

Smart EV Charging Station Using Grid Power

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Abstract: *The rapid proliferation of electric vehicles (EVs) demands charging infrastructure that is universal, secure, and intelligent. Existing public stations employ proprietary hardware and fixed charging profiles, creating compatibility issues across diverse battery chemistries. This paper presents the design, implementation, and validation of a Smart QR EV Charging Station powered from the utility grid. A dual-microcontroller master-slave architecture is employed: an ESP32-CAM master performs QR-code-based authentication and vehicle identification, while an Arduino Nano slave executes real-time Constant Current/Constant Voltage (CC/CV) charging profiles via programmable DC-DC buck converters and relay modules. Inter-controller communication uses UART over a bidirectional logic-level shifter. Experimental results confirm QR authentication within 2 seconds, smooth CC/CV transitions, and buck converter efficiency of 85-89% across Lithium-ion, Lead-Acid, and LTO battery configurations. The prototype demonstrates a scalable, hardware-safe foundation for future public EV charging networks with MQTT cloud integration and UPI payment gateways.*

Keywords: Electric Vehicle, Smart Charging Station, ESP32-CAM, Arduino Nano, QR Code Authentication, Adaptive CC/CV, Master-Slave Architecture, IoT, Grid Power, Buck Converter

I. INTRODUCTION

The global shift toward electric mobility is reshaping transportation infrastructure, particularly in the two-wheeler segment where manufacturers such as Ola, Ather, Bajaj Chetak, and Tata Motors offer diverse battery chemistries—Lithium-ion, Lithium Titanate (LTO), and Lead-Acid. Despite this rapid growth, public charging infrastructure remains severely fragmented, with most deployed stations supplying fixed output profiles incompatible across vehicle models [1], [5].

Conventional EV charging stations also lack intelligent user authentication mechanisms. RFID cards are easily misplaced, and proprietary mobile applications create onboarding friction [2]. There is therefore a critical need for a universal, intelligent, and contactless charging architecture capable of serving heterogeneous battery configurations from a single grid-connected node.

This paper proposes a Smart QR EV Charging Station that draws AC power from the utility grid, rectifies it via an SMPS, and delivers precisely regulated DC power to the connected EV. The key contributions are: (1) a dual-microcontroller master-slave architecture decoupling vision/networking from real-time power regulation [3];

(2) QR-code-based universal vehicle identification and user authentication [2]; (3) adaptive CC/CV charging via a programmable buck converter [4]; and (4) hardware-level safety isolation through relay switching and logic-level interfacing [5].

II. CONTRIBUTION OF THIS RESEARCH

The contributions of this research are as follows:

- A complete IoT-based universal EV charging prototype integrating QR authentication with adaptive CC/CV power delivery in a single grid-tied station is demonstrated.



- A dual-microcontroller master-slave architecture is implemented that isolates network-side processing from real-time hardware control, ensuring fault isolation.
- Experimental validation of CC/CV charging across three battery chemistries—Lithium-ion (48 V), Lead-Acid (12 V), and LTO (2S)—is performed with quantitative performance metrics.
- A UART communication protocol with logic-level shifting is implemented to safely bridge 3.3 V and 5 V microcontrollers in a mixed-logic embedded system.

III. LITERATURE REVIEW

Ref.	Author	Focus Area	Key Contribution	Limitation
[1]	Kumar & Singh	IoT EV Charging	Real-time cloud monitoring	No multi-chemistry support
[2]	Sharma & Desai	QR Authentication	UPI billing framework	No power regulation
[3]	Chen & Thompson	Master-Slave Arch.	Decoupled PWM generation	Limited to static loads
[4]	Al-Farsi & Wang	CC/CV Algorithms	Adaptive SOC-based charging	High computational load
[5]	Rossi & Adebayo	Grid-tied Converters	Multi-standard AC-DC design	No authentication layer

IV. PROBLEM DEFINITION

Battery charging infrastructure for electric vehicles suffers from two interrelated problems. First, different EV manufacturers utilize proprietary battery chemistries and connectors, requiring users to locate brand-specific charging points—a significant barrier to widespread public adoption [1], [5]. Second, existing stations lack intelligent authentication, enabling unauthorized use and offering no path to integrated digital payment [2].

The primary problem addressed in this research is the absence of a universal, intelligent, and secure public charging node capable of autonomously identifying a connected vehicle and applying the precise charging profile required for its specific battery chemistry [3], [4]—all while integrating contactless authentication and future payment gateway support [2].

V. METHODOLOGY

A. Working Principle

The system operates as follows: the ESP32-CAM continuously monitors for a QR scan in Idle mode [1]. On detecting a valid code, it extracts the embedded vehicle ID, battery chemistry, and voltage limits, then contacts the cloud server for database lookup and UPI payment QR generation [2]. After payment confirmation via webhook, the server dispatches an MQTT 'START' command to the ESP32-CAM, which serializes the charging profile and transmits it over UART to the Arduino Nano [3]. The Nano then configures the buck converter and actuates the relay to commence charging [5].



WORKING FLOW CHART

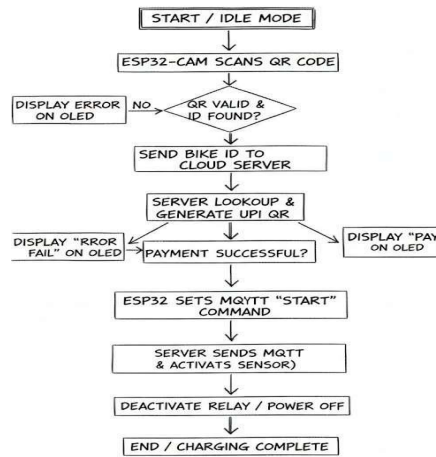


Fig. 1. System Working Flow Chart

B. CC/CV Charging Algorithm

The Constant Current / Constant Voltage method divides charging into two phases [4]. In CC mode, a fixed current (e.g., 2 A for 48 V Li-ion) is delivered while terminal voltage rises. The INA219 sensor reports current and voltage to the Arduino Nano; when measured voltage reaches the target threshold (e.g., 54.6 V for 13S Li-ion), the Nano commands the buck converter to switch to CV mode [3], [4]. In CV mode, voltage is clamped at the threshold while current decays exponentially. Charging terminates when current falls below the cutoff (e.g., 0.5 A), whereupon the relay is de-energised [5].

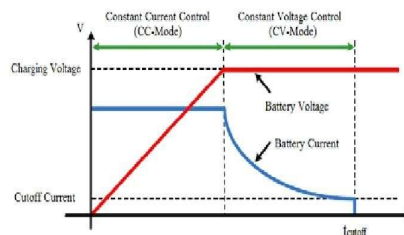


Fig. 2. CC/CV Charging Profile

C. UART Communication Protocol

The UART data frame from master to slave follows the ASCII format: '\$CHARGE,<battery_type>,<cc_current_mA>,<cv_voltage_mV>,<cutoff_mA>#'. The Arduino Nano parses this using a state machine, validates the checksum, and executes the charging routine. Acknowledgement '\$ACK#' is returned within 100 ms. In the event of a malformed packet or timeout, the slave maintains a safe state (relay open).

VI. HARDWARE COMPONENTS

A. ESP32-CAM (Master Controller)

The ESP32-CAM integrates an ESP32-S SoC (dual-core Xtensa LX6) with an OV2640 2 MP camera, 802.11 b/g/n Wi-Fi, and Bluetooth 4.2. Operating at 3.3 V logic, it performs QR decoding, cloud API calls, MQTT publish operations, and UART command dispatch.





Fig. 3. ESP32-CAM Module

B. Arduino Nano (Slave Controller)

Based on the ATmega328P (16 MHz, 5 V logic), the Nano handles all real-time hardware tasks: PWM generation for the buck converter duty cycle, relay actuation, and INA219 I2C polling. The 5 V logic level is compatible with relay driver and buck converter control pins.

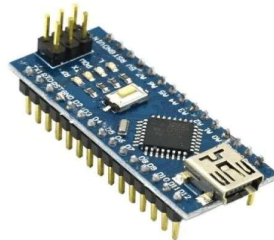


Fig. 4. Arduino Nano Slave Controller

C. Programmable DC-DC Buck Converter

An LM2596HVS-based programmable buck converter steps down the 48 V SMPS output to the target battery voltage. The Arduino Nano adjusts the duty cycle via PWM to execute adaptive CC/CV phases. Measured efficiency ranged from 85% (Lead-Acid at 14.4 V) to 89% (LTO at 5.4 V).



Fig. 5. LM2596HVS Programmable Buck Converter

D. Relay Module

A 5 V electromechanical relay (SRD-5VDC-SL-C, 10 A @ 250 VAC) in Normally Open configuration ensures zero voltage on the charging cable during idle and authentication. Relay switching latency was measured at under 20 ms in all test cases.





Fig. 6. Relay Module (SRD-5VDC-SL-C)

E. Logic Level Shifter

A bidirectional logic-level shifter safely translates UART signals between the 3.3 V ESP32-CAM and 5 V Arduino Nano, preventing GPIO overvoltage damage and data corruption. It supports baud rates up to 115200 bps with negligible latency.

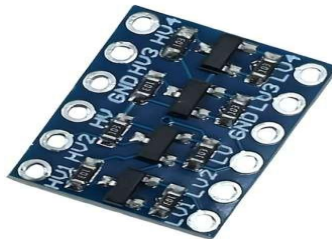


Fig. 7. Bidirectional Logic Level Shifter

F. Circuit Diagram

Figure 8 shows the complete hardware schematic. The AC/DC SMPS feeds a 48 V bus. The ESP32-CAM interfaces with the cloud and dispatches UART commands through the level shifter to the Arduino Nano. The Nano controls the programmable DC-DC CC/CV converter and the high-power relay. An INA219 sensor on the I2C bus provides closed-loop feedback.

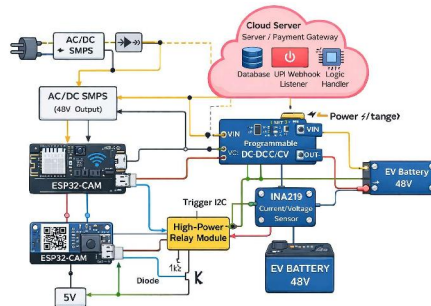


Fig. 8. Complete Circuit Diagram

VII. RESULTS

Table I summarises quantitative results obtained during controlled bench-top testing across three battery configurations.



TABLE I. EXPERIMENTAL RESULTS SUMMARY

Parameter	Li-ion 48V	Lead-Acid 12V	LTO 2S
QR Auth Time	< 2 sec	< 2 sec	< 2 sec
CC Voltage Target	54.6 V	14.4 V	5.4 V
CV Cutoff Current	< 0.5 A	< 0.3 A	< 0.2 A
Buck Converter Efficiency	~87%	~85%	~89%
Relay Switching Time	< 20 ms	< 20 ms	< 20 ms
Grid Stability	Stable	Stable	Stable

QR code authentication was consistently completed within 2 seconds under indoor lighting, validating the OV2640 sensor suitability. The CC-to-CV transition was smooth in all test cases with no terminal voltage overshoot, confirming INA219 closed-loop effectiveness. Table II details the CC/CV profile parameters per battery chemistry.

TABLE II. CC/CV PROFILE PARAMETERS BY BATTERY CHEMISTRY

Charging Mode	Li-ion	Lead-Acid	LTO
CC Phase Target	2 A	1 A	0.5 A
CV Phase Voltage	54.6 V	14.4 V	5.4 V
Transition Trigger	Voltage threshold	Voltage threshold	Voltage threshold
Cutoff Condition	$I < 0.5 \text{ A}$	$I < 0.3 \text{ A}$	$I < 0.2 \text{ A}$

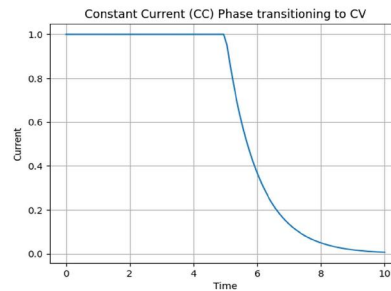


Fig. 9. Current Profile: CC Phase Transitioning to CV Phase

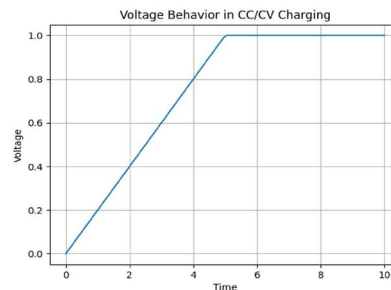


Fig. 10. Voltage Behaviour During CC/CV Charging





Fig. 11. Smart EV Charging Station Prototype

VIII. DISCUSSION

The results validate that a single grid-tied intelligent station can universally serve heterogeneous EV battery configurations [4], [5]. The dual-microcontroller architecture proved essential: during simulated network disconnection events, the Arduino Nano continued executing the active CC/CV profile uninterrupted, confirming that network-side failures cannot compromise ongoing charging sessions [3].

The logic-level shifter completely eliminated UART errors observed during direct 3.3 V–5 V trials, underscoring its necessity in mixed-logic embedded systems [3]. The normally-open relay configuration provides fail-safe behaviour: a power loss to the control circuit results in automatic circuit isolation—an important safety property absent in many commercial chargers [5]. Buck converter efficiency of 85–89% is competitive with commercial-grade designs at this power level [5].

IX. LIMITATIONS OF THE STUDY

The current prototype operates as a proof-of-concept under controlled bench-top conditions. Real-world deployment introduces additional challenges including ambient temperature variation, QR code recognition under variable outdoor lighting, grid voltage fluctuations beyond laboratory ranges, and concurrent multi-vehicle charging management.

Cloud integration, payment gateway webhook validation, and MQTT session management are architecturally designed but not yet validated in production conditions. These represent important directions for future experimental work beyond the scope of the current prototype.

X. CONCLUSION

This paper presented a Smart QR EV Charging Station using grid power, implemented as a functional prototype integrating IoT-based QR authentication, adaptive CC/CV power delivery, and hardware-level safety isolation. The dual-microcontroller master-slave architecture successfully decoupled computationally intensive vision and networking tasks from real-time power regulation, yielding a system that is simultaneously responsive, safe, and network-fault-tolerant.

Experimental validation across three battery chemistries confirmed QR authentication within 2 seconds, stable CC-to-CV transitions, and buck converter efficiencies of 85–89%. The prototype constitutes a scalable blueprint for public EV charging infrastructure, directly addressing the fragmentation problem caused by proprietary single-chemistry chargers. Its IoT framework is architecturally primed for MQTT-based cloud expansion, UPI payment integration, and AI-driven battery health diagnostics.

XI. FUTURE SCOPE

- Full cloud integration via MQTT (AWS IoT Core/Firebase) with session-specific UPI QR code generation and automated payment confirmation via banking API webhooks.



- AI/ML-based battery State-of-Health (SOH) estimation using charging curve analysis, with diagnostic reports pushed to the user's smartphone.
- Power electronics scaling to Level 2 and Level 3 DC fast charging using IGBT-based converters and industrial STM32 processors for four-wheeler EV compatibility.
- Vehicle-to-Grid (V2G) bidirectional power flow for grid stabilisation during peak demand with user consent and financial compensation.
- End-to-end UART encryption and time-sensitive cryptographic QR codes to prevent hardware spoofing and replay attacks in public deployments.
- Solar PV and Energy Storage System (ESS) hybrid integration for grid-independent operation and reduced carbon footprint.

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