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FPGA-BASED CHARGING STATIONS FOR ELECTRIC VEHICLES: A REVIEW

Rasha Waleed Hamad[1], Maysara A. Qasim[2] and Sara Raed [3]
[1, 2]Electronic Engineering Department, Electronics Engineering College, Ninevah University, Mosul, Iraq
[3]Computer and Information Engineering Department, Electronics Engineering College, Ninevah University, Mosul, Iraq
[1]rasha.hamad@uoninevah.edu.iq, [2]Maysara.qasim@uoninevah.edu.iq, [3]sara.raed@uoninevah.edu.iq

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Abstract:

The rising popularity of electric vehicles (EVs) has led to a growing need for an expansive charging infrastructure. This kind of vehicle utilizes electricity by plugging into the grid and storing it in the battery which is the core of the electric car. Therefore, the charging station is a critical subcomponent of enhancing the usage of electricity-powered cars as it offers an opportunity to charge an EV's battery efficiently. Consequently, the employment of Field Programmable Gate Arrays (FPGAs) has become a potential way to improve charging stations' performance and capabilities. Researchers have explored FPGA technology to implement optimal and flexible charging of electric vehicles through fast charging stations. In this paper, the objective is to discuss the current and future state of charging stations most especially the FPGA-based ones for electric vehicles, the advancements in the technological side, and the realization strategies as well as wireless charging technologies for EVs. The results show the potential of FPGA-based charging stations to improve the charger efficiency, stability of the power grid, and power quality in addition to scaling up charging capabilities to meet the increasing demand for electric vehicles.

Keywords: *Electric Vehicles, Charging Stations, Real-time Control, Battery Charger, and Field Programmable Gate Array (FPGA).*

1 INTRODUCTION

An electric vehicle abbreviated as EV is a car that employs electric motors. Electric motors use energy stored in batteries. The battery stores energy it has gotten from charging stations or other sources of clean energy. To recharge the battery and sustain the photovoltaic cell's power, a DC-DC converter is necessary. Additionally, an electric motor facilitates movement (Williamson et al., 2007). An autonomous electric vehicle has multiple power options, including solar panels, batteries, a generator converting gasoline to electricity, or an external collector system and electric motor. EVs are categorized into three types based on their propulsion electricity source: Plug-In Hybrid Electric Vehicle (PHEV), Hybrid electric vehicle (HEV), and Battery Electric Vehicle (BEV). Figure 1 depicts the three different types of electric vehicles (Lu et al., 2013) (Abd El et al.,2022). HEVs combine an internal combustion engine and an electric motor, enabling operation in both gasoline and electric modes. This system helps to reduce emissions and improve fuel efficiency compared to traditional vehicles. PHEVs are even one step ahead with a larger battery that can be charged externally from an external power source, such as the electrical grid. This allows for a greater electric-only driving range before the internal combustion engine is needed. BEVs are vehicles powered by an electric motor and an electric rechargeable battery without a gasoline engine (Mi et al., 2017) (Williamson et al.,2013). Compared to fossil fuel vehicles, Electric vehicles are much more environmentally friendly. EVs employ battery systems in their structure and gain from advancements in electronic equipment. They have better acceleration, efficiency, and operating costs when compared to internal combustion vehicles (Xu et al., 2020). With the ever-rising demand for electric vehicles, developing efficient and reliable charging stations becomes essential to support their widespread adoption (Kapustin et al., 2020). Electric vehicle charging stations also known as electric vehicle supply equipment (EVSE) is one of the most important components for future of EV.

Corresponding author: rasha.hamad@uoninevah.edu.iq

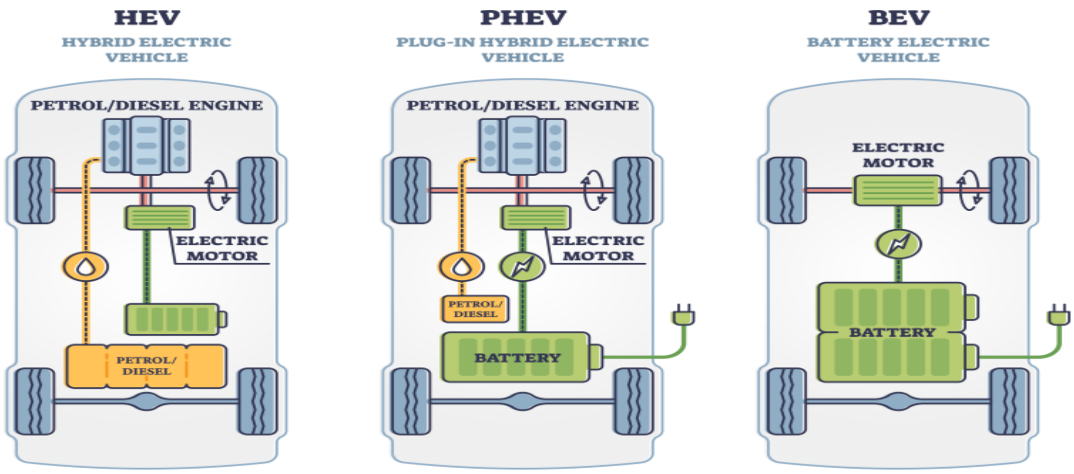

Figure 1: Types of electric vehicles

Its primary function involves converting alternating current to regulated direct current to recharge the vehicle's energy storage device, typically a battery. It can also power other electrical systems within the vehicle. The battery serves as the core component of electric vehicles, making the charger crucial in EV technology (Adhanom et al., 2022)(Dericioglu et al., 2018). The main organization of the charging stations for EVs is demonstrated in Figure 2. The EV charging system consists of essential three components transformer, rectifier, and converter as shown in Figure 3 (Ghasemi et al., 2022)(Ashish et al., 2018).

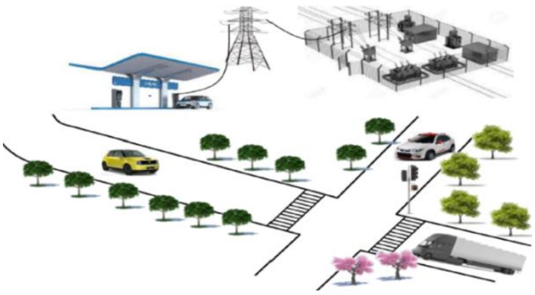

Figure 2: Main structure of an EV charging station

Depending on the charging current, how the charging system is integrated, and where the charging infrastructure is done, there are different types of EVSE. Based on the nature of the charging current, EVSE is broadly classified into two primary categories (Sivaraman et al., 2021):

a) AC EVSE.
b) DC EVSE.

Depending on the type of integration of the CS with the power grid, EVSE is categorized into types (Mohammad et al. 2020 – He et al., 2020):

a) grid-connected EVSE.
b) Sustainable energy integrated and Grid EVSE.
c) Sustainable energy integrated and Grid EVSE with energy storage.
d) Off-grid Sustainable energy-powered EVSE with energy storage.
e) Off-grid Sustainable energy-powered EVSE without energy storage.

Depending on the power levels that has been used when charging, EVSE is categorized into three types (Iannuzzi et al., 2021) (Bossche et al., 2010).

a) Normal EVSE (Level 1 EVSE).
b) Semi-fast EVSE (Level 2 EVSE).
c) Fast EVSE (Level 3 EVSE) .

Depending on mobility, EVSE is categorized into two types (Atmaja et al., 2015):

a) Fixed EVSE.
b) Mobile EVSE.

To meet the growing demand for fast and dependable charging stations, researchers and engineers are actively investigating advanced technologies and creative solutions. Among these technologies, FPGAs have emerged as a notable contender. FPGAs provide the ability to customize power conversion and control systems, enabling intelligent and efficient charging procedures.

These programmable integrated circuits offer high flexibility, allowing for the design and implementation of digital circuits and systems suitable for various applications (Boutros et al., 2020).

Corresponding author: rasha.hamad@uoninevah.edu.iq

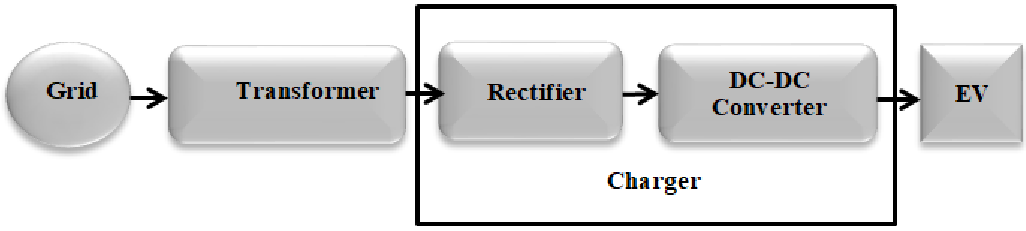

Figure 3: An EV charging station block diagram

The most recent overview literature on EV charging stations has been included and listed in Table 1. These are literature summaries and they are expected to improve the readers' knowledge across the various sections of this paper. This review article aims to offer essential and relevant information for the readers by including a broader range of factors associated with EV charging. It is the first time it synthesizes studies on charging stations that employ FPGA technology, which has gained attention due to their ability to manage the charging process efficiently. The manuscript makes the following contributions:

1) The manuscript proposes a comprehensive literature review that focuses on the effective approaches for implementing charging stations based on FPGAs. It synthesizes and analyzes existing knowledge, highlighting the advancements and potential applications of FPGA technology in the context of EV charging.
2) The paper focuses on the integration of FPGA technologies in EV charging systems, where the importance of performance and flexibility offered by FPGA is discussed. The paper also marks the advantages of utilizing FPGAs based on their ability to incorporate reconfigurable hardware and complex control algorithms into a charging system to support the efficiency of EV charging.

The rest of the paper is structured as follows: Section 2 provides a summary of the previous research carried out in the literature, and especially works on the topic of EV charging stations that adopt FPGA. Section 3 examines the new trends in the existing and emerging research data concerning EV charging stations, as identified by leading researchers. Last of all, section 4 of this article will contain the conclusion for this article.

2 LITERATURE REVIEW OF EV CHARGING STATIONS BASED FPGA

The following review aims to examine the utilization of FPGAs in Electric charging stations in the last decade. It reviews articles of the period between 2014 and 2024, partnering with published scholars using reliable databases such as Elsevier, Springer, IEEE, MDPI, and Wiley among others. By comparing various research efforts, the review offers valuable insights for researchers in the EV charging station design field using FPGA technology.

(Michail, et al., 2014) developed a flexible EV charging station with integrated split battery storage, based on the M2PET concept. It has three conversion stages and a global control structure for managing power flow and system unbalances. The control system maintains current symmetry during asymmetric load conditions and demonstrates the impact of submodule SoC balancing power on power distribution.

(Ridhi et al., 2014) presented implementation of a PIN code authentication system for secure transactions at unattended EV charging stations. Using Verilog HDL, they successfully implemented secure authentication for a four-digit code. The research findings can be extended to a hardware implementation by integrating essential components such as FPGA, Internet-compatible devices, and keypads, enabling secure charging of electric vehicles at self-service stations.

(Rivera, et al., 2015) addressed the challenge of the electric system's inability to meet increasing power demand with the rise of Plug-in Electric Vehicles during peak charging hours. They introduced a unique bus concept based on bipolar DC three-wire distribution system accompanied by the grid-connected three-level neutral point clamped conversion stage at high power level. This innovative approach aims to enhance efficiency and overcome operational limitations under varying dc loads.

Corresponding author: rasha.hamad@uoninevah.edu.iq

Table 1. A review of some of the recent literature reviews carried out on EV charging stations

Author	Year	Main Findings
Ahmad et al.	2017	• The research paper comprehensively reviews wireless charging technologies for EVs, including static, dynamic, and quasi-dynamic charging. • It discusses roadblocks like coil design, frequency limitations, power constraints, and misalignment, and proposes solutions. • The paper examines standards to provide an overview and emphasizes the importance of standardization in wireless charging. • It highlights the sustainable benefits of wireless charging, including safety, reliability, reduced environmental impact, and advantages over wired charging. • The study also addresses research gaps in grid management, infrastructure deployment optimization, policy coordination, and the impact of electromagnetic fields on human health.
ElGhanam et al.	2020	• The paper optimizes dynamic wireless charging (DWC) deployment in city infrastructures for EVs. • Optimization models maximize energy, minimize costs, improve battery performance, and optimize charging power. • Mobile energy disseminators (MEDs) optimize EV routes based on distance, time, and energy consumption. • Macro allocation models determine optimal charging coil locations for energy reception during idle periods.
Chandwani et al.	2020	• The paper investigated DIS on the EV charger power electronic hardware and suggested strategies for countering cyber threats. • Adverse scenarios arising from cyberattacks include interfering with an FPGA logic, establishing fake communication, and disrupting the battery management system. • Vulnerabilities in a specific OBC system model prompt the proposal of software and hardware protection mechanisms. • MATLAB/Simulink validates countermeasures, enhancing cybersecurity by preventing faults during data integrity attacks through design-level precautions.
Rajendran et al.	2021	• DC fast-charging networks promote the sustainable transportation revolution's significance. • Power converters ensure efficient operation and meet standard specifications. • International standards like IEC-62196, ANSI/UL, NFPA, and ISO ensure safety and interoperability. • Challenges: high vehicle costs, range limitations, and inadequate charging infrastructure. • Advancements in battery technology are needed to improve EV efficiency and cost.
Qahtan et al.	2022	• IoT technology locates charging stations easily, reducing search time. • AUKF and LSSVM predict lithium battery SOC with minimal training. • Possible charging types are presented as solar, wind, and diesel for charging stations. • Wireless charging provides advantages than that of plug-in charging for stationary vehicles.
Alrubaie et al.	2023	• The paper reviews the EV market, requirements, infrastructure, and grid implications. • PV-powered stations reduce carbon footprints and enhance microgrid stability. • Challenges in implementing PV-powered stations need to be addressed.

Corresponding author: rasha.hamad@uoninevah.edu.iq

		• The study explores controlling EV charging, including harmonics, disharmonics, and integration methods.
Sawant et al.	2024	• The study analyzed 100+ publications on DC fast charging for EVs from 2000 to 2023, covering design, sizing, location, time, cost, and power impact. • Optimizing positions and designs reduces costs, considering demand, user behavior, power, and location. • Energy storage in stations mitigates grid stress, lowers expenses, and improves power quality.

(Ivan, et al., 2016) presented a measurement system prototype for EVSE that goes beyond battery charging. It measures transferred energy, handles billing, communicates with the car, detects faults, and secures payments. The prototype's digital core units are on an FPGA board, providing flexibility for reconfiguration and adaptation. The paper stressed the importance of flexibility in the development of charging stations, addressing diverse requirements and safety concerns. The goal is to enhance functionality and efficiency.

(Ivan et al., 2016) utilized smart electronic circuit breaker technologies for EVSE with special attention in regard to the constant observing of the charging process in terms of the current and voltage values. The system detected over-currents and over-voltages, with automatic adjustments based on charging mode. The paper explores hardware implementation using a Zed Board by Xilinx. The importance of stable system conditions is emphasized, with specific trip levels for signals and timing ensuring safe and efficient charging.

(Daniel et al., 2016) presented a design for a combined residual current device, energy monitor, and phase switch for EV charging. Intended for Chargestorm, the design includes components like hall sensors, switches, current transformers, and differential amplifiers, all controlled by an FPGA. Specific isolation requirements prevent arcing, and the prototype design is on a six-layer PCB for high current conduction and thermal management. Testing and evaluation are needed to validate its real-world performance. This design is effective in increasing the efficiency and safety of the charging operations.

Ivan et al. (2016) suggested a platform for evaluating the performance of the sensor data fusion algorithms using MPSoCSim's NoC with ARM and MicroBlaze processors. The platform provided a simple means of exchanging the sensor models and the fusion algorithms besides moving complex algorithms to FPGA logic to enable real time sensor data fusion. The paper introduced a new approach for the evaluation of the sensor data fusion algorithms with the help of the MPSoCSim tool that can support energy measuring FPGA devices for charging stations. Results demonstrate the effectiveness of the approach, with NoC infrastructure enhancing efficiency in sensor data fusion.

In (Sorina et al., 2017) a bidirectional buck-boost converter was used for controlling energy transfer in the HESS. The study proposed the creation of an RTMiL simulator based on an FPGA and using Lab VIEW FPGA. The simulation also entailed identifying the load power of EV based on the stored energy using an NEDC. The RTMiL platform incorporated a lead acid battery, ultracapacitor, a buck-boost bidirectional DC-DC converter, PWM generator, and the converter controller on ZYNQ FPGA.

(Wenwen et al., 2018) created a pivotal modular system for electric vehicle infrastructure growth, focusing on DC charging pile field testing. Their FPGA-based system employed moving average smoothing, 1D median filtering, and Butterworth filtering to curb high-frequency components effectively. Leveraging FPGA's pipeline structure and parallel computation, these methods ensure efficient implementation. The FPGA facilitates integrated control logic, ADC interface, and CAN bus, offering a comprehensive solution for EV charging system testing.

(Ivan et al., 2018) described a NoC based platform for sensor data fusion algorithms testing and evaluation. It presented a physical development system based on simulation insights, provided equations for deriving fused data variance, and finding the minimum, crucial for sensor data fusion simulations. It demonstrated the simulation of sensors using MicroBlaze processors, enabling rapid prototyping of charging stations with simulated sensors close to physical counterparts.

(Wang et al., 2019) proposed a wireless EV charging system using adjustable DC power modules. The design included circuit connections, communication architecture, a communication protocol, and a three-stage control algorithm for battery charging. The main circuit and communication architecture were analyzed and designed for the wireless EV charging system, with wired and wireless communication protocols developed. Three-stage charging curve and PID

Corresponding author: rasha.hamad@uoninevah.edu.iq

controller were presented for the fast charging. A laboratory prototype was created and conducted on a group of 1.2 kW power batteries to prove the feasibility and advantages of the system.

((Hao et al., 2019) utilized topology partitioning to develop a real time model of an EV charger on an FPGA platform. This solved issues that were associated with a high frequency of switching in DC-DC resonant converters. The implementation was performed using Kintex-7 XC7K410T FPGA and verified by closed-loop experimentation. The paper also discussed the modeling of power switches like IGBT and MOSFET, providing insights into circuit representation and conduction losses.

Tudor et al., 2019) presented an FPGA based real time simulator of the PEV's on board battery charger to cut down the development costs and time using HIL simulations. The developed simulator implemented the time step of 40ns using Xilinx's Vivado tool and then implemented it on a Zynq board. The developed IP aims to reduce the time and cost in developing the charger's control system by applying HIL simulations.

(Zirun et al., 2020) used the C-EMTP algorithm to charge an EV station with multiple high-frequency chargers in the FPGA platform. The suggested algorithm upgraded the simulation precision and split the procedure into two simultaneous sub-tasks along with the usage of the ADC switch model to increase the representation of switching moments. This approach significantly reduced simulation execution time compared to traditional methods, allowing for high-precision simulations with a small-time step of 250 ns. The study also analyzed hardware resource consumption and time latency to showcase the efficiency of the proposed algorithm.

(Al-Hitmi et al., 2020) presented a DAB based fast charging system for three EVs with different power ratings. It used a CC-CV strategy controlled by PI controllers based on SOC. The system delivered 25 kW, 100 kW, and 600 kW to charge 15.5 kWh, 60 kWh, and 375 kWh batteries from 0 to 80% SOC in 30 minutes. The paper utilized FPGA Virtex-5 for hardware controller implementation and demonstrated a novel wireless power transfer approach for efficient and rapid EV charging.

(Hassan et al. 2022), proposed an IPT controller with a coordinated active and zero state count to control levels of charging. This FPGA-based controller regulated power transfer by injecting energy during active states to increase the IPT resonant current and allow free oscillation during zero states. The design is suitable for single-stage AC-AC matrix converters or dual-stage AC-DC-AC setups offering ease of implementation, and cost-effectiveness. The proposed IPT controller achieved up to 90.73% efficiency due to soft-switching techniques (ZVS and ZCS). The paper provided simulation results using ModelSim-Quartus and experimental validations to demonstrate the effectiveness of the controller in regulating power transfer for EV charging.

(Ammar et al., 2022) introduced a stand-alone EV charging station that combines solar panels to generate DC power, which is converted to AC power to charge EVs. This reduces reliance on traditional power sources and promotes sustainable energy. The station is simulated and tested using Compact RIO and LabView, ensuring efficient operation. An experimental prototype confirms its functionality and performance, meeting EV charging requirements. The integration of FPGA, Compact RIO, and LabView showcases advanced technology in sustainable energy applications, enabling future advancements in charging infrastructure.

(Ahsan et al., 2022) highlighted embedded system limitations for complex control algorithms due to low computational power, advocating FPGA usage. FPGAs enable concurrent execution of advanced control algorithms with power electronic hardware like bidirectional DC-DC converters, enabling sophisticated control strategies. The study prototypes a closed-loop control system for a 20-kW bidirectional DC-DC converter using FPGA in an HIL setup. It involved converter design, discrete PI controller implementation on FPGA, and performance evaluation of the feedback controller. The paper demonstrated MATLAB Simulink-based modeling and simulation of the converter, interfacing it with an FPGA-based controller in HIL for electric vehicle battery systems, serving as an efficient prototyping proof of concept.

(Porselvi et al., 2023) proposed grid-based charger topologies, focusing on a single-phase off-board EVSE. They used the Instantaneous current generation approach to enhance the grid-connected EV battery system, improving power quality and battery management. An FPGA-based algorithm controlled the converter switches based on battery and reference voltage using a hysteresis controller. The paper implemented PWM pulses for inverter and bidirectional converter control schemes, achieving current maintenance below 5 THD for better power quality. The method involved generating compensating current by comparing grid voltage with a reference voltage to enhance power quality by canceling non-linear current components. (Ayush et al., 2023) designed PWM signals for Power Inverters in Static Wireless Charging for

Corresponding author: rasha.hamad@uoninevah.edu.iq

EVs. They proposed using Xilinx Spartan-6 FPGA to drive the inverter at 85kHz. The study demonstrates the feasibility of low-cost FPGA technology for high-frequency PWM generation, potentially enhancing wireless charging efficiency. Through VHDL programming, four pulse signals were successfully generated to control a full H-bridge inverter with SiC MOSFET switches for efficient power transfer. Experimental results validate the FPGA-based inverter's operation at the desired 85 kHz switching frequency, confirming the practical applicability of the proposed design.

(Minjoon et al., 2023) proposed the usage of the EKF for SOC estimation in BMSs. A specialized algorithm was developed to estimate SOH and SOC from the temperature, current, and voltage of cells in a module managing up to 16 battery cells. A logic circuit followed by GUI was mapped and run on an FPGA testbed interfacing with a true battery and AFE board. The SOC and SOH estimation algorithms, hardware architecture, and performance results were detailed, showing a performance time of 0.65 µs at 100 MHz.

(Mohammad et al, 2024). employed an IEMS to optimize PV-EV charging stations. Their approach reduced peak power demand by half and efficiently utilized buffer batteries. By incorporating solar generation and EV load predictions, they optimized the IEMS for the Indian power scenario using adaptive neuro-based fuzzy control. The research employed a HIL Typhoon real-time simulator and validated the results with a real-time experimental setup. This study demonstrated the effectiveness of the proposed intelligent energy management scheme in minimizing the impact of EV charging on the distribution grid while reducing system losses.

(Emin et al., 2024) utilized a real-time digital simulator to create a complex distribution grid model for EV charging tests. Two methods, end-node voltage measurements, and primary node voltage measurements, were used to predict power demand and compared. The AIMD algorithm was chosen as the charging controller for fair resource allocation during congestion. Least-squares linear regression was employed to train the Voltage-to-power demand mapping model, ensuring accurate predictions. The paper introduced a novel approach to predict substation feeder total demand using historical voltage and apparent power data, improving real-time decision-making in EV charging scenarios.

(Chintala et al., 2024) introduced a modified bidirectional Zeta-KY converter for fast EV charging stations, addressing previous converter limitations. Optimization techniques like Grey Wolf Optimizer, Genetic Algorithm, Particle Swarm Optimization, and Dragonfly Algorithm were utilized. The Chaotic Dragonfly Optimized PI controller was chosen for the control strategy. They designed a reliable grid-connected EV charging station, reducing harmonic currents. An FPGA controller integrated with the bidirectional Zeta-KY converter and Chaotic Dragonfly Optimized PI controller improves control performance by utilizing chaos theory.

Table 2. presents a brief review of the literature on FPGA-based charging stations for electric vehicles.

Corresponding author: rasha.hamad@uoninevah.edu.iq

Table 2: Literature Review Summary

Author, Year	Research Focus	Methodology	Limitations	FPGA Kit Type
Michail, et al., 2014	Power electronic transformer for versatile ultrafast EVSE	A multiport PET-based concept for medium-voltage UFEVCSs	The prototype used in the experiments only includes one CHB-BESS branch, limiting the scope of the testing and implementation of certain algorithms	N/A*
Ridhi et al., 2014	A secure authentication system for EV charging stations	Developed a Verilog-based digital PIN lock system to ensure secure transactions at unmanned public EVSE stations.	The digital lock system implementation lacks scalability details, security threat analysis, performance metrics, and platform compatibility	N/A*
Rivera, et al., 2015	A High power fast CS designed for Plug-in Hybrid EVs	Proposed a centralized PEV charging station architecture utilizing a three-level NPC converter for efficient power conversion and distribution.	The paper discussed the limitations of unbalanced scenarios that the system can handle while keeping the midpoint voltage controlled. It mentions that the system's ability to handle unbalanced scenarios is limited, which could impact its overall performance	Altera Cyclone
Ivan, et al., 2016	Measurement system for EVSE	Developed a prototype measurement system for EVSE using an FPGA board for flexibility in configuration	The paper mentioned the implementation of security features to ensure accurate measurements. Nevertheless, the paper has failed to provide a comprehensive analysis of the effectiveness of these security measures and also the weaknesses or threats that may have been faced	ZedBoard Zynq-7000
Ivan et al., 2016	Electronic circuit breaker techniques for EVSE	Involved in the development of advanced electronic circuit breaker techniques tailored for EVSE	Limited analysis of cost implications for integrating new circuit breaker techniques in EV charging infrastructures may hinder widespread adoption	ZedBoard
Daniel et al., 2016	A combined residual current device for EVSE	Utilized a design-based research methodology to develop a combined residual current device, energy monitor, and phase switch for EV charging stations	The paper lacks a discussion on the challenges and limitations of implementing the isolated high-voltage side, including safety concerns and technical difficulties	N/A*
Ivan et al., 2016	Sensor data fusion algorithms	Evaluate sensor data fusion techniques using a NoC infrastructure simulated by MPSoCSim.	The paper's simulation platform enables easy sensor model and algorithm exchange but lacks critical hardware and resource information for effective implementation	N/A*
Sorina et al., 2017	An efficient HESS for light electric vehicles	Utilizes a bidirectional buck-boost converter to regulate the flow of energytransfer between the Battery-ultra capacitor elements	The paper focuses on the simulation and analysis of a hybrid energy storage system for EVs, lacking practical implementation and testing	Zynq
Wenwen et al., 2018	A modular system using FPGA for testing of the EV charging piles	Describes two field testing methods for EV charging piles: high frequency component, constraint butterworth filter	The paper lacks details on FPGA system scalability. Understanding the ease of scaling for diverse charging infrastructures and EV technologies is crucial	N/A*

Corresponding author: rasha.hamad@uoninevah.edu.iq

Ivan et al., 2018	Sensor data fusion algorithms based on NoC	Use different sensors and MicroBlaze processors to generate data points for rapid prototyping and evaluation of sensor models in charging stations	The paper highlights the cost-reduction benefits of using inexpensive sensors for data fusion but overlooks trade-offs in accuracy and reliability with less precise sensors	Zynq-7000
Wang et al., 2019	A system for wireless charging utilizing adaptable DC power modules.	Utilization of an efficient and wireless system for charging EVs by employing a developed DC power supply.	The experimental validation of the wireless charging system is limited to a specific set of conditions and battery types, which may lead to the fact that the results cannot be applied to a number of other electric vehicles and charging conditions.	Spartan-6
Hao et al., 2019	Realizing an FPGA based real time model of an EV battery charger	Utilization of effective topology partitioning to enable a parallel structure for an FPGA model, reducing computational latency.	The paper touches on scaling variables and fixed-point representation for efficiency but omits potential drawbacks or limitations of this method	Kintex-7
Tudor et al., 2019	Real-time simulation system for an on board charger of PEV	Utilized Real-Time simulation techniques to model a PEV on-board charger, achieving implementation with the Vivado	The specific methodologies or algorithms used for modeling switching effects in power converters are not thoroughly explained in the paper	ZYNQ
Zirun et al., 2020	Real-time simulation of an EVSE equipped with multiple high-frequency chargers.	Employs a C-EMTP algorithm for FPGA-based real time simulation of an EVSE	The study focuses on a specific scenario of an EV station with a two-level rectifier and five DAB EV chargers, limiting the generalizability of the findings	N/A*
Al-Hitmi et al., 2020	A DAB for multiple port EVSE	Proposes a DAB based wireless power transfer system for EVSE	The paper notes charging three EVs with varying power requirements but lacks a detailed exploration of system scalability for multiple vehicles or power grid impact	Virtex-5
Hassan et al., 2022	Design and implementation of an IPT power level controller	Design an IPT power level controller that aims at controlling the power delivered to the load by adjusting active and zero state counts of the converter	The research paper's experiments focused on low power levels due to lab constraints, potentially limiting the findings' applicability to higher power ranges	N/A*
Ammar et al., 2022	Stand-alone EV charging station that utilizes solar panels	Utilized solar panels for DC power generation and DC/DC converters for voltage regulation and boosting	The paper does not address the scalability of the proposed stand-alone EV charging station design, such as its adaptability to different power capacities or charging requirements, limiting the broader applicability of the research	N/A*
Ahsan et al., 2022	A fast design of a bidirectional DC-DC converter control.	Designing and analyzing a non-ideal bidirectional DC-DC converter for continuous conduction buck and boost modes using small-signal modeling	The paper emphasizes FPGA's rapid prototyping in power electronics but lacks depth on FPGA control strategy scalability across power levels or converter types	Zynq-7000
Porselvi et al., 2023	Enhancing the grid-connected EV battery system	Involves controlling the output current by adjusting gating signals using a hysteresis	Simulation shows reduced THD in current, but lacks empirical data or real-world	N/A*

Corresponding author: rasha.hamad@uoninevah.edu.iq

		controller, which compares battery voltage and reference voltage	testing to confirm FPGA algorithm's efficacy across diverse conditions	
Ayush et al., 2023	Design and development of PWM signals for static wireless charging applications.	Utilizing Pulse Width Modulation techniques to generate high-frequency signals for an H-Bridge inverter used in wireless EV chargers	The paper highlights high-frequency PWM signals for wireless power transfer via FPGA-based inverters. It successfully demonstrates power transfer but lacks details on challenges, efficiency optimization, and interference, crucial for real-world use	Spartan-6
Minjoon et al., 2023	Implementation of SOC and SOH estimation for EV battery management systems	Developing a VLSI design for estimating SOC and SOH in EV BMSs	The SOH and SOC estimation logic circuit's error remained within 5% after convergence, which could impact precision in estimation	Zynq-7020
Mohammad et al., 2024	An IEMS for grid-connected PV-powered EV charging stations	Involves the development and implementation of an IEMS-based coordinated control for PV-based EV charging stations.	The study on India's power scenario lacks global comparative analysis, limiting generalizability	Altera cyclone-IV
Emin et al., 2024	Design and implementation of a HIL testbed for a decentralized EV charging control algorithm	Involves analyzing the relationship between squared voltage magnitudes of network nodes and total power demand in a power distribution network.	The research explores end-node and primary-node voltages' effects on congestion and charging regulation but lacks insight into predicting secondary network congestion	Spartan-3
Chintala et al., 2024	Design of an efficient charging station utilizing a PV system, and an optimized control	Involved in testing the proposed bidirectional Zeta-KY converter approach using a MATLAB simulation model, considering dynamic operating conditions and variations in temperature and irradiation levels	The Chaotic Dragonfly Optimized PI controller offers stability and robustness but may face tuning and performance limitations	Spartan-6E

3 TREND DIRECTIONS OF THE RESEARCHER

This section introduced a brief overview of the major trends that were provided by prominent researchers on EV charging stations and on the FPGA-based EV charging stations which will be useful for the new researchers as a reference and to begin with (Li et al., 2020) (Gupta et al. , 2023) (Venkatesh et al. , 2024 – Zhang et al. , 2023).

- C-EMTP algorithm.
- High-Frequency Pulse Width Modulation Generation for H-Bridge Inverter.
- Topology of ultra-fast EV charging station using DAB converter and MMC structure.
- Genetic Algorithms.
- Hexagonal Fuzzy MCDM Methodology.
- Dynamic K-means clustering.
- DC microgrid.
- Spherical fuzzy D-CRITIC and CPT–CoCoSo method.
- Modified metaheuristic technique.

Corresponding author: rasha.hamad@uoninevah.edu.iq

4 Conclusions

In recent years, the use of electric vehicles has been on the rise which has spurred the need to explore and develop charging technology and power converter devices.

This necessity is due to the goal of creating a charging system that is as adaptable, safe, and economical as possible to ensure the best charging environment for electric vehicle batteriesThis review has tried to explore all the technologies used in the EV charger based on the FPGA. The study has looked at and on aspects concerning FPGA based EV chargers with the objective of obtaining systematic knowledge regarding their capabilities, benefits, limitations, and potential applications. FPGA technology is highly versatile and reprogrammable, allowing the control algorithms to be tailored to a wide array of grid conditions and electric vehicle charging prerequisites. The utilization of FPGA-based implementation can streamline the incorporation of sophisticated control strategies, like agent-based real-time control mechanisms or Vehicle-to-Grid (V2G) services, creating a foundation for enhancing the intelligent energy management system further. Using FPGAs also has the potential to bolster the scalability of systems for extensive EV charging networks and diverse grid infrastructures, ensuring sturdy performance and adaptability across varying operational scenarios. Collecting many functions into a single FPGA increases system integration and reduces the need for additional hardware elements. Additionally, this paper expands the existing literature on FPGA-based EV chargers which are crucial for researchers, engineers, or anyone interested in studying the infrastructure for electrical vehicles. The research outcomes can be beneficial in designing better and more efficient FPGA-based charging techniques that enhance the prospects of EV charging. Finally the recommendations, The most influential and groundbreaking research, adding fundamental concepts to science and innovation, includes Michail et al. (2014), Zirun et al. (2020), and Mohammad et al. (2024).

REFERENCES

Williamson S. S., A. Emadi, and K. Rajashekara, (2007). Comprehensive efficiency modeling of electric traction motor drives for hybrid electric vehicle propulsion applications. IEEE Trans. Veh. Technol., vol. 56, no. 4, pp. 1561–1572.

Lu L., X. Han, J. Li, J. Hua, and M. Ouyang (2013). A review on the key issues for lithium-ion battery management in electric vehicles. J. Power Sources, vol. 226, pp. 272–288.

Abd El, A. A. E. B., Halim, E. H. E. B., El-Khattam, W., & Ibrahim, A. M. (2022). Electric vehicles: a review of their components and technologies. International Journal of Power Electronics and Drive Systems (IJPEDS), 13(4), 2041-2061.

Mi, C., & Masrur, M. A. (2017). Hybrid electric vehicles: principles and applications with practical perspectives. John Wiley & Sons.

Williamson, S. S. (2013). Energy management strategies for electric and plug-in hybrid electric vehicles (Vol. 1). New York: Springer.

Xu M., Q. Meng (2020). Optimal deployment of charging stations considering path deviation and nonlinear elastic demand. Transp. Res. Part B Methodol. 135, 120–142.

Kapustin N. O. and D. A. Grushevenko (2020). Long-term electric vehicles outlook and their potential impact on electric grid. Energy Policy, vol. 137, pp. 111103, DOI: 10.1016/j. enpol.2019.111103.

Adhanom, S., & Coffin, D. (2022). Electric Vehicle Supply Equipment (EVSE) in the United States. Office of Industries, US International Trade Commission.

Dericioglu, Cagla, et al. (2018). A review of charging technologies for commercial electric vehicles. International Journal of Advances on Automotive and Technology 2.1, 61-70.

Ghasemi-Marzbali, A. (2022). Fast-charging station for electric vehicles, challenges and issues: A comprehensive review. Journal of Energy Storage, 49, 104136.

Ashish Kumar Karmaker (2018). Optimization of Hybrid Renewable Energy Based Electric Vehicle Charging Station. PhD Thesis.

Sivaraman, P., & Sharmeela, C. (2021). Power quality problems associated with electric vehicle charging infrastructure. In Power Quality in Modern Power Systems (pp. 151-161). Academic Press.

Mohammad, A.; Zamora, R.; Lie, T.T. (2020). Integration of electric vehicles in the distribution network: A review of PV based electric vehicle modelling. Energies, 13, 4541.

Khan, S.; Ahmad, A.; Ahmad, F.; Shemami, M.S.; Alam, M.S.; Khateeb, S. (2017) A comprehensive review on solar powered electric vehicle charging system. Smart Sci., 6, 54–79.

Corresponding author: rasha.hamad@uoninevah.edu.iq

Zhou, B.; Littler, T.; Meegahapola, L.; Zhang, H. (2016). Power system steady-state analysis with large-scale electric vehicle integration. Energy, 115, 289–302.

He, F.; Fathabadi, H. (2020). Novel standalone plug-in hybrid electric vehicle charging station fed by solar energy in presence of a fuel cell system used as supporting power source. Renew. Energy, 156, 964–974.

Iannuzzi, D.; Franzese, P. (2021). Ultrafast charging station for electrical vehicles: Dynamic modelling, design and control strategy. Math. Comput. Simul., 184, 225–243.

Bossche, P.V.D. (2010). Electric Vehicle Charging Infrastructure; Elsevier BV: Amsterdam, Netherlands, pp. 517–543.

Atmaja, T.D.; Amin; Amin, M.S. (2015) Energy storage system using battery and ultracapacitor on mobile charging station for electric vehicle. Energy Procedia, 68, 429–437.

Boutros, A., & Betz, V. (2021). FPGA architecture: Principles and progression. IEEE Circuits and Systems Magazine, 21(2), 4-29.

Ahmad, A., Alam, M. S., & Chabaan, R. (2017). A comprehensive review of wireless charging technologies for electric vehicles. IEEE transactions on transportation electrification, 4(1), 38-63.

ElGhanam, E. A., Hassan, M. S., & Osman, A. H. (2020). Deployment optimization of dynamic wireless electric vehicle charging systems: A review. In 2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS) (pp. 1-7). IEEE.

Chandwani, A., Dey, S., & Mallik, A. (2020). Cybersecurity of onboard charging systems for electric vehicles—Review, challenges and countermeasures. IEEE access, 8, 226982-226998.

Rajendran, G., Vaithilingam, C. A., Misron, N., Naidu, K., & Ahmed, M. R. (2021). A comprehensive review on system architecture and international standards for electric vehicle charging stations. Journal of Energy Storage, 42, 103099.

Qahtan, M. H., Mohammed, E. A., & Ali, A. J. (2022). Charging Station of Electric Vehicle Based on IoT: A Review. Open Access Library Journal, 9(6), 1-22.

Alrubaie, A. J., Salem, M., Yahya, K., Mohamed, M., & Kamarol, M. (2023). A comprehensive review of electric vehicle charging stations with solar photovoltaic system considering market, technical requirements, network implications, and future challenges. Sustainability, 15(10), 8122.

Sawant, V., & Zambare, P. (2024). DC fast charging stations for electric vehicles: A review. Energy Conversion and Economics, 5(1), 54-71.

Vasiladiotis, Michail, and Alfred Rufer (2014). A modular multiport power electronic transformer with integrated split battery energy storage for versatile ultrafast EV charging stations." IEEE Transactions on Industrial Electronics 62.5, 3213-3222.

Saini, Ridhi. (2014). Secured charging of electric vehicles at unattended stations using Verilog HDL. 2014 IEEE 6th India International Conference on Power Electronics (IICPE). IEEE.

Rivera, S., et al. (2015). Analysis, Design and Implementation of a High Power Fast Charging Station for Plug-in Hybrid Electric Vehicles (PHEVs).

Stoychev, Ivan, Jan-Christoph Tebbe, and Jürgen Oehm. (2016). A measurement system for electric car charging stations utilising a FPGA board for flexibility in configuration. IEEE International Symposium on Circuits and Systems (ISCAS). IEEE.

Stoychev, Ivan, and Jürgen Oehm (2016). Advanced electronic circuit breaker techniques for the use in electric vehicle charging stations. IEEE International Conference on Electronics, Circuits and Systems (ICECS). IEEE.

Hedberg, Daniel, and Erik Wetterin (2016). Combined RCD, power manager and phase-switcher for electric vehicles charging, controlled by an FPGA.

Stoychev, I., Wehner, P., Rettkowski, J., Kalb, T., Göhringer, D., & Oehm, J. (2016). Sensor data fusion with MPSoCSim in the context of electric vehicle charging stations. In 2016 IEEE Nordic Circuits and Systems Conference (NORCAS) (pp. 1-6). IEEE.

Ciornei, Sorina-Maria, et al. (2017). Real-time FPGA simulator for electric vehicle power supply systems. International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP). IEEE.

Zhou, Wenwen, and Xiaopeng Zhu (2018). An FPGA based modular system for electric vehicle charging pile field testing. IEEE Vehicle Power and Propulsion Conference (VPPC). IEEE.

Stoychev, Ivan, et al (2018). Sensor data fusion in the context of electric vehicles charging stations

Corresponding author: rasha.hamad@uoninevah.edu.iq

using a Network-on-Chip. Microprocessors and Microsystems 56, 134-143.

Wenbin, W., Jianbo, X., Qiong, L., Tianqi, M., Zhifan, L., & Ao, Z. (2019). Development of Wireless Charging System for Electric Vehicles based on Adjustable DC Power Module. In 2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA) (pp. 1419-1424). IEEE.

Bai, H., Luo, H., Liu, C., Paire, D., & Gao, F. (2019). Real-time modeling and simulation of electric vehicle battery charger on FPGA. IEEE 28th International Symposium on Industrial Electronics (ISIE) (pp. 1536-1541). IEEE.

Gherman, T., Petreus, D., & Teodorescu, R. (2019). A Real Time Simulator of a PEV's On Board Battery Charger. International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2019 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) (pp. 329-335). IEEE.

Li, Z., Xu, J., Wang, K., Wu, P., & Li, G. (2020). FPGA-based real-time simulation for EV station with multiple high-frequency chargers based on C-EMTP algorithm. Protection and Control of Modern Power Systems, 5(4), 1-11.

Al-Hitmi, M. A., Iqbal, A., Rahman, S., Maroti, P. K., Meraj, M., & Mehrjerdi, H. (2020). A dual active bridge based wireless power transfer system for EV battery charging controlled using high speed FPGA. IEEE International Conference on Informatics, IoT, and Enabling Technologies (ICIoT) (pp. 372-376). IEEE.

Jafari H. and A. I. Sarwat (2022). Resonant AC-AC Converter With Multi-Power Level Controller for Inductive EV Charging Systems," in IEEE Transactions on Vehicular Technology, vol. 71, no. 11, pp. 11589-11602, Nov., doi: 10.1109/TVT.2022.3194011.

Ammar et al. (2022). Stand-alone Electric Vehicle Charging Station Using FPGA. In book: Automated Systems, Data, and Sustainable Computing ,https://doi.org/10.55432/978-1-6692-0001-7_11

Ali, A., Faisal, N., Zia, Z., Makda, I., & Usman, A. (2022). Rapid prototyping of bidirectional dc-dc converter control using FPGA for electric vehicle charging applications. IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG) (pp. 1-6). IEEE.

Porselvi, T., Nandhagopal, M., Shalini, P. J., Hemalatha, M., Jaiakash, S., & Sai, G. C. (2023). FPGA Based Power Quality Improvement of Grid Connected EV Battery System. In 2023 4th International Conference on Signal Processing and Communication (ICSPC) (pp. 400-405). IEEE.

Gupta, A., Aganti, M., & Bharatiraja, C. (2023). FPGA Based High Frequency PWM Generation for H-Bridge Inverter in Wireless EV Chargers. Fifth International Conference on Electrical, Computer and Communication Technologies (ICECCT) (pp. 1-5). IEEE.

Kim, M., & So, J. (2023). VLSI design and FPGA implementation of state-of-charge and state-of-health estimation for electric vehicle battery management systems. Journal of Energy Storage, 73, 108876.

Amir, M., Zaheeruddin, Haque, A., Bakhsh, F. I., Kurukuru, V. B., & Sedighizadeh, M. (2024). Intelligent energy management scheme-based coordinated control for reducing peak load in grid-connected photovoltaic-powered electric vehicle charging stations. IET Generation, Transmission & Distribution, 18(6), 1205-1222.

Ucer, E., & Kisacikoglu, M. J. (2024). Development of a Hardware-in-The-Loop Testbed for a Decentralized, Data-Driven Electric Vehicle Charging Control Algorithm. IEEE Transactions on Industry Applications.

Venkatesh, C., & Yesuraj, S. (2024). Efficient and Reliable Fast Charging Station for Electric Vehicles: Integrating PV System and Optimized Control. Electric Power Components and Systems, 1-21.

Raboaca, M. S., & Mihaltan, T. C. (2023). Hydrogen Technology Integration for Energy Support of Electric Vehicle Charging Stations. In Hydrogen Fuel Cell Technology for Mobile Applications (pp. 134-156). IGI Global.

Barresi, M., Ferri, E., & Piegari, L. (2023). An MV-Connected Ultra-Fast Charging Station Based on MMC and Dual Active Bridge with Multiple dc Buses. Energies, 16(9), 3960.

Lazari, V., & Chassiakos, A. (2023). Multi-Objective optimization of electric vehicle charging station deployment using genetic algorithms. Applied Sciences, 13(8), 4867.

Zapotecas-Martínez, S., Armas, R., & García-Nájera, A. (2024). A multi-objective evolutionary approach for the electric vehicle charging stations problem. Expert Systems with Applications, 240, 122514.

Corresponding author: rasha.hamad@uoninevah.edu.iq

Ghosh, A., Ghorui, N., Mondal, S. P., Kumari, S., Mondal, B. K., Das, A., & Gupta, M. S. (2021). Application of hexagonal fuzzy MCDM methodology for site selection of electric vehicle charging station. Mathematics, 9(4), 393.

Srividhya, V., Gowriswari, S., Antony, N. V., Murugan, S., Anitha, K., & Rajmohan, M. (2024). Optimizing Electric Vehicle Charging Networks Using Clustering Technique. In 2024 2nd International Conference on Computer, Communication and Control (IC4) (pp. 1-5). IEEE.

Bilal, M., Ahmad, F., & Rizwan, M. (2023). Techno-economic assessment of grid and renewable powered electric vehicle charging stations in India using a modified metaheuristic technique. Energy Conversion and Management, 284, 116995.

Arya, H., & Das, M. (2023). Fast charging station for electric vehicles based on DC microgrid. IEEE Journal of Emerging and Selected Topics in Industrial Electronics.

Zhang, H., & Wei, G. (2023). Location selection of electric vehicles charging stations by using the spherical fuzzy CPT–CoCoSo and D-CRITIC method. Computational and Applied Mathematics, 42(1), 60.

Biography

Rasha Waleed Hamad received the BSc and MSc in Electrical Engineering in 2008 and 2012 from University of Mosul, IRAQ. She is work as assistant lecturer in Electronic Engineering Department, Electronics Engineering College, Ninevah University Mosul, IRAQ. She has many researches in the field of digital signal processing with different applications.

Maysara A. Qasim received the BSc and MSc in Electrical Engineering in 2005 and 2009 from University of Mosul, IRAQ. He is work as assistant lecturer in Electronic Engineering Department, Electronics Engineering College, Ninevah University, Mosul, IRAQ. His research interests include control systems and renewable energy.

Sara Raed obtained her B.Sc. in Computer Engineering from Mosul University in 2013, and her M.Sc. and Ph.D. in Computer Engineering from the same university in 2018 and 2022 respectively. She is working as a lecturer in the Computer and Information Engineering Department, Electronics Engineering College, Ninevah University, Mosul, Iraq. She is interested in doing research in cross-layer design for WSNs, Routing Protocols, Body Area Networks, IoT, and Network Security.

Corresponding author: rasha.hamad@uoninevah.edu.iq