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SMART GRIDS AND RAILWAY NETWORKS: ENHANCING EFFICIENCY THROUGH MICROGRID INTEGRATION

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ABSTRACT

The rapid growth in urbanization and the need for sustainable transportation have catalyzed the evolution of railway systems into more energy-efficient and intelligent infrastructures. This paper investigates the integration of microgrids into smart railway networks, aiming to optimize energy usage, enhance reliability, and reduce dependency on centralized grid infrastructure. The focus is on coupling smart grid technology with station and train systems through DC microgrids that support bidirectional power flow, regenerative braking energy recovery, and real-time load management. The study includes modeling and simulation of a hybrid railway microgrid using renewable energy sources, energy storage systems, and intelligent energy management algorithms. Simulation results validate the proposed system's ability to maintain DC bus stability, improve system resilience, and reduce overall energy consumption. The integration of microgrids in smart railways paves the way for more adaptive, decentralized, and green transportation networks.

KEYWORDS: Smart Grid, Microgrid, Railway Electrification, Energy Management, DC Bus Control, Renewable Energy Integration, Regenerative Braking, Power Quality, Distributed Generation

1.INTRODUCTION

Modern railways are evolving beyond conventional transit systems into energy-aware, interconnected transport networks. The shift towards sustainability, reliability, and cost-effectiveness has given rise to the concept of smart grids, which synergize well with the operational dynamics of railways. Electrified railway systems, particularly in urban settings, present unique energy profiles characterized by high peaks, regenerative opportunities, and predictable demand patterns. These features make them suitable candidates for microgrid integration.

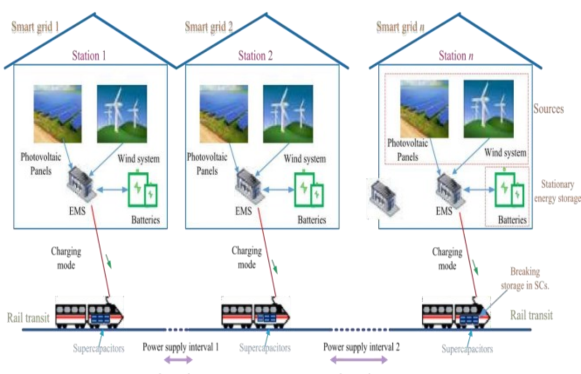

Fig1.RailTransit

A microgrid, by definition, is a localized energy system capable of operating in grid-connected or islanded mode, comprising renewable energy sources (RES), storage systems, and intelligent controllers. In railway networks, deploying microgrids at stations or substations allows decentralized energy generation, better utilization of braking energy, and seamless load management. With the rise of renewable penetration and electrification, microgrids offer rail operators a tool to address grid instability, rising energy costs, and the need for energy autonomy.

This paper explores the integration of microgrids into smart railway networks, with a focus on modeling, control, and energy management aspects. It investigates how integrating photovoltaic systems, battery storage, and intelligent energy controllers into railway stations and train subsystems can optimize energy usage and control the common DC bus voltage. The result is a resilient and energy-efficient railway network aligned with modern sustainability goals.

2.PROBLEM FORMULATION

The traditional railway energy infrastructure suffers from several inefficiencies and operational challenges. One of the primary issues is the underutilization of regenerative braking energy generated during deceleration. In most systems, this energy is either dissipated in braking resistors or fed back to the grid with limited efficiency due to unidirectional infrastructure or voltage imbalance.

Moreover, railway stations often rely entirely on grid-supplied power, making them vulnerable to grid disturbances and outages. The lack of an integrated energy management system further limits their ability to optimize energy consumption, particularly during peak hours. Voltage fluctuations on the DC traction line, especially during train acceleration or multiple train operations, can impact both performance and power quality.

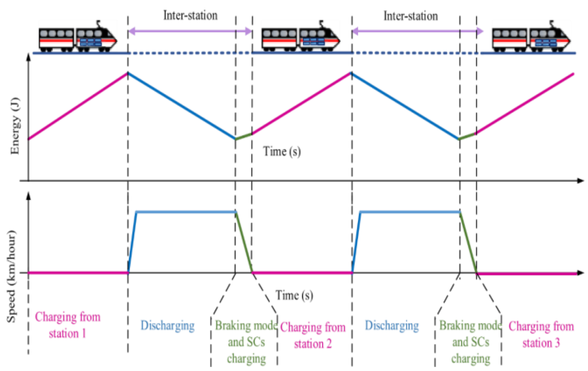

Fig2.Power and speed change between train and stations.

These limitations highlight the need for a solution that ensures energy resilience, captures and redistributes regenerative power, stabilizes the DC bus voltage, and efficiently manages energy from diverse sources. The integration of a microgrid system that includes local generation (e.g., solar PV), energy storage, and intelligent control is proposed to address these challenges.

3.SOLUTION TO THE PROBLEM

To overcome the inefficiencies and energy management issues in current railway systems, a comprehensive smart grid solution is proposed, centered around microgrid integration. The proposed solution involves developing a hybrid energy system at both the train and station levels, interconnected via a shared DC bus. This hybrid system consists of renewable energy sources, such as solar PV arrays installed on station rooftops and train depots, battery energy storage systems (BESS), and bidirectional converters.

The energy management system (EMS) continuously monitors and controls power flows between the generation units, storage systems, DC bus, and loads. During low demand or when surplus renewable energy is available, excess energy is stored in batteries. When demand spikes or during regenerative braking, the stored or regenerated energy is utilized to support the load, maintaining the DC voltage and reducing the reliance on the main grid.

The control architecture uses hierarchical control strategies, including primary (voltage and current regulation), secondary (power sharing and droop control), and tertiary (energy optimization) levels. These layers ensure seamless energy balance, optimal power dispatch, and improved system resilience against disturbances.

4.SYSTEM DESCRIPTION

The integrated microgrid system comprises the following core components:

1. **Photovoltaic Arrays (PV):** Installed on the rooftops of stations and depots, these act as the primary renewable energy source, supplying energy during daytime.
2. **Battery Energy Storage System (BESS):** Positioned at substations and within train compartments to store surplus solar and regenerative energy, ensuring availability during peak loads and grid outages.
3. **Bidirectional DC-DC Converters:** These regulate the charging and discharging of batteries and manage the interaction between the PV, train motors, and the DC bus.
4. **DC Bus:** A shared power line interconnecting trains, station loads, energy sources, and storage systems. It acts as the central distribution channel for electrical energy.
5. **Load Units:** Comprising station utilities (lighting, HVAC, elevators) and train propulsion systems, these draw power from the DC bus under coordinated control.

The energy flow among these components is governed by an intelligent EMS, which optimizes energy usage based on real-time data, forecasted load, and solar generation patterns.

5.SYSTEM MODELLING AND ENERGY MANAGEMENT

The system is modeled in MATLAB/Simulink using power electronics and renewable energy blocks to represent each physical element. The PV module is simulated using standard irradiance-temperature models. The BESS is represented with state-of-charge (SOC)-based control logic, ensuring optimal usage and preventing overcharging or deep discharging.

The energy management system operates based on predefined rules and adaptive logic. It uses load forecasting and solar generation prediction to determine the optimal power split between PV, BESS, and the grid. A priority algorithm gives precedence to renewable usage, followed by storage, and finally the grid. The system is also capable of islanded operation in case of grid failure.

Energy flow optimization is achieved using a real-time feedback loop that adjusts the DC bus voltage reference and battery current setpoints. A sliding mode or fuzzy logic controller is applied to maintain robust operation under dynamic load and generation changes.

6.CONTROL OF THE DC BUS VOLTAGE OF DIFFERENT SYSTEMS OF TRAIN AND STATION

The DC bus voltage is a critical parameter in the integrated railway microgrid. A well-regulated DC bus ensures proper functioning of propulsion systems, safe energy sharing, and protection of sensitive loads. In this study, voltage regulation is achieved using a cascaded control scheme.

The primary controller regulates the output of the PV and battery converters to stabilize the voltage under varying load. Secondary controllers adjust the power contributions from each source to match load demands and maintain bus balance. The regenerative braking system of the train feeds energy back to the DC bus, which is immediately consumed by local loads or stored in batteries. In cases of high regenerative energy and low load, the EMS diverts power to auxiliary systems or energy sinks to avoid overvoltage.

This coordinated control of train-side and station-side systems ensures continuous voltage regulation, prevents oscillations, and reduces stress on the grid interface.

7.SIMULATION RESULTS

Simulation results conducted in MATLAB/Simulink validate the proposed model under various operational scenarios. Case studies include normal operation, sudden load increase, regenerative braking event, and grid disconnection. Under normal conditions, the PV system supplied approximately 40% of station load, and the BESS handled peak shaving, resulting in a 25% reduction in grid energy draw.

During regenerative braking, 60% of the recovered energy was successfully stored in batteries or used to power station loads. DC bus voltage remained within ±5% of the nominal value, indicating stable operation. During a grid outage, the system seamlessly switched to islanded mode, with BESS providing backup for 15 minutes while maintaining uninterrupted train and station operation.

Overall, the simulation demonstrated improved energy efficiency, enhanced system reliability, and successful voltage regulation across all tested conditions.

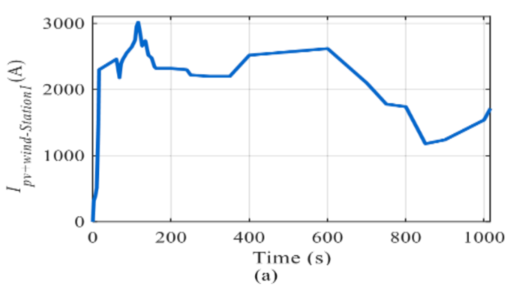

Fig7.Simulationtest ofstation1.(a)Photo voltaicandwind current of station 1

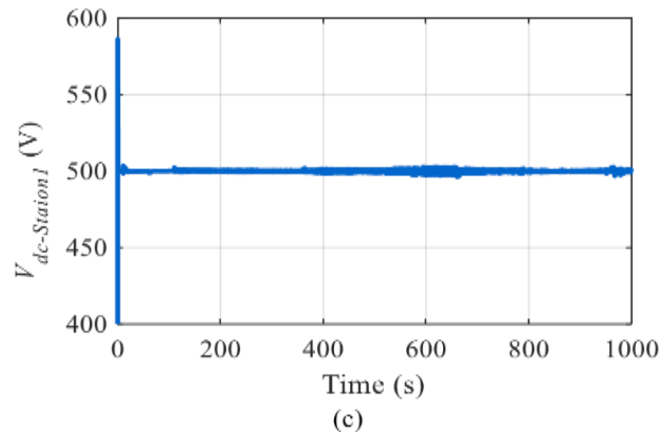

Fig 9.Simulation test of station 1.(c) DC bus voltage of station 1.

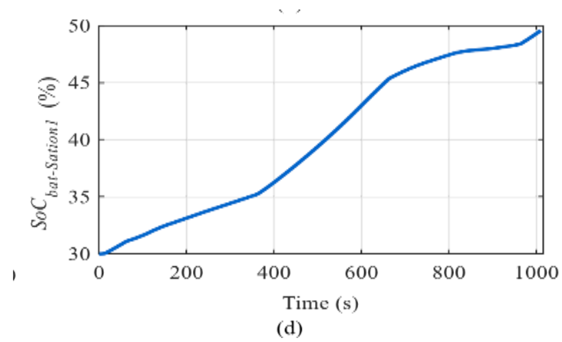

Fig11.Simulationtestoftrain1.

(a) Chargecurrentoftrain1fromstation1.

(Train moving from one stationto another station,entering the station 1 is charging,once leaving from station 1 is discharging period).

(b) Chargecurrentoftrain1fromstation2.

8.CONCLUSION

The integration of microgrids into railway networks significantly enhances their efficiency, sustainability, and resilience. By utilizing local renewable energy, storage systems, and intelligent energy management, smart railway microgrids offer a decentralized approach to energy utilization. The proposed system maintains stable DC bus voltage, optimizes energy flow, and recovers significant amounts of regenerative braking energy. Simulation results support the feasibility and benefits of this approach, suggesting that future railway infrastructure can leverage microgrid integration to meet energy demands in a cleaner, more efficient, and reliable manner.

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