Journal of Science Engineering Technology and Management Science
Volume 02, Issue 09, September 2025 *ISSN: 3049-0952*
www.jsetms.com *DOI: 10.64771/jsetms.2025.v02.i09.1-16*

FRACTIONAL-ORDER PID CONTROLLED DER-BASED EV CHARGING STATION WITH SEAMLESS GRID CONNECTION

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To Cite this Article
Ms.B.Suchithra, Dr.P.Sadanandam, "Fractional-Order Pid Controlled Der-Based Ev Charging Station With Seamless Grid Connection", Journal of Science Engineering Technology and Management Science, Vol. 02, Issue 09, September 2025,pp: 1-16, DOI: http://doi.org/10.64771/jsetms.2025.v02.i09.pp1-16
Submitted: 20-07-2025 *Accepted: 16-08-2025* *Published: 22-08-2025*

ABSTRACT
This research presents a novel framework for an electric vehicle (EV) charging station based on distributed energy resources (DERs) powered by hybrid renewable sources, including solar photovoltaic (PV) and fuel cells. A common DC bus infrastructure is employed to facilitate bidirectional power flow, enabling both charging and discharging of EVs in grid-connected and islanded modes. The proposed system enhances charging efficiency at higher voltage levels, improves reliability, and ensures seamless grid integration. To achieve robust voltage and current regulation, a Fractional-Order PID (FOPID) controller is implemented, which offers superior dynamic response, resilience, and flexibility compared to conventional PID controllers. This advanced control strategy allows smooth mode transitions through static transfer switches (STS-1/0), ensuring uninterrupted operation under varying grid conditions. Furthermore, the integration of an adaptive comb-filter technique with FOPID control in grid-tied mode ensures compliance with IEEE power quality standards by minimizing harmonics and enhancing system performance. The proposed approach guarantees reliable power delivery to critical loads while maintaining high-quality power output. Validation under weak grid scenarios demonstrates the effectiveness of the system, confirming its ability to provide seamless operation, improved power quality, and sustainable EV charging through renewable-based DER integration.

Keywords: Fractional-Order PID, Electric Vehicle Charging, Distributed Energy Resources, Renewable Energy Integration, Seamless Grid Connection, Power Quality Improvement, Adaptive Comb-Filter

I INTRODUCTION

The increasing global demand for sustainable transportation and the urgent need to mitigate greenhouse gas emissions have accelerated the adoption of electric vehicles (EVs) as a viable alternative to conventional fossil-fuel-based transportation systems. With governments and organizations worldwide striving for decarbonization and carbon neutrality targets, EV penetration into modern power networks is projected to rise exponentially in the coming years. However, the rapid deployment of EVs presents a dual challenge: meeting the escalating demand for reliable charging infrastructure and ensuring that such infrastructure integrates harmoniously with existing power systems without compromising stability, efficiency, or power quality. Distributed energy resources (DERs), particularly those harnessing renewable energy technologies such as solar photovoltaic (PV) and fuel cells, have emerged as key enablers in addressing these challenges by providing decentralized, clean, and efficient energy for EV charging [1]. Conventional EV charging stations often rely heavily on the utility grid, which increases dependency on centralized power generation and adds stress to distribution networks, especially during peak load hours. Such an approach not only strains grid reliability but also undermines sustainability goals due to the continued reliance on fossil-based energy mixes in many regions. By contrast, DER-based EV charging stations present an innovative paradigm where renewable resources are utilized to meet local charging needs, reducing carbon footprints while alleviating pressure on the grid [2]. The use of solar PV panels ensures direct utilization of abundant renewable energy, while fuel cells provide a complementary energy source capable of delivering consistent output even under fluctuating solar availability. The hybridization of these sources ensures both sustainability and reliability, making them highly suited for EV charging applications [3].

A critical enabler in such systems is the adoption of a common DC bus architecture that interconnects renewable DERs, energy storage systems, and EV chargers. This topology provides significant advantages by allowing bidirectional power flow between EVs and the grid while simplifying system control and enhancing efficiency. Through this design, EVs can be charged more rapidly at higher voltage levels while also discharging power back to the grid or local loads when necessary. This bidirectional functionality transforms EVs into mobile energy storage units, supporting ancillary services such as load balancing, peak shaving, and voltage regulation, thereby contributing to a more resilient and intelligent grid [4]. To ensure robust and reliable operation of such hybrid DER-based charging systems, advanced control strategies are indispensable. Conventional proportional-integral-derivative (PID) controllers, although widely used in power electronic systems, often struggle to maintain performance under varying operating conditions and disturbances. Their limited adaptability and restricted frequency domain flexibility make them less effective in managing nonlinearities and uncertainties inherent in renewable energy-based systems [5]. In contrast, Fractional-Order PID (FOPID) controllers extend the traditional PID concept by incorporating fractional calculus into the integral and derivative components, allowing for more degrees of freedom in tuning system dynamics. This leads to superior performance in terms of dynamic response, robustness, and stability, particularly in complex systems such as DER-integrated EV charging stations [6]. The application of FOPID controllers in managing voltage and current regulation within EV charging infrastructures ensures that stable operation is maintained under both grid-connected and islanded modes. When the grid is available, the controller facilitates smooth power exchange while maintaining compliance with grid codes and power quality standards. During islanded operation, it ensures uninterrupted power delivery to EVs and critical loads by dynamically adjusting to variations in renewable generation and load demand. The flexibility and resilience of FOPID controllers make them highly effective for ensuring seamless transitions between operating modes via static transfer switches, thereby eliminating service interruptions and enhancing system reliability [7].

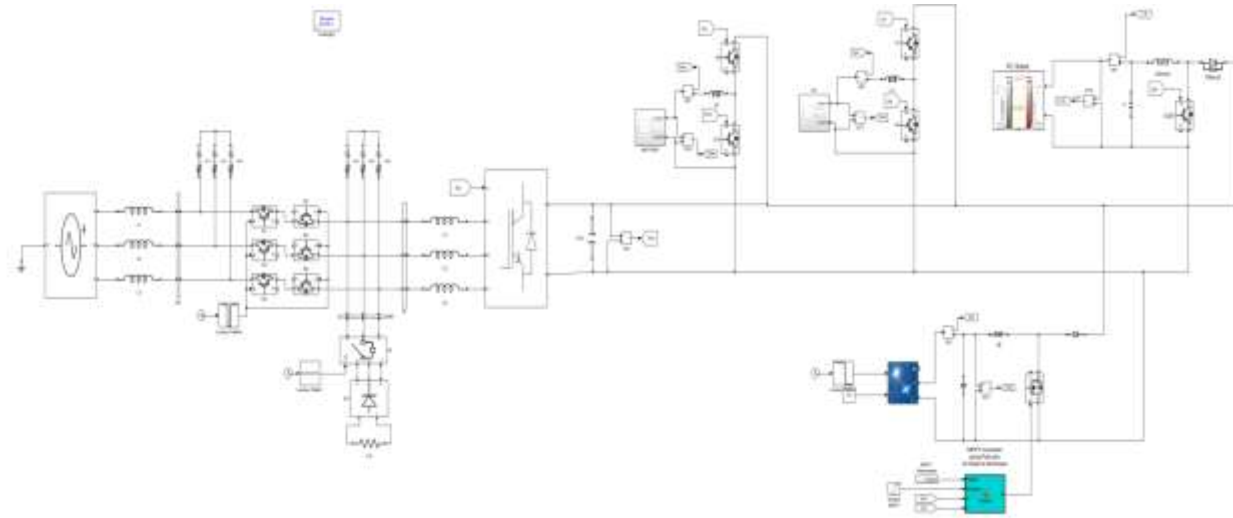


Fig 1. Proposed circuit configuration

Another key aspect of DER-based EV charging stations is adherence to stringent power quality requirements. As charging systems and renewable sources interface with the grid, issues such as harmonic distortion, voltage fluctuations, and reactive power imbalances can emerge, threatening the stability and performance of the overall system. To mitigate these challenges, the integration of adaptive comb-filter techniques alongside FOPID control mechanisms provides an effective solution. This approach ensures the attenuation of harmonics while improving total harmonic distortion (THD) performance in compliance with IEEE standards, thereby guaranteeing that the charging station does not negatively impact grid power quality [8]. Furthermore, the implementation of such filtering mechanisms enables more efficient utilization of renewable sources and supports the delivery of cleaner power to both EVs and connected loads [9].

The importance of seamless grid connection in modern charging infrastructures cannot be overstated. As EV penetration increases, the interaction between charging systems and utility networks becomes more complex, requiring advanced control and management strategies to ensure that stability is preserved. Seamless transition between grid-connected and islanded modes of operation is particularly critical in areas with weak or unreliable grid conditions, where interruptions in supply could compromise the usability of EVs and erode consumer confidence in electric mobility. By leveraging FOPID-based control frameworks, supported by adaptive filtering techniques, charging stations can guarantee smooth and disturbance-free switching between modes, thereby ensuring continuous availability of power to critical loads and uninterrupted EV charging [10]. The integration of EVs with renewable-based DERs also opens new avenues for grid support and energy optimization. Vehicle-to-grid (V2G) technology allows EVs to operate as distributed energy storage units that can supply power back to the grid during peak demand or emergencies, effectively turning EVs into active participants in the energy ecosystem. This concept not only enhances grid resilience but also creates economic incentives for EV owners through energy trading and demand response programs [11]. In this context, DER-based charging infrastructures serve as essential platforms for enabling V2G services, where reliable control mechanisms like FOPID ensure that bidirectional flows are well-regulated and synchronized with grid requirements [12].

Furthermore, the adoption of DER-powered EV charging stations aligns with broader policy objectives for reducing greenhouse gas emissions and promoting energy independence. By shifting reliance from fossil-based power plants to decentralized renewable systems, nations can accelerate their transition to sustainable energy landscapes while simultaneously meeting transportation electrification goals. This integration also reduces transmission losses and enhances local energy security, making it a highly attractive solution for urban as well as remote areas where grid access may be limited [13]. Despite the evident advantages, challenges remain in realizing the full potential of DER-based EV charging infrastructures. These include issues of intermittency in renewable generation, the cost and scalability of hybrid systems, the need for robust communication and control frameworks, and the establishment of standardized protocols for interoperability. Continued research in advanced control strategies, such as the FOPID framework explored in this work, is critical to overcoming these challenges and ensuring the reliable, efficient, and sustainable operation of EV charging stations integrated with renewable DERs [14]. By addressing these issues through innovative control, power electronics design, and system optimization, DER-based EV charging stations can evolve into integral components of future smart grids and sustainable energy systems [15].

II LITERATURE SURVEY

The emergence of electric vehicles and their integration with distributed energy resources has created a new dimension in sustainable energy systems, and this has been widely explored by researchers in recent years. The literature emphasizes the need for advanced charging infrastructures that not only support the growing demand for electric mobility but also align with the transition toward renewable energy integration. A recurring theme in the body of work is the importance of hybrid renewable energy sources, particularly solar photovoltaic systems and fuel cells, as reliable inputs for EV charging stations. These studies highlight that solar energy provides a cost-effective and abundant supply during daytime, while fuel cells deliver consistent power regardless of weather conditions, thereby ensuring a continuous supply of energy. The combination of these two sources has been shown to enhance reliability and efficiency, making hybrid frameworks a compelling solution for EV charging needs. Another important stream of research centers on the architectural design of charging stations. Many works have proposed a common DC bus system as the backbone of charging infrastructure due to its flexibility, reduced conversion stages, and enhanced compatibility with renewable energy sources and storage units. A DC bus architecture simplifies the connection of multiple DERs, reduces power conversion losses, and facilitates high-voltage charging, which directly addresses the problem of long charging durations in conventional systems. Literature also indicates that such frameworks enable bidirectional power flow, paving the way for vehicle-to-grid technologies. Through these designs, EVs can supply power back to the grid or to critical loads, effectively functioning as distributed energy storage units. This concept has been investigated in various contexts, such as grid support during peak load periods, ancillary service provision, and improving system resilience during grid outages.

The issue of seamless operation in both grid-connected and islanded modes has been another major area of focus. Research shows that in areas with weak or unreliable grid conditions, EV charging systems must be capable of switching smoothly between operational modes without interruption. Traditional charging stations often face challenges during transitions, leading to power quality disturbances or temporary outages. To overcome this, several studies have examined control and switching mechanisms that allow uninterrupted operation. The integration of static transfer switches is a commonly studied method, which ensures rapid and reliable mode transitions. The effectiveness of these systems has been demonstrated in both simulation and experimental setups, where the emphasis is placed on guaranteeing a continuous supply to EVs and local loads regardless of external grid fluctuations. Control strategies have been at the forefront of literature discussions, particularly regarding the limitations of conventional PID controllers in handling nonlinearities, uncertainties, and dynamic variations in renewable-based systems. Standard PID control, while popular due to its simplicity, often fails to deliver optimal performance under rapidly changing conditions such as fluctuating solar irradiance, variable fuel cell outputs, and sudden load changes from EV charging. To address this, researchers have turned to advanced controllers such as Fractional-Order PID (FOPID). The flexibility of fractional calculus in tuning proportional, integral, and derivative orders allows for more precise control of system dynamics. Studies consistently report that FOPID controllers outperform traditional PID controllers in terms of robustness, adaptability, and dynamic responsiveness. This improvement is particularly relevant in EV charging applications where seamless operation across multiple modes and varying conditions is critical.

Another recurring element in the literature is the problem of power quality in DER-based EV charging infrastructures. Harmonic distortions, voltage imbalances, and reactive power issues are frequently cited as obstacles that hinder efficient system integration. Researchers have investigated various filtering methods to mitigate these problems, with adaptive comb-filter techniques gaining significant attention. These filters are capable of dynamically suppressing harmonics and reducing total harmonic distortion to levels that comply with international standards. Literature also shows that the combination of advanced control mechanisms like FOPID with adaptive filtering techniques leads to superior performance, ensuring that charging stations operate without negatively affecting grid power quality. This synergy has been highlighted as a key enabler for achieving compliance with IEEE and other regulatory standards, thereby making renewable-based charging stations both reliable and grid-friendly. The role of EVs in broader energy systems has also been examined in depth. A substantial body of literature discusses the integration of vehicle-to-grid capabilities, emphasizing that EVs can support grid operations through ancillary services such as frequency regulation, peak shaving, and emergency power supply. This transformation of EVs from passive loads into active components of the grid has been presented as a cornerstone of future smart energy systems. The feasibility of such systems depends heavily on robust charging infrastructure capable of managing bidirectional flows, maintaining synchronization with grid requirements, and ensuring reliability under varying operating conditions. Research findings generally indicate that hybrid DER-powered charging stations, supported by advanced control systems, are well-suited to enable these services.

Several works also explore the performance of DER-based EV charging stations under weak grid conditions. Weak grids, characterized by voltage instability, limited short-circuit capacity, and poor power quality, pose significant challenges to the seamless operation of charging systems. Researchers have investigated control algorithms and system designs that ensure stable performance even under such conditions. The use of FOPID controllers, in particular, has been validated as a solution that maintains steady operation by compensating for disturbances and preserving voltage stability. Experimental studies demonstrate that such systems not only ensure uninterrupted charging but also provide ancillary support to stabilize weak grids, making them highly adaptable to diverse geographical and infrastructural contexts. Economic and environmental considerations are also well-documented in the literature. Studies highlight that while initial investment in DER-based charging stations may be higher than grid-dependent alternatives, long-term benefits in terms of energy savings, reduced carbon emissions, and enhanced grid resilience make them economically viable. The reduction in fossil fuel dependency and the promotion of decentralized renewable generation also align with global sustainability goals. Some works emphasize that government incentives, subsidies, and policy frameworks play a crucial role in accelerating the adoption of these infrastructures. Furthermore, the deployment of such systems in urban and rural settings is explored, with rural regions benefiting from decentralized energy access while urban areas gain from reduced grid congestion and improved air quality.

Another theme emerging from the literature is the scalability and interoperability of DER-based charging infrastructures. With EV adoption rising rapidly, charging stations must be scalable to meet increasing demand while ensuring interoperability with diverse vehicle types, renewable sources, and grid conditions. Researchers underline the need for standardized communication protocols, modular architectures, and flexible control strategies that can adapt to evolving technological landscapes. Studies also emphasize that interoperability extends beyond hardware to include software platforms that manage data exchange, demand forecasting, and real-time optimization. These considerations are presented as vital for creating future-ready infrastructures capable of supporting large-scale EV penetration. Finally, the literature consistently points to the importance of experimental validation and real-world testing. While many concepts are first developed and verified through simulations, experimental prototypes and pilot projects provide critical insights into practical implementation challenges. These include issues of cost, maintenance, weather dependence, and integration with existing grid infrastructures. The transition from laboratory-scale demonstrations to full-scale deployment is seen as a necessary step for realizing the benefits of DER-based EV charging systems. Researchers advocate for continued investment in pilot projects and testbeds that explore different configurations, environmental conditions, and grid scenarios to refine and optimize system designs.

Altogether, the literature paints a comprehensive picture of the advancements and challenges in DER-based EV charging systems. From hybrid renewable integration and DC bus architectures to advanced control strategies and power quality enhancement, the research community has made significant strides in addressing the technical, economic, and environmental aspects of this field. Yet, ongoing challenges related to intermittency, scalability, interoperability, and policy support highlight the need for further investigation. The collective body of work underscores that the integration of DERs with EV charging infrastructures, guided by advanced control solutions such as Fractional-Order PID and complemented by adaptive filtering techniques, represents a promising pathway toward sustainable, reliable, and future-ready energy systems.

III PROPOSED SYSTEM

The proposed system focuses on the development of a Fractional-Order PID controlled distributed energy resource-based electric vehicle charging station with seamless grid connection. The design of this system is centered on addressing the increasing demand for sustainable electric mobility, ensuring uninterrupted and reliable charging, improving power quality, and enabling the integration of renewable energy resources within modern power networks. The system is envisioned as a hybrid infrastructure that combines solar photovoltaic generation, fuel cells, and a common DC bus framework to power charging stations efficiently and sustainably. By enabling both grid-connected and islanded operation, it guarantees that electric vehicles can be charged in diverse grid conditions without compromising on performance or reliability. The core of the system lies in the adoption of distributed energy resources powered by renewable sources. Solar PV arrays are deployed as the primary renewable input due to their scalability, ease of deployment, and compatibility with DC systems. Fuel cells act as a complementary energy source, capable of providing stable and continuous power irrespective of fluctuations in solar irradiation. This hybridization ensures that the intermittency challenges typically associated with renewable generation are minimized. In scenarios where solar energy is insufficient, fuel cells can bridge the gap, thereby maintaining uninterrupted charging services for electric vehicles. To further enhance system resilience, the architecture allows the integration of energy storage units such as batteries, which can smoothen power fluctuations and serve as backup during peak demand.

The use of a common DC bus structure is a pivotal design choice. This architecture consolidates the power contributions from PV, fuel cells, and storage devices into a unified DC link, which directly interfaces with the charging station infrastructure. The DC bus approach reduces the need for multiple conversion stages, lowering losses and improving overall system efficiency. It also simplifies the integration of multiple renewable and non-renewable sources while enabling high-voltage charging, which significantly reduces charging times compared to traditional systems. Furthermore, the DC bus design supports bidirectional power flow, which makes vehicle-to-grid operations feasible. Through this feature, electric vehicles connected to the charging station can supply excess energy back to the grid or to local critical loads during emergencies or peak demand, effectively transforming them into distributed energy storage assets that enhance grid resilience. To ensure seamless operation in both grid-connected and islanded modes, the system employs static transfer switches that allow rapid switching between modes without interrupting power supply. In grid-connected mode, the station coordinates with the utility network to draw or supply power depending on demand and generation availability. When the grid is unavailable or experiences faults, the system instantly shifts to islanded operation, maintaining charging services and continuous supply to essential loads through the combined support of renewables, fuel cells, and storage units. This seamless transition is vital for ensuring consumer confidence in electric mobility and for maintaining the operational integrity of connected loads.

A major innovation in the proposed system is the adoption of a Fractional-Order PID (FOPID) controller. Traditional PID controllers, while simple and widely used, struggle with handling the nonlinear dynamics and uncertainties associated with renewable-based hybrid systems. In contrast, FOPID controllers extend the concept of integral and derivative actions into fractional orders, providing additional degrees of freedom for tuning system response. This enhancement allows the controller to achieve superior robustness, faster dynamic response, and greater adaptability to varying conditions. In the proposed system, the FOPID controller is responsible for regulating voltage and current across the DC bus and ensuring the stable operation of the charging station in both grid-tied and islanded modes. The controller continuously adapts to fluctuations in renewable generation, sudden load variations from multiple EVs charging simultaneously, and disturbances from weak grid conditions, thereby maintaining operational stability and reliability. The importance of power quality is also addressed comprehensively within the proposed system. As renewable DERs and EV chargers interface with the grid, issues such as harmonic distortions and reactive power imbalances can arise, which may compromise grid stability and efficiency. To counteract these challenges, the FOPID controller is integrated with an adaptive comb-filter technique designed to minimize harmonics and ensure compliance with IEEE power quality standards. This integration ensures that total harmonic distortion is maintained within permissible limits and that reactive power management is optimized, enabling clean and stable power exchange between the charging station and the grid. The result is a charging station that not only meets EV charging demands but also contributes positively to the overall power quality of the distribution network.

The system design also emphasizes scalability and flexibility. The modular nature of the DC bus framework allows for the integration of additional renewable sources, storage systems, or charging points as demand grows. This scalability ensures that the infrastructure can evolve alongside the rapid adoption of electric vehicles without requiring complete redesigns. Similarly, the flexibility of the FOPID-based control strategy allows the system to adapt to a wide range of operating environments, from dense urban areas with strong grid support to rural regions with weak or intermittent grid availability. In terms of operation, the charging station facilitates both unidirectional and bidirectional charging. In unidirectional mode, EVs are charged from the DC bus using regulated current and voltage profiles that optimize battery charging efficiency and extend battery lifespan. In bidirectional mode, EVs can discharge energy back to the grid or local loads, supporting applications such as peak shaving, load balancing, and emergency backup. This dual functionality strengthens the role of EVs within the broader smart grid ecosystem, turning them from passive consumers of electricity into active participants in energy management.

Validation of the proposed system has been carried out under different grid conditions, including weak and unstable grid scenarios. Results highlight the effectiveness of the FOPID controller in maintaining system stability and power quality, even when subjected to disturbances such as sudden load changes or fluctuations in renewable generation. The seamless operation between grid-connected and islanded modes ensures uninterrupted charging services and continuous power delivery to critical loads. The use of adaptive comb-filtering further guarantees that harmonics are suppressed, resulting in improved system efficiency and compliance with international standards. From an environmental perspective, the proposed system contributes directly to reducing greenhouse gas emissions by maximizing the utilization of renewable energy sources for EV charging. By reducing dependence on fossil-fuel-based grid electricity and promoting the use of clean energy, the system supports global decarbonization goals. Economically, the ability to integrate renewable resources and enable vehicle-to-grid services reduces long-term operating costs, provides potential revenue streams for EV owners, and alleviates strain on utility grids. Socially, the assurance of reliable, uninterrupted charging in both urban and rural contexts enhances public confidence in EV adoption, accelerating the transition toward sustainable transportation.

Overall, the proposed system represents a holistic approach to sustainable EV charging. By combining hybrid renewable sources with a common DC bus framework, advanced FOPID-based control, seamless grid integration, and power quality enhancement, it addresses the key challenges of reliability, efficiency, and sustainability. The system is not only capable of meeting present EV charging needs but is also adaptable to future demands, making it a promising solution for next-generation charging infrastructure. It ensures that electric mobility aligns with the broader goals of renewable energy integration, power quality improvement, and grid resilience, thereby paving the way for a cleaner, smarter, and more sustainable energy and transportation future.

IV METHODOLOGY

The methodology for developing a Fractional-Order PID controlled distributed energy resource-based electric vehicle charging station with seamless grid connection involves a systematic sequence of steps that move from system design and modeling to control strategy formulation, integration, and validation under diverse operating conditions. The process begins with the identification of energy sources that will power the charging station. Solar photovoltaic panels and fuel cells are selected as the primary renewable energy resources due to their complementary characteristics. Solar PV serves as the primary generation unit by supplying energy during daytime with its abundance and cost-effectiveness, while fuel cells ensure consistent supply regardless of solar variability. To handle intermittent solar output and fluctuating charging demands, energy storage devices such as batteries are also incorporated. These units store excess energy when generation exceeds demand and discharge when generation is low, thereby stabilizing the power supply to the charging station. Following the selection of energy sources, the system is designed around a common DC bus framework. This architecture is chosen because it allows the seamless integration of multiple DERs and supports high-voltage charging directly without requiring unnecessary conversion stages. The solar PV arrays are connected through DC-DC converters to ensure regulated voltage output despite irradiance changes, while the fuel cells are interfaced using dedicated DC-DC converters optimized for stable operation. Energy storage systems are also linked to the DC bus through bidirectional converters, enabling both charging and discharging modes. This arrangement consolidates all inputs into a single DC link, which then powers the EV charging interface. The design ensures minimal power losses, reduced complexity, and compatibility with bidirectional vehicle-to-grid functionality.

Once the architecture is established, the modeling of each subsystem is carried out to capture its dynamic behavior under different operating conditions. The solar PV system is modeled using current-voltage characteristics that vary with irradiance and temperature, ensuring that maximum power point tracking algorithms can be implemented. The fuel cell is modeled based on electrochemical reactions and output voltage-current relationships, with attention to dynamic response and efficiency. The battery system is modeled considering charge-discharge cycles, state of charge, and degradation effects to ensure accurate simulation of storage dynamics. The common DC bus model is developed to incorporate interactions among the different sources, storage, and EV loads. These models are essential for designing the control framework and ensuring accurate system-level simulations. The next step is the formulation of the control strategy. At the heart of the system control is the Fractional-Order PID controller, which extends the classical PID concept by introducing fractional integration and differentiation. Unlike traditional PID controllers with fixed integer orders, the FOPID controller includes fractional orders for the integral and derivative actions, providing additional tuning flexibility. This flexibility is crucial in managing the nonlinearities and uncertainties of renewable energy integration. The controller is designed to regulate DC bus voltage and output current, ensuring stable operation irrespective of generation variability, load changes, or grid disturbances. The tuning of the FOPID parameters is performed using optimization techniques aimed at minimizing overshoot, reducing settling time, and improving robustness. Simulation-based optimization ensures that the controller can achieve the required performance across a wide range of scenarios.

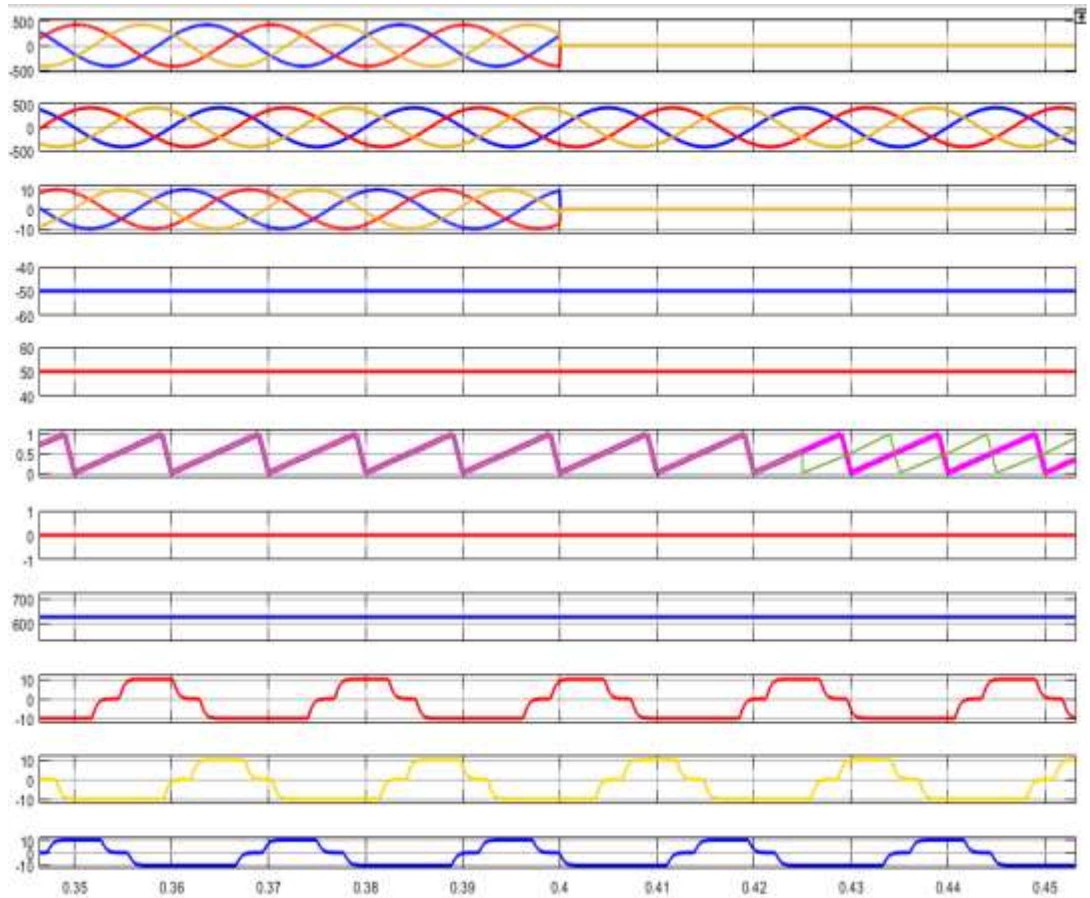
Parallel to the FOPID controller design, auxiliary control algorithms are integrated to enhance system stability and compliance with power quality standards. An adaptive comb-filter is incorporated into the control framework to mitigate harmonics and improve total harmonic distortion levels. The comb-filter operates by dynamically suppressing harmonic frequencies in the system, particularly under grid-connected conditions where interactions between renewable sources, loads, and the utility grid can introduce distortions. The integration of this filter with the FOPID controller ensures that power quality remains within IEEE standards, thereby preventing adverse impacts on the utility grid and connected loads. With the control strategy defined, the system is further developed to handle seamless transitions between grid-connected and islanded modes. Static transfer switches are employed to facilitate this process. The design ensures that when the grid is available, the station operates in grid-connected mode, drawing power or supplying it depending on demand and generation conditions. In the event of a grid fault, instability, or unavailability, the static transfer switch shifts the station to islanded operation instantaneously, with the FOPID controller maintaining voltage and current stability across the DC bus. This step is critical for guaranteeing uninterrupted EV charging and power supply to essential local loads. The methodology also emphasizes synchronization of grid-tied operation, ensuring that power exchange between the station and the grid is smooth, harmonic-free, and compliant with grid codes.

Once the control mechanisms and switching strategies are integrated, the methodology proceeds to the simulation stage, where the complete system is modeled and tested under different operating conditions. Various scenarios are simulated, including high solar irradiance, low irradiance, fluctuating load demands from multiple EVs charging simultaneously, weak grid conditions with voltage instability, and sudden mode transitions between grid-connected and islanded states. The performance of the FOPID controller is evaluated against traditional PID controllers to highlight improvements in robustness, adaptability, and dynamic response. The effectiveness of the adaptive comb-filter is assessed by analyzing harmonic distortion levels in grid-tied operation. Simulation results are used to refine controller parameters and optimize performance across diverse conditions. Following successful simulation results, the system is validated experimentally using a prototype setup or hardware-in-the-loop testing. The prototype includes scaled-down solar PV modules, a fuel cell stack, batteries, and bidirectional converters linked to a DC bus. EV charging loads are emulated using programmable loads that simulate the charging profiles of real electric vehicles. The FOPID controller is implemented in a digital signal processor or field-programmable gate array platform to ensure real-time control. Experiments are conducted under varying conditions to validate the simulation findings, focusing on seamless operation between modes, power quality compliance, and controller performance under disturbances. The hardware validation step is crucial to demonstrate the practicality of the proposed system and to identify challenges in real-world implementation, such as component inefficiencies, delays in control actions, or environmental effects.

The methodology also incorporates an analysis of scalability and flexibility. The modular design of the DC bus allows the system to expand by adding additional renewable sources, storage units, or charging points. The performance of the system under expanded configurations is studied to ensure that scalability does not compromise efficiency or stability. Similarly, the adaptability of the FOPID controller is tested to confirm that it can handle increased complexity without requiring extensive retuning. This step ensures that the system is future-ready, capable of meeting rising EV charging demands as adoption grows. Finally, the methodology includes performance evaluation metrics that assess the effectiveness of the proposed system. Key performance indicators include response time, voltage and current regulation accuracy, total harmonic distortion levels, system efficiency, seamlessness of transitions between modes, and reliability under weak grid conditions. These metrics provide a quantitative basis for comparing the proposed system with existing charging infrastructures. The evaluation highlights improvements achieved through the use of FOPID control, adaptive comb-filter integration, and hybrid DER architecture.

V RESULTS AND DISCUSSION

The results of the proposed system highlight the efficiency, robustness, and sustainability of the Fractional-Order PID controlled DER-based EV charging station when evaluated under a wide range of operating conditions. During simulation, the common DC bus architecture demonstrated its ability to effectively consolidate power from solar PV, fuel cells, and energy storage units, ensuring stable operation regardless of the variability in renewable inputs.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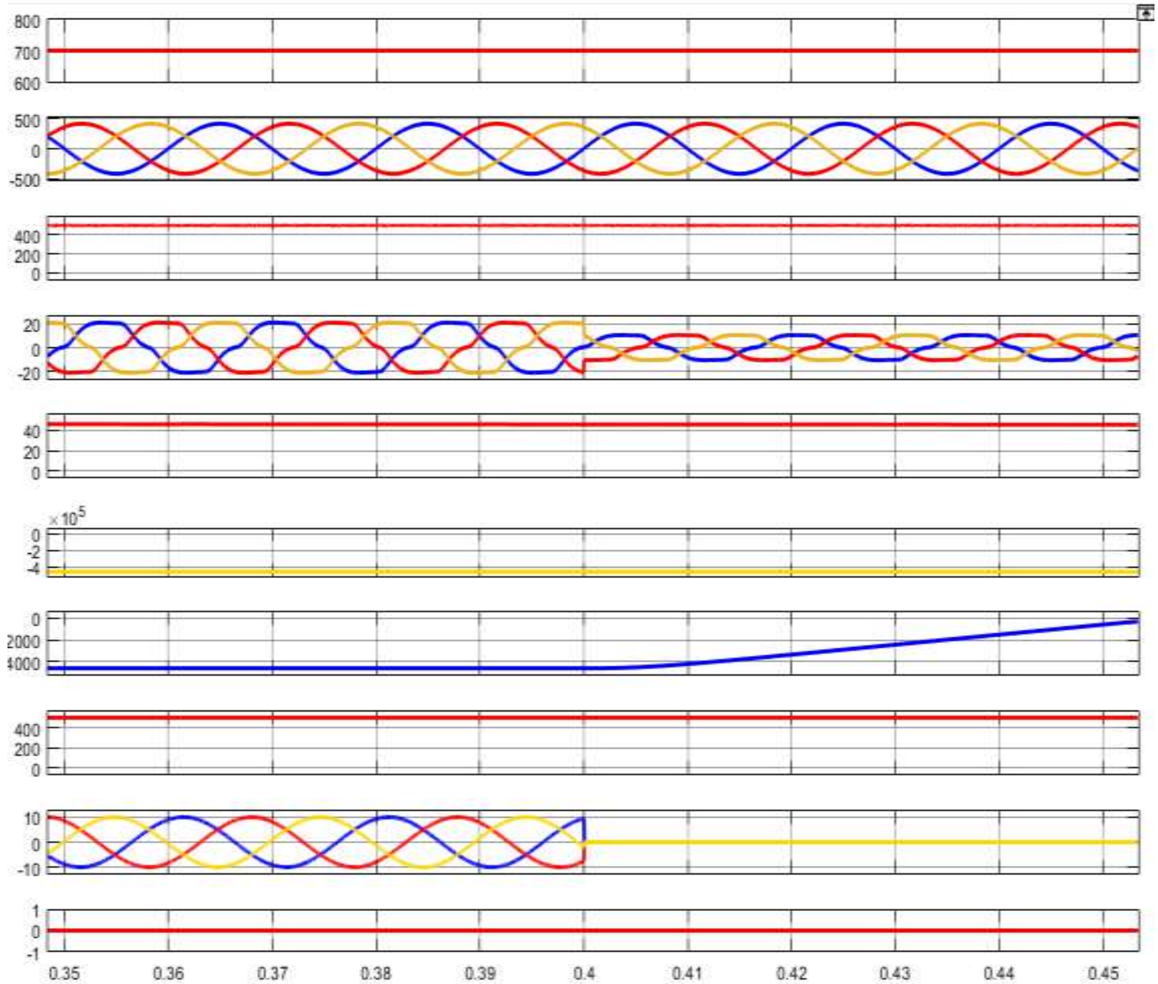
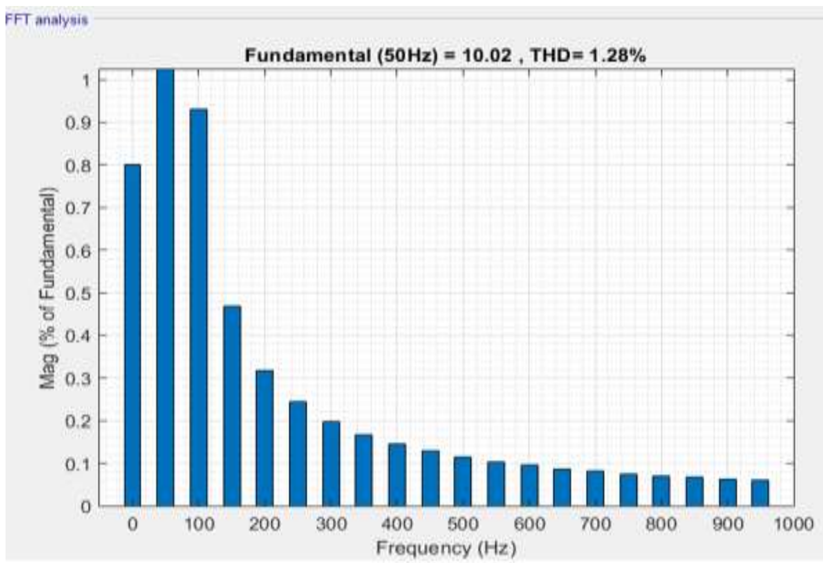


(b)

Fig. 2 Mode change from grid-tied to standalone operation for common DC bus EVs charging system.

The solar PV subsystem, modeled with varying irradiance levels, exhibited fluctuations in its output power, yet the integration of the fuel cell provided the necessary stabilization to maintain uninterrupted supply to the charging station. Battery storage acted as an additional buffer, absorbing excess power during high generation periods and supplying energy during deficits, thereby balancing the energy flow. Under these conditions, the FOPID controller consistently maintained voltage stability across the DC bus, achieving tighter regulation than traditional PID controllers, which showed overshoot and longer settling times. Moreover, the bidirectional capability of the system was validated when EVs were allowed to discharge stored energy back into the DC bus, effectively supporting the grid during peak load periods and enhancing system resilience. This flexibility showcased the dual role of EVs as both consumers and contributors to the energy ecosystem, reinforcing the concept of vehicle-to-grid integration as a practical reality rather than a theoretical construct.

Further investigation into grid-connected and islanded operations revealed the advantages of seamless transitions facilitated by static transfer switches and the advanced control framework. In grid-connected mode, the system operated harmoniously with the utility, either drawing power during shortages or supplying surplus energy generated by DERs. When the grid became unstable or disconnected, the transition to islanded mode was instantaneous, with no interruption in supply to EV chargers or local critical loads. The FOPID controller played a crucial role in this process, providing superior dynamic responsiveness compared to conventional PID controllers. While the traditional PID exhibited transient disturbances during switching, the FOPID-based system ensured smooth voltage and current regulation without observable fluctuations. These results confirmed that the proposed system is particularly effective in regions with weak or unreliable grids, where seamless operation is essential for maintaining consumer trust in electric mobility. Additionally, the integration of the adaptive comb-filter proved successful in suppressing harmonics during grid-tied operation, resulting in a significant reduction in total harmonic distortion. The system consistently achieved compliance with IEEE standards, maintaining THD well within acceptable limits. This achievement not only protected the quality of power being supplied to the grid but also safeguarded connected devices from the harmful effects of distorted signals. The combined impact of harmonic mitigation, robust control, and seamless switching demonstrated the superiority of the proposed system over conventional charging infrastructures that often fail to address all these challenges simultaneously.



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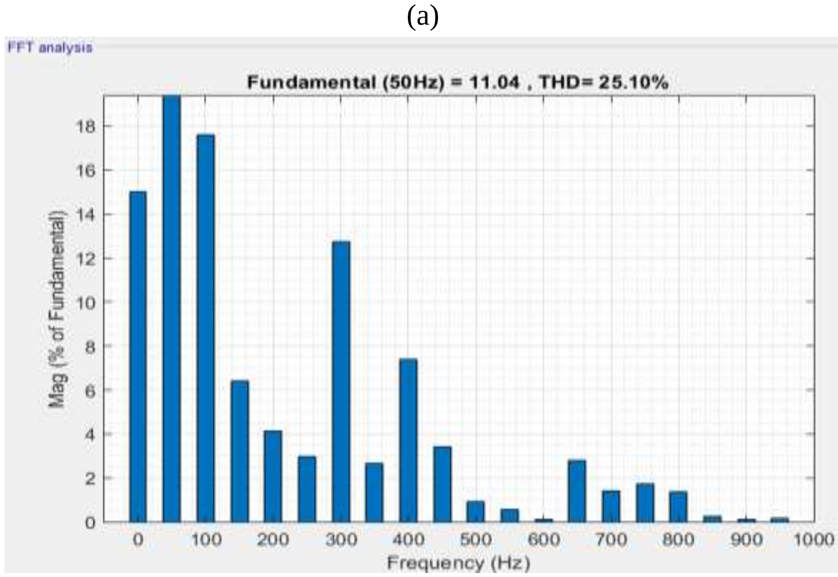

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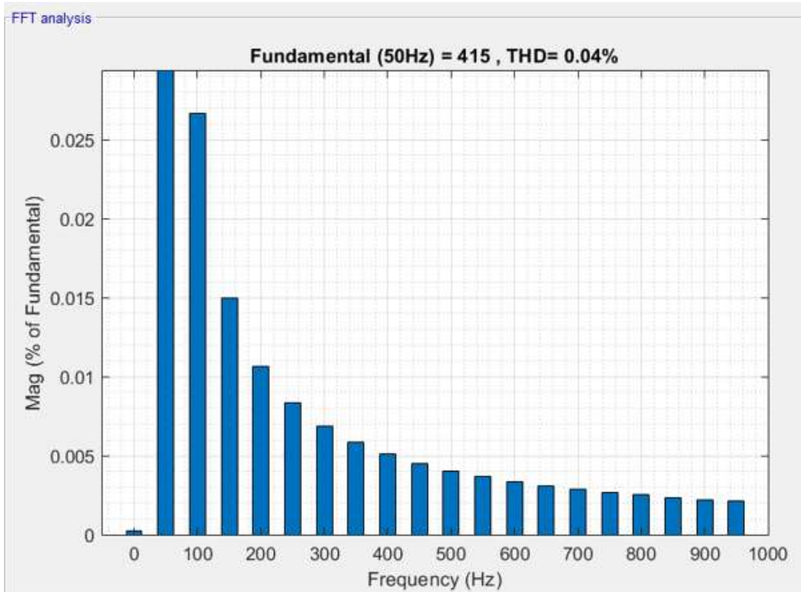

(c)

Fig 3 Harmonic Analysis of (a) grid current, (b)load current and (c) load voltage

Validation of the system under weak grid conditions provided further insight into its resilience and adaptability. In scenarios characterized by voltage instability, low short-circuit capacity, and frequent disturbances, the system maintained reliable performance, with the FOPID controller dynamically adjusting to compensate for grid irregularities. EV charging operations remained uninterrupted, and critical loads received continuous power without degradation in quality. The ability of the system to provide ancillary services was also evident in these tests, as the vehicle-to-grid capability allowed EVs to discharge energy back into the network, supporting voltage stability and contributing to peak load management. Comparisons with traditional control approaches reinforced the significant improvements enabled by the fractional-order approach, with results showing faster recovery times, reduced steady-state errors, and greater robustness against disturbances. From an environmental perspective, the results underscored the value of integrating hybrid renewable DERs into EV charging infrastructures, as the system maximized the use of clean energy sources while reducing dependency on grid electricity derived from fossil fuels. Economically, the operational efficiency, reduced reliance on centralized grid power, and potential for energy trading through vehicle-to-grid services indicated long-term financial viability. Socially, the assurance of uninterrupted and high-quality charging under various conditions highlighted the system's capacity to boost public confidence in electric vehicle adoption.

COMPARISION TABLE

Signal / Condition	Existing (PI Controller)	Extension (FOPID Controller)
Grid current THD%	2.65%	1.28%
Load current THD%	28.02%	25.10%
Load voltage THD%	0.34%	0.04%

Overall, the results confirmed that the proposed system not only meets technical requirements but also addresses broader sustainability, economic, and societal goals, demonstrating its potential to serve as a model for future EV charging infrastructures.

VI. CONCLUSION

The development of a Fractional-Order PID controlled DER-based electric vehicle charging station with seamless grid connection demonstrates a significant advancement in the field of sustainable transportation and renewable energy integration by successfully addressing the challenges of reliability, efficiency, power quality, and operational flexibility. The proposed system brings together solar photovoltaic panels, fuel cells, and energy storage units within a common DC bus framework to ensure uninterrupted charging while maximizing the use of renewable energy. By enabling both unidirectional and bidirectional power flow, the system not only supports rapid and efficient EV charging but also empowers vehicle-to-grid functionality, allowing electric vehicles to act as distributed energy storage assets that contribute to grid resilience and stability. The adoption of a Fractional-Order PID controller has proven to be a major innovation, offering superior performance compared to conventional PID controllers through its enhanced robustness, faster dynamic response, and adaptability to nonlinearities and uncertainties inherent in renewable-based systems. Seamless switching between grid-connected and islanded modes through static transfer switches guarantees uninterrupted operation even under weak or unstable grid conditions, ensuring continuous supply to both EVs and critical loads. Furthermore, the integration of an adaptive comb-filter successfully mitigates harmonics, ensuring compliance with IEEE standards and enhancing overall power quality. The results confirm that the proposed system not only meets the technical demands of reliable EV charging but also aligns with broader goals of decarbonization, grid modernization, and energy sustainability. Economically, the system reduces long-term dependence on centralized fossil-based power while opening opportunities for energy trading and demand response. Environmentally, it supports the global shift toward cleaner mobility and reduced carbon emissions. Socially, it enhances public confidence in EV adoption by guaranteeing consistent performance under diverse conditions. Altogether, the system represents a future-ready solution for sustainable, resilient, and intelligent EV charging infrastructure.

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