

Advances in Power Flow Optimization in Solar EV Charging Microgrids Focus on Flywheel Storage

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Abstract

The increasing adoption of electric vehicles (EVs) and the integration of renewable energy sources have driven the development of solar EV charging microgrids. These systems aim to reduce fossil fuel dependency and enhance energy efficiency through decentralized and clean energy solutions. This study explores power flow optimization in solar microgrids that utilize photovoltaic (PV) generation, flywheel energy storage systems (FESS), and intelligent control strategies. Emphasis is placed on the role of evolutionary algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) for real-time, adaptive energy management. The integration of flywheels offers fast response times, high durability, and low maintenance, making them well-suited for the dynamic demands of EV charging networks. The research identifies the technical and economic benefits of combining FESS with intelligent optimization and discusses challenges such as high capital costs, safety concerns, and computational complexity. This work highlights the potential of smart microgrids in enabling resilient, sustainable, and cost-effective EV charging infrastructure.

Keywords: Electric Vehicles (EVs), Solar Microgrids, Power Flow Optimization, Flywheel Energy Storage System (FESS), Evolutionary Algorithms, Genetic Algorithm (GA), Particle Swarm Optimization (PSO).

I. Introduction

Electric vehicles are becoming popular due to their less emissions and lower fossil-fuel dependency. The renewable energy sources used in distribution networks, in connection with charging station electrification of smart grids, provide a choice for high power conversion efficiency and emission reduction. The microgrid consists of a group of distributed energy sources and energy storage units utilized locally by different types of loads and operated in a grid-connected or islanding mode. A typical EV charging station, as part of a microgrid infrastructure, is shown in Figure 1. However, large capacity penetration of EV charging points increases the demand in charging infrastructure; this impact raises the demand on the utility grid. To mitigate the problems related to power demand, powers generated locally from the RES are integrated with suitable power converter topologies [1].

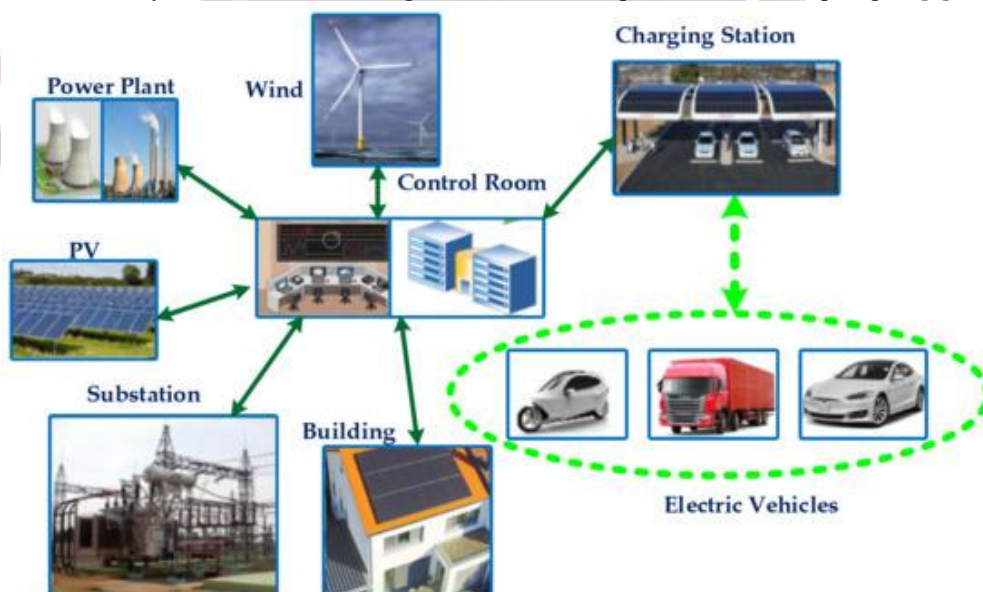


Figure 1 An EV-charging station as part of the microgrid infrastructure [1].

Solar electric vehicle charging microgrids are an alternative of a fast-growing nature that attempts to curb fossil-fuel dependency and provide for increasing energy consumption by transportation. This type of system manifests a mutual relationship of PV solar generation and local EV charging infrastructure with some form of energy storage, allowing for a decentralized and green concept of charging electric vehicles. Energy management in such

microgrids is now becoming a big challenge with better integration of renewable energy sources coupled with an exponential increase in EV adoption [2]. It becomes a dynamic situation with solar power generation variability added to random EV charging profiles, needing accurate and smart energy management. Power flow optimization in this regard would improve the efficiency of systems, reduce operational costs, maintain voltage stability, and ensure the reliability of energy supply. With the utilization of significant optimization tools coupled with fast-response storage--girded mainly by flywheels as storage elements--solar EV microgrids can better maintain the balance between generation and consumption during real-time load variations and keep the system running under diverse conditions in a stable manner [3].

II. Importance of Power Flow Optimization in EV Microgrids

Power flow optimization has its major applications in enhancing and sustaining the EV microgrid, thus improving energy efficiency, cutting costs, and supporting clean transportation. In energy flow management of solar PV generation and storage, the optimized power flow reduces losses and ensures that the energy is being properly fed into the loads, and it also prevents the inefficient charging or discharging of storage systems, thereby improving energy efficiency. On the economic front, it also leads to off-peak reliance on grid power, thereby reducing demand charges and creating improved balance in control of voltage and frequency, hence providing system stability [4]. This stability in turn minimizes incidences of blackouts and postpones expensive infrastructure upgrades. In the context of sustainable transportation, EVs should be charged under optimized power flow conditions with clean, local solar energy, hence minimizing greenhouse gas emissions and associated reliance on fossil fuels. It, therefore, stabilizes the renewable-powered EV charging platform and is an enabler in the larger developmental objectives of evolving into smart, green, and resilient urban energy networks [5].

A. Energy Efficiency

EV microgrid power flow optimization ensures the most effective use of energy from solar PV and stored in energy storage systems. By minimizing power losses in the distribution network and intelligently controlling load distribution, power flow optimization increases system efficiency. A better match is achieved between generation and demand; unnecessary energy conversions are prevented, along with overcharge or underutilization of storage elements. The best-out-of-energy resources use increases the utility of renewable inputs and reduces the load on secondary or standby power systems, hence improving the energy performance of the microgrid [6].

B. Cost Savings and Grid Stability

Optimized power flow greatly contributes to diminishing operational expenses in EV microgrids. Electric vehicle operators schedule charging sessions such that local solar generation supplies load during maximum possible hours, whereas storage systems are discharged during peak demand times in order to avoid costly energy purchases from the main grid and demand charges [7]. Intelligent power flow controls also prevent grid congestion, voltage imbalances, and frequency fluctuations--about negatives in high-renewable systems. This helps maintain grid stability, lower endangerment to potential outages, or damages to equipment and decreases the necessity for expensive reinstatements to the grid. The economic advantages from such optimization thus flow-through to consumers and utility providers, arising out of lowered electricity bills and more stabilized grid operations [8].

C. Role in Sustainable Transportation

Electric mobility is one key pillar towards sustainability goals across the globe, and optimized solar microgrid integration plays an essential role in this transition. Power flow optimization, therefore, optimizes the charging of EVs with local renewable energy in stable and efficient ways to mitigate GHG emissions and dependency on fossil fuels. Thus, the working of a more resilient and greener energy system, in line with the concept of green transportation. Moreover, power flow optimization optimizes the bullishness and scalability of EV charging infrastructure, thereby hastening the adoption of EVs and laying the foundation for smart carbon-neutral cities [9].

III. Architecture of Solar EV Charging Microgrids

A solar EV charging microgrid requires an architecture that effortlessly integrates numerous energy and control components to enable the efficient, sustainable charging of electric vehicles. These principal components include, a solar photovoltaic (PV) array that converts sunlight into electricity, EV chargers to power the vehicles, energy storage systems (batteries or flywheels, for instance) to store excess energy for later use, and control systems that manage the entire operation of the microgrid [10]. The controllers keep track of the power generation, regulate charging patterns, and maintain voltage and frequency stability, all while optimizing energy usage in real time. Through such coordinated action and control of these individual components, load balancing and power flow management can be carried out effectively--tasks that are paramount in maintaining good reliability and performance when dealing with variable solar output and a fluctuating EV charging demand [11].

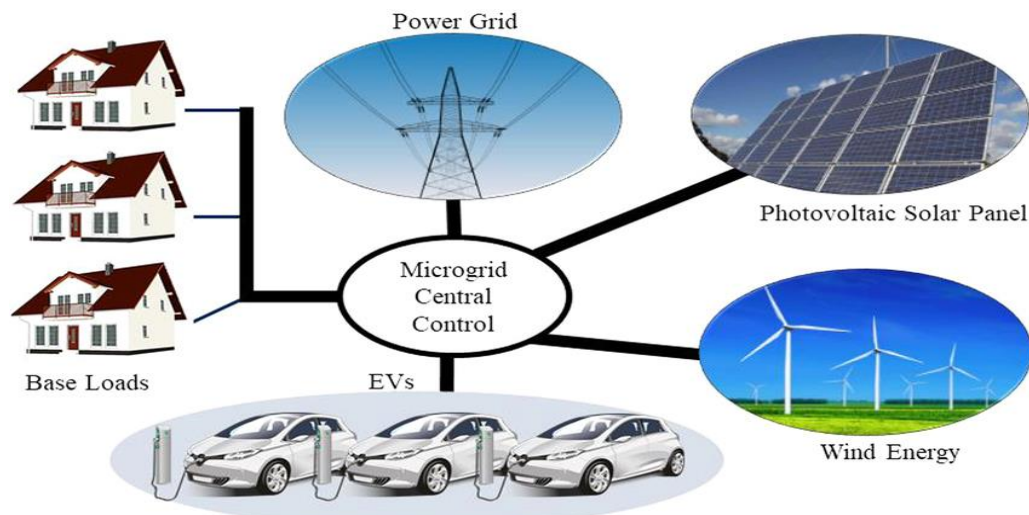


Figure 2 General architecture of modern microgrids [12]

The figure 2 shows a schematic of a typical microgrid concept where a central unit has control over the energy flow between base loads, EVs, the main power grid, inherently solar-based photovoltaic panels, and wind sources. Solar EV microgrids can be executed either in a grid-tied or islanded manner, each harbouring unique operational characteristics. The grid-connected microgrids link up with the main utility grid and power flows on a bi-directional basis. This connection makes it possible to either export surplus solar-generated power into the grid or draw upon the grid power supply whenever local generation falls short, thereby contributing to the stability and flexibility of the system [13]. Standalone on the other hand settle and operate away from any connection to the utility grid and must entirely depend on local generation and storage resources and are particularly suited for more remote or off-grid end-user applications. However, standalone types require a much higher level of energy management to ensure functionality when solar generation is low or charging demand is high. Several factors determine the choice of these two configurations: location, energy access, infrastructure availability, and charging specifics. Therefore, from the point of view of their structure and mode of operation, solar EV microgrids determine their efficiency, resilience, and extent of support toward cleaner transportation [14].

IV. Flywheel Energy Storage Systems (FESS)

Flywheel Energy Storage Systems (FESS) are mechanical energy storage devices that store and release energy through the principle of rotational kinetic energy. When electrical energy is available, a motor is used to spin a heavy rotor (the flywheel) at very high speeds, converting the electrical input into kinetic energy. This energy remains stored as long as the flywheel keeps spinning, and when electricity is needed, the motor acts as a generator, converting the kinetic energy back into electrical form with high round-trip efficiency [15]. The process is rapid, clean, and highly repeatable, making FESS an attractive option for applications requiring frequent charge and discharge cycles. Since flywheels do not rely on chemical reactions, unlike traditional batteries, they do not suffer from chemical degradation over time, offering an exceptionally long operational life and consistent performance. They are well-suited for use cases involving high power output over short durations, such as load balancing, voltage regulation, frequency stabilization, and bridging short interruptions in power supply [16].

Compared to conventional battery systems, flywheels offer several distinct advantages, particularly in scenarios that demand high reliability, rapid response, and durability. One of the key benefits is their extremely high cycle life—flywheels can endure hundreds of thousands of charge-discharge cycles with minimal performance degradation, unlike batteries which degrade progressively with each cycle. Flywheels can respond to load changes in milliseconds, making them ideal for applications that require immediate power compensation, such as EV fast-charging stations where sudden demand surges are common [17]. They also have lower maintenance requirements, do not involve hazardous materials, and are less sensitive to environmental conditions, making them more sustainable and safer for long-term use. Their robustness, combined with quick energy release capabilities, makes them a strong complement to battery storage in hybrid systems, especially in dynamic environments like solar-powered EV microgrids [18].

However, integrating flywheel energy storage into solar EV microgrids presents a number of technical and economic challenges. The initial capital cost of flywheel systems remains relatively high due to precision manufacturing requirements and the need for specialized magnetic bearings or vacuum chambers to reduce friction and energy loss. Safety is another concern, as the system must be designed to contain the high-speed rotor safely in case of mechanical failure [19]. Additionally, flywheels require sophisticated control algorithms and power electronics to effectively coordinate with other microgrid elements such as PV inverters, EV chargers, and battery banks. Despite these integration hurdles, the applications of FESS are expanding rapidly, particularly in areas that

benefit from their unique properties. These include frequency regulation in smart grids, power smoothing for intermittent renewable sources like solar and wind, short-duration backup power, and high-speed energy buffering for EV fast-charging networks. As advancements in materials and control systems continue, flywheel technology is poised to play an increasingly important role in enhancing the performance, efficiency, and reliability of renewable energy-based microgrids [20].

V. Optimization Techniques in Power Flow Control

Power flow control is a critical function in the operation of solar EV charging microgrids, aiming to manage the distribution and flow of electricity efficiently among generation sources, storage units, base loads, and electric vehicle charging stations. To achieve optimal performance, various optimization techniques are employed, which can broadly be classified into conventional and intelligent methods. Conventional methods typically involve deterministic and mathematical approaches such as linear programming (LP), nonlinear programming (NLP), and Newton-Raphson or Gauss-Seidel methods for solving power flow equations [21]. These methods are well-established and effective for stable and predictable systems; however, they often fall short in handling the nonlinearities, uncertainties, and dynamic behavior inherent in renewable-based microgrids and EV charging networks [22].

To overcome these limitations, intelligent optimization techniques have gained significant traction in recent years. These include metaheuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), and Artificial Neural Networks (ANNs), which are designed to mimic natural or social processes to find near-optimal solutions in complex, multidimensional search spaces. Unlike conventional methods, intelligent techniques are better suited for real-time control and adaptive decision-making in systems with fluctuating generation and load demands [23]. The primary objectives of power flow optimization, whether using conventional or intelligent methods, include minimizing energy losses in the distribution network, maintaining voltage profiles within acceptable limits, and reducing operational costs. These goals are critical for ensuring the efficient use of renewable energy, prolonging the life of equipment, avoiding overloading, and maintaining a high level of reliability and power quality. In the context of solar EV microgrids, where variable solar input and unpredictable EV charging patterns coexist, the use of intelligent optimization methods is especially advantageous for achieving sustainable, cost-effective, and resilient energy management [24].

VI. Advantages of Using Flywheel Storage and Evolutionary Algorithms

Flywheel storage systems and evolutionary algorithms each offer distinct advantages that, when combined, significantly enhance the performance of solar EV charging microgrids. One of the key benefits of flywheel storage is its fast response time. Unlike conventional batteries, flywheels can instantaneously supply or absorb power, making them ideal for stabilizing microgrids during sudden load fluctuations or renewable output variability [25]. This characteristic is particularly valuable in EV charging systems where high power demands can occur unpredictably. Additionally, flywheels boast a very high cycle life due to their mechanical nature and lack of chemical degradation. They can handle hundreds of thousands of charge-discharge cycles with minimal performance loss, making them a long-lasting and cost-effective solution for frequent, short-term energy balancing. Their durability and quick energy transfer capability make them well-suited for high-throughput systems like smart EV charging stations integrated with solar power [26].

When coupled with intelligent optimization techniques such as evolutionary algorithms, the benefits of flywheel storage are further amplified. Evolutionary algorithms—like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and others—excel at solving complex, nonlinear, and dynamic optimization problems. These algorithms adaptively search for optimal control strategies to manage power flow, storage utilization, and load scheduling in real time [27]. As a result, they enable improved optimization outcomes by minimizing power losses, reducing operational costs, and maintaining voltage and frequency stability even under uncertain and fluctuating conditions. Furthermore, the integration of flywheel storage with evolutionary control enhances the overall reliability and sustainability of the microgrid. The system becomes more robust against disruptions, maintains better power quality, and ensures more consistent service for EV users. Together, these technologies support a cleaner, smarter, and more resilient energy infrastructure aligned with the goals of sustainable transportation and renewable energy adoption [28].

VII. Challenges and Research Gaps

The integration of flywheel energy storage systems (FESS) and evolutionary algorithms in solar EV charging microgrids involves several technical, economic, and operational challenges that must be addressed for practical deployment. One of the most significant barriers is the high initial capital cost of flywheel systems. These systems require specialized materials, precision manufacturing, and complex mechanical components such as magnetic bearings and vacuum enclosures, all of which increase system costs compared to conventional battery technologies. Additionally, safety considerations are critical, as flywheels operate at very high rotational speeds. In the event of a mechanical failure, there is a risk of structural damage or energy release, which necessitates the use of reinforced containment units and additional safety mechanisms—adding further cost and design constraints. The lower energy density of flywheels also limits their suitability for long-duration energy storage, making them

more effective for short bursts of high power rather than extended supply scenarios. These factors reduce flexibility in certain system configurations, particularly in microgrids with large energy demand or limited physical space. From a computational perspective, the application of evolutionary algorithms (EAs) for power flow control introduces complexity related to processing time and real-time execution. While EAs are effective for handling non-linear and multi-variable problems, they often require many iterations to converge toward acceptable solutions. This can hinder their use in time-sensitive operational environments where rapid control decisions are needed. Furthermore, tuning algorithm parameters—such as population size, mutation rate, and crossover probability—can significantly affect performance. Identifying the most effective settings often requires extensive testing and domain expertise. The integration of EAs into physical microgrid control platforms also demands advanced computational infrastructure, including real-time controllers and communication systems capable of handling dynamic updates and optimization tasks. This level of technological integration may not be feasible in all deployment settings, especially in locations with limited technical support or outdated infrastructure. Finally, achieving interoperability between flywheel storage units, EV chargers, inverters, and the grid requires detailed coordination at both hardware and software levels, increasing system complexity and maintenance requirements.

This comprehensive body of research explores various strategies to optimize and enhance Electric Vehicle (EV) charging infrastructure through renewable energy integration, advanced optimization algorithms, and smart energy management systems. Studies focus on hybrid systems like Photovoltaic-Wind-Battery/EV Charging Stations (PVWB/EVCS) optimized using MOO techniques (MOPSO, NSGAII, NSGAIII, MOEA/D), showing NSGA-II as most effective [29], and hybrid solar-wind stations leveraging B-GOA and NCSOA for improved performance and reduced grid reliance [30]. Other works address EV charging station placement [31], transformer load management through deadline-energy prioritization [32], AI-based intelligent scheduling systems [33], global trends in RE-enabled smart charging [34], and the broader integration of EVs into power grids for enhanced sustainability and reduced emissions [35]. Collectively, these studies contribute to the development of resilient, efficient, and sustainable EV charging solutions.

Table 1 Comparative Analysis of Research Studies on Sustainable Electric Vehicle Charging Infrastructure

Study Ref	Main Focus	Methods/Algorithms	Key Findings	Sustainability Contribution	Outcomes
[29]	Optimization of PV-Wind-Battery/EV Charging Station (PVWB/EVCS)	MOPSO, NSGAII, NSGAIII, MOEA/D; HOMER comparison	NSGA-II performs best; high resilience and adaptability; economic feasibility confirmed via DCF	Promotes renewable energy and sustainable EV charging	Robust and cost-effective PV-Wind-Battery system for EV charging; NSGA-II outperforms others
[30]	Hybrid solar-wind fast charging station with ESS	Monte Carlo simulation, B-GOA, NCSOA, Erlang B model	Scenario IV most viable (NPV 1,025,895.32€); 5 chargers, 4 wind generators optimal	High RES penetration reduces grid reliance	Hybrid optimization shows better performance; economic viability confirmed with flexible configurations
[31]	EV charging station location optimization	Reservation-based location model	Reservation services reduce cost and improve utilization	Supports sustainable cities and healthier lifestyles	Improved station utilization and cost reduction through reservation service; case study supports model
[32]	Managing EV charging to avoid power system overload	Deadline and energy-based EV prioritization	33% more EVs served than earliest deadline method	Efficient load management supports grid stability	Enhanced transformer load management and energy delivery to EVs; prioritization model proves effective
[33]	EV-Intelligent Energy Management	AI-based management system with	Performs well under	Enhances smart energy management	Effective under varied traffic densities; secures

	and Charging Scheduling System (EV-EMSS)	secure communication	dense/sparse traffic conditions	and data security	data and improves energy management decision-making
[34]	Review of RE-enabled smart EV charging	Review paper – various global implementations	Highlights global trends, challenges and smart RE-based charging approaches	Promotes RE integration and policy standardization	Identifies best practices globally; comprehensive review aids stakeholders in sustainable EV infrastructure
[35]	EV integration with power grid	Impact analysis on transmission/distribution systems	EVs improve grid efficiency but need standardization and updated infrastructure	Facilitates sustainable mobility and carbon reduction	Recommends upgrades for infrastructure and integration; supports carbon reduction via grid-enhanced EV usage

VIII. Conclusion

This study underscores the transformative potential of solar EV charging microgrids enhanced by flywheel storage systems and intelligent optimization algorithms. Flywheels, with their rapid response and long cycle life, complement solar variability and EV demand surges, while evolutionary algorithms enable efficient power flow control under uncertainty. Together, they contribute to improved energy efficiency, grid stability, and sustainability. Despite challenges such as high initial costs and integration complexity, ongoing technological advancements are likely to mitigate these barriers. The adoption of such hybrid energy systems supports global goals for green transportation and urban sustainability, positioning solar EV microgrids as a cornerstone for future energy infrastructures.

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