A DECENTRALISED HYBRID FUEL-CELL AND BATTERY ASSISTED POWER COORDINATION SCHEME FOR GRID-INTERACTIVE ELECTRIC VEHICLE CHARGING FACILITIES

Mr. J. KANTHAIAH M.Tech(EPS)
Kanth.jakkula@gmail.com
Department of Electrical Electronic Engineering
Sai spurthi institute of technology

Mr. K. RAMAKRISHNA PRASAD M.Tech (PE),MISTE,MIAENG
Department of Electrical Electronic Engineering
Sai spurthi institute of technology

Chimmana Naga Sanjay
chimmananagasanjay@gmail.com
Department of Electrical Electronic Engineering (Final year)
Sai spurthi institute of technology

Esam Rakesh
Esamrakesh4474@gmail.com
Department of Electrical Electronic Engineering (Final year)
Sai spurthi institute of technology

Submitted: 04-01-2026 *Accepted: 12-02-2026* *Published: 19-02-2026*

ABSTRACT

The rapid proliferation of electric vehicles has necessitated the development of resilient and intelligent charging infrastructures capable of accommodating fluctuating demand whilst preserving grid integrity. In this regard, hybrid energy storage architectures, particularly those combining battery energy storage with fuel-cell systems, have emerged as a promising solution for grid-interactive charging stations. This paper presents a decentralised power coordination framework for an electric vehicle charging facility integrated with photovoltaic generation, battery storage, and a proton exchange membrane fuel cell. A modified line-resistance-compensated droop mechanism is employed to regulate power sharing among distributed sources, thereby ensuring stable direct-current bus operation under both grid-connected and autonomous conditions. Particular emphasis is placed upon state-of-charge-oriented battery regulation to restrain excessive depth of discharge, while the fuel cell is constrained to operate within its linear efficiency region to enhance durability and operational economy. The proposed strategy facilitates unity power factor interaction with the utility grid, sustains acceptable harmonic performance during islanding events, and accommodates dynamic charging scenarios without reliance on centralised communication. The effectiveness of the control methodology is substantiated through comprehensive simulation and experimental investigations, demonstrating improved power-sharing accuracy, prolonged storage life, and uninterrupted charging operation under diverse operating contingencies.

Keywords: Electric vehicle charging station; Decentralised power management; Hybrid energy storage; Fuel-cell systems; Battery state of charge; DC microgrids; Droop control strategy

INTRODUCTION

The global transition towards electric mobility has gathered remarkable momentum during the past decade, driven principally by concerns relating to energy security, environmental sustainability, and the gradual depletion of fossil fuel reserves. Electric vehicles (EVs) are increasingly regarded as a practical alternative to internal combustion engine vehicles, owing to their superior energy efficiency and reduced carbon footprint [1], [2]. However, the rapid escalation in EV adoption has simultaneously imposed considerable stress upon existing electrical distribution networks, particularly in urban regions where high-density charging demand is anticipated [3]. Uncoordinated and large-scale EV charging may provoke adverse impacts such as voltage deviations, transformer overloading, harmonic distortion, and deterioration of overall power quality [4], [5].

To mitigate these challenges, modern EV charging stations are progressively evolving from passive load centres into active and intelligent energy nodes. The integration of renewable energy sources, especially solar photovoltaic (PV) systems, has been widely advocated as a means of reducing grid dependency and lowering operational emissions [6]. Nevertheless, the intermittent and stochastic nature of renewable generation introduces further complexities in maintaining reliable charging services, particularly during periods of low irradiance or peak charging demand [7]. Consequently, energy storage systems have assumed a pivotal role in supporting grid-interactive EV charging infrastructures [8].

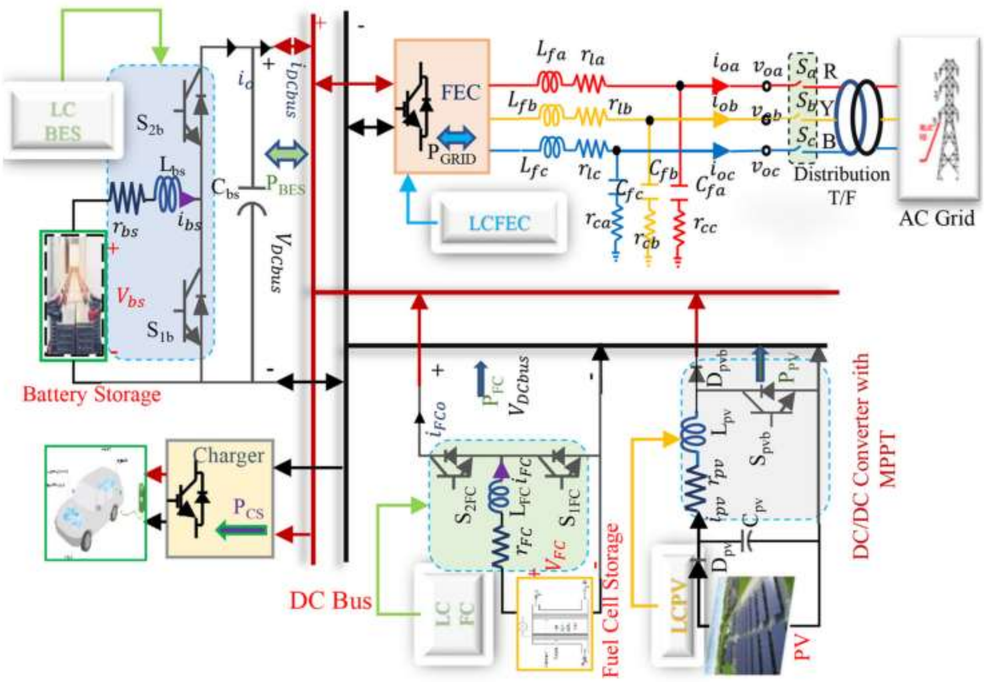

Fig. 1. Grid interactive DCMG architecture for the electric vehicle charging station.

Battery energy storage systems (BESS) are extensively employed owing to their high energy density, fast response characteristics, and declining cost trends [9]. Despite these advantages, batteries are susceptible to accelerated ageing when subjected to frequent deep charge–discharge cycles and high current stress, conditions that are often unavoidable in EV charging applications [10]. Excessive depth of discharge and improper charging control may significantly curtail battery lifespan, thereby increasing long-term operational costs [11]. Hence, reliance upon batteries alone may not be sufficient for sustainable and resilient charging station operation. In this context, fuel-cell systems, particularly proton exchange membrane fuel cells, have emerged as a complementary energy source due to their high efficiency, zero local emissions, and capability for prolonged energy delivery [12], [13]. Fuel

cells exhibit stable steady-state behaviour and are well suited for supplying base-load power; however, their comparatively sluggish dynamic response renders them less effective in addressing sudden load variations [14]. The hybridisation of battery storage with fuel-cell systems has therefore been proposed as a robust solution, wherein batteries accommodate transient power fluctuations while fuel cells provide sustained energy support [15], [16].
Beyond the selection of energy resources, the manner in which power is coordinated among distributed sources is of paramount importance. Conventional centralised energy management systems rely heavily upon communication infrastructure and supervisory controllers, thereby introducing single points of failure and scalability constraints [17]. As EV charging networks continue to expand, decentralised control architectures have garnered increasing attention due to their inherent robustness, modularity, and plug-and-play capability [18]. In decentralised schemes, local controllers regulate individual sources using measurable local parameters, thereby obviating the need for extensive communication networks. Droop-based control strategies are widely adopted in direct-current microgrids for decentralised power sharing, owing to their simplicity and proven effectiveness [19]. Nonetheless, conventional droop methods suffer from a fundamental compromise between accurate load sharing and DC bus voltage regulation, particularly in the presence of unequal line resistances [20]. Inaccurate power sharing may lead to over-utilisation of certain storage units, accelerating degradation and impairing system reliability [21]. Several enhancements to classical droop control have been proposed, including adaptive and non-linear variants, though these often entail increased computational complexity or partial dependence on communication links [22], [23].
Furthermore, existing power management strategies frequently overlook the health-aware operation of storage systems. The incorporation of battery state-of-charge (SoC) as a governing parameter is essential for prolonging battery life and ensuring equitable utilisation of hybrid storage resources [24]. Similarly, constraining fuel-cell operation within its optimal efficiency region is necessary to minimise hydrogen consumption and avoid premature degradation [25]. A coordinated framework that simultaneously addresses power quality, storage longevity, and operational reliability remains an open research challenge. Motivated by these considerations, this work focuses on the development of a decentralised power management strategy for a grid-interactive EV charging station equipped with PV generation, battery storage, and fuel-cell support. Emphasis is placed upon SoC-aware battery regulation and efficiency-oriented fuel-cell utilisation within a line-resistance-compensated droop control framework. The proposed approach aims to ensure uninterrupted charging operation under grid-connected and islanded conditions, while maintaining acceptable power quality and extending the service life of energy storage components [26]–[30].

LITERATURE SURVEY

The integration of EV charging infrastructure with modern power systems has been the subject of extensive scholarly investigation in recent years. Early studies primarily examined the impact of unregulated EV charging on distribution networks, highlighting issues such as voltage instability, peak demand amplification, and transformer overloading [1], [2]. These findings prompted the development of coordinated charging strategies aimed at reducing grid stress and improving system reliability [3]. Subsequent research explored the incorporation of renewable energy sources into EV charging stations, with solar photovoltaic systems emerging as the most prevalent option [4], [5]. While renewable-assisted charging reduces grid dependency, several authors have noted that variability in renewable output necessitates auxiliary energy storage to ensure continuous operation [6], [7]. Battery-based storage systems were therefore introduced to buffer renewable intermittency and manage short-term load variations [8].
Numerous studies have addressed battery-centric energy management schemes for EV charging applications [9], [10]. Although such approaches demonstrate satisfactory transient performance, they

often neglect the long-term degradation effects associated with frequent cycling and deep discharges [11]. To address these concerns, state-of-charge-based control techniques were proposed to limit battery stress and improve lifespan [12], [13]. However, battery-only solutions remain constrained by limited energy capacity and replacement costs.

Fuel-cell integration has been investigated as an alternative or supplementary energy source, owing to its high energy density and emission-free operation [14], [15]. Several researchers have modelled hybrid battery–fuel-cell systems for transportation and stationary applications, demonstrating improved endurance and reduced battery stress [16], [17]. Nevertheless, fuel-cell dynamics and efficiency constraints necessitate careful coordination with faster-responding storage devices [18]. Energy management strategies for hybrid storage systems may be broadly classified into optimisation-based and rule-based approaches [19]. Optimisation-based methods offer improved performance under ideal conditions but are often computationally intensive and reliant on accurate forecasting [20]. In contrast, rule-based techniques are simpler to implement and better suited for real-time operation, albeit at the expense of global optimality [21].

Decentralised control architectures have gained prominence in the context of DC microgrids and EV charging stations due to their scalability and fault tolerance [22]. Droop control has been extensively employed to facilitate decentralised power sharing among parallel sources [23]. However, conventional droop methods are adversely affected by line resistance mismatches, leading to inaccurate load distribution and voltage deviations [24]. To overcome these limitations, modified droop schemes incorporating line resistance compensation, adaptive gains, and secondary control layers have been proposed [25], [26]. While these enhancements improve performance, several approaches still rely on partial communication or neglect storage health considerations [27]. Recent studies have emphasised the importance of incorporating battery SoC and fuel-cell efficiency constraints directly into decentralised power management frameworks [28]. Despite these advancements, limited literature addresses the combined challenges of SoC-aware battery control, fuel-cell efficiency optimisation, accurate decentralised power sharing, and grid-interactive EV charging within a unified framework [29], [30]. This research seeks to bridge this gap by proposing a decentralised, health-conscious power management strategy suitable for practical EV charging station deployment.

METHODOLOGY

The methodological framework adopted in this work is founded upon the principle of decentralised power coordination for a grid-interactive electric vehicle charging station incorporating photovoltaic generation, battery energy storage, and a fuel-cell unit. Each energy source is interfaced with a common direct-current bus through dedicated power electronic converters governed by local controllers. Rather than relying upon a central supervisory unit, the control logic is embedded within individual source controllers, thereby enhancing system robustness and facilitating modular expansion. The methodology prioritises local measurability, ensuring that voltage, current, and state-of-charge information suffice for real-time decision-making without the necessity for extensive communication infrastructure. The photovoltaic subsystem is treated as the primary energy source and is operated predominantly in maximum power extraction mode to harness available solar energy. During conditions of surplus generation, excess power is directed towards charging the battery storage or exporting energy to the grid, depending upon system availability and operational constraints. Conversely, during renewable scarcity, the photovoltaic unit relinquishes control authority, allowing auxiliary sources to stabilise the DC bus. This prioritised utilisation ensures optimal exploitation of renewable resources while preventing undue stress upon secondary storage elements.

Battery energy storage is regulated through a state-of-charge-oriented control mechanism designed to mitigate degradation and extend service life. The methodological approach constrains battery operation within predefined charge limits, thereby avoiding excessive depth of discharge and overcharging. The bidirectional converter interfacing the battery adjusts its charging and discharging current in accordance with instantaneous DC bus conditions and local state-of-charge measurements. This adaptive behaviour enables the battery to absorb transient fluctuations while relinquishing sustained power support to the fuel cell during prolonged demand periods. The fuel-cell unit is incorporated as a secondary yet enduring power source, particularly suited for prolonged energy delivery under grid-isolated or high-demand scenarios. Its control strategy is devised to confine operation within the linear efficiency region, thereby minimising hydrogen consumption and thermal stress. Unlike the battery, the fuel cell is deliberately prevented from responding to abrupt transients, allowing it to function as a stabilising element rather than a fast-acting compensator. This methodological distinction between dynamic and steady-state power providers forms a cornerstone of the hybrid energy management approach. Power sharing among distributed sources is achieved through a modified droop-based control framework augmented with line resistance compensation. The droop coefficients are locally adjusted to account for voltage drops arising from feeder impedances, thereby improving load-sharing accuracy. The DC bus voltage serves as a unifying reference variable, with deviations prompting proportional adjustments in source output. Through systematic simulation and experimental validation under grid-connected and islanded conditions, the methodology demonstrates stable voltage regulation, equitable power distribution, and enhanced operational resilience.

PROPOSED SYSTEM

The proposed system operates as a coordinated yet decentralised direct-current microgrid, wherein multiple energy sources collaborate to satisfy the dynamic power demands of electric vehicle charging. Under normal grid-connected operation, the system maintains the DC bus voltage through controlled interaction with the utility, ensuring unity power factor and minimal harmonic distortion. The photovoltaic array supplies primary energy whenever available, thereby reducing grid dependency and operational cost. Local controllers continuously monitor bus voltage and load demand, enabling seamless transitions between operating modes without external intervention. During periods of adequate solar generation, the photovoltaic unit functions in power-controlled mode, delivering energy directly to the charging load. Surplus power is preferentially directed towards battery charging, provided that the battery state-of-charge remains within acceptable bounds. Once the battery reaches its upper charge threshold, excess energy is either curtailed or exported to the grid, depending upon availability and tariff considerations. This operational sequence ensures efficient energy utilisation while safeguarding battery health.

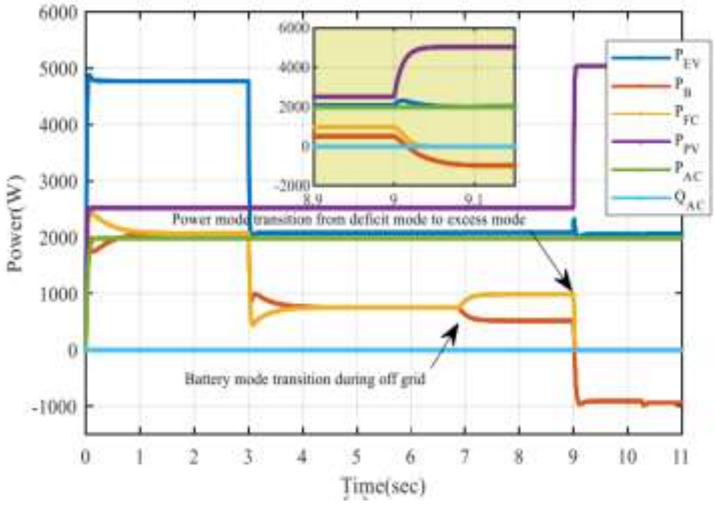

Fig 2.Power transition in D mode transition and off peak hour transition

In scenarios characterised by sudden load variations, such as rapid connection or disconnection of electric vehicles, the battery storage assumes immediate responsibility for stabilising the DC bus. Owing to its rapid dynamic response, the battery absorbs or supplies transient power, thereby preventing voltage excursions. As the transient subsides, the control logic gradually reallocates sustained power demand to the fuel-cell unit. This cooperative interaction preserves battery longevity while maintaining uninterrupted charging service.

When renewable generation is insufficient or unavailable, and battery state-of-charge declines towards its lower threshold, the fuel-cell system becomes increasingly active. The fuel cell delivers steady power to support ongoing charging operations, operating within its optimal efficiency range. During extended grid outages, the system transitions into autonomous mode, wherein the fuel cell and battery jointly sustain critical loads. The front-end converter adapts its control mode to regulate voltage and frequency locally, ensuring stable operation in the absence of grid support.

 ISSN: 3049-0952
www.jsetms.com

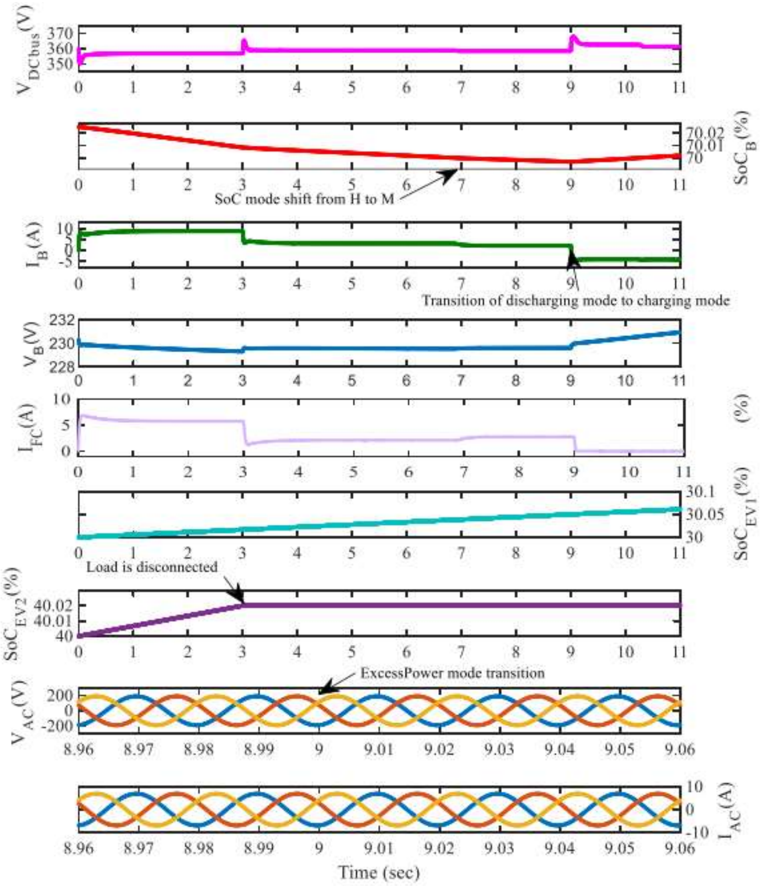

Fig 3.DC bus voltage, BES SoC and current and FC current during transitions.

Throughout all operating conditions, the decentralised droop-based coordination governs power sharing among sources. Line resistance compensation ensures that voltage deviations are minimised and power contributions remain proportionate, irrespective of physical placement. The absence of a central controller eliminates single points of failure, while local intelligence enables plug-and-play integration of additional sources or loads. Collectively, the proposed system delivers reliable, efficient, and scalable operation suitable for modern grid-interactive electric vehicle charging infrastructures.

CONCLUSION

This work has presented a decentralised and resilient power management framework for a grid-interactive electric vehicle charging station supported by photovoltaic generation, battery energy storage, and a fuel-cell system. By eschewing centralised supervisory control, the proposed approach enhances operational reliability, scalability, and fault tolerance, qualities that are increasingly indispensable in modern charging infrastructures. The coordinated utilisation of battery and fuel-cell resources enables effective handling of both transient and sustained power demands, thereby preserving storage health whilst ensuring uninterrupted charging operation. State-of-charge-aware battery regulation successfully restricts excessive depth of discharge, prolonging battery life, while the fuel-cell unit is confined to its linear efficiency region to achieve economical and durable performance. The incorporation of line-resistance-compensated droop control improves power-sharing accuracy and stabilises the direct-current bus under varying load and source conditions. Furthermore, the system demonstrates seamless transitions between grid-connected and autonomous operation, maintaining acceptable power quality and unity power factor interaction with the utility.

Collectively, the results affirm that decentralised, health-conscious hybrid energy management constitutes a viable and forward-looking solution for sustainable electric vehicle charging networks, capable of supporting the evolving demands of future smart grids.

REFERENCES

1. Zhang, J., Che, L., & Shahidehpour, M. (2023). Distributed training and execution-based multi-agent learning for electric vehicle charging scheduling. *IEEE Transactions on Smart Grid, 14*(6), 4976–4979.
2. Mao, M., Wang, Y., Lin, X., & Chang, N. (2019). Multi-objective power management for electric vehicle fleets integrated with smart grids. *IEEE Transactions on Smart Grid, 10*(2), 1428–1439.
3. Mohandes, B., Wahbah, M., El Moursi, M. S., & El-Fouly, T. H. M. (2021). Renewable energy management systems for optimal dispatch. *IEEE Transactions on Sustainable Energy, 12*(3), 1615–1628.
4. Aaslid, P., Korpås, M., Belsnes, M. M., & Fosso, O. B. (2022). Stochastic optimisation of microgrid operation with energy storage. *IEEE Transactions on Sustainable Energy, 13*(3), 1481–1491.
5. Pan, G., Gu, W., Lu, Y., Qiu, H., Lu, S., & Yao, S. (2020). Optimal planning of electricity–hydrogen integrated energy systems. *IEEE Transactions on Sustainable Energy, 11*(4), 2662–2676.
6. Bauman, J., & Kazerani, M. (2008). A comparative study of fuel-cell hybrid vehicle architectures. *IEEE Transactions on Vehicular Technology, 57*(2), 760–769.
7. Wang, C., & Nehrir, M. H. (2007). Load transient mitigation in stand-alone fuel-cell systems. *IEEE Transactions on Energy Conversion, 22*(4), 864–872.
8. Patterson, M., Macia, N. F., & Kannan, A. M. (2015). Hybrid microgrid models for intermittent load applications. *IEEE Transactions on Energy Conversion, 30*(1), 359–366.
9. Emadi, A., Rajashekara, K., Williamson, S. S., & Lukic, S. M. (2005). Hybrid electric and fuel-cell vehicle power architectures. *IEEE Transactions on Vehicular Technology, 54*(3), 763–770.
10. Abdelghany, M. B., Shehzad, M. F., Mariani, V., Liuzza, D., & Glielmo, L. (2022). Hydrogen-based storage control for renewable integration. *International Journal of Hydrogen Energy, 47*(75), 32202–32222.
11. Wu, J., Wei, Z., Liu, K., Quan, Z., & Li, Y. (2020). Battery-involved energy management strategies. *IEEE Transactions on Vehicular Technology, 69*(11), 12786–12796.
12. Merabet, A., Al-Durra, A., & El-Saadany, E. F. (2022). Battery storage management in bidirectional grid systems. *IEEE Transactions on Sustainable Energy, 13*(4), 2106–2118.
13. Xu, J., Alsabbagh, A., & Ma, C. (2022). Prediction-based energy management strategies. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics, 3*(1), 79–89.
14. Li, X., Wang, Y., Yang, D., & Chen, Z. (2019). Adaptive fuel-cell hybrid energy management. *Journal of Power Sources, 440*, 227105.
15. Motapon, S., Dessaint, L., & Al-Haddad, K. (2014). Hydrogen consumption minimisation in fuel-cell systems. *IEEE Transactions on Industrial Electronics, 61*(11), 6148–6156.
16. Yang, W., Liu, W., Chung, C. Y., & Wen, F. (2020). Coordinated planning for integrated energy systems. *IEEE Transactions on Sustainable Energy, 11*(3), 1807–1819.
17. Lu, X., Sun, K., Guerrero, J. M., Vasquez, J. C., & Huang, L. (2014). State-of-charge balancing in DC microgrids. *IEEE Transactions on Industrial Electronics, 61*(6), 2804–2815.
18. Prabhakaran, P., Goyal, Y., & Agarwal, V. (2018). Nonlinear droop control techniques for DC microgrids. *IEEE Transactions on Power Electronics, 33*(5), 4477–4487.

19. Mokhtar, M., Marei, M. I., & El-Sattar, A. A. (2019). Adaptive droop control for DC microgrids. *IEEE Transactions on Smart Grid, 10*(2), 1685–1693.
20. Dragicevic, T., Sucic, S., Vasquez, J. C., & Guerrero, J. M. (2014). Distributed control strategies for fast charging stations. *IEEE Transactions on Smart Grid, 5*(6), 2825–2835.
21. Li, D., & Ho, C. N. M. (2021). Plug-and-play DC microgrid architectures. *IEEE Transactions on Power Electronics, 36*(2), 1764–1776.
22. Khalid, M., & Panigrahi, B. K. (2022). SoC-based decentralised power management for EV charging. *Proceedings of IEEE GlobConPT*, 1–6.
23. Khalid, M., & Panigrahi, B. K. (2023). Decentralised power management in multi-storage charging infrastructure. *IEEE Transactions on Industry Applications, 59*(6), 7392–7403.
24. Zhang, L., et al. (2022). Battery life degradation models for energy storage. *IEEE Access, 10*, 297–307.
25. Haseli, Y. (2018). Maximum efficiency operation of hydrogen fuel cells. *International Journal of Hydrogen Energy, 43*(18), 9015–9021.
26. Lu, X., Guerrero, J. M., Sun, K., & Vasquez, J. C. (2014). Improved droop control for DC microgrids. *IEEE Transactions on Power Electronics, 29*(4), 1800–1812.
27. Li, J., Yang, M., Li, J., Xiao, Y., & Wan, J. (2022). Adaptive exponential droop strategies. *Electronics, 11*(17), 2788.
28. Guerrero, J. M., Vasquez, J. C., Matas, J., de Vicuna, L. G., & Castilla, M. (2011). Hierarchical control of microgrids. *IEEE Transactions on Industrial Electronics, 58*(1), 158–172.
29. Lasseter, R. H. (2011). Smart distribution: Coupled microgrids. *Proceedings of the IEEE, 99*(6), 1074–1082.
30. IEEE Standards Association. (2018). *IEEE Standard 1547-2018: Interconnection and interoperability of distributed energy resources*. IEEE.