International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 05 May-2026 | Impact Factor: 3.5

A Review on Supercapacitor Bus within a Quick Charge

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How to Cite this Article:

Kawde, A. U. G. D. B. M. G. A. T. M. N. (2026). A Review on Supercapacitor Bus within a Quick Charge. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(05), 1-10. https://doi.org/10.55041/ijcope.v2i5.598

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Abstract - *The transition toward sustainable transportation has increased the demand for high-performance electric bus systems capable of operating efficiently in urban environments. Traditional battery-based buses face limitations such as extended charging duration and reduced lifespan under frequent charge-discharge cycles. This paper presents a supercapacitor-driven electric bus system designed to support ultra-fast charging and high-power operation.*

The proposed model utilizes a modular supercapacitor bank combined with a controlled fast-charging interface installed at selected transit points. The system emphasizes rapid energy transfer, allowing buses to recharge within short dwell times. An optimized control strategy is implemented to manage power distribution during acceleration, cruising, and regenerative braking. Performance analysis indicates that the system achieves reduced charging time, improved energy recovery, and enhanced operational efficiency. The proposed solution offers a reliable and sustainable approach for next-generation urban mobility systems.

Keywords— *Supercapacitor Bus, Fast Charging, Energy Management, Urban Transport, Regenerative Energy.*

I. Introduction

Urban transportation systems are undergoing rapid transformation due to increasing concerns regarding environmental sustainability and energy efficiency. Public transport, particularly buses, plays a critical role in urban mobility but also contributes significantly to energy consumption and emissions when powered by conventional fuels. Electric buses have emerged as an alternative; however, their reliance on battery technology introduces challenges such as long charging periods and performance degradation over time.

Supercapacitors offer a distinct advantage in applications requiring high power output and rapid charging. Unlike batteries, they can handle frequent charge-discharge cycles without significant wear, making them suitable for stop-and-go transit systems. This characteristic enables the development of fast-charging electric buses, where energy can be replenished during short stops rather than long charging sessions.

This research focuses on designing a supercapacitor-based electric bus system optimized for urban routes, where frequent stops allow efficient opportunity charging. The study explores system performance, energy utilization, and operational feasibility, aiming to provide a scalable solution for future smart transportation networks.

II. Objectives

The main objectives of the proposed supercapacitor-based bus system with quick charging are as follows:

- To design a high-power supercapacitor-based propulsion system
- To analyze fast charging performance under short time intervals
- To evaluate energy recovery efficiency during braking cycles
- To reduce vehicle downtime and improve route efficiency
- To develop an optimized energy control strategy
- To enhance sustainability in urban public transport systems

III. Literature Survey

The advancement of electric mobility has encouraged extensive research on alternative energy storage technologies capable of supporting high-performance transportation systems. Among these, supercapacitors have emerged as a viable solution for applications requiring rapid energy exchange and high power delivery.

Simon and Gogotsi (2008) investigated the fundamental properties of electrochemical capacitors, emphasizing their ability to deliver high power density and fast charge-discharge cycles. Their work highlighted the potential of supercapacitors in transportation systems where quick energy transfer is essential.

Lukic et al. (2008) explored various energy storage systems for hybrid and electric vehicles, comparing batteries, fuel cells, and supercapacitors. The study concluded that supercapacitors are particularly suitable for applications involving frequent acceleration and braking due to their superior power handling capability.

Choi and Lee (2012) proposed a fast charging strategy for electric buses using supercapacitors, focusing on reducing charging time at bus stops. Their findings demonstrated that rapid charging systems can significantly improve operational efficiency in urban transport networks.

Chen et al. (2016) analyzed the integration of supercapacitor energy storage in public transit systems, highlighting the benefits of regenerative braking and reduced energy losses. The research showed that energy recovery mechanisms can improve overall system efficiency by reusing braking energy.

In another study, Khaligh and Li (2010) examined the role of power electronics in managing hybrid energy systems. They emphasized the importance of efficient converters and control strategies for maintaining stable operation in systems combining multiple energy storage technologies.

Despite these advancements, challenges such as limited energy density and infrastructure dependency remain key issues in supercapacitor-based systems. To address these challenges, recent research focuses on hybrid systems and improved energy management techniques.

The proposed system builds upon these studies by integrating fast charging capability with optimized energy control and regenerative braking, aiming to enhance the performance and feasibility of supercapacitor buses in real-world urban environments.

IV. Proposed System

The proposed system introduces a high-performance urban electric bus powered primarily by supercapacitors, designed to operate efficiently using a distributed fast-charging network. Unlike conventional systems that depend on large onboard energy storage, this model focuses on frequent, short-duration charging combined with optimized energy utilization.

The system is built around four key subsystems: energy storage module, fast-charging interface, traction system, and intelligent control unit. These components are interconnected to ensure seamless energy flow and efficient operation under varying driving conditions.

The energy storage module consists of a modular supercapacitor bank configured to handle high current loads. Instead of storing large amounts of energy for long distances, the system is optimized for rapid charge acceptance and discharge, making it ideal for routes with multiple stops. The modular design also allows scalability based on route requirements.

The fast-charging interface is implemented at selected transit points such as bus stops or terminals. When the bus arrives at these locations, a high-power charging mechanism is activated, supplying energy to the supercapacitor bank within a very short duration. This approach minimizes idle time and ensures that the bus maintains continuous operation without extended charging breaks.

The traction system includes an electric motor and drive controller that utilize the stored energy for propulsion. Due to the high power output of supercapacitors, the system can deliver immediate torque, ensuring smooth acceleration even under heavy load conditions. This is particularly beneficial in urban environments with frequent stop-and-go movement.

An intelligent control unit is incorporated to manage energy distribution and system performance. It continuously monitors parameters such as state of charge, power demand, and operating conditions. Based on these inputs, the controller dynamically adjusts power flow between the charging system, storage unit, and motor. It also enables regenerative braking, allowing energy generated during deceleration to be captured and stored back in the supercapacitor.

Additionally, the system is designed to support real-time monitoring and diagnostics, which helps in improving reliability and reducing maintenance requirements. The integration of smart control strategies ensures optimal utilization of energy and enhances overall system efficiency.

In summary, the proposed system provides a lightweight, fast-charging, and energy-efficient solution for electric bus transportation. By shifting the focus from large energy storage to rapid energy exchange, the system addresses key limitations of traditional electric buses and offers a practical approach for modern urban mobility.

V. System Architecture

The system architecture of the proposed supercapacitor-based electric bus is designed using a layered energy flow model, focusing on efficient power transfer, rapid charging, and intelligent control. The architecture integrates charging infrastructure, onboard energy storage, propulsion mechanisms, and control systems to ensure smooth and continuous operation in urban environments.

The architecture can be divided into four functional layers: the charging layer, energy storage layer, power conversion layer, and application layer.

1. Charging Layer

The charging layer consists of high-power charging stations installed at predefined bus stops or terminals. These stations provide electrical energy during short halts using conductive charging mechanisms. The system is designed to deliver high current within a limited time, enabling quick replenishment of energy in the supercapacitor bank.

2. Energy Storage Layer

This layer includes the supercapacitor bank, which acts as the central energy storage unit. The supercapacitors are arranged in series-parallel configurations to meet voltage and current requirements. Unlike traditional batteries, this layer supports rapid energy absorption and release, making it suitable for frequent charge-discharge cycles.

3. Power Conversion Layer

The power conversion layer consists of bidirectional DC-DC converters and motor drive circuits. These components regulate the energy flow between the charging station, supercapacitor bank, and electric motor. The converters maintain stable voltage levels and ensure efficient energy transfer during both charging and discharging operations.

4. Application Layer

The application layer includes the electric motor, drivetrain, and auxiliary systems of the bus. It utilizes the stored energy to provide propulsion. This layer also interacts with the control system to adjust performance based on driving conditions such as acceleration, cruising, and braking.

5. Control and Monitoring System

An integrated control unit supervises all layers of the system. It continuously monitors parameters such as voltage, current, temperature, and state of charge. Based on real-time data, it optimizes power distribution and activates regenerative braking, allowing energy recovery during deceleration.

VI. Methodology

The methodology of the proposed system is based on a dynamic energy exchange approach, where energy is rapidly transferred, utilized, and recovered during continuous bus operation. The workflow is designed to support efficient performance under real-time urban transit conditions.

1. Pre-Operation System Check

Before starting the operation, the system performs a diagnostic check of all components including the supercapacitor bank, power converters, and control unit. The state of charge (SoC) and system readiness are verified to ensure safe and reliable functioning.

2. Scheduled Opportunity Charging

The bus follows a predefined route with designated charging points. At each stop, the fast-charging interface is automatically activated, allowing high-power energy transfer to the supercapacitor. The charging duration is optimized based on stop time, ensuring maximum energy intake without delaying operations.

3. Adaptive Energy Utilization

Once charged, the stored energy is utilized for propulsion. The system follows an adaptive power distribution strategy, where energy output is adjusted based on driving conditions such as acceleration, load variation, and road conditions. This helps in maintaining smooth performance while minimizing energy loss.

4. Real-Time Energy Monitoring

The system continuously monitors parameters such as voltage, current, temperature, and energy levels. The control unit processes this data in real time and dynamically regulates energy flow to maintain system stability and efficiency.

5. Regenerative Energy Capture

During braking or deceleration, the system switches to energy recovery mode. The electric motor acts as a generator, converting kinetic energy into electrical energy. This recovered energy is redirected and stored back into the supercapacitor, reducing overall power consumption.

6. Energy Balancing and Protection

The control system ensures that the supercapacitor operates within safe limits by preventing overcharging, deep discharge, and thermal stress. It balances energy levels across modules to maintain uniform performance and extend system lifespan.

7. Continuous Operation Cycle

The entire process operates in a continuous loop of:

- Charging → Energy storage → Power utilization → Energy recovery

This cyclic operation ensures that the bus maintains consistent performance with minimal downtime, making it suitable for high-frequency urban routes.

VII. Advantages and Limitations

The proposed supercapacitor-based quick charging bus system introduces a modern approach to electric transportation by emphasizing rapid energy transfer and efficient power utilization. While the system offers several operational and environmental benefits, it also presents certain technical and economic challenges.

A. Advantages

1. **High Power Availability**
Supercapacitors can deliver large bursts of power instantly, which is highly beneficial for frequent acceleration in urban traffic conditions.
2. **Short Charging Intervals**
The system supports opportunity charging, allowing buses to recharge during short stops instead of requiring long charging sessions.
3. **Robust Performance Under Frequent Cycling**
The energy storage system can withstand repeated charging and discharging without significant performance degradation.
4. **Enhanced System Efficiency**
The combination of fast charging and regenerative braking improves overall energy utilization and reduces wastage.

5. **Reduced Thermal Stress**
Supercapacitors generate less heat compared to batteries during rapid charging, improving system safety and reliability.
6. **Improved Fleet Productivity**
Reduced downtime leads to better vehicle availability and improved scheduling efficiency for public transport systems.
7. **Lower Long-Term Operational Costs**
Due to longer lifespan and reduced maintenance requirements, operational costs can be minimized over time.

VIII. Results

The performance of the proposed supercapacitor-based bus system was evaluated under simulated urban operating conditions, including frequent stops, varying load demands, and repeated acceleration–deceleration cycles. The analysis focused on key parameters such as charging duration, energy efficiency, power delivery, and system stability.

The quick charging system demonstrated highly efficient performance, with the supercapacitor bank achieving a substantial charge level within a short dwell time at bus stops. Compared to conventional battery-based systems, the charging duration was significantly reduced, enabling continuous operation with minimal interruption. This confirms the effectiveness of opportunity charging in maintaining service frequency.

In terms of power delivery, the system exhibited rapid response during acceleration. The supercapacitor provided immediate high current output, ensuring smooth vehicle movement even under peak load conditions. This characteristic makes the system highly suitable for urban routes where frequent speed variations are required.

The energy recovery mechanism also showed promising results. During braking, a considerable portion of kinetic energy was successfully converted into electrical energy and stored back in the supercapacitor. This improved the overall system efficiency and reduced dependency on external charging.

Additionally, the system maintained stable performance over multiple charge-discharge cycles, indicating high reliability and durability of the supercapacitor-based storage system. Unlike batteries, no significant performance degradation was observed during repeated operation.

However, the analysis also revealed that the system requires well-distributed charging infrastructure to ensure uninterrupted operation. The limited energy storage capacity necessitates frequent charging, which may affect performance in areas with inadequate charging facilities.

Overall, the results demonstrate that the proposed system provides fast charging, efficient energy utilization, and reliable performance, making it a strong candidate for next-generation urban electric transportation systems.

IX. Future Scope

The proposed supercapacitor-based quick charging bus system presents a strong foundation for modern electric transportation; however, several advancements can further enhance its efficiency, scalability, and practical deployment.

One promising direction is the development of hybrid energy storage configurations, where supercapacitors are combined with advanced battery systems. This approach can overcome the limitation of low energy density by providing extended driving range while still maintaining fast charging capability. Such hybrid systems can optimize both energy and power requirements for diverse route conditions.

Another area of improvement is the implementation of dynamic charging infrastructure, where buses can receive energy while in motion through embedded road systems or overhead conductive lines. This would significantly reduce dependency on stationary charging points and enable uninterrupted operation.

Future research can also focus on smart energy management using artificial intelligence, where predictive algorithms analyze route patterns, passenger load, and traffic conditions to optimize charging schedules and energy utilization. This would enhance system efficiency and reduce unnecessary energy consumption.

Advancements in supercapacitor materials and design can also play a crucial role. The development of high-capacity electrode materials can increase energy storage capability, making supercapacitors more competitive with conventional batteries.

Additionally, integrating the system with renewable energy sources, such as solar-powered charging stations, can further reduce environmental impact and support sustainable energy ecosystems.

With continuous innovation in energy storage technology and infrastructure, the proposed system has the potential to evolve into a highly efficient, intelligent, and sustainable transportation solution, contributing significantly to the future of smart urban mobility.

X. Conclusion

The proposed supercapacitor-based electric bus system with quick charging presents an efficient alternative to conventional battery-powered transportation. By utilizing high-power supercapacitors and opportunity charging at regular intervals, the system significantly reduces charging time and improves operational continuity. The integration of fast energy transfer, adaptive control, and regenerative braking enhances overall system performance and energy efficiency, making it suitable for urban transit environments.

Despite its advantages, the system requires a well-developed charging infrastructure and faces limitations related to energy storage capacity. However, with ongoing advancements in energy storage technology and smart grid integration, these challenges can be effectively addressed. Overall, the proposed approach offers a promising direction for developing reliable, sustainable, and high-performance public transportation systems.

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