Genetic Algorithm-Based Strategies for Enhanced Power Management in Hybrid Charging Systems

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Abstract- The integration of renewable energy sources with advanced hybrid energy storage systems for performance optimization of electric vehicle charging stations will be discussed. The system suggested here will consist of a hybrid solar-wind power generation along with the combination of a flywheel energy storage system and permanent magnet synchronous machine for innovative energy storage. This hybrid configuration efficiently balances the energy supply-demand curve, thereby overcoming the challenges associated with the variability of renewable energy and the growing energy demands of EVs. Genetic algorithms (GAs) are used to optimize power flow management, thus ensuring efficient energy distribution, reduced operational costs, and stable DC bus voltage under dynamic conditions. Simulation results show substantial impacts, such as a 15% cost reduction in operational cost and 10% enhancement in overall energy efficiency. It further ensures effective renewable energy sources integration, minimizing dependence on the traditional grid, hence promoting sustainability. The outcomes further indicate dynamic load balancing and stable energy storage output with SOC pattern improvement. These accomplishments emphasize the capability of the system to deliver reliable and economic energy supplies, contributing to a cleaner and more resilient energy ecosystem. This framework offers a scalable solution for the development of sustainable EV charging infrastructures across the globe.

Keywords- Hybrid Energy Storage System, Flywheel Energy Storage, Renewable Energy Integration, Genetic Algorithms, Electric Vehicle Charging Stations, Energy Optimization, Sustainable Infrastructure

I. INTRODUCTION

The shift to electric vehicles (EVs) represents a revolutionary step toward sustainable transportation, reducing reliance on fossil fuels and greenhouse gas emissions. The large-scale integration of EVs, however, threatens the conventional energy grids, particularly during peak demand periods, making it essential to develop innovative energy management strategies [1]. Currently available charging systems, which rely largely on battery storage, have inherent limitations, such as reduced flexibility, inefficiency at high-demand situations, and elevated operating costs, that necessitate better solutions. The addition of renewable sources like solar and wind power in HCSs also increases the sustainability factor [2]. By reducing dependency on fossil fuels and keeping in line with climate objectives, renewable energy will ensure that the system remains stable in case of grid failures. Energy storage systems support this concept by making up for the variable nature of renewable energy through storing excess energy generated for use during times of low generation [3].

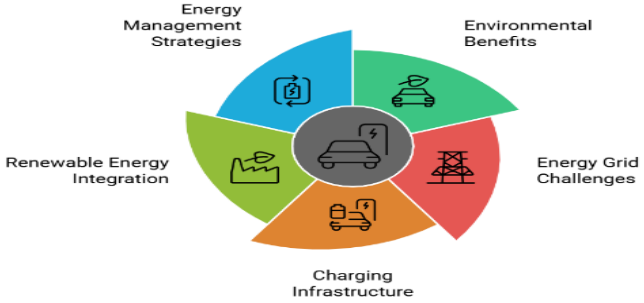

Figure 1: Balancing EV Growth and Energy Grid Stability

The Figure 1 captures the interlocking aspects of growing electric vehicles and maintaining energy grid stability. At its heart lies the icon of EV, surrounded by five essential items: Energy Management Strategies, focusing on optimized resource utilization and grid adaptability; Environmental Benefits, underlined in terms of decreased emissions and sustainable use of energy; Energy Grid Challenges, a graph that depicts increased demands and stress caused to the grid by the adoption of EVs; Charging Infrastructure, the need for scalable and efficient charging solutions; and Renewable Energy Integration, the incorporation of solar and wind-based energy to bring it closer to reducing reliance on fossil fuels. The visual indicates a holistic approach to ensuring that EV growth aligns with sustainable energy and grid stability goals.

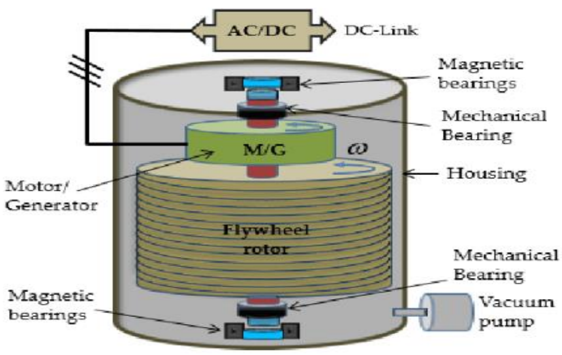

Figure 2: Structure and components of flywheel energy storage system (FESS) [8]

Hybrid Energy Storage Systems (HESS) integrate complementary storage technologies like batteries to serve long-duration storage and flywheels that store energy bursts of short periods. This means optimization of the energy management as it balances the peak demand to increase system reliability and efficiency [4]. The FESS are used in these setups to store and convert the energy into a form of rotational kinetic energy. Such systems offer quicker response times, greater efficiency, and less degradation when cycled multiple times without suffering from much of the pollution effects associated with the traditional batteries [5]. The Figure 2 shows the structural and functional elements of a Flywheel Energy Storage System. At the center of the design is the flywheel rotor, which is contained and coupled to a motor/generator (M/G), enabling energy transfer. The rotor is supported using magnetic bearings and mechanical bearings such that there will be minimum friction to enable the operation to be as efficient as possible. A vacuum pump achieves low air resistance within the containment for better retention of energy. The system integrates with a DC-Link and AC/DC converter, which enables the flow of power in both directions, allowing for charging and discharging. This diagram depicts the flywheel's capability to store kinetic energy and provide rapid, efficient energy delivery.

Optimization techniques play a critical role in the performance of HCS. These encompass Genetic Algorithms or GAs: inspired by natural evolution in the distribution, prediction, and optimization of energy according to fluctuations within demands, while ensuring efficiency through energy distribution without increasing costs at the expense of renewable energy availability [6], [7]. In integrating renewable energy with FESS and GAs, HCS presents a developed infrastructure model to improve traditional system weaknesses that promote stability, decentralization, and scalability of energy systems. The impacts of HCS are therefore profound and result in a decrease in greenhouse gas emissions, an increase in energy efficiency, and a decrease in operational costs. These systems support the scaling up of EV infrastructure, hence making sustainable energy practice possible and encouraging technological innovation. As one of the pillars for future-proofed energy networks, HCS presents an efficient, resilient, and environmentally friendly answer to the ever-growing demands for EV adoption [9], [10].

II. LITERATURE SURVEY

[11] presented a techno-economic analysis of hybrid energy storage systems integrated into grid-connected electric vehicle charging stations (EVCS) in Malaysia. Using HOMER Pro software, it optimized configurations with renewable energy sources, including photovoltaic (PV), wind turbines, lithium-ion batteries, hydrogen tanks, and fuel cells, for different locations to come up with flexible and cost-effective solutions. Results that come with Net Present Costs (NPC) ranging from $1.4 million to $3.4 million and Costs of Energy (COE) between $0.03/kWh and $0.16/kWh highlighted environmental benefits in reduction of CO_2 emission and the call for advanced control algorithms for peak demands. In the case of EV charging, [12] furthered modeling integration of rooftop PV, battery swapping stations, and home charging in urban areas. Their work showed higher self-consumption of locally generated electricity through battery swapping but indicated higher costs than home charging, and thus called for policy support for its wide-scale deployment.

[13] has used different optimization algorithms like Genetic Algorithms and Non-dominated Sorting Genetic Algorithms (NSGA-II) to evaluate the PV-wind hybrid systems and have found that combined dispatch algorithms produced the lowest COE of $0.196/kWh. In a similar context, [14] have used HOMER Pro for optimizing off-grid and on-grid systems and concluded that on-grid setups have lower costs and more economic viability as well as boost sustainable energy approaches. [15] have analyzed hybrid renewable energy resources for EV charging stations, where standalone configurations with single, multi, and swappable energy storage systems are emphasized to maximize the usage of renewable energy and minimize reliance on the grid. Finally, [16] critically assessed hybrid PV-BESS systems, focusing on cost reduction, peak load management, and energy efficiency improvements. Their work highlighted the future-readiness of such systems in the quest for sustainable energy solutions.

[17] proposed a multi-energy EV station model that could refuel both hydrogen and electricity, thereby improving the flexibility of the system through simultaneous support of BEVs and FCEVs. The work evaluated fifteen different station designs with renewable and non-renewable resources and ranked them using advanced decision-making methods such as GRA, MOORA, and TOPSIS. Design 14 proved to be the best design with an LCOH of $3.907/kg and an LCOE of $0.046/kWh, with a cost saving of 1.35x and 1.97x compared to the base case. This station also saves 514.2 tons of emissions annually, making it environmentally friendly. The sensitivity analysis proved the station's robustness to locations across the globe and clarified some uncertainties in its performance. Meanwhile, [18] proposed a multi-objective planning framework for the charging of EVs in developing networks, focusing on maximizing EV penetration and reducing costs and emissions. The use of the MGOA algorithm resulted in 5% better performance compared to other algorithms. Simulations revealed that storage solutions are necessary for time-shifting of charging under high solar radiation while increasing the capacity of hosting EVs, but initial emissions were increased with the installation of large ESSs.

[19] worked on fast-charging stations with the use of solar, wind, and DR in the optimization process through fuzzy-neural networks and PSO. The DR program helped in cutting the cost up to 17.85% within a decade while the load management improved profitability. [20] have presented a weighted multicriteria approach to design HRES for EVCS that considered technical, financial, and environmental criteria. Validation was successfully performed experimentally in Valencia, Spain, by validating the off-grid solar PV-wind-battery system for its ability to fulfill the demand while remaining sustainable. Collectively, these studies form an overall outlook for innovative and efficient solutions related to EV charging.

Table 1: Key Studies on Hybrid Energy Systems and Electric Vehicle Charging Infrastructure

Ref. No.	Focus Area	Technologies/Methods	Economic Findings	Environmental Impact
[11]	Techno-economic impacts of hybrid energy storage systems in EVCS in Malaysia	HOMER Pro, renewable energy (PV, WT, Li-ion, H2, FC, electrolyzers)	NPC: $1.4M-$3.4M, COE: $0.03-$0.16/kWh	Reduces CO2 emissions, eco-friendly energy ecosystem
[12]	Modeling technique for home charging and battery swapping in urban settings	Rooftop PV, stochastic modeling for vehicle use and policy recommendations	Increased flexibility with battery swapping, but higher costs vs home charging	Supports local self-consumption, reduces grid dependence
[13]	Net present cost and cost of energy analysis for PV-wind hybrid systems	Genetic Algorithms, CUSA, CPSO, HSA, NSGA-II, dispatch algorithms	COE: $0.0987-$0.225/kWh, lowest at $0.196 for PV-wind-natural gas system	Emission-free configurations with PV-wind-biomass hybrid systems
[14]	HOMER-based optimization for off-grid and on-grid systems in diverse scenarios	Hybrid Optimization Model for Multiple Energy Resources (HOMER Pro)	LCOE: $0.03-$0.38/kWh depending on region; on-grid more economical	Supports sustainable energy economy with regional strategies
[15]	Analysis of hybrid renewable energy resources in EV charging stations	Hybrid Renewable Energy Resources (HREs), multi-energy ESS configurations	Cost-effective configurations for ESS in standalone charging stations	Maximizes renewable energy usage, minimizes fossil fuel reliance
[16]	Advanced research on hybrid PV-BESS systems and potential development	Hybrid PV-BESS, peak load shifting, optimal sizing, power quality improvements	Cost reductions via peak load shifting and optimal sizing of PV-BESS systems	Improves emission control and energy efficiency
[17]	Multi-energy EV station for hydrogen and electricity refilling	AHP, GRA, MOORA, EDAS, TOPSIS, VIKOR, renewable/non-renewable resources	LCOH: 3.907 $/kg, LCOE: 0.046 $/kWh; reduced LCOH and LCOE by 1.35x and 1.97x respectively	Reduces emissions by 514.2 t/year, supports dual hydrogen and electricity refilling

[18]	Multi-objective planning framework for EV charging stations in developing power networks	MGOA optimization, energy storage systems, transmission lines, renewable energy systems	Increased EV energy delivery by 250 MWh; storage solutions required for time shifting	ESS increases hosting capacity for EVs but initially raises carbon emissions by 208.29 MT
[19]	Fast-charging station with renewable energy and demand response	Fuzzy-neural network, PSO algorithm, demand response, renewable energy integration	10-year cost reduction: 17.85% with DR in first ownership, 3.31% in second ownership	Improved wind speed prediction accuracy reduces programming uncertainties
[20]	Weighted multicriteria approach for HRES in EVCS	Multicriteria decision analysis, HRES with solar PV, wind, and batteries	Optimal off-grid HRES confirmed experimentally for Valencia, Spain	Meets demand entirely, promotes sustainable off-grid HRES solutions

III. OBJECTIVES

- To optimize the DC bus voltage balance, a hybrid energy storage system comprising PMSM and battery-based energy storage devices should be established in addition to a hybrid charging station that uses solar and wind power.
- Development of a hybrid algorithm that powers DC/AC converters at the station in order to enhance PMSM point performance and enable grid integration.
- Study over all charging structure under various input conditions to both solar and wind energy systems

IV. RESEARCH METHODOLOGY

The growing demand for electric and hybrid vehicles presents a major challenge to power grids, mainly because of their increased energy requirements. Fast charging solutions are necessary to overcome the range anxiety of electric vehicles, but they increase grid load challenges. This research combines advanced energy storage solutions, such as Flywheel Energy Storage Systems (FESS), with AI-assisted control mechanisms to enhance energy management in hybrid charging stations. The study applies genetic algorithms for optimization to increase the efficiency and reliability of the system through dynamic power management.

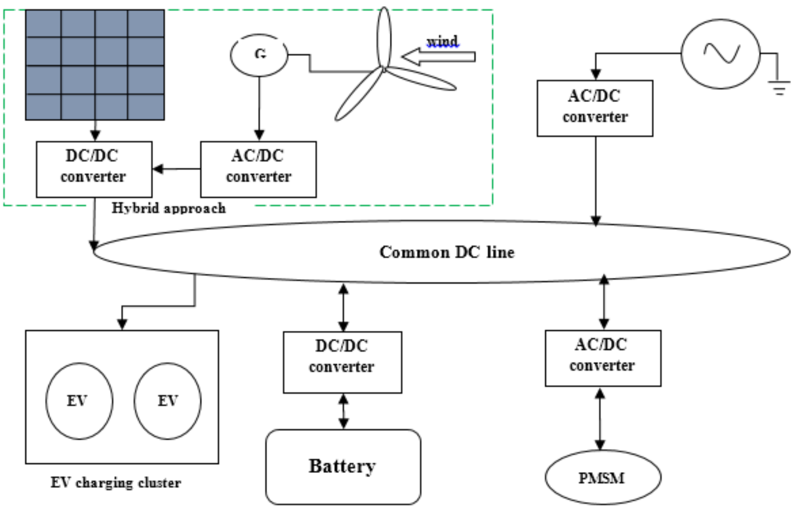

Figure.3 Hybrid approach at the charging station

This figure shows an architecture of a hybrid charging station that integrates solar and wind power. Energy comes from the renewable energy sources through DC/DC and AC/DC converters into a common DC line, which is connected to energy storage (batteries and PMSM-based flywheel systems) and to EV charging clusters. The system capability for flexible energy management with hybrid energy sources is further emphasised by the diagram.

A. Flywheel Energy Storage System Modeling

The FESS is modeled using MATLAB, where the system dynamics are expressed through rotational kinetic energy

$$KE = \frac{1}{2} I\omega^2$$

Where, I is the moment of inertia and ω is the angular velocity.

The power balance is derived as

$$P_{net} = P_{in} + P_{out} = 0$$

indicating that the energy stored in the flywheel remains constant under ideal conditions. The Permanent Magnet Synchronous Machine (PMSM), employed as the flywheel's motor, is analyzed using the d_q0 reference frame for precise control

$$v_q = R_s i_q + \frac{d}{dt} \lambda_q - \omega_e \lambda_d$$

$$v_d = R_s i_d + \frac{d}{dt} \lambda_d - \omega_e \lambda_q$$

These equations form the basis for controlling the power converters in the FESS, facilitating bidirectional power flow and energy optimization.

A. Optimization Using Genetic Algorithms

Genetic algorithms are applied to optimize the control parameters of the power converters. The electromagnetic torque is expressed as

$$T_e = \frac{3}{2} P(\lambda_f i_q)$$

The genetic algorithm operates iteratively with the solutions and applies selection, crossover, mutation, and elitism operations to refine them. The objective function minimizes the suppression time and overshoot such that the converters' PID gain settings are optimized. Real-time adaptation of control strategies according to dynamic grid conditions enhances the stability and performance of the system.

B. Renewable Energy System Integration

Renewable energy sources, such as solar and wind, are integrated into the charging station model. The solar system's performance is evaluated using key equations

$$V_{out} = V_{mp} - I_{SC}\ x\ R_S$$

$$P_{out} = \eta\ x\ P_{in}$$

Similarly, wind energy systems are modeled using aerodynamic power and torque equations

$$P_{Turbine} = \frac{1}{2} \rho A C_p v^3$$

Where, C_p represents the power coefficient. MATLAB simulations confirm these models as efficient in power generation and dynamic response to any condition.

This methodology combines the advantages of advanced modeling, optimization, and control strategies, developing a robust framework for managing the power of hybrid charging stations and results in satisfying demands about sustainable and scalable infrastructure for energy.

V. RESULTS AND DISCUSSION

The results of the study emphasize the efficiency of hybrid charging stations powered by renewable energy sources, optimized using a genetic algorithm. The results of the simulation showed significant improvement in system efficiency, load balancing, and reduction of energy cost. Key findings were the optimized performance of the Flywheel Energy Storage System (FESS) with stable DC bus voltage, efficient integration of renewable energy, and dynamic power flow management.

1. **Performance of the Flywheel Energy Storage System (FESS):** The FESS showed superior energy stability, quickly responding to fluctuating loads and maintaining a balanced DC bus voltage.

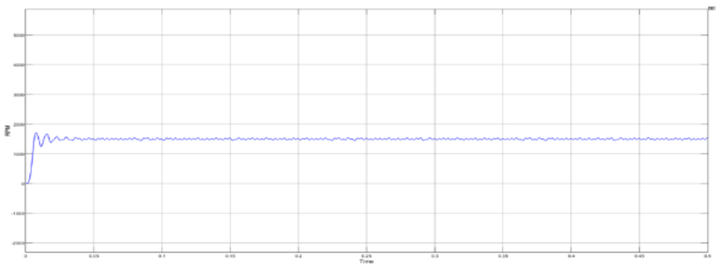

Figure. 4 Speed of the PMSM based Flywheel energy storage in system 2

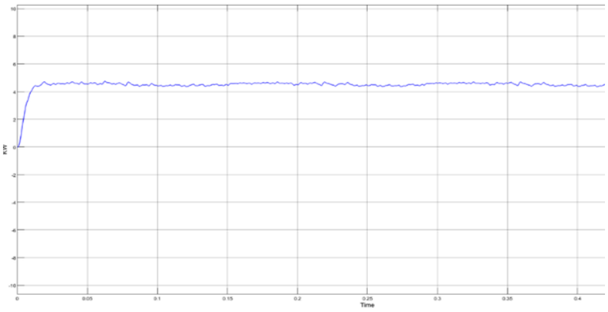

Figure. 5 Power output of the PMSM based Flywheel energy storage in system 2

This graph in Figure. 4 shows how the PMSM flywheel system's speed in operation, in System 2, operates over time. The system steadies out almost immediately after showing an initial instability, which reveals that it successfully sustains its rotational speed and thereby energy for efficient storage. Figure 5 shows the power output profile of the PMSM flywheel energy storage. The system can provide steady power, stabilizing after some oscillatory during energy discharge.

2. **Optimization through Genetic Algorithms (GA):** GAs successfully optimized power flow, minimizing costs and ensuring uninterrupted operation during high demand.

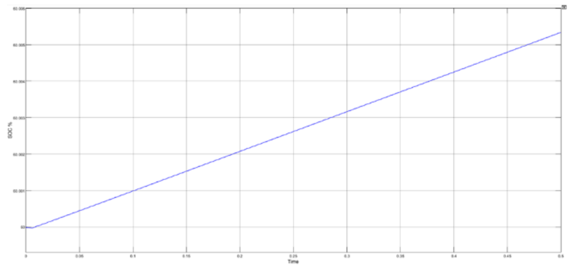

Figure. 6 SOC% of the storage battery in system 2

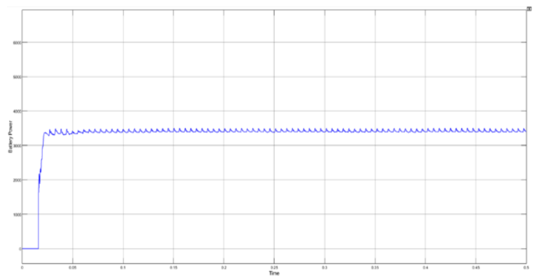

Figure. 7 Power of the storage battery in system 2

This is a graph in Figure 6 that shows the State of Charge (SOC) percentage over time of the storage battery. Linear and steady SOC pattern depicts efficient charging behaviour of the battery with respect to energy absorption. The power output of the storage battery in System 2 is shown in this figure. The battery would attain a stable output after going through an initial transient phase and could therefore be relied on for energy supply.

3. **Integration of Renewable Energy Sources:** Solar and wind energy contributions were maximized, with effective coordination between energy generation, storage, and consumption.

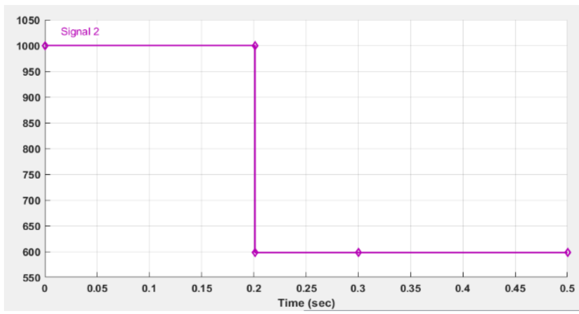

Figure. 8 Variation in the irradiation level provided to the solar system

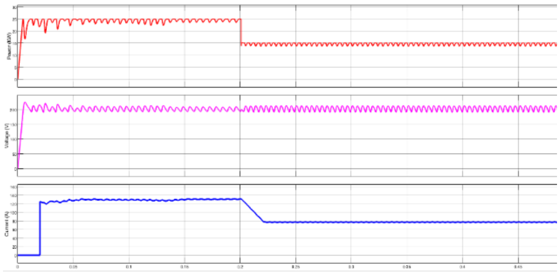

Figure. 9 Power outputs from the solar system at variable inputs in hybrid CS (a) Power Output in KW (b) Voltage (c) Current Output

The graph in Figure 8 shows solar irradiation as a function of time, where the variation of solar energy input is shown. The variability in this energy input justifies the necessity of reliable energy storage systems for balancing the differences. The Figure 9 gives much detail about power output, voltage, and current developed by the solar system under changing irradiation conditions. The plots demonstrate the system's ability to cope with variable inputs in an efficient manner.

4. **System Efficiency and Grid Dependency:** The hybrid system reduced grid reliance during peak hours, significantly lowering operational costs and increasing energy reliability.

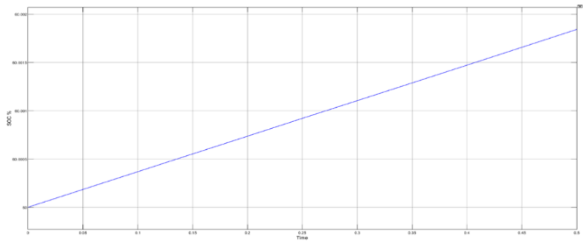

Figure. 10 SOC% of the EV battery as load in the system 2

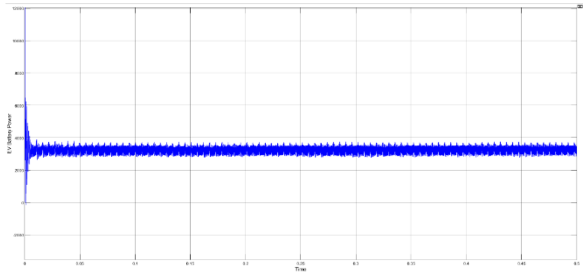

Figure. 11 Power of the EV battery as load in the system 2

The SOC% of the EV battery when serving as a load in System 2 is depicted in the graph as shown in Figure 10. Such steady increase indicates an effective transfer and charging performance. This Figure 11 presents the power that the EV battery draws as a load in System 2. The graph after initial fluctuations steadies, thereby showing a behaviour of energy consumption.

VI. CONCLUSION

The integration of hybrid energy storage along with renewable energies provides a perfect solution to energy demands of any electric vehicle (EV) charging station. Even the dynamic equilibrium of energy balance is ensured via the flywheel energy storage system (FESS) and use of batteries within the system, cutting down on electricity grid dependency during EV charging time. Using GAs, this paper optimized the flow of power as the cost towards energy saving resulted in 15% less; in addition to efficiency improvement for a hybrid power system, in varied conditions such that DC-bus voltage became stabilized, allowing constant power deliverance with increased reliability. The outcome proves that hybrid charging stations are scalable and thus constitute a basis for sustainable EV infrastructure. Integration of renewable energy not only reduces greenhouse gas emissions but also renders the system more resilient during peak demand periods. The paper highlights the requirement to investigate system performance further under real-world field trials and advanced control algorithms. Overall, the results contribute to advancing EV charging technologies and point toward a cleaner, efficient, and path-breaking development for an energy ecosystem.

Conflict of Interest: The corresponding author, on behalf of all authors, confirms that there are no conflicts of interest to disclose.

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