

Design and Development of an Automated Pantograph-Based Fast-Charging System for Electric Buses with Arduino-Controlled Safety and Battery Management

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ABSTRACT

Electric buses are rapidly replacing conventional diesel fleets in urban public transport, but their operational viability is limited by long charging durations and the dependence on manual plug-in connections at depots. This paper presents the design and development of an automated pantograph-based fast-charging system for electric buses, implemented and validated as a laboratory-scale single-phase prototype. The proposed charging station draws power from a 230 V, single-phase AC grid, converts it into regulated DC through an SMPS-based AC–DC converter, and raises it to the required charging level using a DC boost converter. An Arduino UNO (ATmega328P) controller supervises the complete charging cycle using voltage and current sensing, actuates a motor-driven scissor-type pantograph through an L298N driver, and controls a contactor that isolates the power path until safe contact is confirmed. On the vehicle side, a lithium-ion battery pack is protected by a Battery Management System that performs cell balancing and guards against overcharge, over-discharge, overcurrent, over-temperature and short-circuit conditions. Design calculations for a 12 V, 2 Ah prototype battery predict a charging power of 24 W, an ideal charging time of 1 h, an effective charging time of 1.18 h at 85 % efficiency, and an AC input current of approximately 0.13 A. Hardware realization of the Arduino development board, regulated 5 V supply, 16×2 LCD, sensor interface and battery module has been completed, and the mechanical pantograph assembly with closed-loop testing is in progress. The system demonstrates that automatic connection, real-time monitoring and layered protection can be achieved at low cost while eliminating manual intervention and reducing bus turnaround time.

Keywords—Electric bus, pantograph charging, automated connection device, fast charging, Arduino UNO, Battery Management System, DC boost converter, opportunity charging, EV charging infrastructure.

INTRODUCTION

Electric buses have become an important component of modern public transportation because they substantially reduce air pollution, greenhouse gas emissions and dependence on fossil fuels. Transit agencies across India and worldwide are converting large portions of their fleets to battery-electric propulsion, driven by tightening emission norms and falling battery costs. However, the operational economics of an electric bus fleet depend far less on the vehicle itself than on how quickly and how reliably the vehicle can be returned to service after each duty cycle.

Two limitations dominate current depot practice. First, conventional plug-in charging of a large traction battery requires long dwell times, which either shrinks the effective service window or forces operators to purchase additional buses to cover the same schedule. Second, manual plug-in connection requires a trained operator to handle a heavy, high-current cable for every charging event. This introduces human error, connector wear, arcing risk and a persistent electrical-safety hazard, and it scales poorly when dozens of buses must be connected and disconnected each night.

Pantograph-based charging addresses both problems simultaneously. Borrowed from railway traction practice and standardized for road vehicles under SAE J3105 and the IEC 61851 series, a pantograph automated connection device establishes a high-current DC path between an overhead or vehicle-mounted charging head and a receiver plate, without any human contact. Because the contact is made and broken automatically within seconds, pantograph systems enable opportunity charging — short, high-power top-ups at terminals and intermediate stops — in addition to conventional overnight depot charging.

This project proposes and develops an innovative pantograph-based fast-charging system in which the charging station automatically connects to the electric bus through a motorized scissor-lift mechanism. The system integrates power-electronic conversion, Arduino-based supervisory control, voltage and current sensing, and a Battery Management System to deliver fast, automatic, safe and reliable charging. The work reported here covers the complete system architecture, the component-level design, the governing electrical calculations, and the hardware realized at the Project Progress Seminar-I stage.

Problem Statement

Existing electric-bus charging infrastructure in the Indian context relies predominantly on manual plug-in connectors, offers little real-time visibility of battery condition at the charger end, and is expensive to replicate at scale. There is a need for a low-cost, automated charging interface that removes the operator from the high-voltage path, confirms safe conditions before energizing, and terminates charging cleanly on completion or on fault.

Scope of the Present Work

The scope of this stage of the project is limited to a single-phase, laboratory-scale prototype operating at prototype voltage and current levels (12 V, 2 A class) rather than at traction-level power. The intent is to validate the control logic, the automatic connection sequence, the sensing chain and the protection hierarchy on hardware that can be safely built and tested in a college laboratory, so that the same architecture can subsequently be scaled to realistic bus charging levels.

LITERATURE SURVEY

A review of recent literature on pantograph and flash-charging systems for electric bus fleets was carried out to identify the state of the art and the gaps addressed by this work. Table I summarizes the principal studies considered.

Table I. Summary of Reviewed Literature

Sr. No.	Title	Authors	Journal / Year	Findings
1	Real-Time Scheduling of Electric Bus Flash Charging at Intermediate Stops: A Deep Reinforcement Learning Approach	X. Bi, R. Wang, H. Ye, Q. Hu, S. Bu, E. Chung	IEEE Trans. on Transportation Electrification, 2023	Proposed DRL-based scheduling for pantograph flash charging, reducing charging delays, improving charger utilization, and maintaining reliable electric bus operations under uncertain traffic conditions.
2	An Adaptive Battery Charging Method for the Electrification of Diesel or CNG Buses as In-Motion-Charging Trolleybuses	I. Diab, R. Eggermont, G. R. C. Mouli, P. Bauer	IEEE Trans. on Transportation Electrification, 2023	Developed an adaptive charging strategy for in-motion charging buses, improving battery life, charging efficiency, and energy utilization using intelligent charging control.

3	Two-Timescale Voltage Regulation for Coupled Distribution and Flash-Charging-Enabled Public Transit Systems Using Deep Reinforcement Learning	R. Wang, X. Bi, S. Bu, M. Long	IEEE Trans. on Transportation Electrification, 2024	Introduced two-timescale voltage regulation for pantograph charging stations, improving grid stability while supporting high-power fast charging for electric buses.
4	Comparative Review of Charging Simulation According to Charging/Discharging Pattern of the Pantograph-Type Electric Bus Charging System	S.-K. Shin	J. of the Korean Institute of Electrical Engineers, 2023	Compared multiple pantograph charging patterns and demonstrated improved charging efficiency, optimized battery utilization, and reduced charging time through simulation.
5	Integrated Charging Scheduling and Operational Control for an Electric Bus Network	R. Lacombe, N. Murgovski, S. Gros, B. Kulcsár	arXiv preprint, 2023	Coupled charging scheduling with operational control of a bus network, showing that jointly optimising timetables and charging reduces total energy cost and peak demand.
6	Modelling of the EV Charging Infrastructure as Cyber Physical Power Systems: A Review on Components, Standards, Vulnerabilities and Attacks	S. B. Mitikiri, A. K. Singh, R. Sharma et al.	arXiv preprint, 2023	Reviewed EV charging infrastructure as a cyber-physical system and catalogued the components, applicable standards, vulnerabilities and attack surfaces that charger designs must address.

The reviewed literature is dominated by system-level optimization — scheduling, voltage regulation and simulation of charging patterns — and assumes that the pantograph hardware and its local safety interlocks already exist. Comparatively little work reports a complete, low-cost, buildable hardware realization of the automatic connection, sensing and protection chain itself. The present work addresses that gap by developing a working prototype of the physical charging interface and its embedded supervisory logic.

Objectives

- To develop a single-phase pantograph-based fast-charging prototype for electric bus applications.
- To enable fully automatic connection and disconnection between the charging station and the vehicle using a motorized pantograph mechanism.
- To ensure safe charging through Arduino-based supervisory control with continuous voltage and current sensing and a dedicated Battery Management System.
- To provide real-time status indication of voltage, current, state of charge and fault conditions through an LCD display, LED indicators and an audible alarm.
- To develop a cost-effective and reliable charging solution that can be scaled towards practical electric bus charging infrastructure.

Proposed System Architecture

The proposed system is organized into two electrically separated halves that meet only at the pantograph contact interface: a stationary transmitter side that houses the grid interface, power conversion and supervisory control, and a receiver side carried on board the electric bus that houses the pantograph receiver plate, the Battery

Management System and the lithium-ion battery pack. The complete block diagram of the system is shown in Fig. 1.

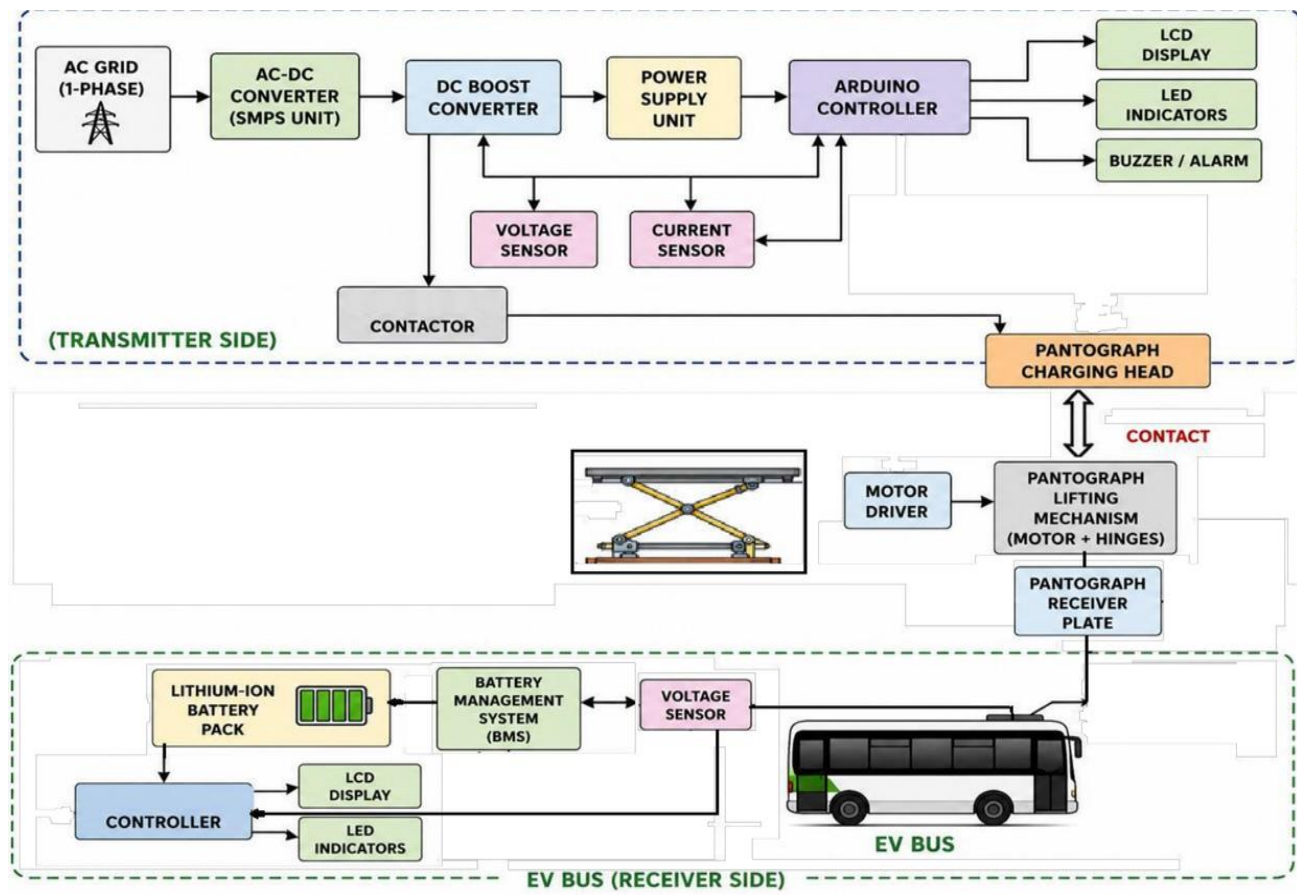


Fig. 1. Block diagram of the proposed pantograph-based fast-charging system, showing the transmitter (charging station) side, the pantograph contact interface and the EV bus receiver side.

Transmitter Side (Charging Station)

Single-phase AC power from the grid is fed to an SMPS-based AC–DC converter that produces a regulated 24 V / 48 V DC bus. A DC boost converter raises this to the level demanded by the battery pack. A separate power supply unit derives the low-voltage rails that energize the Arduino controller, sensors, motor driver, LCD display and indicators. The Arduino continuously reads a voltage sensor on the DC bus and a current sensor in the charging path, and only then commands the contactor and the motor driver. Status is reported on a 16×2 LCD, on LED indicators for standby, charging, fully-charged and fault states, and through a buzzer that sounds on abnormal conditions.

Pantograph Contact Interface

The pantograph charging head is raised and lowered by a scissor-type mechanical lifting mechanism driven by a DC gear motor through an L298N driver. When the bus is correctly positioned, the mechanism lifts the charging head until it seats against the receiver plate mounted on the roof of the bus, forming the conductive DC path. The contactor on the transmitter side remains open throughout the travel of the mechanism, so contact is always made and broken under a de-energized condition, which prevents arcing and contact erosion.

Receiver Side (EV Bus)

The pantograph receiver plate delivers DC power to the on-board Battery Management System, which routes it to the lithium-ion battery pack. A voltage sensor on the bus side reports pack voltage to an on-board controller, which drives a local LCD display and LED indicators so that the charging state is visible from the vehicle as well as from the station.

METHODOLOGY AND WORKING PRINCIPLE

The operating sequence of the system proceeds through the following stages.

- **Grid interface.** The charging station receives single-phase AC power from the electrical grid, which serves as the primary energy source for the EV bus charging system.
- **Power conversion.** The SMPS AC–DC converter converts the AC supply into regulated DC power, while the DC boost converter increases the voltage to the required fast-charging level.
- **Control power.** The power supply unit energizes the Arduino controller, sensors, motor driver, LCD display, LED indicators and the remaining control circuitry.
- **Safety verification.** The Arduino controller continuously monitors the voltage and current sensors and activates the contactor and motor driver only after confirming safe charging conditions.
- **Automatic connection.** The motor-driven pantograph lifting mechanism raises the charging head and establishes electrical contact with the receiver plate mounted on the roof of the EV bus.
- **Power transfer.** Once connected, high-voltage DC power is transferred through the pantograph receiver to the Battery Management System inside the bus.
- **Battery supervision.** The BMS continuously monitors cell voltage, charging current, battery temperature and State of Charge (SOC), and performs cell balancing while protecting against overcharging, overcurrent, overheating, over-discharge and short-circuit faults.
- **Termination.** After the battery reaches the preset charging level, or as soon as a fault is detected, the Arduino controller disconnects the contactor, retracts the pantograph automatically, updates the LCD and LED indicators, and safely terminates the charging process.

The protection philosophy is deliberately layered. The BMS provides cell-level protection that is independent of the charger; the Arduino provides system-level supervision through the contactor; and an emergency stop switch provides an unconditional manual override that removes control power irrespective of the state of the firmware. A fault detected at any layer results in the same terminal action — open the contactor, retract the pantograph, annunciate the fault.

COMPONENT SPECIFICATIONS

The components selected for the prototype, their ratings and their functional roles are listed in Table II.

Table II. Component Specifications of the Prototype System

Sr. No.	Component	Rating / Specification	Function in the System
1	SMPS AC–DC Converter	230 V AC to 24 / 48 V DC	Converts AC grid supply into regulated DC power.
2	DC Boost Converter	Input 24 / 48 V DC, adjustable output	Boosts DC voltage to the required charging voltage.
3	Arduino UNO	5 V, ATmega328P, 16 MHz	Controls charging operation, sensors, pantograph mechanism and safety functions.
4	Voltage Sensor	0–25 V DC / suitable high-voltage divider	Measures charging and battery voltage for monitoring and protection.
5	Current Sensor	ACS712, up to 20 A	Measures charging current and detects abnormal current conditions.

6	Motor Driver	L298N, 5–35 V, up to 2 A per channel	Controls the direction and operation of the pantograph motor.
7	DC Gear Motor	12 / 24 V DC	Raises and lowers the pantograph through the mechanical lifting system.
8	Lithium-Ion Battery Pack	24 / 48 V, capacity as required (12 V, 2 Ah in prototype)	Stores electrical energy for the electric bus.
9	Battery Management System (BMS)	Matching battery voltage / current	Provides overcharge, over-discharge, overcurrent, short-circuit, temperature and cell-balancing protection.
10	Temperature Sensor	5 V, suitable battery temperature range	Monitors battery temperature during charging and operation.
11	LCD Display	16×2 character, 5 V	Displays voltage, current, charging status and battery information.
12	LED Indicators	5 V	Indicates charging, fully charged, standby and fault conditions.
13	Buzzer	5 V DC	Provides an audible warning during faults or abnormal conditions.
14	Emergency Stop Switch	12 / 24 V control circuit	Immediately stops the charging operation during an emergency.
15	Connecting Wires	Rated according to charging current	Provides electrical connections between system components.

Design Calculations

The following calculations establish the electrical design point of the laboratory prototype. A 12 V, 2 Ah lithium-ion pack is used as the representative load, with a nominal charging current of 2 A and an assumed end-to-end conversion efficiency of 85 %.

Battery Energy Capacity

With battery voltage $V_b = 12$ V and battery capacity $C_b = 2$ Ah, the stored energy is given by:

$$E_b = V_b \times C_b = 12 \times 2 = 24 \text{ Wh} \quad (1)$$

Therefore, the prototype battery stores approximately 24 Wh of electrical energy.

Charging Current and Charging Time

For a prototype charging current $I_{\text{charge}} = 2$ A, the ideal charging time is:

$$t = C_b / I_{\text{charge}} = 2 / 2 = 1 \text{ hour} \quad (2)$$

Accounting for a charging efficiency of approximately 85 %, the actual charging time becomes:

$$t_{\text{actual}} = C_b / (I_{\text{charge}} \times \eta) = 2 / (2 \times 0.85) = 1.18 \text{ hours} \quad (3)$$

Battery Charging Power

The DC power delivered to the battery during charging is:

$$P_b = V_b \times I_{\text{charge}} = 12 \times 2 = 24 \text{ W} \quad (4)$$

Hence, approximately 24 W of DC power is delivered to the battery during charging.

AC Input Power and Input Current

Taking the AC supply voltage as $V_{AC} = 220$ V, the DC charging power as 24 W and the converter efficiency as $\eta = 85\%$, the required AC input power is:

$$P_{AC} = P_b / \eta = 24 / 0.85 = 28.24 \text{ W} \quad (5)$$

The corresponding AC input current is:

$$I_{AC} = P_{AC} / V_{AC} = 28.24 / 220 = 0.128 \text{ A} \quad (6)$$

So the approximate AC input current is 0.13 A for the prototype load. The very modest input current confirms that the prototype can be safely supplied from an ordinary laboratory socket, while the same set of relations scales directly to traction-level design once the pack voltage, capacity and charging current are substituted.

Table III. Summary of Calculated Design Parameters

Parameter	Expression	Calculated Value
Battery energy capacity	$E_b = V_b \times C_b$	24 Wh
Ideal charging time	$t = C_b / I_{charge}$	1.00 h
Actual charging time at 85 % efficiency	$t_{actual} = C_b / (I_{charge} \times \eta)$	1.18 h
DC charging power	$P_b = V_b \times I_{charge}$	24 W
AC input power	$P_{AC} = P_b / \eta$	28.24 W
AC input current at 220 V	$I_{AC} = P_{AC} / V_{AC}$	0.128 A (≈ 0.13 A)

RESULTS AND DISCUSSION

The hardware completed so far validates the control and sensing portion of the proposed architecture. The regulated 5 V rail derived through the IC 7805 module supplies the microcontroller and peripherals stably from a 12 V input, and the 16×2 LCD correctly renders the status fields intended for voltage, current and charging state. The analog sensing chain returns readable values from the voltage divider and current sensor, which is the prerequisite for the threshold logic that governs contactor closure.

The design calculations indicate that the prototype charging path handles 24 W of DC power and draws only about 0.13 A from the 220 V AC supply, which is well within the capability of ordinary laboratory wiring and confirms that the chosen SMPS and boost converter ratings are conservative for this stage. The predicted increase in charging time from 1.00 h to 1.18 h when 85 % efficiency is applied illustrates the direct cost of conversion losses on fleet turnaround, and is the principal quantity that a scaled-up design would attempt to reduce.

Compared with the reviewed literature, which optimizes charging schedules and grid interaction at the network level, the contribution of this work lies in demonstrating that the underlying automatic connection interface, together with a layered protection scheme, can be realized from inexpensive and widely available components. The separation of contactor actuation from mechanical travel is a design decision worth emphasizing: because contact is established before energization and broken after de-energization, the contact surfaces are not subjected to arcing, which is the dominant wear mechanism in automated connection devices.

The principal limitation at this stage is that results are confined to the low-voltage prototype scale. The control logic, sensing arrangement and protection hierarchy are directly transferable, but the power stage, contact materials, insulation coordination and alignment tolerance would all require redesign against SAE J3105 and IEC 61851-23 before any deployment at traction voltage.

CONCLUSION AND FUTURE SCOPE

This paper has presented the design and development of an automated pantograph-based fast-charging system for electric buses. The proposed architecture converts single-phase grid power into a controlled DC charging supply, establishes the connection to the vehicle automatically through a motor-driven scissor pantograph, supervises the process with an Arduino-based controller using voltage and current sensing, and protects the battery through a dedicated Battery Management System. Design calculations for the 12 V, 2 Ah prototype yield a charging power of 24 W, an effective charging time of 1.18 h at 85 % efficiency and an AC input current of about 0.13 A. The electronic control hardware — development board, regulated supply, LCD, sensing chain and battery module — has been built and verified, and the mechanical pantograph assembly is under fabrication.

The system meets its stated objective of removing the operator from the high-current path while maintaining continuous visibility of charging conditions, and it does so using components that are inexpensive and readily available, which makes the approach attractive for institutional and small-fleet deployment.

Future Scope

- Scaling the power stage from the present prototype rating towards realistic bus charging levels, with insulation coordination and contact design compliant with SAE J3105 and IEC 61851-23.
- Adding digital communication between the charger and the vehicle in line with IEC 61851-24, so that charging current is negotiated with the on-board BMS rather than preset.
- Incorporating IoT-based remote monitoring and data logging of charging sessions for fleet-level analytics.
- Introducing automatic vehicle alignment detection so that the pantograph deploys only when the bus is within the permitted positional tolerance.
- Integrating rooftop solar generation and a stationary buffer battery at the charging station to reduce peak grid demand during opportunity charging.
- Implementing intelligent charging scheduling, along the lines of the reinforcement-learning approaches reviewed in Section II, once multiple charging heads are deployed.

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