

CHAPTER 1

Introduction

1.1 Background

Electricity has long been a cornerstone of modern civilization, powering industries, homes, transportation systems, communication networks, and virtually all aspects of daily life. The journey of electricity began in the 18th and 19th centuries when early discoveries in electrical theory and technology set the foundation for its widespread use. Pioneering scientists such as Benjamin Franklin, Alessandro Volta, Michael Faraday, and James Clerk Maxwell made groundbreaking contributions that deepened our understanding of electricity and magnetism. Franklin's famous kite experiment in 1752 helped establish the link between electricity and lightning, while Volta's creation of the first chemical battery in 1800 paved the way for the study of electric current. Faraday's discovery of electromagnetic induction in 1831 revealed that electricity could be generated by moving a conductor through a magnetic field, which led to the invention of the electric generator. Meanwhile, Maxwell's equations unified the principles of electricity and magnetism, establishing the foundation for modern electromagnetic theory.

With these scientific advancements, the practical application of electricity began to flourish. In 1879, Thomas Edison invented the electric light bulb, and soon after, in 1882, he established the first electric power station in New York, known as the Pearl Street Station, marking the beginning of centralized electricity generation. The system was based on the idea of generating electricity at large power plants, typically fuelled by fossil resources such as coal, oil, or natural gas, and transmitting it over long distances to homes and businesses. This centralized model enabled the electrification of cities and industries, triggering an era of rapid urbanization and industrialization. Electricity technological advancements revolutionized manufacturing processes and transformed daily life by providing reliable lighting, heating, and communication systems. It played a crucial role in shaping the modern world, enabling economic growth and global interconnectedness.

However, while the centralized power model powered industrial growth and urbanization, it also brought several challenges. One of the most significant issues was the inefficiency of long-distance electricity transmission. As electricity travelled from power plants to consumers, a portion of it was lost as heat due to resistance in power lines. This energy loss reduced the overall efficiency of the system, making it less sustainable. Additionally, fossil fuel-based power plants, particularly those relying on coal, released harmful pollutants into the atmosphere, including carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x), which contributed to air pollution and climate change. These environmental concerns have

prompted global efforts to transition away from fossil fuels and toward more sustainable energy solutions. Moreover, the centralized grid model is vulnerable to disruptions, such as natural disasters, equipment failures, or cyberattacks. A failure in one part of the grid can lead to widespread blackouts, demonstrating the need for more resilient and adaptive energy systems.

Role of Renewable Energy Sources (RESs)

As concerns about the environmental impact of fossil fuels and the vulnerabilities of centralized power systems have grown, the shift toward renewable energy sources (RESs) has become a critical priority in the quest for a sustainable future. Renewable energy sources, such as solar, wind, hydro, geothermal, and biomass, offer cleaner alternatives to traditional fossil fuels, with much lower environmental footprints. The need for renewable energy arises primarily from the growing recognition that fossil fuels are finite resources, and their extraction and use contribute significantly to environmental degradation. The burning of coal, oil, and natural gas for electricity generation emits large amounts of carbon dioxide (CO₂), a leading cause of global warming. The widespread environmental damage caused by fossil fuels such as rising global temperatures, more frequent extreme weather events, and the depletion of natural resources has spurred the global transition to cleaner energy sources.

Renewable energy sources provide a solution to these challenges by offering abundant, sustainable, and cleaner alternatives. Solar energy, for example, harnesses the power of sunlight using photovoltaic (PV) panels, which convert sunlight directly into electricity. Solar technology has advanced significantly in recent years, and its costs have dropped dramatically, making it an increasingly accessible option for residential, commercial, and industrial use. Wind energy is another rapidly growing source of renewable power. By converting the kinetic energy of wind into electricity using turbines, wind power offers a clean, renewable solution for power generation. Advances in turbine technology and cost reductions have made wind power more competitive, especially in regions with high wind speeds, such as coastal areas and plains. Hydroelectric power, which generates electricity through the movement of water, has been in use for centuries and continues to play a significant role in renewable energy production. Large-scale hydroelectric plants, as well as smaller-scale systems, provide substantial amounts of electricity, although large dams can have environmental impacts on local ecosystems.

Geothermal energy, which taps into the Earth's internal heat, is another key renewable resource. Geothermal power plants can provide a consistent and reliable energy supply, as the Earth's

heat is virtually inexhaustible. In areas with significant volcanic or tectonic activity, such as Iceland or parts of the United States, geothermal energy has become a viable source of electricity. Biomass energy, derived from organic materials like wood, agricultural residues, and waste, can be used to generate electricity or heat. While biomass combustion produces carbon emissions, it is considered carbon-neutral because the plants used for biomass absorb CO₂ during their growth phase. These renewable energy sources are increasingly showing as an essential component of a diversified and sustainable energy mix.

Figure 1.1 represents the contribution of different renewable energy sources to the total energy generation mix, as reported by the Ministry of New and Renewable Energy (MNRE), Government of India. Solar power emerges as the largest contributor, accounting for 58.73% of the total share, reflecting its significant adoption due to abundant solar resources and advancements in photovoltaic technology. Wind power follows with a 30.65% share, showcasing its vital role in renewable energy generation. Biomass-based energy, particularly from bagasse cogeneration, contributes 6.34%, while non-bagasse biomass cogeneration adds a smaller portion of 0.60%. Small hydropower makes up 3.28%, emphasizing its importance in providing localized energy solutions. Waste-to-energy technologies contribute modestly, with off-grid waste-to-energy systems at 0.23% and waste-to-power at 0.16%, highlighting the integration of sustainable waste management practices. Overall, the chart underscores India's growing reliance on solar and wind power, complemented by other renewable sources, to achieve a diverse and sustainable energy mix. The growing adoption of renewable energy is not just driven by environmental concerns but also by the desire to enhance energy security[1].

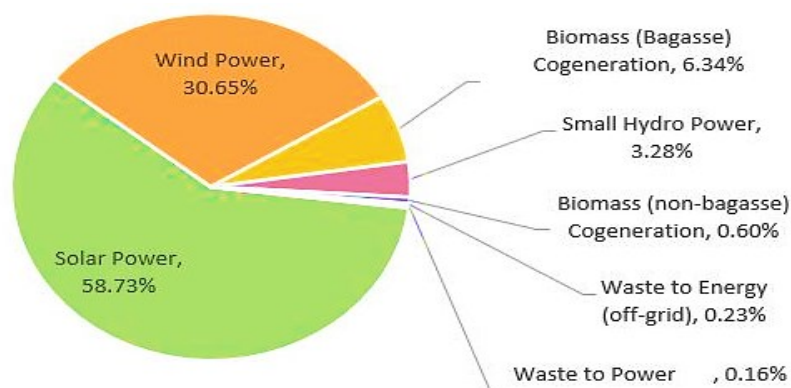


Figure 1.1 India Renewable Energy (September 2024) (MNRE)

Unlike fossil fuels, often imported from politically unstable regions, renewable energy sources are abundant and locally available. This reduces dependence on foreign energy supplies, enhancing national energy security. Additionally, renewable energy systems are often more

decentralized than traditional power plants, allowing for localized electricity generation [2]. Technologies like rooftop solar panels and small wind turbines allow individuals, businesses, and communities to generate their power, reducing reliance on large, centralized power plants. 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 [3][4]. 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[5]. 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 [6], campuses [7], [8], military installations[9], 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.

One of the main advantages of microgrids is their ability to enhance grid resilience. Traditional centralized grids are often susceptible to widespread outages caused by faults at a single point in the grid. Microgrids, on the other hand, are more resilient because they can operate independently when needed, minimizing the impact of disturbances. The flexibility of microgrids makes them highly suitable for critical infrastructure, such as hospitals, military bases, and emergency services, where an uninterrupted power supply is essential. Moreover, microgrids contribute to energy efficiency by optimizing the generation and consumption of electricity at a local level, reducing transmission losses, and enhancing overall system reliability.

A major challenge with renewable energy, particularly solar and wind, is its intermittent nature, which fluctuates throughout the day and across seasons. To address this challenge, energy storage technologies are playing an increasingly important role [10]. These technologies can store excess energy generated during periods of high production and release it when demand is high or generation is low. This capability helps to stabilize the system and ensures that renewable energy can be used reliably.

Rise of DC Microgrid

A recent and innovative development in the field of microgrids is the Direct Current (DC) microgrid [11]–[13]. Unlike traditional alternating current (AC) grids, which are typically used in most power systems today, DC microgrids use direct current for energy distribution. DC microgrids are particularly suited for environments where renewable energy sources like solar panels and batteries are used, as these technologies inherently generate and store electricity in DC form [14]. DC microgrids are also advantageous for integrating renewable energy systems, such as solar photovoltaics, batteries, and fuel cells, as they all naturally produce or operate on DC power. This alignment results in simpler and more efficient systems with reduced conversion losses. Furthermore, DC microgrids enable more flexible and precise control of energy flow, offering the potential for advanced applications in energy storage, electric vehicles, and high-efficiency appliances [15]. In these systems, energy storage devices, such as batteries, supercapacitor can be seamlessly integrated, ensuring the continuous supply of electricity even when renewable generation is low. The application of DC microgrids is particularly promising in off-grid and remote locations, where the decentralized nature of these systems can significantly improve energy access.

1.2 Structure and Function of DC Microgrid

The global energy transition toward renewable and sustainable sources, coupled with the increasing demand for efficient and reliable energy systems, has led to the rise of DC microgrids as a promising solution. This section explores the structural components and operational mechanisms of DC microgrids.

1.2.1 Structure of a DC Microgrid

The DC microgrid is a decentralized energy system designed to generate, distribute, and consume direct current (DC) power. Its structure is composed of several interconnected subsystems, each serving specific functions.

1.2.2 Energy Generation Units

Energy generation units in a DC microgrid consist of both renewable and backup power sources, ensuring a reliable and sustainable energy supply.

- Renewable Energy Sources (RES):
 - Solar Photovoltaic (PV) Panels: Solar PV systems are a primary component of DC microgrids, generating DC electricity directly from sunlight [16].
 - Wind Turbines: Equipped with rectifiers to convert AC output into DC, wind turbines contribute to diversified energy generation.
 - Biomass and Fuel Cells: These systems provide additional generation capacity, producing DC power through chemical or biological processes.
- Backup Generators:
 - Diesel or natural gas generators act as emergency power sources, ensuring reliability during periods of low renewable energy generation.

1.2.3 Energy Storage Systems (ESS)

Energy storage systems (ESS) play a crucial role in maintaining power stability within a DC microgrid by storing surplus energy and supplying it when needed.

- Batteries:

Lithium-ion is commonly used to store surplus energy generated by RES [17]. They release stored energy during peak demand or low generation periods, ensuring a stable power supply [18].

- Supercapacitors (ELDC):

These are used for short-term energy storage, offering rapid charge-discharge cycles and supporting transient load demands [19].

- Hybrid Energy Storage Systems (HESS):

Combining batteries and supercapacitors leverages the high energy density of batteries and the high-power density of supercapacitors, improving efficiency and response times [20].

1.2.4 Distribution Network

The distribution network in a DC microgrid facilitates efficient power transmission by interconnecting generation, storage, and load units while ensuring system protection and stability.

- DC Busbar:

A central DC bus connects all generation, storage, and load units, enabling efficient power distribution. Multiple voltage levels (e.g., 48V, 380V) may exist within the network to accommodate various devices.

- Power Converters:

- DC-DC Converters: Adjust voltage levels to suit specific loads or storage requirements [21].
- Rectifiers and Inverters: Allow seamless integration with the main AC grid or AC loads when necessary.

- Protection Devices:

Fuses, circuit breakers, and surge protectors safeguard the system against faults and over-currents.

1.2.5 DC Loads

DC loads in a microgrid encompass a variety of applications across residential, commercial, industrial, and transportation sectors, benefiting from direct DC power distribution.

- Residential Loads: LED lighting, electronics, and home appliances optimized for DC operation.
- Commercial and Industrial Loads: Data centers, telecommunication systems, and automation machinery.
- Electric Vehicles (EVs): Direct DC charging stations for EVs.

1.2.6 Control and Communication Systems

Control and communication systems are essential for ensuring the efficient operation, stability, and reliability of a DC microgrid.

- Power Management System (PMS):

Monitors and optimizes the operation of the microgrid, ensuring a balance between supply and demand [22]. Implements demand-side management and prioritizes critical loads during shortages.

- **Controllers:**

Regulate power flow, voltage levels, and system stability. Enable seamless switching between grid-tied and islanded operations.

1.2.7 Function of a DC Microgrid

DC microgrids are designed to achieve multiple operational objectives while addressing the unique challenges of modern energy systems [23]. Their functions can be categorized into the following:

- **Energy Generation and Distribution**

Direct generation of DC power from renewable sources eliminates the need for AC-DC conversion, enhancing efficiency. Distribution through the DC network reduces transmission losses and simplifies the system architecture.

- **Energy Storage and Management**

Storage systems play a crucial role in managing intermittency in renewable generation. The combination of batteries and supercapacitors allows for both long-term energy storage and rapid response to load fluctuations.

- **Interaction**

In grid-tied mode, the DC microgrid can exchange power with the utility grid, exporting surplus energy or importing power during deficits. In islanded mode, the microgrid operates autonomously, ensuring energy security during grid outages.

- **Load Balancing**

Real-time monitoring and control systems ensure an optimal balance between energy supply and demand, avoiding overloading or underutilization.

- **Voltage Regulation**

DC-DC converters and controllers maintain stable voltage levels across the network, ensuring compatibility with connected loads.

1.2.8 Advantages of DC Microgrid

DC microgrids offer several benefits, making them a promising solution for modern energy systems [24], [25],[26]:

- **Energy Efficiency:** Reduced conversion losses due to the inherent DC nature of renewables and storage systems.
- **Renewable Energy Integration:** Simplified integration of solar PV, wind turbines, and other RES.

- **Enhanced Reliability:** Localized generation and storage reduce dependency on centralized systems.
- **Cost Effectiveness:** Lower operational costs due to energy savings and reduced infrastructure requirements.
- **Scalability:** Modular design enables easy expansion to meet growing energy demands.
- **Environmental Benefits:** Supports the transition to a low-carbon energy system.

1.2.9 Challenges in DC Microgrid

Despite their advantages, DC microgrids face several challenges that require innovative solutions:

- **Intermittency of Renewables:** The variable nature of renewable energy requires advanced control algorithms for real-time energy balancing, leveraging AI and predictive modeling [27].
- **Energy Storage Optimization:** Improving the efficiency, durability, and cost-effectiveness of hybrid energy storage systems (e.g., Ni-MH batteries and ELDC supercapacitors) is essential [28].
- **DC Link Voltage Maintenance:** Ensuring stable DC link voltage is critical for reliable operation, requiring advanced control strategies to handle dynamic changes in load and generation.

1.3 Problem Statement

During rapid load variations in DC microgrids, voltage fluctuations significantly challenge voltage stability and reliability [29]. Traditional Hybrid Energy Storage Systems (HESS), which combine lithium-ion (Li-ion) batteries with Li-ion supercapacitors, have been employed to mitigate these issues, however, they suffer from several limitations, including slow response times, inconsistent voltage regulation, and accelerated battery degradation caused by frequent charging and high discharge rates [30], [31]. Although Li-ion batteries have a high energy density for long-term storage, they are not designed to withstand abrupt changes in load power [32]. Conversely, while faster than batteries, Li-ion supercapacitors still struggle with limited power density and a shorter cycle life.

A novel HESS configuration combining Nickel-Metal Hybrid (Ni-MH) batteries with Electric Double-Layer Capacitors (EDLC) supercapacitors is proposed in this research as an innovative approach to overcome the above limitations.

1.4 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.

1.5 Motivation for the Research

The increasing global demand for reliable, sustainable, and efficient energy systems has intensified the need for innovative solutions in energy generation, distribution, and storage. Traditional centralized power grids face significant challenges, including energy losses during long-distance transmission, grid instability, and environmental concerns from fossil fuel-based energy sources. These limitations necessitate a transition to decentralized energy systems that can better integrate renewable energy sources (RES).

Renewable energy technologies, such as solar photovoltaic (PV), have gained prominence for their environmental benefits. However, their intermittent and variable nature poses challenges to maintaining a stable energy supply. To address these issues, microgrids localized and flexible energy systems have emerged as a transformative solution. Among them, DC microgrids offer several advantages, including higher energy efficiency, reduced conversion losses, and better compatibility with modern DC-based devices and energy storage systems.

A critical aspect of DC microgrids is the effective management of energy storage systems (ESS). Hybrid Energy Storage Systems (HESS), combining technologies like Ni-MH batteries and ELDC supercapacitors, provide a promising approach by leveraging the strengths of both components high energy density from batteries and high-power density from supercapacitors. Optimizing HESS for seamless integration into DC microgrids is crucial for enhancing system performance and ensuring resilience against energy fluctuations.

To validate the system's effectiveness, simulations are first conducted in MATLAB Simulink. These simulations model various operational scenarios in the DC microgrid, focusing on the performance of the Ni-MH battery and ELDC supercapacitor under fluctuating load demands and intermittent solar energy generation. Key performance metrics such as 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, advanced hybrid optimization approaches are employed to further enhance system performance. 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.

This research is motivated by the need to overcome existing challenges in DC microgrid implementation, such as maintaining stable DC link voltage, improving the response time of hybrid energy storage systems, and optimizing energy management strategies. This work aims to contribute to the advancement of sustainable energy systems and support the global transition toward a low-carbon future.

1.6 Major Research Contributions

The following key research contributions are presented:

1 Development of an Advanced DC Microgrid Model

This research contributes to the modeling and simulation of a DC microgrid integrated with a Hybrid Energy Storage System (HESS) comprising Ni-MH batteries and ELDC supercapacitors. A comprehensive MATLAB-based model has been created to simulate real-world scenarios of fluctuating solar energy generation and dynamic load demands. This model forms the foundation for further optimizations and improvements in system performance.

2 Optimization of Hybrid Energy Storage Systems (HESS)

A novel approach for optimizing the performance of hybrid energy storage systems in DC microgrids is presented. This includes enhancing the energy sharing mechanism between the Ni-MH battery and the ELDC supercapacitor to ensure efficient power utilization, longer lifespan, and quicker response times to load changes and renewable energy fluctuations.

3 Hybrid Optimization Approaches for Enhanced Performance

This research introduces hybrid optimization approaches, specifically PSO-ABC and ABC-GWO, to further improve the performance of the DC microgrid system. These hybrid algorithms combine the strengths of individual swarm intelligence techniques, enabling better exploration and exploitation of the solution space. The hybrid methods focus on improving the response times of hybrid energy storage systems and maintaining stable DC link voltage under varying operating conditions.

1.7 Thesis Organization

The content of the thesis is summarized as:

Chapter 1: This chapter describes the brief history and overview of the research problem. It also introduces the objectives of the research work and the scope of the improvement in existing methods.

Chapter 2: Covers a literature assessment of DC microgrid control under various scenarios.

Chapter 3: Various Mathematical Models for the DC Microgrid

Chapter 4: Describes the Proposed Methods with algorithms in each task: Using Control strategies simulation and Control of novel HESS configuration.

Chapter 5: Discuss the detailed metaheuristic optimization techniques applied to the DC Microgrid.

Chapter 6: Implement Hybrid optimization methods integrate different optimization strategies in DC Microgrid.

Chapter 7: Concludes with the remarks regarding proposed solutions and their applicability under various situations. Future work in the area is also suggested.