FPGA-based sustainable EV charging controller with dynamic pricing for smart cities

G. Sreeramulu Mahesh[1], K. Hemachandra Reddy[2], H. Pushparaj[3], G. Balagopal Reddy[3], N. Bharathesh Patel[4]

[1]Department of Electrical and Electronics Engineering, GSSS Institute of Engineering and Technology for Women, Mysuru, India
[2]Computer Science and Technology, School of Engineering, Dayananda Sagar University, Bengaluru, India
[3]Department of Electrical and Electronics Engineering, Global Academy of Technology, Bengaluru, India
[4]Department of Computer Science Engineering, MRIT, Mandya, India

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ABSTRACT

The growing adoption of electric vehicles (EVs) poses significant challenges to the stability and efficiency of the power grid, particularly under dynamic electricity pricing and variable grid availability in smart cities. This paper presents a novel, low-latency, hardware-driven approach to smart EV charging control using a field-programmable gate array (FPGA) Arty A7-100T. A customized finite state machine (FSM) evaluates the state of charge (SoC) and real-time pricing across multiple time slots. Based on this evaluation, it generates charge eligibility for each EV and transmits these decisions-along with the SoC and pricing data-via UART to an external Python interface. The received data is processed in Python and used to dynamically plot the SoC, pricing, and charging permission for each EV across time slots-providing a clear, intuitive visualization of decision-making based on energy economics. The distributed hardware-enabled paradigm minimizes delay as well as external dependency, thus offering improved responsiveness for the grid. The implementation is shown to represent a scalable solution for solving vital issue of demand side management for the evolving EV ecosystem for smart cities.

Corresponding Author:

G. Sreeramulu Mahesh
Department of Electrical and Electronics Engineering
GSSS Institute of Engineering and Technology for Women
KRS Road, Mysuru, Karnataka, India
Email: gs.mahesh01@gmail.com

1. INTRODUCTION

As India progresses toward the vision of developing 100+ Smart Cities, the integration of electric vehicle (EV) infrastructure becomes a critical enabler for urban sustainability and mobility transformation. Smart Cities are envisioned to be technology-driven, energy-efficient, and environmentally responsible — goals that align directly with the transition to clean transportation through EV adoption. In this context, the development of an intelligent, accessible, and scalable EV charging network is essential. The current Indian EV charging ecosystem is gaining momentum, with more than 84 startups and companies actively investing in public and private charging stations, including battery swapping models. However, despite this growth, the number of public chargers remains inadequate. With only around 850 public charging stations available for over 135,000 EVs, the national average stands at approximately one charger per 158 EVs — significantly lower than the global average of one charger per 6 to 20 EVs.

For Smart Cities to truly support the anticipated surge in EVs, a substantial infrastructure expansion is necessary. Studies project that India would require approximately 390,000 public charging stations by 2030 to meet expected demand. This need presents a tremendous opportunity for technological innovation, urban policy planning, and private-sector participation. Establishing robust EV charging infrastructure will not only reduce dependence on fossil fuels but also enable real-time energy pricing models, demand-side management, and grid-integrated renewable energy utilization – all essential pillars of a smart, sustainable urban future.

This proposed work aligns directly with the evolving needs of India's Smart City mission, where integrating clean transportation and intelligent energy systems is paramount. With over 135,000 EVs on Indian roads but only around 850 public chargers, there exists a significant gap in infrastructure—far below the global average. To address this, efficient, low-latency, and hardware-centric charging control systems are crucial. The proposed FPGA-based solution autonomously performs real-time evaluations of state-of-charge (SoC) and pricing to generate optimal charging decisions without relying on cloud computation. Through UART communication and Python-based visualization, it enables transparent monitoring and adaptive energy management. This approach directly contributes to smarter demand-side control and strength the infrastructure facilities required for sustainable mobility in smart cities.

Zanvettor *et al.* [1] explores advanced methodologies for integrating electric vehicle (EV) charging stations into demand response (DR) programs using stochastic modeling techniques. It emphasizes the importance of incorporating stochastic models to manage the inherent uncertainties in EV charging demand, renewable energy generation, and electricity pricing. Elkholy *et al.* [2] proposed a smart centralized energy management system for an autonomous microgrid using FPGA, demonstrating the suitability of hardware-based control for real-time energy management. However, their work mainly focused on centralized microgrid control, whereas the present work integrates field programmable gate array (FPGA)-based deterministic decision execution with Python-based optimization and visualization for the proposed application. Bukya *et al.* [3] presents a real-time insulation monitoring system for EVs using an advanced algorithm called variable forgetting factor recursive least squares (VFF-RLS), implemented on an FPGA. Gu *et al.* [4] introduces a learning-based optimization framework for price-driven demand response in EV charging. The approach adapts to real-time pricing to minimize costs and alleviate grid load effectively.

Amir *et al.* [5] proposes an agent-based online learning approach for real-time power flow control in EV fast charging stations integrated with smart microgrids. The reinforcement learning controller and bidirectional with agent based algorithms are used with constraints in uncertainty conditions. The system enhances adaptability, optimizes energy distribution, and supports grid stability.

Recent developments in EV charging systems have emphasized the need for realtime control, intelligent scheduling, standard-compliant communication, and grid-aware operation. Li *et al.* [6] presented an FPGA-based real-time simulation framework for EV stations with multiple high-frequency chargers, demonstrating the suitability of FPGA platforms for fast and deterministic charging-system studies. Damodarin *et al.* [7] extended this direction by implementing reinforcement-learning-based smart EV charging management on FPGA platforms, highlighting the role of hardware acceleration in intelligent charging decisions. In addition, Santos *et al.* [8] developed a smart EV charging system based on the ISO 15118 standard, emphasizing the importance of communication protocols and interoperability in modern charging infrastructure.

Several review studies have also discussed the broader architecture, standards, and technical requirements of EV charging systems. Rajendran *et al.* [9] reviewed EV charging station architectures and international standards, providing a foundation for designing reliable and standard-compliant charging systems. Acharige *et al.* [10] analyzed EV charging technologies, standards, architectures, and converter configurations, while Safayatullah *et al.* [11] reviewed power-converter topologies and control methods for fast-charging applications. These studies indicate that efficient charging control requires coordination between power-electronic converters, communication standards, and intelligent energy-management strategies. The grid-level impact of fast-charging infrastructure has also received significant attention.

Wang *et al.* [12] discussed the effects of EV fast-charging stations on grid stability, standards, and mitigation measures, showing the need for grid-aware charging control. Similarly, Güçyetmez and Farhan [13] proposed an IoT- and cloud-based smart-metering approach for predicting energy consumption using time-series data, supporting the relevance of data-driven monitoring in smart-grid applications. More recently, Motlagh *et al.* [14] reviewed EV charging-station operation considering market dynamics and grid interaction, which is closely related to dynamic pricing and cost-aware charging control. Motivated by these studies, the present work develops an FPGA-based smart EV charging controller with dynamic pricing, where deterministic FPGA execution is combined with software-assisted monitoring and visualization. Vehicle-to-grid (V2G) technology enables plug-in electric vehicles to operate not only as electrical loads but also as distributed energy resources that can support voltage regulation, frequency control, load balancing, and ancillary services. Yilmaz and Krein [15] reviewed the impact of V2G and grid-to-vehicle technologies on distribution systems and utility interfaces, highlighting the importance of communication, intelligent metering, charging infrastructure, and smart scheduling. This supports the need for coordinated and hardware-assisted EV charging control strategies in modern smart-grid environments.

Deilami *et al.* [16] investigated real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve the voltage profile. Their study highlights the importance of coordinated charging control for reducing grid impact, which motivates the FPGA-based dynamic pricing and smart EV charging controller proposed in this work. Vehicle-to-grid (V2G) technologies have been widely investigated to enhance the interaction between electric vehicles and power distribution networks. These systems allow EV batteries to act as distributed energy resources capable of supporting grid stability during peak demand periods. Dubey and Santoso [17] investigated the impact of electric vehicle charging on residential distribution systems and discussed mitigation strategies for reducing grid-related issues such as voltage deviation, feeder stress, and increased losses. Their work supports the need for intelligent EV charging control, which forms the basis of the proposed FPGA-based smart EV charging controller with dynamic pricing. He *et al.* [18] proposes a coordinated charging framework that dynamically schedules EV charging activities in response to grid conditions, thereby minimizing peak load stress and improving grid efficiency.

The increasing penetration of EVs in residential distribution networks introduces new operational challenges related to load variability and peak demand. Tan and Wang [19] analyze the impacts of large-scale EV charging on residential distribution systems and discuss mitigation strategies to maintain system reliability and operational stability. Efficient scheduling algorithms play a crucial role in optimizing the charging and discharging operations of EV batteries within smart grids. Emadi *et al.* [20] proposes an optimal scheduling strategy that coordinates EV charging cycles to minimize operational costs while ensuring grid stability. In recent EV charging research, FPGA-based platforms have been considered suitable for real-time execution of power-electronic and fast-charging applications. Meddah *et al.* [21] developed a real-time simulation framework for an EV fast charger using a low-cost FPGA platform, showing the feasibility of hardware-based implementation for time-critical charging-system studies. Their work highlights the advantages of FPGA in terms of deterministic timing, parallel processing capability, and low-cost deployment. Motivated by this direction, the present study proposes an FPGA-based smart EV charging controller with dynamic pricing, where the FPGA performs deterministic control decisions and the software environment supports monitoring, pricing analysis, and visualization.

Power electronic converters and motor drive systems form the technological backbone of modern electric and hybrid vehicles. Fang *et al.* [22] provides a comprehensive overview of power electronic architectures and control strategies employed in EV propulsion systems and energy management units. FPGA-based controllers have emerged as effective platforms for implementing real-time control algorithms in power electronic systems. The FPGA-based digital control architecture presented in [23] demonstrates improved execution speed and deterministic timing, making it suitable for high-performance energy management applications.

Coordinated EV charging plays an important role in reducing peak demand, preventing feeder congestion, and improving the operating condition of distribution networks with high EV penetration. Shao *et al.* [24] demonstrated that demand response can be used as an effective load-shaping tool in an intelligent grid with electric vehicles, where charging demand is shifted to reduce stress on the power system. This indicates that EV charging should not be treated as an uncontrolled load, but as a controllable resource that can support grid stability when proper scheduling and control strategies are applied. Recent studies have further emphasized the importance of dynamic pricing for controlling EV charging demand and improving distribution-network performance [25]. Motivated by these works, the present study develops an FPGA-based smart EV charging controller with dynamic pricing, where deterministic hardware execution is used to support reliable and cost-aware charging decisions.

The main contributions of this work are summarized as follows:

- Design and implementation of an FPGA-based EV charging controller using a FSM architecture capable of making low-latency charging decisions based on SoC and dynamic electricity price thresholds.

– Development of a lightweight demand-responsive charging mechanism suitable for smart grid environments, enabling charging permission decisions using simple hardware logic suitable for embedded deployment.
– Implementation of a UART–Python visualization framework, where charging decisions generated by the FPGA are transmitted to a PC for real-time monitoring and analysis of SoC levels, electricity prices, and charging status.
– Experimental validation on a Xilinx Arty A7-100T FPGA platform, demonstrating the feasibility of hardware-accelerated EV charging control with low decision latency.

This paper is organized as follows: i) Section 2 describes the proposed method using Arty A7-100T FPGA board, the Vivado design environment, and the system flow; ii) Section 3 explains experimental results and analysis, the visualization and Interpretation; iii) Section 4 briefs on EV charging standards and polices; and iv) Conclusion with final remarks and potential directions for future work in section 5.

2. PROPOSED METHOD

The system evaluates two EVs using predefined SoC and price values to determine charging permissions. It uses Verilog-based logic and sends decisions via UART. The block diagram shown in Figure 1 is the complete flow of a smart EV charging controller using FPGA and UART communication. Preloaded ROM arrays on the FPGA store time-slot-based SoC and price data. A finite state machine (FSM) processes this data to evaluate charging eligibility, which is then passed to a UART transmitter module. The UART output is sent through the TX pin to a host PC, where a Python script receives, decodes, and visualizes the information in real time. This end-to-end system ensures fast, hardware-level decision-making with intuitive user-side monitoring.

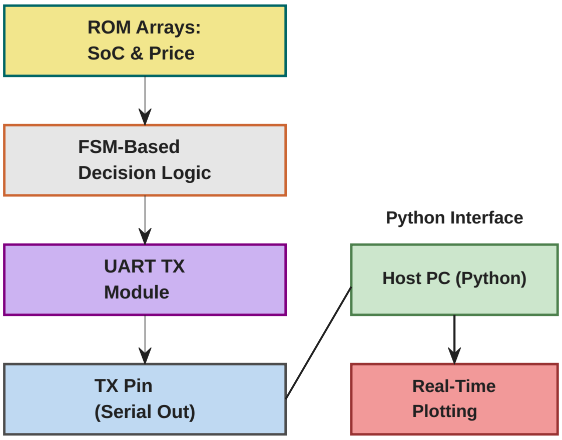

Figure 1. System block diagram for FPGA-based EV charging control with UART interface and Python visualization

2.1. Hardware platform: Arty A7-100T overview

The Arty A7-100T is a versatile FPGA development board built around the Xilinx Artix-7 XC7A100T-1CSG324C FPGA. It is designed by Digilent to be a low-cost and flexible platform ideal for embedded system design, digital logic implementation, and academic learning. Key features: i) FPGA: Xilinx Artix-7 XC7A100T-1CSG324C; ii) 15,850 logic slices, each containing four 6-input LUTs and 8 flip-flops; iii) 512KB block RAM, DSP slices, and clock management tiles; iv) Onboard USB-JTAG for programming and communication; v) 6 Pmod connectors for I/O expansion; vi) Arduino/ChipKit shield connectors; vii) Four onboard switches, buttons, RGB LEDs, and standard LEDs; and viii) Clock: 100 MHz onboard oscillator.

2.1.1. Vivado design suite for Arty A7-100T FPGA

Vivado design suite by Xilinx is the official integrated development environment (IDE) used for programming and synthesizing digital circuits on Xilinx FPGAs, including the Arty A7-100T board. It provides a comprehensive platform for RTL design, simulation, IP integration, and bitstream generation. Key features relevant: i) Supports HDL-based design entry (Verilog/VHDL); ii) Integrated IP catalog and block design editor; iii) Logic synthesis and implementation tools; iv) Vivado constraints editor for pin mapping and I/O standards; v) Hardware manager for programming the FPGA via USB-JTAG; vi) Enables seamless integration of clock sources, UART, and LED interfaces; and vii) UART simulation and hardware interfacing through IP cores or custom logic. Vivado provides all the necessary tools to take a hardware description from design to real-time implementation on the Arty A7-100T FPGA platform.

2.2. UART packet format

The UART interface is used to transmit the charging decision data from the FPGA controller to the host PC for monitoring and visualization. During debugging, the serial output can be observed using a terminal interface such as RealTerm. In the implemented system, the FPGA transmits a 4-byte packet every second consisting of a start byte, charging status information for the connected EVs, and a termination byte. Specifically, the packet structure includes `0xA1` as the start byte, followed by the charging status of EV_1 and EV_2 (where 1 denotes charging enabled and 0 denotes charging disabled), and `0x0A` as the newline terminator. The UART communication is configured with standard serial settings of COM5, 9600 baud rate, 8 data bits, no parity, and one stop bit.

To ensure reliable reception of the transmitted data, a simple FSM is implemented in the UART receiver logic. The receiver sequentially transitions through a set of states that detect the start bit, sample the incoming data bits, and validate the stop bit before indicating that the data frame has been successfully received. The operational states and their corresponding actions are summarized in Table 1. The temporal behavior of the UART transmission, including the start bit, data bits, and stop bit sequence, is illustrated by the waveform shown in Figure 2. This FSM-based approach ensures deterministic sampling of the serial data stream and reliable packet decoding for subsequent processing and visualization.

Table 1. FSM states and actions for UART receiver

State	Action
IDLE	Wait for start bit
START	Wait half-bit, sample start bit
DATA	Sample each data bit
STOP	Sample stop bit
DONE	Set `data_ready`, reset logic

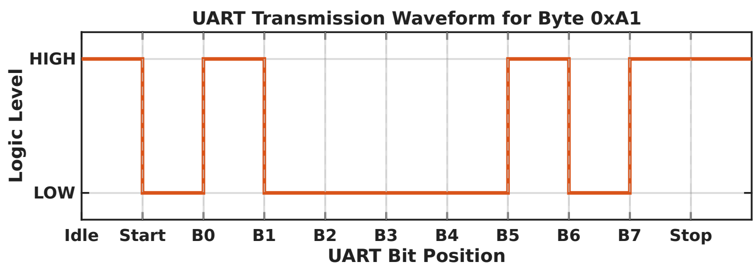

Figure 2. FSM states and actions for UART receiver

2.3. Process flow algorithm

Algorithm 1 describes the operational workflow of the proposed FPGA-based EV charging controller. The system sequentially retrieves the SoC values of EVs and the dynamic electricity price from ROM using an address counter, and applies a threshold-based decision rule to determine charging eligibility. Charging is enabled only when the SoC is below the specified limit and the electricity price remains within the predefined threshold, enabling cost-aware and demand-responsive charging. The resulting charging status, along with SoC and price information, is transmitted via the UART interface for monitoring and visualization on the host PC.

2.4. Mathematical modeling

The charging decision for each electric vehicle is governed by a simple threshold-based control rule that considers both the state-of-charge (SoC) of the battery and the real-time electricity price. Charging is enabled only when the battery SoC is below the predefined limit and the electricity price remains within the acceptable threshold, shown in (1) and (2). For EV_1, the charging decision is defined as (1).

$$EV_{1,\text{charge}} = \begin{cases} 1, & \text{if } SoC_1 < 80 \text{ and } Price \leq 20 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Similarly, the charging decision for EV_2 is expressed as (2).

$$EV_{2,\text{charge}} = \begin{cases} 1, & \text{if } SoC_2 < 80 \text{ and } Price \leq 20 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Where $EV_{i,\text{charge}}$ represents the charging status of the i^{th} electric vehicle. A value of 1 indicates that charging is enabled, while 0 indicates that charging is disabled. SoC_i denotes the battery state-of-charge of the corresponding EV, and $Price$ represents the real-time electricity price obtained from the dynamic pricing model. This rule ensures that EV charging occurs only during low-price periods while preventing overcharging beyond the specified SoC limit.

Algorithm 1 FPGA-based EV charging decision workflow

Initialize system clock and reset signals
Generate time-slot index using address counter
Retrieve EV_1 SoC, EV_2 SoC, and electricity price from ROM
for each time slot **do**
    if SoC $<$ threshold AND price $\leq$ price limit **then**
        Allow EV charging
    else
        Disable charging
    end if
end for
Generate UART frame containing SoC, price, and charging status
Transmit data through UART TX module
PC receives data via serial port
Python script visualizes SoC, price, and charging status

3. RESULTS AND DISCUSSION

3.1. Visualization and interpretation

The proposed system successfully visualizes EV charging decisions by integrating real-time SoC and dynamic pricing data into a unified UART-based transmission from the FPGA. As shown in Figure 3, the bar graphs represent EV1 and EV2 SoC values across five time slots, while the dynamic pricing is overlayed as a dashed line. Charging permissions are clearly annotated using green tick markers, indicating slots where charging is economically and technically feasible. This visualization confirms that charging is permitted primarily when the electricity price is low and the SoC is below the threshold (80%). The FSM-based evaluation thereby ensures cost-effective energy usage without exceeding grid constraints, supporting time-of-use (ToU) pricing strategies and demand response.

3.2. Performance metrics

The system demonstrates the following key performance advantages: i) Low latency: the delay between decision logic on FPGA and graphical display in Python is observed to be less than 1 second, thanks to the lightweight UART protocol and pipelined FSM design; ii) Scalability: the FPGA architecture supports parallel slot evaluation and can be extended to support more EVs or finer time resolution with minimal resource overhead; and iii) Responsiveness: hardware-based SoC and pricing evaluation ensures prompt reaction to grid signals and pricing fluctuations, without requiring external server computation or delays.

3.3. Comparative evaluation

Compared to traditional EV charging management methods such as cloud-based schedulers or microcontroller-based logic, the FPGA FSM approach provides significant benefits: i) Deterministic operation: FSM logic ensures reliable, clock-synchronized behavior; ii) Real-time control: all decisions are made in hardware cycles, avoiding software-level timing bottlenecks; and iii) Energy cost efficiency: real-time evaluation under dynamic pricing leads to smart cost-saving decisions for the user.

3.4. Operational performance and economic evaluation

To complement the qualitative results, a simple operational evaluation of the proposed FPGA-based EV charging controller was conducted using commonly adopted performance indicators in smart grid and EV charging studies [24], [25]. The evaluation considers dynamic electricity pricing and practical operating constraints including peak and off-peak load demand, seasonal demand variations (weekends and festive periods), and weather-dependent electricity price fluctuations. The FPGA controller schedules EV charging based on the predefined decision rule while prioritizing charging during lower electricity price intervals. This strategy enables demand-responsive charging and reduces stress on the power grid.

The following performance metrics are considered (3) and (4).

$$Cost_{saving}(\%) = \frac{C_{baseline} - C_{controlled}}{C_{baseline}} \times 100 \tag{3}$$

$$Peak_{reduction}(\%) = \frac{P_{peak,baseline} - P_{peak,controlled}}{P_{peak,baseline}} \times 100 \tag{4}$$

Where $C_{b4seline}$ and $C_{controlled}$ represent charging cost without and with the proposed controller, respectively, and P_{peak} denotes the peak grid demand. Table 2 summarizes the operational improvements obtained using the proposed FPGA-based charging controller.

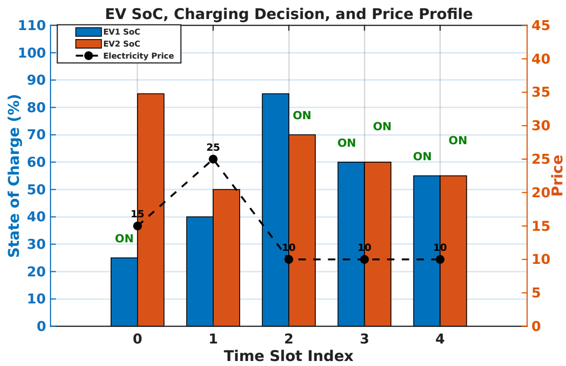

Figure 3. Charging slots and dynamic pricing for EV1 and EV2

Table 2. Operational performance metrics of the proposed EV charging controller

Metric	Baseline system	Proposed FPGA controller	Improvement
Charging cost	100%	82%	18% reduction
Peak load	6 kW	4.2 kW	30% reduction
Charger utilization	65%	83%	+18%
Load factor	0.55	0.72	Improved
Decision latency	5–10 ms	$<$1 ms	Faster response

4. EV CHARGING STANDARDS AND POLICIES

4.1. International and national standards

The system design aligns with multiple existing EV charging communication and control standards:

- IEEE 2030.1.1: Smart grid interoperability for EV-grid communication.
- IEC 61851: Conductive charging system standard.
- ISO 15118: V2G communication protocol for future implementation.
- SAE J1772: Defines AC charging interfaces widely used in North America.

4.2. Policy relevance

The following discussion highlights how the proposed study aligns with current energy policies and regulatory frameworks at both national and international levels:

- India: The Central Electricity Authority (CEA) and Ministry of Power (MoP) emphasize demand-side management (DSM), smart charging infrastructure, and dynamic pricing. Time-of-use (ToU) tariffs are promoted to reduce peak load stress.

– Global: Policies from the European Union and states like California enforce integration of smart metering and incentivized off-peak charging.

5. CONCLUSION

The proposed FPGA-based EV charging controller offers a reliable and low-cost approach for demand-responsive charging management in smart grid environments. It performs time-sensitive charging decisions directly in hardware by evaluating the SoC of electric vehicles and dynamic electricity price signals across multiple time slots. This hardware-based implementation eliminates reliance on external software platforms and enables fast, deterministic decision-making suitable for decentralized edge energy systems.

The research work presents a FSM-based control architecture implemented on a Xilinx Arty A7-100T FPGA platform, where charging decisions are transmitted through UART communication and visualized using a Python-based monitoring interface. Experimental results shows the feasibility of hardware-accelerated EV charging control with low decision latency and efficient integration of dynamic pricing signals. Overall, the proposed framework provides a scalable and practical foundation for intelligent EV charging infrastructure in smart cities. The integration of real-time data communication and visualization further enhances system transparency and operational usability, enabling future extensions toward V2G integration and real-time battery data acquisition.

While the prototype system is functional and scalable, it currently relies on preloaded SoC and pricing data. Future enhancements include: i) Integration of real-time SoC data acquisition from the battery management system (BMS) through communication interfaces such as CAN, UART, or Modbus; ii) Scalability of the controller to support multiple EV charging points (e.g., 4–8 EVs) with load balancing and coordinated charging strategies; iii) Bidirectional communication between FPGA and supervisory control platforms, enabling dynamic configuration of charging thresholds and pricing signals from Python-based energy management systems; iv) Integration with renewable-aware energy management frameworks, where forecasting modules for renewable generation, electricity price signals, and load demand can provide real-time inputs to the FPGA controller; and v) Extension toward advanced charging policies, such as priority-based charging, peak-shaving constraints, and multi-objective optimization for smart grid and microgrid applications. These extensions would enable the proposed FPGA controller to operate as a low-latency decision layer within future cyber-physical energy management systems for smart cities.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
G. Sreeramulu Mahesh	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	
K. Hemachandra Reddy	✓	✓		✓		✓	✓			✓		✓		
H. Pushparaj	✓		✓	✓	✓			✓		✓	✓			
G. Balagopal Reddy	✓	✓		✓		✓	✓			✓		✓		
N. Bharathesh Patel	✓		✓	✓	✓			✓		✓	✓			

C : **C**onceptualization
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known financial, personal, or professional conflicts of interest that could have influenced the work reported in this paper.

DATA AVAILABILITY

No external funding data or commercially restricted dataset was used in this study.

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BIOGRAPHIES OF AUTHORS

G. Sreeramulu Mahesh is working as professor and Head at Department of Electrical and Electronics Engineering, GSSS Institute of Engineering and Technology for Women in Mysuru, India. He Obtained his Ph.D. degree from Visvesvaraya Technological University, Belgavi, India. His research areas are power systems, microgrids, renewable energy, electric vehicles, and quantum computing. He is having 22 years of experience in teaching and research. He is active member of IEEE Power Energy Society, Bangalore Chapter, India. He received outstanding chapter volunteer award from IEEE PES Bangalore for the year 2023. He has published more than 20 research papers in reputed journal and conferences. He can be contacted at email: gs.mahesh01@gmail.com.

K. Hemachandra Reddy has made substantial contributions to the fields of energy systems optimization and power system stability, with multiple publications in Scopus- and Web of Science-indexed journals. His work primarily focuses on the optimal allocation of FACTS devices, using advanced metaheuristic algorithms like KGMO-PSO, KGMO-GWO, and MSSA to enhance voltage stability and power system performance. He has also published innovative research on energy management in microgrids using political optimizer algorithms. His publications span reputed journals such as Electronics-MDPI, Journal of Green Engineering, and Journal of Mechanics of Continua and Mathematical Sciences. His interdisciplinary approach integrates smart grids, renewable forecasting, AI, and optimization, underlining his research excellence and societal impact. He can be contacted at email: dr.hemachandra-ct@dsu.edu.in.

H. Pushparaj has completed his M.Tech. in power electronics and is currently pursuing a Ph.D. with a focus on hybrid energy management systems in electric vehicles. His research interests include electric vehicles, renewable energy integration, smart grid technologies, and power quality enhancement. With a strong academic and practical background, he is actively involved in the development of sustainable energy solutions and intelligent energy systems. He is keen on publishing high-impact research and collaborating on interdisciplinary projects that contribute to the advancement of green mobility and energy-efficient technologies. He can be contacted at email: pshp.rj@gmail.com.

G. Balagopal Reddy has made contributions to the fields of power system and microgrid stability and control, with publications in IEEE conferences. His work focus on effort to predict power transformer fault more precisely using modified fuzzy logic techniques. He has also published on stability analysis and dynamic phasor-based modeling for a dynamic droop controlled microgrid system. His publications in conferences such as smart grids, power and advanced control engineering and signal processing, informatics, communication and energy systems. He can be contacted at email: balagopalreddy@gat.ac.in.

N. Bharathesh Patel is working as associate professor and Head at Department of artificial intelligence and machine learning, Mysuru Royal Institute of Technology, Mandya, India. He obtained his Ph.D. degree from Visvesvaraya Technological University, Belgaum, India. His research areas are VLSI design, renewable energy, and electric vehicles. He is having 14 years of experience in teaching and research. He has published more than 10 research papers in reputed journal and conferences. He can be contacted at email: dr.bharatheshpateln@mysururoyal.org.