Artificial Intelligence-Based MPPT and Energy Management for Solar-Battery EV Charging Stations: Literature Review and Research Gaps

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Abstract: The increasing adoption of electric vehicles (EVs) has created a need for efficient, reliable, and renewable-energy-based charging infrastructure. Solar photovoltaic (PV) generation can reduce the dependence of EV charging stations on utility-grid power; but, variations in solar irradiation and temperature continuously affect PV operating conditions. For that reason, efficient maximum power point tracking (MPPT) is essential for extracting available solar power. Conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) may experience oscillations, slower response, and reduced performance under rapidly changing and partially shaded conditions. Intelligent optimization algorithms, including Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), Whale Optimization Algorithm (WOA), and Ant Lion Optimization (ALO), offer potential for improved PV power extraction. Effective EV charging also requires coordination among PV generation, battery state of charge (SOC), EV charging demand, and grid power. This paper formulates an integrated research problem combining intelligent MPPT with energy management for a solar-battery-powered EV charging station. A focused literature review is presented, and key research gaps are identified, particularly the limited integration of intelligent MPPT with EMS and the limited direct comparison of PSO, GWO, WOA, and ALO under identical operating conditions. These gaps establish the basis for developing a unified AI-based MPPT and energy management framework.

Keywords: AI, MPPT, Solar PV, GWO

1.Introduction

The rapid growth of electric vehicles has increased the demand for efficient and sustainable charging infrastructure. Integrating solar photovoltaic (PV) generation with EV charging stations can reduce dependence on utility-grid electricity and increase the use of renewable energy. PV-battery-EV systems are particularly attractive because battery storage can absorb excess solar energy and supply the charging load when PV generation is insufficient [1]–[4]. The main challenge on the PV side is the continuous variation of the maximum power point caused by changes in solar irradiation and temperature. Conventional MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used, but they can produce oscillations around the maximum power point and may have slower tracking under rapidly changing conditions [5], [6]. Recent studies have therefore investigated intelligent and metaheuristic algorithms such as PSO, GWO, WOA, and ALO for PV maximum power extraction [7]–[15]. Efficient MPPT, however, is only one part of the charging-station problem. The generated PV power must be coordinated with battery charging/discharging, EV

charging demand, and utility-grid power. Several energy management strategies have been developed for PV-battery-EV systems using optimization, model predictive control, and artificial intelligence techniques [1]–[4], [16]–[20]. Nevertheless, the MPPT stage and the EMS are often investigated separately. Therefore, this research focuses on the formulation of a unified framework in which intelligent MPPT provides optimized PV power to an energy management system that coordinates the battery, EV charging load, and utility grid.

2. Problem Statement

The problem is to develop an integrated intelligent MPPT and energy management framework for a solar-battery-powered EV charging station that can efficiently extract maximum power from PV generation while coordinating battery SOC, EV charging demand, and grid power under varying solar irradiation, temperature, and charging conditions.

3. Literature Review

The integration of renewable energy with electric vehicle (EV) charging infrastructure has attracted significant research attention because solar photovoltaic (PV) generation can reduce dependence on utility-grid power. In PV-battery-EV systems, the battery can store excess solar energy during periods of high PV generation and support EV charging when solar generation is insufficient. Engelhardt et al. [1] investigated energy management for renewable-based high-power EV charging using a multi-battery system and considered renewable generation, battery storage, EV charging, and grid interaction. Cheikh-Mohamad et al. [2] developed a real-time optimization-based power management strategy for a PV-powered EV charging station incorporating PV generation, stationary storage, EV batteries, and grid connection. Saleem et al. [3] further considered uncertainties in solar generation and EV demand using stochastic model predictive control. Vanlalchhuanawmi et al. [4] reviewed energy management strategies for systems integrating EVs and battery energy storage and emphasized the importance of coordinated operation of distributed energy resources, storage, and EV charging. Efficient extraction of available PV power requires an appropriate maximum power point tracking (MPPT) technique. Conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used because of their relatively simple implementation. Esram and Chapman [6] compared different PV MPPT techniques, while Sera et al. [5] analyzed the characteristics of P&O and INC methods. Although these techniques are effective under relatively stable conditions, their performance can be affected by rapidly changing irradiation and partial shading, and oscillations around the maximum power point can reduce the extracted energy. Consequently, intelligent and metaheuristic optimization methods have been increasingly investigated for PV MPPT. Guo and Abdul [8] proposed a fuzzy-adaptive Particle Swarm Optimization (PSO)-based MPPT technique for PV systems under partial shading. Del Rio et al. [9] demonstrated the practical application of PSO-based MPPT on a real-time PV system. Grey Wolf Optimization (GWO) has also been investigated for global MPPT, with Motamarri et al. [10] developing a modified GWO technique for partial-shading conditions. Jha and Sharma [11] evaluated GWO-based MPPT under complex operating conditions. Whale Optimization Algorithm (WOA) has similarly been applied to PV MPPT; Yuan et al. [13] investigated a hybrid WOA-P&O approach, while Zemmit et al. [12] studied variable-step GWO and WOA algorithms for PV output power optimization.

Ant Lion Optimization (ALO) is another population-based optimization technique that has been applied to PV maximum power extraction. An ALO-based MPPT approach has been investigated for partially shaded PV arrays [14]. Of particular relevance to the present study, Sreedevi and Geetha [15]

combined ALO, artificial neural networks, MPPT, a high-gain converter, and EV charging, demonstrating the potential of intelligent optimization for PV-powered EV applications. These studies indicate that PSO, GWO, WOA, and ALO are promising alternatives for improving PV power extraction. However, their performance is generally evaluated using different PV configurations, operating conditions, and performance measures, making direct comparison difficult. In parallel with MPPT development, several studies have focused on energy management of PV-battery-EV systems. Raghuveer et al. [16] investigated energy management for a workplace PV-EV charging station while considering power dispatch, transformer aging, and uncertainties. AI-based approaches have also been explored for e-mobility energy management. Yan et al. [17] reviewed AI algorithms for energy management in e-mobility services, while Hua et al. [18] investigated multi-agent deep reinforcement learning for EV energy management. More recent work has considered online energy management, bidirectional EV charging, battery aging, and PV generation [19]. These studies demonstrate the importance of intelligent coordination among PV generation, battery SOC, EV charging demand, and grid power. Overall, the literature confirms significant progress in both intelligent MPPT and energy management. However, these two functions are often investigated separately. The influence of MPPT performance on subsequent energy management is not sufficiently addressed, and a systematic comparison of PSO, GWO, WOA, and ALO under identical PV, converter, battery, and EV charging conditions remains limited. This provides the motivation for developing an integrated intelligent MPPT and EMS framework for solar-battery-powered EV charging stations.

4. Research Gap Identification

The literature review shows substantial progress in intelligent MPPT and PV-battery-EV energy management. However, the identified limitations reveal several research opportunities. These gaps are summarized in Table 2.

Table 1. Research Gap Identification and Proposed Research Direction

Gap No.	Identified Research Gap	Evidence from Literature	Proposed Research Direction
G1	Limited integration of intelligent MPPT and EMS	Most studies investigate MPPT or EMS independently [1]–[4], [8]–[20]	Develop an integrated framework connecting intelligent MPPT with PV-battery-EV energy management
G2	Limited direct comparison of PSO, GWO, WOA, and ALO	Existing studies generally evaluate one or two algorithms under different conditions [8]–[15]	Compare PSO, GWO, WOA, and ALO using identical PV, converter, and operating conditions
G3	Different test conditions in previous MPPT studies	Different PV ratings, converters, irradiation profiles, and performance indices are used [8]–[15]	Establish a common simulation framework for fair algorithm comparison
G4	Limited investigation of MPPT influence on EMS	EMS studies often consider PV power as an available input [1]–[4], [16], [19]	Investigate how MPPT efficiency and power oscillations affect battery and grid power management

G5	Limited systematic evaluation of ALO	ALO has been applied to PV MPPT and EV charging, but fewer comparative studies exist [14], [15]	Include ALO in a common comparative analysis with PSO, GWO, and WOA
G6	Limited combined performance assessment	MPPT studies focus on tracking, whereas EMS studies focus on battery and grid operation	Evaluate both MPPT and EMS performance using common system-level indicators
G7	Need for a unified PV-battery-EV framework	Previous research generally addresses individual subsystems	Develop a unified framework: PV → Intelligent MPPT → EMS → Battery/EV/Grid

5 Conclusion

This paper presented a focused literature review of MPPT techniques and energy management approaches for solar-battery-powered EV charging stations. The review covered conventional MPPT methods, intelligent optimization algorithms including PSO, GWO, WOA, and ALO, and energy management strategies for coordinating PV generation, battery storage, EV charging, and grid power. Based on the reviewed studies, key research gaps were identified, particularly the limited integration of intelligent MPPT with energy management and the limited direct comparison of different optimization algorithms under common operating conditions. These identified gaps provide a clear direction for the subsequent stages of the research. The outcomes of this study will serve as the foundation for developing and evaluating an integrated AI-based MPPT and energy management framework in future

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