Design and Implementation of a Solar PV-Based Smart Electric Vehicle Charging and Monitoring System Using ESP32 and IoT

1. S. Pooja
EEE, GNITS
Hyderabad, India
24251d5402@gnits.ac.in

2. Dr. N. Malla Reddy
EEE, GNITS
Hyderabad, India
mallareddy@gnits.ac.in

***Abstract*—This paper presents the design and implementation of a prototype of solar-based smart electric vehicle (EV) electrical charging and monitoring system using ESP32 microcontroller and IoT technology. The proposed system is developed as a low-cost and compact system for the renewable energy assisted charging by integrating the solar input stage, 3S lithium-ion battery pack, voltage and current sensing modules, a relay-based control unit and a 16x2 LCD for local display. The ESP32 continuously acquires the real-time electrical parameters at both the solar input side and the battery/output side and processes the measured data and sends the monitored values to a web-based dashboard via Wi-Fi for remote supervision. A buck converter is used for regulating the solar input to charging the battery safely, while the control logic ensures safe charging operation. Experimental implementation of the prototype provides real-time effective monitoring, controlled charging and IoT-based visualization which renders the system as a practical proof-of-concept for smart solar EV charging applications.**

***Index Terms*—Solar EV charging, ESP32, IoT monitoring, smart charging system, voltage and current sensing.**

I. Introduction

The rapid growth of electric vehicles (EVs) has increased the need for efficient, intelligent, and sustainable charging infrastructure. Conventional EV charging systems are largely dependent on grid power, which increases pressure on utility networks and limits the environmental benefits of clean transportation. To address this challenge, solar-powered EV charging has emerged as an attractive solution because it combines renewable energy generation with electric mobility and supports cleaner charging practices [1]. Recent research has focused on solar-based EV charging stations coupled with smart battery management in order to improve charging reliability, battery safety, and overall system effectiveness [2]. The use of solar power as a direct energy source for EV charging has also been shown to be a practical and economical approach for small-scale EV charging prototypes and experimental systems [3]. In addition, wireless and solar-assisted charging solutions have been investigated to improve flexibility and energy management in EV systems [4]. Real-time control and optimization of solar energy systems have gained importance in improving charging efficiency and better utilization of available power [5]. At the same time, IoT-based battery monitoring approaches have enabled remote supervision of lithium-ion battery parameters such as voltage, current, and charging status, which is highly useful for smart EV charging applications [6]. Power electronic converters also play a key role in such systems, where advanced DC–DC converter topologies are used to regulate solar energy effectively for charging purposes [7]. Furthermore, low-cost sensing and monitoring techniques have been applied to improve visibility of photovoltaic and EV charging loads, thereby supporting more reliable control and performance evaluation [8]. Although these contributions have significantly advanced the field, there is still a need for a compact and low-cost prototype that combines solar input regulation, voltage and current sensing, battery charging, relay-based control, and IoT-enabled monitoring on a single embedded platform. Therefore, this paper presents the design and implementation of a prototype solar-based smart EV charging and monitoring system using an ESP32 microcontroller. The proposed system integrates solar-side and battery-side measurement, local LCD display, relay-based charging control, and Wi-Fi-based dashboard monitoring, providing a practical proof-of-concept for renewable-energy-assisted EV charging applications.

II. Related Work

Recent research has shown growing interest in solar-based electric vehicle charging systems that are safer, have monitoring and improved energy management. In [9], a solar-based EV charging circuit embedded in a smart battery management system to protect batteries during charging has been developed, emphasizing the need for safe battery operation for renewable energy assisted charging system. In [10], an integrated photovoltaic energy storage charging discharging system was studied in which photovoltaic generation storage and charging/discharging functions can be coordinated in a single energy management framework. Further developments have been made to also consider integration of solar PV directly with battery-supported EV systems. In [11], an on-board solar PV powered electric vehicle coupled with battery energy storage was designed and simulated in the context of demonstrating the feasibility of combining solar generation and battery support in the context of EV-oriented energy systems. A wider review of stand-alone solar-powered EV charging stations has been presented in [12], where the authors discussed standards, design aspects, policies, and future directions. Similarly, [13] gave a comprehensive review on the operating modes of grid-integrated PV solar EV charging systems in terms of control strategies, charging modes and power flow management. Research has also been done in the design and simulation of practical charging stations. In [14], a 4-kW solar power-based hybrid EV charging station was designed and simulated demonstrating the practical feasibility of hybrid solar-assisted charging infrastructure. In [15], the application of renewable energy technologies for EV charging was thoroughly reviewed, which gives us a broader insight into renewable-assisted charging systems and their future potential. Advanced control and optimization methods have also been investigated; in [16], a novel MPPT architecture was proposed for grid-tied EV charging stations, the purpose of which is to enhance the charging performance and the utilization of solar energy. A comprehensive overview of solar-powered EV charging systems was presented in [17] further reinforcing understanding of system configurations, operating principles and design considerations. In addition, intelligent control techniques have been used for the improvement of charging station performance. In [18], real-time dynamic power management based on model predictive control in a grid-connected PV-EV charging station was proposed, which reveals the role of advanced control in improving the system efficiency and operational flexibility. On the whole, the literature reveals great developments in solar powered EV charging, battery protection, PV-storage integration, charging station design and advanced control method. However, the need for a compact and low-cost embedded prototype combining solar input regulation, voltage and current sensing, relay-based charging control, local display and IoT enabled monitoring on a single platform has remained. The present work fills this gap by developing an ESP32-based solar smart EV charging and monitoring prototype for proof-of-concept implementation.

III. METHODOLOGY

The proposed system is designed as a prototype solar-based smart electric vehicle (EV) charging and monitoring platform using an ESP32 microcontroller, Voltage Current sensing module, Relay based control, local display, and IoT enabled supervision of the system. The methodology consists of system architecture, hardware integration, sensing and parameter estimation, charging control, IoT communication, as well as experimental validation.

A. System Architecture

The developed prototype is made of five major functional blocks namely the solar input stage, the power conditioning stage, the energy storage stage, the control and monitoring stage as well as the output charging stage. Solar energy is provided from the input terminal and serves as the main energy source from renewable energy. Since the input voltage from the solar panel may vary and is sometimes above the safe charging level of the battery, a buck converter is then used to step down and regulate the incoming voltage to a suitable charging level. The regulated output is then used to charge a 3S lithium-ion battery pack which is the storage unit of the system.

The ESP32 microcontroller acts as the central control unit of the prototype. It continuously receives electrical parameters from the sensing modules, processes the electrical measured values, updates the display, controls the relay operation, and sends data to the IoT dashboard over the Wi-Fi. The output side of the system acts as the charging/load terminal for the charging of prototype level EV charging demonstration. The architecture of the proposed solar-based EV charging and monitoring system is shown in Fig. 1, in which the solar panel, power conditioning stage, sensing modules, ESP32 controller and charging output are combined on a single prototype platform.

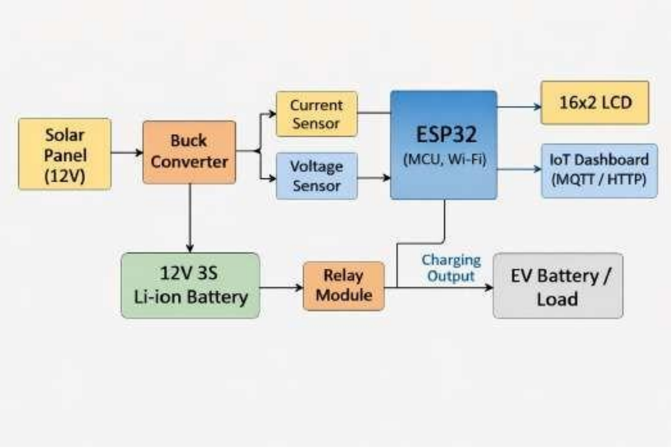

Fig. 1. Block diagram of proposed solar based smart EV Charging and Monitoring System.

B. Hardware Design and Integration

The hardware implementation is divided into the solar input side and load/output side. On the solar side, a voltage sensor is used to measure the incoming source voltage while a current sensor is used to measure the charging current given by the solar input. These measurements provide real-time information on the availability of the source and charging input conditions. The charging path contains a buck converter which serves as the voltage regulation stage for safe battery charging. A 12 V battery pack is used as the storage element in the prototype. To support the low-voltage electronic modules, an auxiliary step-down converter is used to convert the battery voltage to 5V for the powering of ESP32, Relay module, Sensor, LCD. On the output side we have another voltage sensor and current sensor which is used to measure battery-side or load-side parameters. These measurements are used to determine output voltage, output current and power delivered by the system. A relay module is installed in the charging path, which can make ESP32 control the charging/output operation to off or on according to the measured conditions. A boost converter is also included to increase the storage voltage to the required output level during charging demonstration depending on the load requirement. To enhance maintainability and testing flexibility, breakable terminal connectors are provided for each module. This modular layout has individual of the sensors and power stages could be tested, removed and replaced separately in the course of debugging and validation.

C. Sensing and Parameter Estimation

The system monitors source side as well as battery / load side electrical parameters in real time. The input voltage and current sensors are used to obtain measurements of the solar or adapter voltage used to provide the input voltage and current entering the charging path. Similarly, the output voltage and current sensors measure the battery/load voltage and the current that is supplied to the output side.

The ESP32 then reads these analog signals converting them into engineering units using calibration factors. Using the measured values of the voltage and the current, the instantaneous power is then calculated for both the input and the output side. These parameters are used for local display, remote monitoring and charging control. In no-load or disconnected conditions, both small offset readings may be obtained from sensors or random floating readings may occur, these are considered as measurement offset and thus excluded from analysis.

D. Charging Control Logic

A rule-based control strategy for charging is used in the prototype. Battery connection as well as valid source/input conditions are first checked by ESP32. If the battery is not connected, charging remains disabled and no battery is represented by the dashboard. If the battery is connected and the measured voltage is in the operating range, the relay is activated so that a charging or output delivery can be done.

The relay is the switching element to control the path of the charging. This offers a simple and effective method of charging control at the prototype level. The logic also assists in preventing unsafe operation during abnormal conditions such as when a battery is disconnected or when an invalid input is received about charging. Basic overcharge and voltage protection are also aided by the protection circuitry that is built into the battery pack.

E. Local Display and IoT Monitoring

A 16×2 LCD is integrated into the system to provide local real-time display of the main operating parameters. The LCD shows solar-side voltage and current, battery/output-side voltage and current, and overall system status. This allows the user to directly observe the operating condition from the hardware setup.

For remote monitoring, the ESP32 uses its built-in Wi-Fi capability. Once powered, the controller attempts to connect to a predefined hotspot operating on the 2.4 GHz band. After successful connection, the ESP32 hosts a web-based dashboard using its assigned IP address. The dashboard displays solar voltage, solar current, solar power, battery voltage, battery current, battery power, battery percentage, and charging status. A charging control button is also provided; however, charging activation is permitted only when valid battery connection conditions are satisfied. This IoT feature enables browser-based supervision of the charging prototype without requiring external monitoring hardware.

F. Experimental Procedure

The prototype was assembled on a hardware board using the actual sensing, control, and power conversion modules. Initial testing was carried out by powering the system and verifying sensor readings under no-input and no-battery conditions. The LCD and dashboard outputs were checked to confirm zero or idle readings when the solar source and battery were disconnected.

Next, the battery pack was connected to validate battery voltage sensing, battery percentage indication, and system response to storage-side activation. Relay operation was then verified through manual dashboard control under safe battery conditions. To test the solar input side in a controlled manner, a DC power adapter was temporarily used in place of the solar panel during indoor validation. This allowed verification of input voltage and current acquisition, source-side power estimation, and dashboard updating. The methodology also accounts for actual solar panel operation, where a 12 V nominal PV module may provide a higher input voltage under practical conditions.

G. Data Flow and System Operation

The overall operation of the system follows a sequential flow. First, the source and battery conditions are sensed. Second, the ESP32 processes the sensor data and evaluates whether charging conditions are safe. Third, the measured values are displayed locally on the LCD and transmitted to the web dashboard. Fourth, the relay is controlled according to system conditions and user command. Finally, the output side is continuously monitored to ensure that charging/load parameters remain visible during operation.

This methodology enables the implementation of a compact proof-of-concept system that integrates solar-assisted charging, embedded monitoring, local visualization, and IoT-based remote supervision on a single prototype platform.

IV. Results and Discussion

The proposed solar-based smart electric vehicle (EV) charging and monitoring prototype has been implemented and experimentally tested using ESP32 microcontroller, voltage and current sensing modules, and relay-based control along with 16×2 LCD display and IoT dashboard. The obtained results show that the developed system is capable of real-time monitoring, local visualization, remote supervision and control of the charging operation at prototype level.

A. Hardware Implementation Results

The full hardware setup was assembled and tested with the designed modular set up of sensing, control, and power conversion blocks. The prototype was integrated with the solar input stage, buck converter, battery storage unit, ESP32 controller, LCD display, relay module, boost converter and the sensing stage on the output side. The use of detachable terminal connectors simplified module by module debugging and validation. The hardware arrangement also exhibited stable interconnection among all the subsystems during repeated testing.

The setup that was implemented showed that the proposed architecture can be implemented physically as a small prototype for solar-assisted EV charging and monitoring applications. The operation of the systems was stable during successive power-up and test cycles and thus shows the feasibility of the hardware design. Fig. 2 is the experimental set-up of proposed solar-based smart EV charging and monitoring prototype.

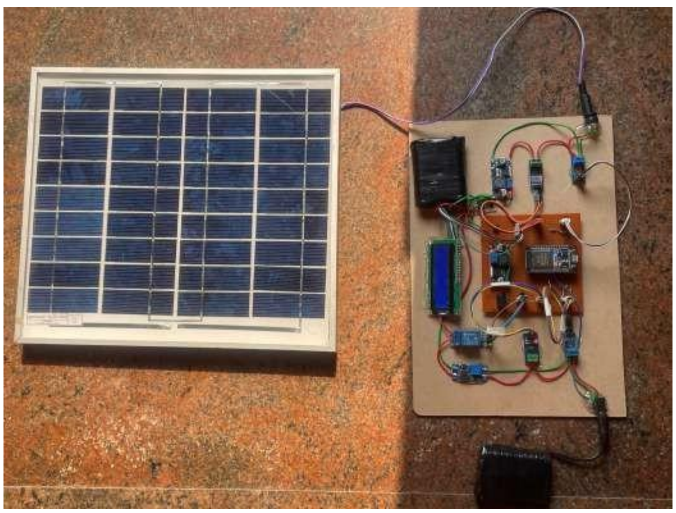

Fig. 2. Experimental setup of proposed solar based smart EV charging prototype.

B. Performance of Sensor Monitoring

The voltage and current sensing unit on both sides on the input side and output side were able to collect the electrical parameters and send it to ESP32 to do the data processing. The measured parameters were displayed locally by the LCD and remotely by the IoT dashboard. The sensors on the input side supplied information of the source voltage, the source current, and the sensors on the output side supplied the battery/load voltage, and the battery/load current.

During no input and no battery conditions, the system showed zero or near zero values for disconnected source and storage conditions. Small floating current values were observed occasionally for disconnected states which is a characteristic in practical implementation of low-cost current sensing modules. These values were considered offset of the sensor and were not used in interpreting performance. Under connected operating conditions, the measured parameters were updated correctly and reflected the system state in real time.

C. Battery Detection and Charging Controlling

The developed prototype was able to detect the status of the connection of the battery and used this information in the charging control logic. When the battery was not connected the dashboard was showing that it was not connected to the battery and charging was not enabled. This behaviour confirmed that the implemented safety-oriented control logic worked well.

Once the battery was connected, the voltage of the battery was measured by the system and the appropriate battery status was presented on the LCD together with the web dashboard. Relay control was tested using dashboard-based operation with valid battery conditions. The relay responded as expected, allowing and making the charging path on or off based on the system status and control input. This shows that the prototype is able to support basic charging supervision and controlled output operation. Fig. 3 is used to compare the system response in battery disconnected and battery connected operating conditions and corresponding charging and relay states.

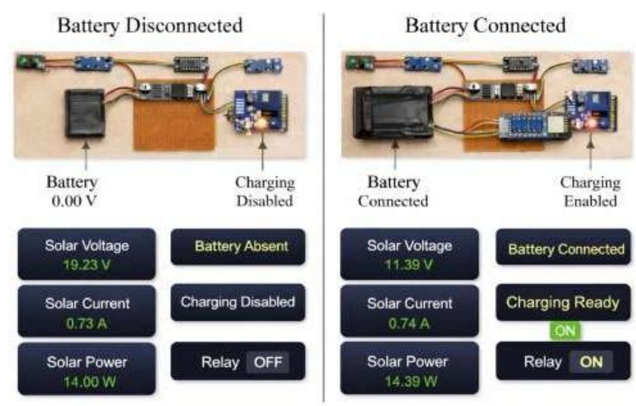

Fig. 3. Comparison of battery disconnected and battery connected operating conditions.

D. LCD and IoT Dashboard Validation

The 16×2 LCD displayed the main operating parameters, including solar-side voltage/current, battery-side voltage/current, and status information. This provided immediate local visibility of the system condition during testing and allowed quick hardware-side verification without relying on external devices.

The IoT dashboard extended system functionality by enabling browser-based remote monitoring. After Wi-Fi connection was established, the ESP32 hosted the dashboard using the assigned IP address. The dashboard displayed solar voltage, solar current, solar power, battery voltage, battery current, battery power, battery percentage, and charging status. The measured values shown on the dashboard were consistent with those observed on the LCD, demonstrating reliable local and remote data presentation. This result validates the implementation of IoT-based monitoring in the proposed prototype. Fig.

4 shows the local LCD display presenting real-time solar and battery parameters of the prototype system.

Fig. 4. LCD display of real time solar voltage, current, battery voltage and battery status.

A web-based ESP32 dashboard for real time monitoring of solar and battery parameters is shown in Fig. 5.

Fig. 5. Web-based dashboard for real time Solar and battery monitoring parameters.

E. Controlled Source-Side Validation

To test the source side sensing and monitoring functions in controlled indoor environment, a DC power adapter was used instead of the solar panel for a few days. This allowed the validity of source voltage acquisition, current sensing and real-time updating of the dashboard to be verified without it being dependent on the solar conditions outside. During this validation we could observe that our system detected the input applied to the system and updated the parameters at the source-side.

This approach to testing showed that the sensing and communication architecture of the prototype works properly in controlled laboratory conditions. It also validates the fact that the proposed framework for monitoring and charging can be responsive to variations in the input in practice. The same methodology can be used for actual solar panel operation in which the nominal 12V PV source can have a higher voltage depending upon irradiance and operating conditions.

F. System-Level Discussion

The results show that the proposed system is effective as a prototype solar-based smart EV charging and monitoring platform. Its main contribution is that it integrates successfully solar input, sensing, embedded control, relay-based switching and local display, and IoT supervision successfully in a compact set-up. The system also enhances visibility of source side and battery side parameters by monitoring in real time and basic safety by preventing the charging in case of invalid battery conditions. However, the work is confined to the prototype level implementation and not a full-scale commercial EV charger. Further improvements are necessary with respect to charging capacity, control strategy as well as practical EV compatibility.

V. Conclusion

This paper presented the design and implementation of a prototype solar-based smart electric vehicle (EV) charging and monitoring system using an ESP32 microcontroller. The developed system successfully combines solar input regulation, battery charging, voltage and current sensing, relay-based control, local LCD display, and IoT-enabled remote monitoring in a compact embedded platform. The proposed prototype was capable of monitoring source-side and battery/load-side electrical parameters in real time, displaying the measured values locally, and transmitting the data to a web-based dashboard via Wi-Fi. The experimental results confirmed the successful operation of the sensing, control, and communication modules under different experimental conditions, including no-battery, battery-connected, and controlled source-input validation. The relay-based charging logic demonstrated safe and effective control of the charging operation at the prototype level by enabling charging only under valid conditions. Overall, the proposed system validates the feasibility of a low-cost and compact solar-enabled EV charging architecture, confirming the concept of monitored and controlled charging for renewable-energy-assisted EV applications. Although the current work is limited to prototype-scale implementation, it provides a practical proof-of-concept for further advancement of intelligent renewable-energy-based EV charging systems in the future.

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