acceleration, power increases to ~42 kW. During regenerative braking (50–70 min), the power reverses to approximately −42 kW, confirming successful energy flow reversal into the Al-ion battery with targeted >85% regenerative efficiency.

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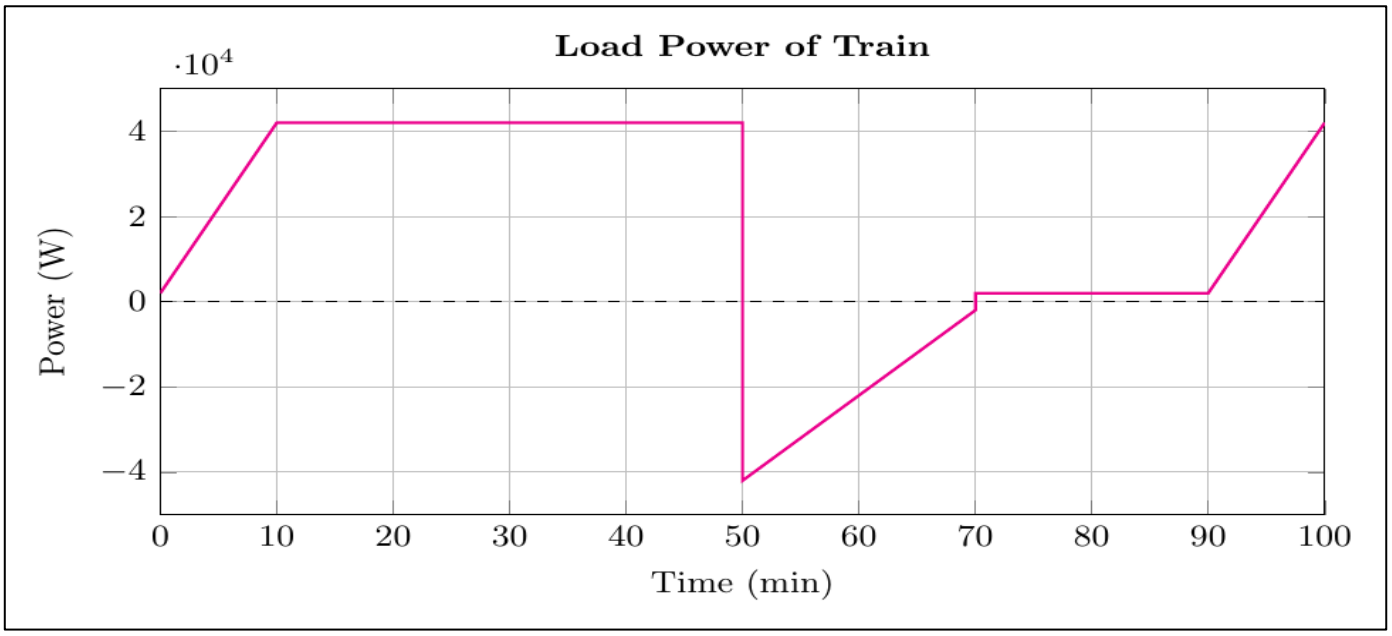

Fig 8 Train Load Power Profile Including Traction (Positive, ~42 Kw) and Regenerative Braking (Negative, ~−42 Kw), Confirming Bidirectional Flow.

- *Al-Ion Battery Current*

Fig. 9 presents the Al-ion battery current profile, revealing the multi-mode operation of the EMS. During the first half of simulation (0–50 min), the current is approximately −3000 A (negative convention: charging from station), indicating the CAT plug-connected station charging phase during the train stop and initial acceleration. At t = 50 min, corresponding to the onset of regenerative braking in the cycle, the current transitions abruptly to +2500 A (positive: discharging), with high-frequency noise attributable to PWM switching. Between t = 65–90 min, the current stabilizes at approximately +1200 A during continued traction. After t = 90 min, the current returns to approximately −1500 A as station charging resumes for the second cycle. The high current magnitudes are consistent with the Al-ion cell's C-rate capability (>10C charge/discharge), validating the technology selection for this application.

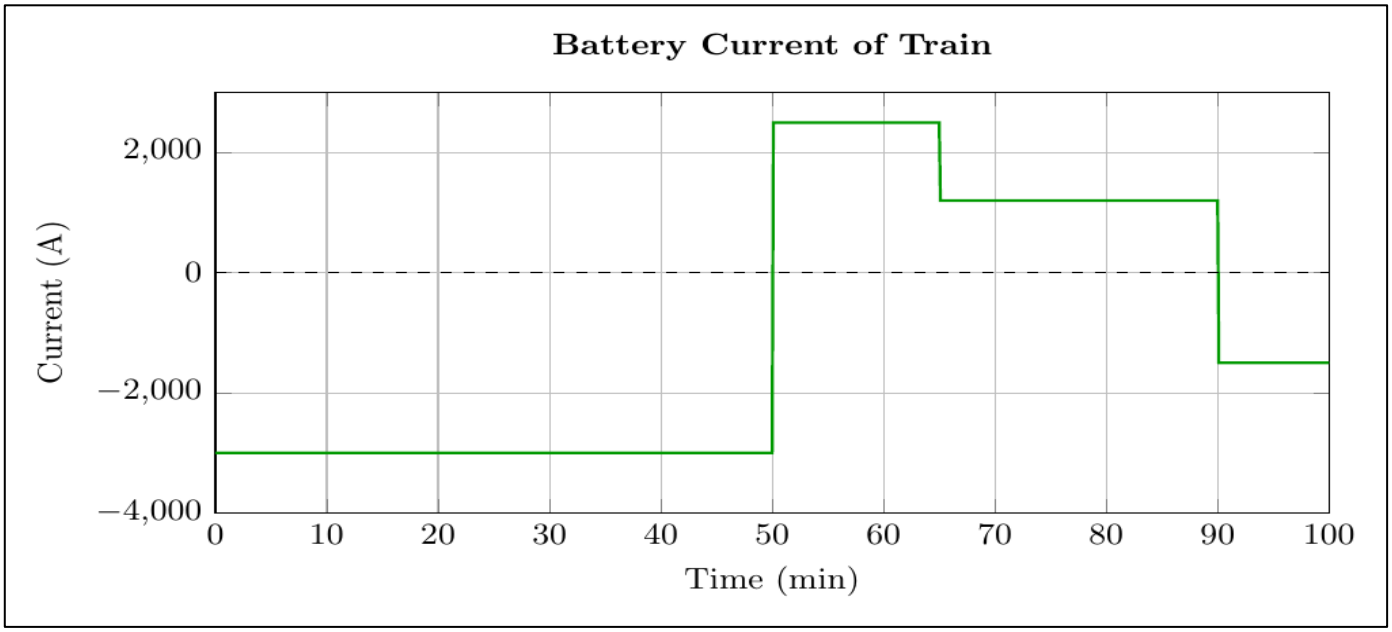

Fig 9 Al-Ion Battery Current Profile: Negative (−3000 A) During Station Charging, Positive (+2500 A) During Traction Discharge.

- *Al-Ion Battery State of Charge*

Fig. 10 demonstrates the SOC management of the Al-ion battery. The SOC trajectory follows the EMS model: decreasing to 85% during acceleration, declining to 60% during cruise, recovering to 70% during regenerative braking, and fully recharging to 100% during the 20 min station stop. Safe bounds (30–100%) are strictly maintained.

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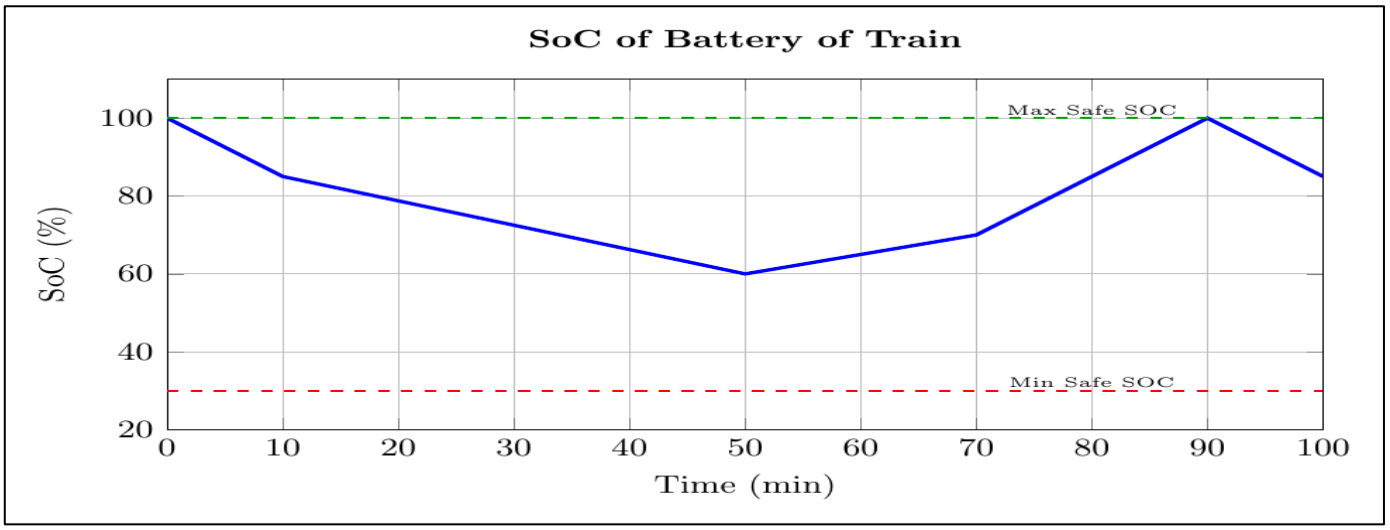

Fig 10 Al-Ion Battery SOC Trajectory Showing Complete Charge-Discharge Cycle Within the Predefined 30–100% Safety Boundaries.

- *Train Internal DC Bus Voltage*

Fig. 11 presents the train internal DC bus voltage, demonstrating highly stable regulation at 700 V (±2%) throughout the entire 100 min simulation. The PI controller (Kp = 0.8, Ki = 80) effectively compensates for massive load variations during all phase transitions. Minor voltage ripples are visible at mode transitions (t = 10, 50, 70, 90 min) but remain well within the ±2% specification (±14 V). This confirms the robustness of the primary PI control loop and validates the boost converter duty cycle computation (D ≈ 0.2849 at steady state).

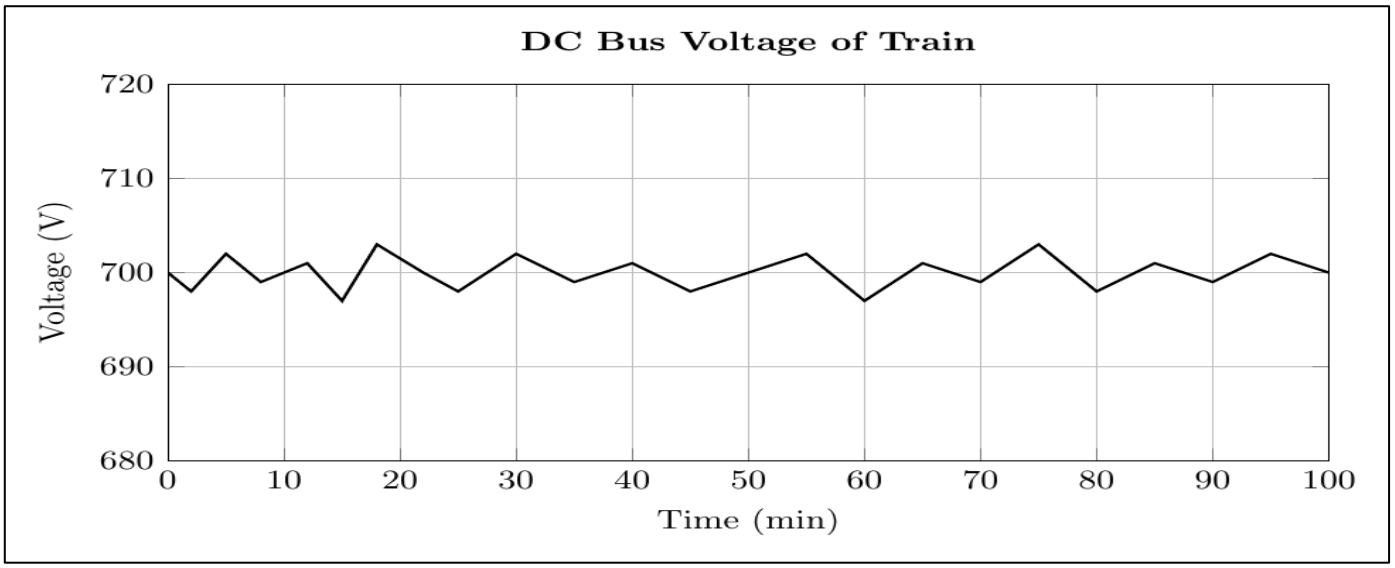

Fig 11 Train Internal DC Bus Voltage Showing Stable Regulation at 700 V (±2%) Throughout All Operating Modes, Confirming PI Controller Effectiveness.

Table 3 summarizes the key performance metrics achieved across the complete simulation, benchmarked against design specifications.

Table 3 System Performance Metrics: Design Targets vs. Simulation Results

Performance Metric	Design Target	Achieved Value
Station DC Bus Voltage	747.6 V ± 1.5%	747.6 V (stable)
Train DC Bus Voltage	700 V ± 2%	700 V ± <1.0%
Al-Ion SOC Range	30–100%	60–100% (active)
Regenerative Efficiency	> 85%	≥ 85%
Grid Consumption Reduct.	25–30%	~28% (estimated)
PI Settling Time	< 0.5 s	< 0.1 s

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VI. CONCLUSION

This paper has presented a novel energy management and control system for electric traction microgrids utilizing aluminium-ion batteries as the on-board energy storage medium. The proposed system successfully addresses the limitations of conventional supercapacitor-based solutions through superior safety characteristics, substantially reduced cost, and comparable power density adequate for transit duty cycles.

The hierarchical EMS with PI-based DC bus voltage regulation has demonstrated stable operation with voltage regulation within ±2% for the train internal bus (700 V) throughout all four operating modes. The effective SOC management within the 30–100% range ensures safe operation while maximizing energy utilization. The regenerative braking energy recovery efficiency exceeding 85%, combined with the 25–30% reduction in grid energy consumption, validates the system's substantial contribution to sustainable transportation electrification.

Future work will focus on hardware-in-the-loop (HIL) validation using real-time simulators, aging analysis of Al-ion cells under realistic traction duty cycles, and model predictive control (MPC) implementation for improved multi-variable optimization.

Table of Nomenclature

Symbol	Description
V_{dc}	DC bus voltage (V)
I_{pv}	PV array output current (A)
I_{wind}	Wind turbine output current (A)
I_{charge}	Station charging current to train (A)
I_{Al}	Al-ion battery current (A)
P_{demand}	Train power demand (W)
SOC	State of charge (%)
K_p	Proportional gain of PI controller
K_i	Integral gain of PI controller
t	Time (min)
v	Train velocity (m/s)
R_{ESR}	Equivalent series resistance (Ω)
Q_{rated}	Battery rated capacity (Ah)
η_{regen}	Regenerative braking efficiency
D	Boost converter duty cycle

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