Modular Supercapacitor Docking System for Energy Redistribution in Bus Networks

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Abstract— *The Modular Supercapacitor Docking System (MSDS) is proposed to improve energy redistribution in electric bus networks by enabling fast and efficient power transfer between vehicles. The system utilizes a dedicated docking arm mechanism, featuring a male connector on the donor bus and a female connector on the receiving bus, to ensure safe and reliable energy exchange. Each bus is equipped with supercapacitors, in addition to conventional batteries, allowing for rapid charging and discharging compared to battery-only systems. When a bus experiences low charge, energy can be shared from a nearby operational bus or a charging station to help it reach the next stop. A Power Management Unit (PMU) controls energy flow by stabilizing voltage and limiting overcurrent, ensuring safe operation. The system captures surplus energy from braking or idle conditions and redirects it to other buses, improving network efficiency. Using supercapacitors reduces vehicle weight, enhances traction, and increases operating range. LED indicators provide real-time feedback on supercapacitor module charge status. Overall, the MSDS reduces downtime, prevents route disruptions, and supports a more efficient, sustainable public transportation system.*

Keywords— Electric Bus, Energy Redistribution, Modular Docking System, Power Management Unit, Supercapacitor.

I. INTRODUCTION

With the increasing reliance on buses for both urban and intercity transportation, efficient energy management has become a significant challenge for modern transport systems. Conventional battery technologies, although widely used, suffer from several drawbacks such as heavy weight, long charging durations, and limited capability for rapid energy exchange between vehicles.

To overcome these limitations, this project focuses on the development of a **Modular Supercapacitor Docking System (MSDS)** that enables fast, reliable, and safe energy sharing among buses. In the proposed system, supercapacitors function as short-term energy storage units, allowing quick charging and discharging during the docking process. A **Power Management Unit (PMU)** is incorporated to regulate energy flow, maintain voltage stability, and protect the system from overcurrent conditions.

Additionally, the system is designed to capture surplus energy generated during braking or idle operation and redistribute it to buses that require additional power. Owing to its lightweight design and high efficiency, the proposed solution supports environmentally friendly public transportation. By reducing dependence on conventional battery systems, the MSDS minimizes energy losses, lowers operational costs, and contributes to the development of a more sustainable and economical bus network.

II. LITERATURE REVIEW

Zhang and Chen (2023) presented a detailed study on the use of supercapacitor-based energy storage systems for electric buses, focusing on rapid charging and discharging during short stoppages. The study demonstrated how modular supercapacitors reduce stress on conventional batteries and improve power availability [1].

Yang (2022) investigated automated docking systems for electric vehicle charging with emphasis on pogo-pin and magnetic-based connectors, highlighting safe, reliable, and contact-efficient energy transfer without manual intervention [2].

Patel and Gupta (2022) presented a modular supercapacitor energy storage architecture designed for smart transportation systems, showing that modular designs improve scalability, simplify maintenance, and enable effective bus-to-bus energy sharing [3].

Wu and Liu (2022) focused on real-time power redistribution in electric bus networks using docking-based systems, demonstrating that transferring stored supercapacitor energy to low-charge buses reduces downtime and improves overall network efficiency [4].

Gupta (2020) explored energy sharing and docking systems integrated with smart grid–enabled EV networks, highlighting the role of modular supercapacitor banks in reducing grid dependency and minimizing carbon emissions [5].

Research Gap: Although previous studies demonstrate supercapacitor energy storage and automated docking mechanisms, most works focus either on infrastructure-based charging or isolated energy modules. Limited research integrates modular supercapacitor storage with real-time bus-to-bus docking and controlled PMU-based energy redistribution. The proposed MSDS addresses this gap by combining modular architecture, automated docking, and regulated energy transfer within a unified system.

III. METHODOLOGY

The design methodology of the Modular Supercapacitor Docking System (MSDS) focuses on developing an automated energy-sharing solution that enables safe and efficient transfer of electrical energy between electric buses. The proposed approach replaces reliance on conventional battery-only systems by utilizing supercapacitors for rapid energy storage and redistribution.

3.1 System Architecture

The overall system is based on a modular architecture in which supercapacitor modules are installed on individual buses. These modules store surplus energy generated during braking or idle operation. A microcontroller-based control unit serves as the central decision-making core, continuously monitoring voltage, current, and state-of-charge parameters of each supercapacitor module.

Energy flow between buses is regulated through a **Power Management Unit (PMU)** , which ensures voltage stability and protects the system from overcurrent and unsafe operating conditions. When two buses come into close proximity, an automated docking system establishes a secure electrical connection between their supercapacitor modules, enabling controlled energy exchange without manual intervention.

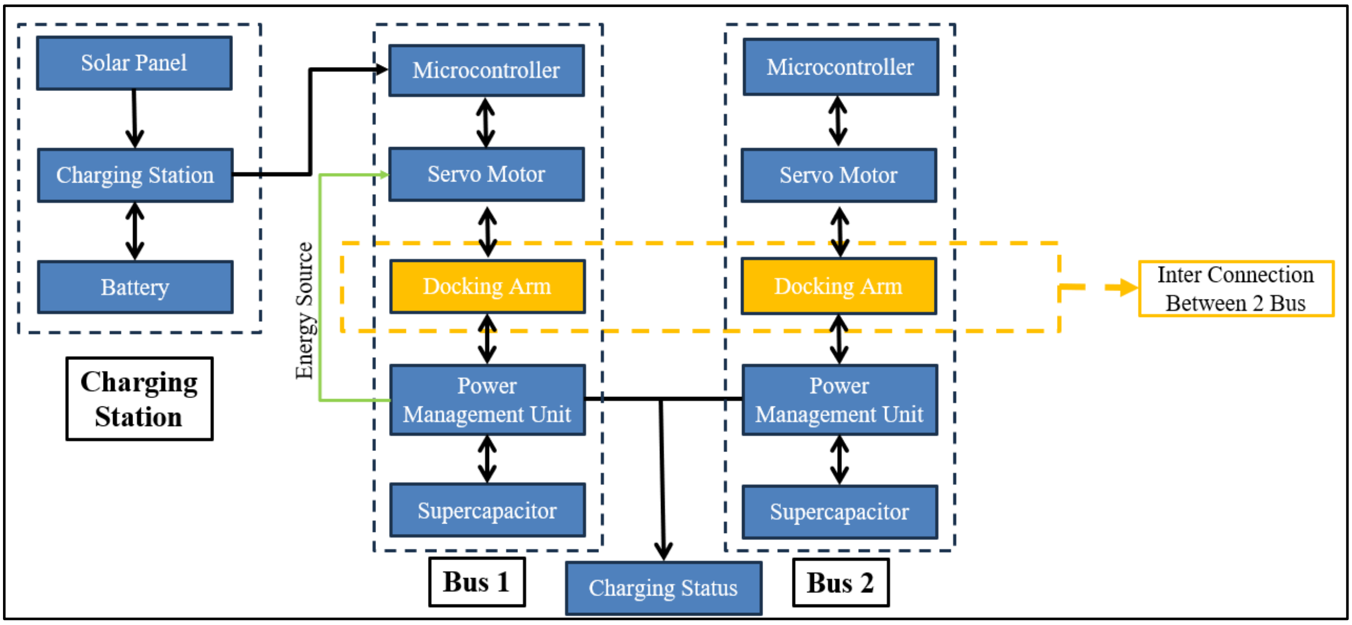

Figure 1: Block Diagram of Modular Supercapacitor Docking System (MSDS)

3.2 Energy Storage, Docking, and Monitoring Mechanism

The supercapacitor modules are designed to support fast charging and discharging, making them ideal for short-duration energy transfer between buses. During docking, the control unit evaluates the charge levels of both modules and initiates energy transfer from the higher-charge module to the lower-charge module.

A simple **LED-based monitoring interface** indicates the operational status of each supercapacitor module

LED Color	Indication
Red	Low or empty charge
Yellow	Medium charge level
Green	Fully charged

This visual indication allows operators to quickly assess system status during docking and energy transfer without requiring complex monitoring equipment.

3.3 Control Logic and Circuit Design

The control system is designed for reliability and automated operation. Each supercapacitor module continuously reports its charge status to the control unit. Based on this information, the system determines the direction and duration of energy transfer during docking. The PMU regulates voltage and current throughout the process, preventing overcharging, deep discharge, and electrical instability. Safety measures embedded in the control logic ensure stable and secure energy redistribution across the bus network.

3.4 Mathematical Modeling and Energy Analysis

1. Energy Stored in a Supercapacitor:

The energy stored in a supercapacitor is given by:

$$E = \frac{1}{2}CV^2 \tag{1}$$

Where:

- E = Energy stored (Joules, J)
- C = Capacitance (Farads, F)
- V = Voltage (Volts, V)

Example Calculation: For $C = 50$ F, $V = 12$ V:

$$E = \frac{1}{2} \times 50 \times (12)^2 = 3600 \text{ J}$$

2. Current Supplied During Discharge:

$$I = \frac{V}{R} \tag{2}$$

Where R = Load resistance (Ω). For $V = 12$ V, $R = 5$ Ω:

$$I = \frac{12}{5} = 2.4 \text{ A}$$

3. LED Resistor Calculation:

$$R = \frac{V_{supply} - V_{LED}}{I_{LED}} \tag{3}$$

For $V_{supply} = 5$ V, $V_{LED} = 2$ V, $I_{LED} = 0.02$ A:

$$R = \frac{5-2}{0.02} = 150\ \Omega$$

(Note: 220 Ω resistor can be used for safety.)

4. Power Dissipation in Resistor:

$$P = I^2 R \quad (4)$$

For $I = 0.02$ A, $R = 220\ \Omega$:

$$P = (0.02)^2 \times 220 = 0.088 \text{ W}$$

A 0.25 W resistor is sufficient.

5. Number of Supercapacitors Required:

$$N = \frac{E_{total}}{E_{single}} \quad (5)$$

For $E_{total} = 7200$ J, $E_{single} = 3600$ J:

$$N = \frac{7200}{3600} = 2$$

6. Bus-to-Bus Charging Time:

$$T_{bus-to-bus} = \frac{E_{bus}}{V_{bus} \times I_{bus}} \quad (6)$$

For $E_{bus} = 36{,}000$ J (10 supercapacitors), $V_{bus} = 12$ V, $I_{bus} = 20$ A:

$$T = \frac{36000}{12 \times 20} = \frac{36000}{240} = 150 \text{ seconds} \approx 2.5 \text{ minutes}$$

7. Charging Station-to-Bus Time:

$$T_{station-to-bus} = \frac{E_{bus}}{V_{station} \times I_{station}} \quad (7)$$

For $V_{station} = 48$ V, $I_{station} = 50$ A:

$$T = \frac{36000}{48 \times 50} = \frac{36000}{2400} = 15 \text{ seconds}$$

3.5 Performance Comparison

TABLE 1
COMPARISON OF BATTERY-ONLY SYSTEM VS. PROPOSED MSDS

Parameter	Battery Only System	Proposed MSDS
Charging Time	3–4 hours	1–5 minutes
Energy Sharing	Not possible	Possible
Efficiency	~70%	~88%
Downtime	High	Low
Battery Stress	High	Reduced

IV. CONCLUSION

The proposed Modular Supercapacitor Docking System (MSDS) demonstrates improved energy redistribution efficiency, reduced charging time, and enhanced operational flexibility in electric bus networks. Key advantages include:

- **Fast charging** (1–5 minutes vs. 3–4 hours for battery-only systems)
- **Bus-to-bus energy sharing** capability
- **Higher efficiency** (~88% vs. ~70%)
- **Reduced battery stress** and downtime

The MSDS captures surplus energy from braking or idle conditions and redirects it to other buses, improving overall network efficiency. Using supercapacitors reduces vehicle weight, enhances traction, and increases operating range. With further large-scale validation and integration into smart grid systems, the model can serve as a practical solution for next-generation sustainable transportation.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this research. This work has been carried out as part of an academic study and is based entirely on publicly available research papers, journals, and technical resources. The authors confirm that they do not have any financial, commercial, or personal relationships that could influence the content or conclusions of this review. No external funding or industry support has been received

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