CHAPTER 7

Concluding Remarks

7.1 Conclusion

This research successfully demonstrates the effectiveness of control, optimization, and power management in enhancing the performance, stability, and efficiency of a 40-kWh 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.

This research focuses on enhancing the dynamics response and performance of HESS by control and optimization strategies aimed at improving battery efficiency, response times, and overall system stability. Specifically, 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 (RES), Hybrid Energy Storage Systems (HESS), and a DC bus, utilized 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 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-kWh DC microgrid, which includes capacity calculations 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 analyze the system's response to dynamic load fluctuations and intermittent renewable energy generation. The results emphasized the critical role of HESS in achieving reliable voltage regulation and fast dynamic stabilization.

In Case 1, where fast-response energy storage was absent, the system displayed moderate voltage regulation, with a peak overshoot of 43.8 V occurring at 2.5 seconds, an undershoot of 42.6 V at 3.5 seconds, and a settling time of 0.5 seconds. In Case 2, which included a battery, the system experienced significant stress due to rapid load variations. This stress restricted the battery's ability to respond effectively, resulting in only marginal improvement in performance. The settling time reduced slightly to 0.4 seconds, but the system still encountered substantial voltage fluctuations. Specifically, the peak overshoot was recorded at 45.02 V at 0.5 seconds, with an undershoot of 60.1 V at 4 seconds. The battery response time was 0.5 seconds, which was insufficient to compensate for the rapid load changes. Consequently, the peak overshoot percentage was 18.46%, and the voltage deviation reached 41.23 V. In Case 3, where both a battery and a supercapacitor were integrated into the Hybrid Energy Storage System (HESS), the system demonstrated significantly enhanced performance. This configuration achieved a peak overshoot of 36 V at 0.5 seconds, an undershoot of 11.6 V at 4 seconds, and a settling time of 0.2 seconds. The battery response time was reduced to 0.1 second, while the supercapacitor exhibited an even faster response time of 0.01 second. The peak overshoot was reduced to 6.5%, and the voltage deviation was 40.6 V, underscoring the superior voltage regulation achieved with this hybrid system. Importantly, the response time objective was fully satisfied with the novel HESS configuration, as the system demonstrated rapid response to transient load fluctuations, meeting the required performance standards for fast dynamic stabilization.

The improved performance observed in Case 3 can be attributed to the complementary roles played by the battery and the supercapacitor. The supercapacitor, with its rapid response time of 0.01 seconds, was able to quickly absorb or release energy in response to transient load variations, while the battery, with a response time of 0.1 seconds, provided more stable energy over longer durations. This synergy between the battery and supercapacitor enabled faster voltage stabilization and more effective regulation. In contrast, Case 2, which relied solely on the battery, was constrained by the slower response to the rapid load fluctuations, resulting in higher voltage deviations, slower stabilization, and larger overshoot. Therefore, in Case 3, where both a battery and supercapacitor were integrated into the Hybrid Energy Storage System (HESS), the response time, voltage stability, and overall performance showed marked improvements compared to Case 2. However, despite the enhanced configuration, further optimization was essential to achieve optimal performance, particularly in terms of minimizing voltage overshoot and settling time.

To further enhance system performance, several advanced metaheuristic optimization algorithms were employed, including Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Grey Wolf Optimizer (GWO). These optimization techniques aimed to fine-tune the system parameters, improving critical performance metrics such as settling time, peak overshoot, and battery efficiency. The PSO algorithm achieved a best score of 9851.56 W in 38 iterations, with a settling time of 0.23 seconds, a peak overshoot of 6.2%, and a battery efficiency of 76%. While PSO showed a noticeable improvement in the overall system response, there were still fluctuations in voltage regulation. The ABC algorithm, on the other hand, achieved a best score of 10522.6 W in 27 iterations. This resulted in a settling time of 0.4 seconds, a peak overshoot of 5.95%, and a battery efficiency of 69%, marking an improvement over PSO, but the settling time and battery efficiency were still not ideal for optimal system performance. The GWO algorithm outperformed both PSO and ABC, achieving the best score of 5327.19 W in 25 iterations. It delivered a settling time of 0.1 seconds, zero overshoot, and the highest battery efficiency of 81%, demonstrating superior optimization capabilities. These results highlight the critical role of optimization algorithms in improving system performance, specifically in reducing settling time, eliminating overshoot, and maximizing battery efficiency, ensuring better voltage regulation and stability in the DC microgrid system.

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 PSO-ABC hybrid technique achieved a best score of 5984.16 W in 11 iterations, with a reduced settling time of 0.05 seconds, a peak overshoot of 7.04%, and a battery efficiency of 78%. The ABC-GWO hybrid approach provided the most optimal performance, with a best score of 4314.63 W in 17 iterations, a settling time of 0.016 seconds, a low peak overshoot of 4.72%, and the highest overall battery efficiency of 85.58%. These results underscore the superior optimization capabilities of hybrid techniques, particularly the ABC-GWO approach, in balancing performance metrics like settling time, peak overshoot, and battery 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. GWO outperformed the other methods in terms of achieving the fastest settling time, zero overshoot, and the highest battery efficiency. Additionally, the hybrid optimization techniques, specifically the ABC-GWO approach, effectively balanced voltage stability and battery lifespan. This research underscores the pivotal role of Hybrid Energy Storage Systems (HESS) in providing stable, high-speed dynamic stabilization and voltage regulation for islanded DC microgrids. 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. Moreover, the Ni-MH and EDLC-based HESS configuration has shown its potential to outperform traditional Li-ion systems, achieving 85.58% battery efficiency, a settling time of 0.016 seconds, and a peak overshoot of only 4.72%, promising superior battery efficiency, faster dynamic response, and enhanced voltage stability.

7.2 Limitations and Future Scope

While the contributions of this research offer significant advancements, several limitations have been identified. These limitations present valuable opportunities for future exploration and development.

The key limitations are outlined below:

1. Fuel cells have a slower response time, which leads to fluctuations in the DC bus voltage link, which must be stabilized through advanced control strategies or auxiliary systems.

2. Further investigation into the integration of Electric Vehicles (EVs) as mobile energy storage units within the DC microgrid could enhance flexibility and increase the capacity for energy management.

3. Expanding the DC microgrid to include grid-tied configurations or hybrid AC/DC systems presents challenges, particularly in terms of synchronization, power quality, and ensuring interconnection stability between the two systems.

4. The lack of solar generation during nighttime operation, combined with insufficient energy storage or backup power, can result in unmet load demands during prolonged periods of low solar availability, highlighting the need for a more robust energy storage solution.