CONTROL AND OPTIMIZATION OF HYBRID ENERGY STORAGE SYSTEM IN MICROGRID

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Introduction

Electricity is a fundamental component of modern civilization, serving as the backbone of industries, homes, transportation, and communication networks. The historical development of electricity began in the 18th and 19th centuries, with notable contributions from pioneers such as Benjamin Franklin, Alessandro Volta, Michael Faraday, and James Clerk Maxwell. These scientific advancements led to the establishment of centralized power generation and distribution systems, which have played a crucial role in industrialization and urbanization.

The centralized power model, despite its contributions to economic growth, presents several limitations. Long-distance electricity transmission results in significant energy losses, reducing overall system efficiency. The reliance on fossil fuel-based power plants has led to environmental challenges, including greenhouse gas emissions and air pollution. Additionally, centralized grids are vulnerable to disruptions caused by equipment failures, cyberattacks, and natural disasters, necessitating the development of more resilient and sustainable energy systems. The transition toward renewable energy sources (RESs) has emerged as a critical solution to address these challenges. Renewable energy technologies, including solar, wind, hydro, geothermal, and biomass, offer sustainable alternatives to fossil fuel-based power generation. The increasing adoption of renewable energy is driven by the need to reduce carbon emissions, mitigate environmental degradation, and enhance energy security.

This decentralization enhances energy resilience, as local generation systems can continue to operate even in the event of grid failures or disruptions. To overcome these challenges, the concept of microgrids has emerged as a game-changing solution. A microgrid is a localized energy system that integrates distributed energy resources (DERs), such as solar panels, wind turbines, and battery storage, with local loads. Microgrids can operate independently or in coordination with the main grid, providing enhanced reliability, reduced transmission losses, and greater resilience against outages. They are particularly beneficial in remote areas, campuses, military installations, and regions prone to the event of grid failures or natural disasters. Microgrids can operate autonomously, ensuring a continuous supply of electricity. These systems can integrate renewable energy sources with energy storage solutions, ensuring a stable and consistent power supply.

The integration of direct current (DC) microgrids represents a significant advancement in modern power systems. Unlike traditional Alternating Current (AC) grids, DC microgrids utilize direct current for electricity distribution, aligning efficiently with renewable energy sources such as solar photovoltaics and battery storage systems. By eliminating unnecessary conversion losses, DC microgrids enhance overall energy efficiency. They also provide improved compatibility with emerging technologies, including electric vehicles and energy storage systems, thereby enhancing grid reliability and flexibility. Research efforts are increasingly focused on optimizing the performance, control strategies, and resilience of DC microgrids. The integration of Hybrid Energy Storage Systems (HESS), which combine batteries and supercapacitors, enhances system stability and ensures a continuous power supply. DC microgrids offer a promising solution for off-grid and remote areas, addressing energy access challenges and promoting sustainable development.

Research Objectives

The research problem formulated takes care of the following objectives:

- To minimize the response time of HESS.
- To minimize voltage fluctuations in the DC bus system.
- To improve battery efficiency.
- To minimize the discharging period of the battery.

Research Methodology

The growing global demand for reliable and sustainable energy has exposed the limitations of traditional centralized power grids, such as significant transmission losses, grid instability, and environmental concerns stemming from fossil fuel dependence. To address these challenges, decentralized energy systems like microgrids have emerged, with a particular focus on incorporating renewable energy sources (RES) such as solar photovoltaics (PV). Despite their environmental advantages, RES introduce variability and intermittency, leading to challenges in maintaining grid stability. DC microgrids offer an effective solution by delivering higher efficiency, reduced conversion losses, and improved compatibility with modern DC-based devices and energy storage systems. These advantages make DC microgrids an ideal platform for integrating Hybrid Energy Storage Systems (HESS), which combine technologies like batteries and supercapacitors to handle both short-term power surges and long-duration energy demands. Advanced control and optimization techniques are essential for ensuring smooth operation, real-time energy balancing, and rapid response to dynamic load changes.

To validate the system's effectiveness, simulations are first conducted in MATLAB Simulink. These simulations model various operational scenarios in the DC microgrid with different control strategies, focusing on the performance of the Ni-MH battery and ELDC supercapacitor under fluctuating load demands and intermittent solar energy generation. By integrating renewable energy sources, hybrid energy storage systems, and a DC bus, utilizing Maximum Power Point Tracking (MPPT) with the Incremental Conductance (INC) method, State of Charge (SOC) management, and Discrete Proportional-Integral (PI) control techniques to improve response time, energy storage efficiency, load balancing, and DC link voltage stability are evaluated. Initial results from the simulations provide a baseline of the system's performance, highlighting areas where optimization is needed.

Following these simulations, several metaheuristic optimization algorithms were employed to enhance system performance by optimizing settling time, peak overshoot, and battery efficiency.

Hybrid optimization approaches were also applied, as they combine the strengths of different algorithms to achieve better and more reliable results. Particle Swarm Optimization-Artificial Bee Colony (PSO-ABC) and Artificial Bee Colony-Gray Wolf Optimization (ABC-GWO) are applied to optimize the energy sharing between the battery and supercapacitor. These hybrid approaches combine the strengths of different swarm intelligence techniques to improve the system's response time, making the battery and supercapacitor react more efficiently to dynamic load changes and fluctuations in solar energy generation. Additionally, these optimization techniques help to stabilize the DC link voltage, ensuring efficient power conversion and improved overall system performance.

The PSO-ABC hybrid method takes advantage of the global search capability of PSO and the local exploitation ability of ABC, while the ABC-GWO hybrid combines the exploration ability of ABC with the exploitation capability of GWO to achieve faster convergence and better optimization results. These hybrid approaches allow the system to adapt in real-time, enhancing efficiency and resilience in DC microgrids.

Key Findings

- The research demonstrates that the proposed Hybrid Energy Storage System (HESS) integrating Nickel-Metal Hydride (Ni-MH) batteries and Electric Double-Layer Capacitors (EDLC) significantly enhances voltage stability, dynamic response, and overall system efficiency in a 40-kW islanded DC microgrid.
- The absence of a fast-response energy storage system results in poor voltage regulation, as observed in Case 1, where the system exhibited a peak overshoot of 43.8V at 2.5 seconds, an undershoot of 42.6V at 3.5 seconds, and a prolonged settling time of 0.5 seconds.
- The battery-only configuration, as examined in Case 2, leads to substantial stress on the battery due to rapid load fluctuations, resulting in a high voltage deviation of 41.23V, a peak overshoot of 45.02V, and a settling time of 0.4 seconds, thereby demonstrating its limitations in handling transient conditions effectively.
- The integration of Ni-MH batteries and EDLC supercapacitors in the HESS, as analysed in Case 3, significantly improves the system's transient response by reducing peak overshoot to 36V, undershoot to 11.6V, and achieving a faster battery response time of 0.1 seconds and a supercapacitor response time of 0.01 seconds, thereby ensuring superior voltage regulation and stability.
- The proposed Ni-MH + EDLC-based HESS configuration outperforms conventional Lithium-ion (Li-ion) battery and supercapacitor systems in terms of transient response, voltage stabilization, and battery lifespan, making it a viable alternative for long-term sustainable energy storage solutions in DC microgrids.
- The optimization results reveal that among the standalone metaheuristic algorithms, the Grey Wolf Optimizer (GWO) achieves the best performance by reducing the system's settling time to 0.1 seconds, eliminating overshoot, and enhancing battery efficiency to 81%, thereby proving its effectiveness in optimizing HESS control parameters.
- The implementation of hybrid optimization techniques, particularly the Artificial Bee Colony-Grey Wolf Optimizer (ABC-GWO) approach, further enhances system performance by achieving a best score of 4314.63W in 17 iterations, reducing settling time to 0.016 seconds, limiting peak overshoot to 4.72%, and improving battery efficiency to 85.58%, establishing its superiority over individual optimization methods.
- The research successfully integrates advanced control strategies, including Maximum Power Point Tracking (MPPT) using the Incremental Conductance (INC) method, State of

Charge (SOC) management, and Discrete Proportional-Integral (PI) control, which collectively improve power distribution, mitigate voltage instability, and extend battery lifespan.

- The optimized Ni-MH + EDLC-based HESS, when coupled with hybrid optimization strategies, provides an effective and scalable solution for future DC microgrid applications by enhancing voltage stability, minimizing response time, and improving overall system efficiency, thereby contributing to the development of more resilient and sustainable energy storage systems.

Conclusion

This research successfully demonstrates the effectiveness of control, optimization, and power management in enhancing the performance, stability, and efficiency of a 40-kW islanded DC microgrid. In this study, Hybrid Energy Storage Systems (HESS) play a critical role in ensuring the stability and efficiency of batteries in DC microgrids by addressing challenges such as voltage instability and rapid battery degradation.

The dynamic response and performance of HESS are controlled and optimized by strategies aimed at improving battery efficiency, response times, and overall system stability. Specifically, it proposes a new HESS configuration that combines Nickel-Metal Hydride (Ni-MH) batteries and Electric Double-Layer Capacitors (EDLC) to overcome the limitations of conventional Lithium-ion (Li-ion) battery and supercapacitor-based systems, especially under conditions of fluctuating loads and intermittent photovoltaic energy generation. By integrating renewable energy sources, hybrid energy storage systems, and a DC bus, utilized with various control techniques to improve voltage stability and system response. The novel HESS configuration combining Ni-MH batteries and EDLC supercapacitors successfully addresses issues such as voltage instability and battery degradation, commonly encountered in traditional Li-ion battery and supercapacitor-based systems.

The modeling and design of the 40-kW DC microgrid, which includes capacity for photovoltaic (PV) arrays, Ni-MH batteries, Proton Exchange Membrane (PEM) fuel cells, and EDLC supercapacitors, ensured optimized power distribution and energy utilization. Various case studies were conducted to analyse the system's response to dynamic load fluctuations and intermittent renewable energy generation. In Case 1, without energy storage, the system had moderate voltage regulation but suffered from significant overshoot (43.8 V) and a long settling time (0.5 sec). Case 2, which included only a battery, showed slight improvement but still faced high voltage fluctuations and stress due to slow response (peak overshoot: 45.02 V, settling time: 0.4 sec). In Case 3, integrating both a battery and a supercapacitor significantly enhanced performance, reducing peak overshoot to 36 V, settling time to 0.2 sec, and achieving faster stabilization. The supercapacitor's rapid 0.01s response complemented the battery's stable energy supply, ensuring superior voltage regulation. Despite these improvements, further optimization was needed to minimize overshoot and enhance system efficiency.

To further enhance system performance, several advanced metaheuristic optimization algorithms were employed to enhance system performance by optimizing settling time, peak overshoot, and battery efficiency. PSO improved response time but had voltage fluctuations, achieving a best score of 9851.56 W in 38 iterations with a 0.23 sec settling time, 13% overshoot, and 76% efficiency. ABC performed better in some aspects, scoring 10522.6 W in 27 iterations, with a 0.4s settling time, 5.95% overshoot, and 69% efficiency. GWO outperformed both, achieving 5327.19 W in 25 iterations with the best results: 0.1 sec settling time, zero overshoot, and 81% efficiency. These results highlight the effectiveness of optimization in improving stability and energy efficiency in DC microgrids.

Hybrid optimization techniques are essential because they combine the strengths of individual algorithms to achieve better overall performance. While each standalone method like PSO, ABC, and GWO improved specific metrics (settling time, overshoot, or battery efficiency), none were able to optimize all aspects simultaneously. By combining these algorithms, hybrid strategies like PSO-ABC and ABC-GWO can balance settling time, peak overshoot, and battery efficiency more effectively. This leads to improved voltage regulation, faster stabilization, and enhanced system performance, making hybrid optimization crucial for DC microgrid systems under dynamic conditions. The ABC-GWO hybrid optimization outperformed other techniques, achieving a best score of 4314.63 W in 17 iterations, with a 0.016 sec settling time, 4.72% overshoot, and 85.58% battery efficiency. The PSO-ABC hybrid also improved performance but was less effective. Hybrid techniques, especially ABC-GWO, proved superior in optimizing settling time, overshoot, and efficiency.

Furthermore, the simulation results were used in conjunction with metaheuristic optimization algorithms to tackle voltage instability, minimize energy dissipation, and optimize energy storage utilization. Additionally, the hybrid optimization techniques, specifically the ABC-GWO approach, effectively balanced voltage stability and battery lifespan. The integration of advanced control strategies, power management systems, and hybrid optimization techniques has led to significant improvements in system performance, energy efficiency, and stability. Among the various optimization approaches, the ABC-GWO hybrid method demonstrated the most effective results in enhancing overall system performance, offering a promising solution for real-world applications.

Recommendations for Future Research

While this research significantly advances the control, optimization, and energy management strategies for DC microgrids, several limitations remain, offering valuable opportunities for further exploration:

- **Enhancing Fuel Cell Response Dynamics:**

The slower response time of Proton Exchange Membrane (PEM) fuel cells results in transient fluctuations in the DC bus voltage. Future research should focus on advanced predictive control strategies, such as Model Predictive Control (MPC) or Reinforcement Learning (RL)-based adaptive controllers, to enhance dynamic response and improve voltage stability. Additionally, auxiliary energy storage solutions, such as hybrid supercapacitor-flywheel systems, could be explored to mitigate response delays.

- **Integration of Electric Vehicles (EVs) as Mobile Energy Storage Units:**

The potential of EVs as decentralized and mobile energy storage units within DC microgrids remains underexplored. Further investigation is required to develop intelligent energy dispatch algorithms that optimize EV charging/discharging schedules while considering battery aging, grid demand fluctuations, and bidirectional power flow constraints. The integration of vehicle-to-grid (V2G) and vehicle-to-microgrid (V2M) frameworks can further enhance energy flexibility and grid resilience.

- **Hybrid AC/DC Microgrid Synchronization and Stability:**

The expansion of DC microgrids into grid-tied or hybrid AC/DC configurations introduces challenges related to synchronization, power quality, and interconnection stability. Future research should focus on developing robust synchronization techniques using adaptive phase-locked loops (APLL) or artificial intelligence (AI)-based predictive controllers to ensure seamless power exchange between AC and DC domains.

- **Advanced Energy Storage Strategies for Continuous Power Availability:**

The intermittent nature of solar energy poses significant challenges, particularly during nighttime operation or prolonged periods of low solar availability. To address this, future work should explore advanced hybrid energy storage systems (HESS) integrating next-generation battery chemistries, such as solid-state or sodium-ion batteries, alongside supercapacitors and fuel cells. Additionally, research on energy forecasting models, leveraging deep learning techniques, can enhance predictive scheduling to optimize energy storage utilization and ensure an uninterrupted power supply.

By addressing these key research gaps, future advancements in DC microgrid technology can further improve resilience, efficiency, and reliability, paving the way for scalable, intelligent, and sustainable microgrid architectures.

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