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Design and development of smart interoperable electric vehicle supply equipment for electric mobility

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ABSTRACT

The transportation industry at present is moving towards electrification and the number of electric vehicles in the market increased with the different policies of the directorate. Consumers, who wish to contribute to green mobility are concerned about the limited availability of charging points due to high manufacturing costs and the interoperability issues related to smart charging. This work proposes an internet of things-based low-cost, interoperable smart electric vehicle supply equipment for deploying in all charging stations. The device hardware is designed to monitor, analyze, and collect consumed energy by the vehicle and transfer this data to a connected network. The pre-defined messages associated with the firmware will help to record this data with a remote management server for further processing. The messages are defined in JavaScript Object Notation (JSON), which helps to overcome the interoperability issue. The device is smart because it can gather energy usage, detect device faults, and be intimate with the controller for a better operational environment. The associated management servers and mobile applications help to operate the smart device remotely and keep track of the usage statics. The developed low-cost, interoperable smart model is most suitable for two and three-wheeler vehicles.

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1. INTRODUCTION

Electric vehicles (EVs) are a paradigm shift in mobility and energy sectors, with the potential to reduce greenhouse gas emissions by incorporating e-mobility. According to various sources, there is an expected increase of 1 billion EVs by 2050 compared to 5.6 million in 2019 [1]. By the end of 2050, roughly 15 terawatt-hours (TWh) of EV batteries will be in hand for backend grid services, compared to 9 TWh in 2020. Electricity has become a captivating economical fuel in the transportation sector in several nations due to the integration of renewable energy sources [2]. A significant increase in EV growth also represents a business occasion for the energy sector. EV fleets have the potential to provide massive amounts of energy repository capacity. It can function as both an elastic bundle and distributed storage resources, allowing for more flexibility in power system operations. EVs are supported with smart charging to eliminate peak demand and load valleys and help live grid balancing by modifying their charging levels [3]. Smart charging refers to tailoring the charging cycle of an EV to the power system conditions as well as the needs of vehicle users. This makes EVs integrate easily while addressing mobility needs. As a result, smart charging is a method of revamping the charging process based on distribution grid restrictions, local renewable energy sources, and consumer preferences. Smart charging gives better control over the duration required to charge the vehicle. Different pricing and technical charge options are available, viz., price per unit, subscription-based, and time-of-use. The time of use is the most basic type that encourages users to shift their charging slot from peak to off-peak periods [4]. At gate spiking levels and for the supply of near-real-time balancing and auxiliary services, more advanced smart charging technologies, such as direct control mechanisms, will be required as a long-term solution. This process ranges from turning on and off the charging process to unidirectional vehicle control (V1G), which allows the EV to increase or decrease the rate of charging, to the precisely challenging bidirectional vehicle-to-grid (V2G), which permits the EV to bear grid services in the discharge mode. Furthermore, vehicle-to-building (V2B) and vehicle-to-home (V2H) are bidirectional charging methods in which EVs are employed as a domestic backup power supply during outages or to increase the self-consumption of on-site energy [5]. Electric mobility is power dense and has a controllable load. The adoption of smart charging for electric mobility is projected to create a pragmatic response with renewables integration. Seventy to eighty percent of the life span of EVs, especially electric cars, is under rest. Along with smart charging and storage capacity, EVs can be a flexible solution for backend energy requirements. The vehicles might transform into grid-connected storage units capable of providing comprehensive services to the entity. Smart charging can alter the load curve to integrate variable renewable energy (VRE) [6] and prevent EV-caused demand peaks. Smart charging solutions would vary depending on the power system characteristics, such as the proportion of renewable energy output, load profile, and available interconnections. The costs of fortifying local electrical systems are reduced with smart charging. It reduces simultaneity and demand peaks as compared to unregulated charging.

In smart charging, the incorporated intelligence will help to balance the grid and improve the driver's experience. The primary purpose of using grid power to charge a vehicle's battery will remain unaltered. Advanced communication between the vehicle and the charging point is required for smart charging. It allows for vehicle charging and discharging as per a schedule and based on electric rates. This allows the vehicle to be charged most conveniently to the driver. Furthermore, each EV can hand out the power grid's balancing [7]. Balancing the electricity system is complex, where the renewable energy sources like photovoltaic or wind power are used. Aside from these features, smart charging enables precise control over the start and stop of the charging process. It also allows authentication and security for the vehicle's driver, the charging point, and the data transmission. This could be used for public charging station payment schemes. Standardized solutions are required to enhance the communication and interoperability between EVs and the infrastructure. The most widely used smart charging standard for the interface between an EV and a charging station in Europe is ISO 15118 [8]. Open charge point protocol (OCPP) interacts between the charging station and a central management system. The SAE J2847/1-3 standards for smart charging are also defined by the American Society of Automotive Engineers (SAE). The established communication protocols are generally implemented in type three devices with charging and discharging scenarios. The development costs of these devices are a bit expensive due to the hardware and communication configurations, and they are mainly used for fast charging. Compared with type 3, type 1 and type 2 devices are used primarily in slow residential charging. Incorporating the communication protocol for smart charging, the hardware is a bit expensive in type 1 and 2 devices. From different stakeholders, such as users, energy providers, and service providers' perspectives, keeping track of energy utilization is very important. The supply device should be smart enough to communicate with the central management server to record the consumed energy. In such a scenario, this research proposes an internet of things (IoT)-based interoperable low-cost smart EV supply equipment (EVSE) for satisfying the charging requirements of an EV. The proposed model is suitable for slow charging and can incorporate the existing communication standards in electric mobility for data exchange and charging.

The research related to smart electric mobility elucidates different aspects of charging, communication, safety, and operational requirements. A charging station must meet the basic design and management standards for providing consumers with an uninterrupted, secured, and conflict-free charging environment [9]. This includes safety, logistics, durability, and user interface. A charging station's most important safety aspect is to avoid the risk of electric shock while charging or discharging a vehicle. Any physical contact or connection that could be hazardous to EV users should not exist. All standards should follow the IEC or SAE standards. The software in and around the charging station and the accompanying network connection should be safe and secured [10]. Fraudulent acts should be avoided in all conditions. Before energy may flow to the vehicle, there must be some initial contact between the EV and the supply equipment or the central management server (CMS) [11]. The energy flow begins once the conversation is completed, and the user is validated. User interface pages in EVSE are required to communicate with the vehicle and CMS. According to their activities, users must receive suitable pleasant and warning messages. During the charging process, the user interface should provide the charging status, state of charge, the time required for full payment, and so on.

Considering various factors such as power and voltage rating, place of application, EV populations, and other demographic importance, EV charging facilities can be classified into three categories. Domestic and residential charging facilities, public and commercial area charging facilities, and fast charging facilities in selected strategic areas [12]. These three charging facilities can be used in inductive and conductive charging technology. Inductive charging methods are not extensively used, and most charging stations now employ the conductive charging technique. Currently, most EV customers have a household EV charging unit. Soon, both fast and slow public and commercial charging facilities will be required to meet our user requirements, such as charging several EVs, discharging the battery, integrating with renewable energy sources, energy monitoring, auto disconnect detection, and auto-updating the free charging slots with a central server. All these charging stations follow SAE or IEC standards to charge EVs. According to this standard, domestic and residential charging facilities employ SAE level 1 or IEC mode one and mode two. SAE level 2 or IEC mode two and IEC mode three are used for charging the vehicle in public and commercial areas [13]. Commercial fast charging stations in strategic locations use either SAE level 3 or IEC mode four conductive charging standards. All the public and commercial charging stations ensure that EVs are charged safely and securely.

There are various modes of EV charging equipment available. A low-cost energy usage recording and billing system for EVs are proposed by Nagar *et al.* [14]. This work implements an energy meter-based system with a web interface. The energy meter is part of the processing unit, which includes a memory unit and communication interface. The collected energy meter information is transferred to the web interface via the communication module for further processing. The system works on the principles of traditional fuel filling stations. Once the charging process is over, the bill amount will be generated. Devendra *et al.* [15] developed an IoT-enabled smart charging station architecture for EV charging. The IoT part collects the state of charge (SoC) of the battery and transmits this information to Adafruit IO. Here the user can view the data and locate the nearby charging points. The designed system can transfer power in bidirectional mode, operating for charging and discharging. The collected information is transferred to cloud storage for further analysis. Muharam *et al.* [16] proposed a smart metering infrastructure for EV charging points. Their model has a smart energy meter, electronic payment system, smart card for user authentication, and a communication layer for data transfer. The smart EVSE system includes security parameters for reliable and hurdle-free power flow. The user interface screen attached to this module helps to get the live usage statics to the EV driver. The initial prototype for the system is developed and includes remote monitoring using web or mobile-based applications in the future.

A smart charging strategy for multiple charging points in a public EV network was presented by Razo and Jacobsen [17]. This work demonstrated different capacity and pricing options for the charging points. The user can adopt the charging strategy which is most suitable for their vehicles with minimum cost and delay. Zhang *et al.* [18] proposed a fast-response smart EV charging infrastructure. Their proposed smart EVSE was incorporated with a smart charging algorithm for efficient power transfer. The proposed power information collector reduces the response time to one-third as compared to the original time for data transmission. Here smart charging algorithms are implemented in control centers and local charging stations. The implemented charging algorithm reduces the traffic between the control center and charging points. This led to a faster response time for the system. As a result, this infrastructure can serve the significant components of smart grid systems. Ahmad and Zaman [19] proposed an IoT-based smart system for monitoring and exchanging agricultural data with a backend storage facility. The developed sensor-based model can collect the field sensor data and transmit it to the server over the network. This model has a global system for mobiles (GSM), Bluetooth, controller module, and memory and sensor module. The designed system is associated with a smartphone application for getting the data remotely. The associated web server processes the collected data for better growth in the future. An IoT-based EV application using boosting algorithm for smart cities which helps to monitor the real-time parameter like distance covered, battery capacity, and cost for the smooth functioning of EVs is presented [20]. The IoT-enabled system collects and transfers this information for further processing and prediction. The additional feature included in their model is the display of the number of vehicles charged in the nearby charging station.

As presented above, researchers have proposed different smart charging strategies for EVs, and it is essential that the basic safety measures are to be followed in the charging stations. Few of the proposed works develop hardware for EV charging and software for transmitting the data with entities like management servers. But none of the above results considers the interoperability feature associated with the EVSE. Our proposed research considers the design and development of IoT-based interoperable smart hardware for charging EVs, which can frame a set of messages to control and coordinate various activities in the hardware.

2. DESIGN AND MANAGEMENT OF EV CHARGING FACILITY

The world is swiftly moving towards an EV revolution, and several concerns are deterring the widespread use of EVs. The significant problems that are of concern are battery storage capacity, infrastructure for charging the EV, and uninterruptible power supply from the utility grid. Our proposed architecture works closely with an EV charging and discharging environment that manages the charging activity. The proposed research work is focused on IoT [21] and machine-to-machine (M2M) [22] connectivity models. The charging process and time required to charge an EV depend on various factors such as the type of EV, the amount of energy needed, the quality of the utility grid, and the underlying station technology [23]. To deal with the situation, the charging station and its network must be smart, allowing the users to manage, control, and schedule their EV charging activities using the smart charging station and associated mobile application. The EV driver can look for local charging stations/points, schedule a charging session, check the charging station/point's availability, manage, monitor energy usage, and keep track of tariff changes. This will help to avoid the underutilization of charging stations. That is the primary reason the charging station has evolved as a smart and intelligent device.

Figure 1 depicts the proposed IoT-based smart vehicle charging station for commercial and residential use. For EV charging, the proposed smart charger can offer up to 3.3 kW of power and is best for charging two and three-wheelers. Under-voltage protection, overvoltage protection, over-current, earth leakage, and other security features are added to it. The main components of the proposed IoT-enabled smart charging station are smart EV supply equipment, message queue telemetry transport (MQTT) broker, central management server (CMS), and mobile application for user activity.

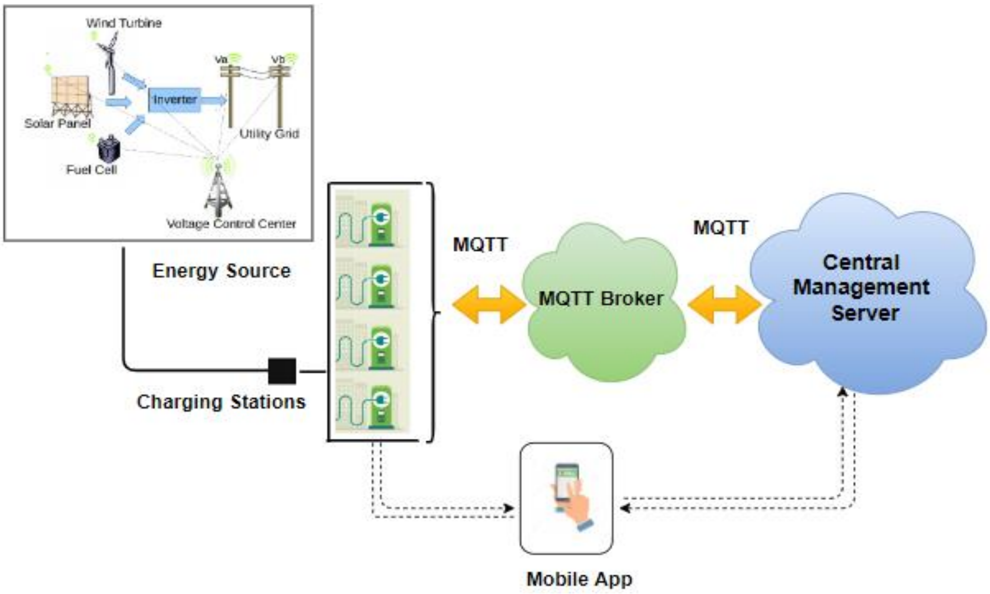

Figure 1. IoT-based smart charging station

2.1. Smart EV supply equipment

The smart EVSE device is designed to charge an EV at a rate of 3.3 kW per hour and is commonly used for two and three-wheelers. The device is designed with a plug-in socket for charging, and the vehicle owner can use their own charging gun. The device is intelligent as it can sense, monitor, and control charging activity on its own and stream the data to a web-based central management server through the MQTT protocol. A unique QR code is connected to each smart EVSE device. This one-of-a-kind QR code serves as the device's unique identifier. The charging session begins with the mobile app scanning the QR code. The smart device controls the charging process, which also monitors the safety mechanisms. The smart hardware and associated firmware help the EVSE to manage and coordinate all the activities smoothly. The internal architecture of smart EVSE is depicted in Figure 2.

At present, there are significant numbers of embedded devices with Wi-Fi connectivity. For inexpensive, high-computing Wi-Fi modules, and a small form factor, ESP8266 is one of the solutions [24]. The ESP8266 microcontroller controls and coordinates all the charging and communication activity in the proposed smart EVSE. It is a 32-bit reduced instruction set computer (RISC) CPU with an 80 MHz clock speed, serial peripheral interface (SPI), universal asynchronous reception and transmission (UART), analogue-to-digital converter (ADC), inter-integrated-circuit (I2C), and 17 general-purpose input/output (GPIO) support. It has a built-in low-cost Wi-Fi microchip and a 3 to 3.3 V operational voltage range. Among the other major features are high durability, compactness, and a power-saving architecture. A Wi-Fi module is mounted to the top, which serves as an interface between the Wi-Fi network and the internet and communicates with a real-time web server. The circuit board is connected to the PZEM-004T [25] for getting current, voltage, active power, and energy. It aids in the detection of under voltage, overvoltage, and overcurrent. The light-emitting diode (LED) indicators that come with the module assist users in identifying the device's various states, namely idle state, charging state, and error state. Idle mode is shown by a blue LED, charging mode is indicated by a green LED, and error mode is indicated by a red LED. The device is equipped with an emergency stop button that can be used to bring the machine to a halt in the event of an emergency. A lower bound of 200 V is specified for under voltage, and a higher bound of 265 V is set for overvoltage. The current threshold is set at 16 A. To control the device remotely, the module contains a two-channel 5 V relay unit. When the input voltage falls below 200 V or rises above 265 V, the relay closes, and the appropriate notification messages are sent to the CMS server. Figure 3 shows the status of smart EVSE being powered up and Tables 1 and 2 shows the messages related to basic operation and safety mechanisms. The smart hardware and associated firmware support the EVSE to control and coordinate the charging activities smoothly.

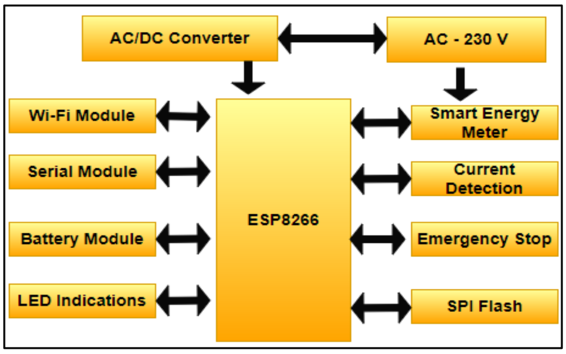

Figure 2. Smart EVSE architecture

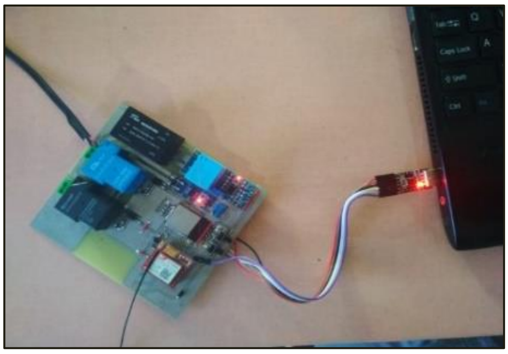

Figure 3. Smart EVSE

Table 1. Basic operation messages

S No.	Message ID	Message	Description
1	1000	`Boot_Notification`	To register the smart device to the CMS server.
2	1001	`Device_Health`	The device is ready to charge the EV.
3	1002	`Device_Charge`	EV Charging using the smart device.
4	1003	`Device_StopCharge`	Smart device stops the EV charging process.
5	1006	`Remote_Start`	Remotely start the charging process via CMS server.
6	1007	`Remote_Stop`	Remotely stop the charging process via CMS server.

Table 2. Safety messages

S No.	Message ID	Message	Description
1	1008	`Device_LowPower`	EVSE is running on low power.
2	1009	`Device_LowVolt`	EVSE detects low voltage.
3	1010	`Device_HighVolt`	EVSE detects high voltage.
4	1011	`Device_OverCurrnt`	EVSE detects over current.
5	1012	`Network_Error`	GSM network error.

2.2. MQTT broker

The smart EVSE device connected with the MQTT broker exchanges the status information with the web-based management server over the MQTT protocol. There are different message types, representing the different statuses of smart EVSE devices. The primary message types used to describe device status are shown in Tables 1 and 2, respectively. The MQTT broker [26] acts as a post office, having a different topic to subscribe to and publish. In this scenario, there are two kinds of devices connected with the MQTT broker. The first one is the smart, intelligent EVSE box, and the second one is the management server. Both the units are publishing and subscribing to different operation messages with the MQTT broker. When the device is powered up, it continuously publishes a `Boot_Notification()` message with the MQTT broker. The central management server subscribes to `Boot_Notification()` and all other smart EVSE. Whenever a new event happens, it notifies the central management server. Upon receiving the `Boot_Notification()` message along with a unique device ID say `Dev_ID`, the management server searches for the received `Dev_ID` number within the database. If the `Dev_ID` is found in the server database, then the device can register successfully, and it can continuously publish `Device_Healthy()` message to the MQTT broker. This is the general scenario for connecting the smart device with the management server. Once the device is successfully registered with the server, the users can charge their vehicle via the mobile app or management server. Users use

`Device_Start()` and `Device_StopCharging()` messages for charging and finishing the EV charging process. Once the charging process starts, the smart device continuously checks for error messages listed in Table 2. If any error happens during the charging stage, it immediately publishes the respective error message to the MQTT broker, and the device stops the charging process. The management server can receive and record this error message in the server's database. Generally, MQTT web socket [27] messages are transferred as JSON formatted [28].

2.3. Central management server

The management server is designed to control and coordinate all the activities related to smart charging. The objectives include maintaining the charging activity and dynamically scheduling the smart EVSE device for charging points. The additional services offered by the CMS server are recording energy usage, monitoring device status, and searching nearby devices. The smart device has only a charging socket and no charging gun; it can support all vehicles for slow AC charging. On the CMS server profile page, the administrator can add different charging stations by entering the necessary details such as the device's unique `Dev_ID`, device name, device location, number of charging pins, and QR code [29]. Once the required data related to the charging point is entered, it will be available in the management server database and the status of the device shows "Not Connected". Whenever the smart device is powered up, it starts sending a `Boot_Notification()` message along with a unique `Dev_ID` via the GSM or Wi-Fi unit. Upon receiving this message at the CMS server, the server changes the device status to "Connected" and the device is ready to charge the EV. For setting up the vehicle, the users must create their profile on the CMS server. Admin can do this via the admin panel, or users can create via the home page. Once the user is registered by providing the details, the CMS server provides a limited unit of energy in kWh to users. The users can charge their vehicle using this unit and once it is exhausted, the user needs to add energy to their account for further charging. Depending on the usage statics, the credited energy gets reduced, and once it reaches zero, an alert message will be passed to registered users. The critical configuration added in smart EVSE is that the CMS server can control and monitor the device remotely with the help of messages shown in Tables 1 and 2. The general-purpose messages named `Remote_start()` and `Remote_stop()` are used in exceptional cases. To start the charging session remotely, the server can trigger the `Remote_stop()` message, and to stop the charging process, the server can begin the `Remote_stop()` message. Before triggering this message, the server must ensure enough load is connected at the EVSE side. Otherwise, errors will happen. These are messages which are initiated from the server side. During the charging process, the smart EVSE continuously shares its charging data in JSON format, and these JSON messages are recorded in the server database. Along with the charging message, if any kind of error or fault happens, those messages are also recorded. The recorded messages are further used for analysis, prediction, and forecasting purposes [30]. The forecasting over the stored data will help the CMS server for dynamic demand scheduling of charging points. This results in dynamic demand scheduling over the charging points, reducing the underutilization problem, and aids to revenue. The developed management server works closely with the smart EVSE, and it can control and coordinate all the charging activities for the EV.

2.4. Mobile application

The IoT-based smart charging architecture is associated with a mobile application with limited features. Developing the mobile application is needed to start and stop the charging session remotely and monitor the usage statistics. The user can start the charging session by scanning the QR code attached to each EVSE device. Upon successfully checking the QR code, users can create the charging session with sufficient energy in their account. `Remote_start()` and `Remote_stop()` are the messages used for starting and finishing the sessions. The management server acts as a middleman between the mobile application and smart EVSE. The mobile application communicates only with the management server, and there is no direct communication with the smart EVSE. The management server receives the commands from the mobile application, and the server redirects this message to smart EVSE over the MQTT broker. Usage statics, balance energy, charging history, and other related information are available in the CMS server database and the user can get this data on the mobile application. With the help of the mobile application, the charging process becomes contactless and is a good support for the post-Covid-19 world.

3. RESULTS AND DISCUSSION

The model elaborated in Figure 1 is validated with a simple test setup. The testing environment consists of smart EVSE hardware, a management server, an MQTT box, and a mobile application. The hardware and the management server software are communicated over the MQTT broker, and the device was under a Wi-Fi network. The MQTT box bypasses the management server, and it can communicate with the smart EVSE directly. Figure 3 shows the basic hardware setup with the smart EVSE device. The device is powered with a 3.5 V input supply and is programmed with an Arduino Uno editor as shown in Figure 4. The built-in packages ESP8266wifi.h and PZEM004Tv30.h are used for Wi-Fi connection and reading the data from the hardware unit.

The smart EVSE relates to the MQTT Box and the management server for live data exchange. The messages shown in Tables 1 and 2 are tested successfully. In the initial stage, the status of the smart EVSE shows not connected. The operator needs to register the smart EVSE with the management server and once the registration is successful, the device status will be changed to "connected", otherwise it shows as "not connected". For registration purposes, the device starts sending the `Boot_Notification()` message to the management server. Once the CMS server receives this message, it processes it and changes the smart EVSE status to "connected' as in Figure 5. The connected device starts to share its status information with the management server over a defined time interval using the `Device_Healthy()` message. The management server has start and stop buttons available on the server web page and it helps to control the charging process remotely. Once the smart EVSE starts charging, the charging information and device status messages are forwarded to the management server and are stored in the backend database. The operator can use this information in the future for business analysis purposes. The operator can identify the status of each smart EVSE by viewing the status message in their profile. Figure 6 shows the status message, which is available in the operator profile.

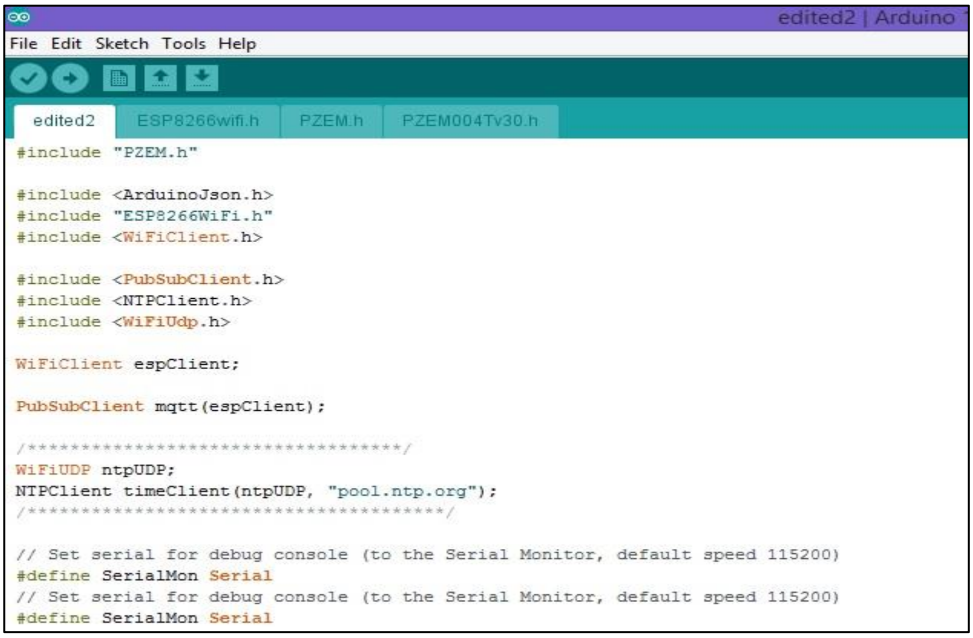

Figure 4. Arduino setup

Figure 5. Device status

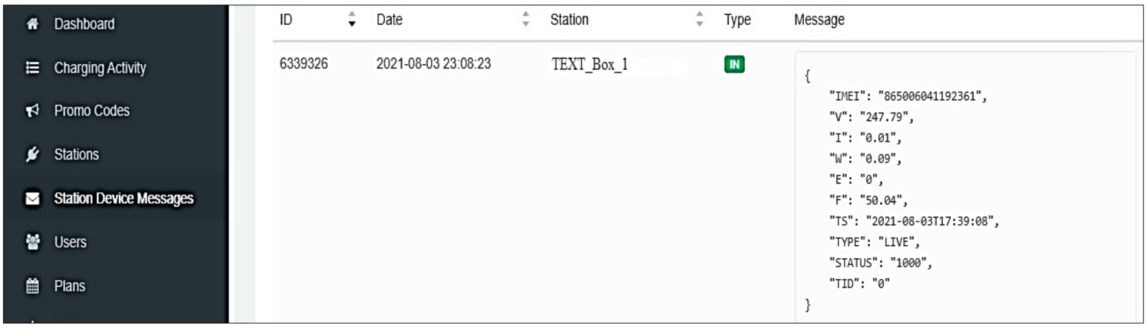

Figure 6. Smart EVSE status message

The operator or user can control the smart EVSE either by the management server or by the associated mobile application. The developed mobile application can create user accounts, control the charging activity remotely, and analyze usage statics. The user can create their account by providing their first name, last name, email id, mobile number, and password. Once the registration process is successful, the user can log in and start the charging process by scanning the QR code along with the device and can be able to operate the smart device remotely. Figure 7 shows the account creation form and Figure 8 shows the beginning of the charging process. The charging process can be controlled over the mobile application or by the management server. By default, when the state of charge of the battery reaches its maximum, the smart device automatically stops the charging process. The user only needs to unplug the EV from the smart EVSE, and it is ready for charging the next EV. All the needed information such as total energy usage, balance energy in the user account, user details, and battery details are stored in the back-end database for future analysis and forecast purposes.

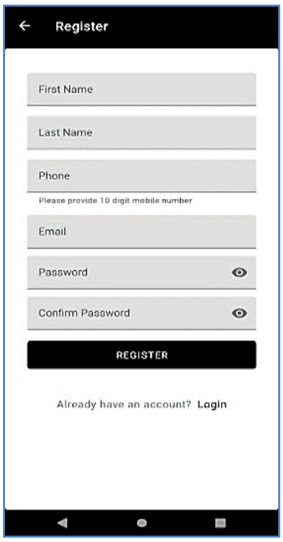

Figure 7. User account form

Figure 8. Charging process

4. CONCLUSION

The work proposes an IoT-based smart EV charging system that is suitable for two and three-wheeler EVs and overcomes the interoperability hurdle in the EV charging field. The developed smart EVSE is tested with the present conditions in the charging environment and is suitable to occupy in the field. The work demonstrates the design, implementation, and an IoT-enabled smart EVSE and the backend management server. During the charging session, the device continuously collects the energy and device-related data and dispatches this data to the back-end server. The continuous status updating of smart EVSE with the management server helps the user to identify the device's status. During this status checking, if any fault is identified, the smart EVSE stops the present charging session and switches to an idle state. The backend server can receive messages from the smart EVSE, located remotely. The received messages are stored in a database for further processing like energy usage calculation, device status updating, finding nearby charging points, locating charging points with low prices per unit, charging pattern analysis, and other business and technical analysis. The management server can operate the smart EVSE remotely with the help of the associated mobile application. The mobile application helps the user to operate the device quickly. The user can get charging status and usage statics over the mobile application. By comparing the available smart EVSE in the market, the proposed device can charge the battery at a 3.3 kW rate and is most suitable for two- and three-wheelers. The experimental result shows that the smart EVSE is ready to occupy the present market and it can fulfill the various charging requirements of EV users.

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