CHAPTER 2

State of Art

2.1 Background

Microgrids play a crucial role in mitigating challenges posed by intermittent power generation and consumption by heterogeneous loads, ensuring efficient frequency and voltage regulation, reducing power losses, and modernizing grids. The structure of microgrids (DC, AC, or AC-DC) should be chosen optimally to maintain power quality parameters, increase the reliability of power supply, and design a customized control system based on the specific characteristics of DERs, microgrid structures, and electrical loads. Microgrids were developed to address the complex grid structure and provide power to underserved areas.

DC microgrids have been established due to their higher efficiency, better integration with renewable energy sources and energy storage systems, and simpler control systems. DC microgrids have gained significant attention as an efficient and reliable alternative to conventional AC-based power distribution systems. With the growing adoption of renewable energy sources (RES) such as solar Photovoltaic (PV) and wind energy, the interest in DC microgrids has increased due to their compatibility with these sources and their potential for enhanced energy efficiency.

2.2 Control Strategies and Operational Challenges in Islanded DC Microgrids

DC microgrids have gained significant attention due to their potential to enhance power supply efficiency, reliability, and resilience. The increasing penetration of Distributed Energy Resources (DERs) and advancements in power electronics have accelerated research in DC microgrid control strategies. A DC microgrid can operate in two distinct modes: grid-connected and islanded. In the grid-connected mode, it interfaces with the main utility grid, facilitating bidirectional power flow, load balancing, and ancillary service support. Conversely, in islanded mode, the microgrid operates autonomously, ensuring a stable and uninterrupted power supply in the absence of grid connectivity. While grid-connected DC microgrids contribute to urban electricity distribution and renewable energy integration, their primary advantage lies in their ability to function independently during grid disturbances, making them highly suitable for critical applications such as emergency power supply, disaster resilience, and remote electrification.

The microgrid is decoupled from the primary utility grid and must rely entirely on local generation and energy storage systems to supply power to its connected DC loads in islanded mode. Studies and real-world implementations demonstrate that an islanded DC microgrid can effectively address power supply challenges in small rural or remote areas, where communities lack access [33] to the centralized utility grid due to technical limitations and economic constraints.

Employing an islanded DC microgrid with an optimized power generation system that integrates renewable energy sources, such as photovoltaic panels and wind turbines, along with Hybrid Energy Storage Systems (HESS), including batteries and supercapacitors, is a more cost-effective and sustainable approach for electrifying off-grid neighbourhoods.

In islanding mode, the microgrid operates autonomously, without any grid support, necessitating robust control strategies to maintain stability and reliability. The absence of grid reinforcement introduces significant control complexities due to the presence of multiple nonlinear loads [34], including power electronic converters, Electric Vehicle (EV) chargers, and variable-speed motor drives. These nonlinear loads contribute to voltage and current distortions, which degrade power quality and pose operational challenges in islanded DC microgrids. Maintaining stable voltage while dynamically balancing power generation and consumption becomes increasingly difficult, especially when nonlinear loads interact unpredictably, leading to harmonic distortions, transient disturbances, and voltage fluctuations.

Extensive research in the literature explores various advanced control methodologies for stabilizing islanded DC microgrids and mitigating power quality issues. The first section provides an in-depth analysis of the critical control challenges associated with islanded DC microgrid operation, particularly in systems integrating distributed energy resources and hybrid energy storage. The subsequent section presents a comprehensive review of hierarchical control architectures [35], including primary, secondary, and tertiary control strategies, for ensuring voltage stability, power-sharing accuracy, and enhanced system resilience in an islanded DC microgrid.

2.3 Stability Challenges and Control of Constant Power Loads in Islanded DC Microgrids

The successful operation of a DC microgrid in islanded mode necessitates the maintenance of a stable voltage and acceptable transient performance across a range of loading conditions.

Insufficient load support and inadequate disturbance-damping capabilities are primary contributors to instability and suboptimal transient behavior. DC microgrids commonly employ a diverse array of power electronic devices, including converters for cascade, parallel, drive, and isolation configurations. Collectively, these devices form a multi-converter power electronic-based system, which is critical for satisfying the dynamic and varied requirements of the interconnected loads, thereby ensuring stable and reliable microgrid operation in islanded mode [36], [37].

To maintain the desired system characteristics, such as voltage stability and power sharing among multiple generators, these converters must be regulated through appropriate control mechanisms. This regulation is particularly important during transient events or unexpected increases in load demand [38]–[40]. Consequently, the converter plays a critical role in the control architecture of the DC microgrid. When control is tightly applied, the load converter exhibits the characteristics of a Constant Power Load (CPL). These CPLs are characterized by negative incremental impedance, which can destabilize the system. The negative impedance at the output of the source converter terminals reduces system damping, leading to the development of limit cycle oscillations. These oscillations manifest as internal fluctuations between the capacitor and inductor connected to the source converters, resulting in an unstable DC-bus voltage and placing additional stress on the control of the source converters.

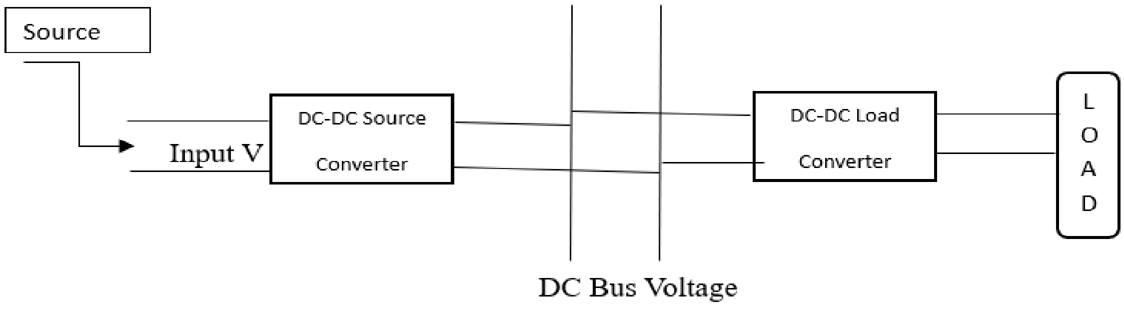

Figure 2. 1 Power electronic based multi converter system connected to Load

As illustrated in Figure 2.1, a load is connected to the DC bus through an interface that actively regulates its output power. Consequently, the load maintains a piecewise constant power output, which remains unaffected by voltage or current disturbances. Nonlinear Constant Power Loads (CPLs), however, exhibit negative impedance behavior, meaning that the voltage across a CPL decreases as the current injection increases, in contrast to constant current or impedance loads.

This negative impedance characteristic effectively reduces the system's resistive damping, which can exacerbate stability challenges.

For instance, a large CPL could cause a significant drop in the DC microgrid's voltage level, potentially destabilizing the system. Moreover, a DC microgrid with inadequate damping is highly susceptible to excessive voltage oscillations when subjected to external disturbances, further compromising system stability and reliability.

2.4 Renewable Energy Sources using PV Array

Renewable energy plays a crucial role in sustainable development by reducing carbon dioxide emissions and supporting applications in residential, industrial, and commercial buildings [41]. An energy management system based on renewable energy sources can enhance power generation efficiency. Similarly, implemented a prototype for photovoltaic power generation integrated with Battery Energy Management Systems (BEMS) [42] to ensure the continuous operation of load systems. The BEMS control strategies perform critical tasks, and preliminary test results confirm the effectiveness of these strategies.

In [43], addressed the challenge posed by the use of converters and their control systems, which prevent frequency adjustments in renewable energy systems. This issue becomes significant when integrating large numbers of renewable energy sources while maintaining stable frequency and voltage. The performance of wind power, PV power generation, and energy storage systems. When the system frequency drops, the active power output of wind and PV systems must be increased to maintain stability [44]. To optimize system frequency, the wind-PV energy storage system must be strategically managed to maximize the output of the main power source. Additionally, a three-phase voltage source inverter converts DC voltage to AC voltage, ensuring synchronization with the grid when the AC voltage matches the grid power. In [45], highlighted that while renewable energy is sustainable, clean, and cost-effective, it faces limitations due to dependency on weather conditions. To address this, hybrid power generation systems are necessary to meet peak demand.

In [46], discussed the implementation of a DC-DC converter to regulate voltage efficiently. Another proposed strategy aims to limit operational challenges associated with renewable energy storage. This approach enhances system efficiency, particularly in power generation, as demonstrated by simulation results. However, despite the cost advantages of renewable energy, it has two significant drawbacks: dependency on weather conditions and misalignment with peak demand [47], [48]. To mitigate these challenges, renewable distributed generators (DGs) are often supported by energy storage systems to stabilize power fluctuations and synchronize generation with demand. However, energy storage solutions remain expensive.

2.5 Modeling and Control of Energy Storage System

The integration of renewable energy technologies poses significant challenges to the stability of the electrical grid due to the inherent variability and intermittency of renewable energy sources. This unpredictability arises from dependence on meteorological conditions such as solar irradiance and wind velocity. For instance, a sudden increase in cloud cover or an abrupt cessation of wind can lead to a substantial reduction in power output from photovoltaic systems and wind turbines. To mitigate these fluctuations, advanced Energy Storage Systems (ESS) are essential for storing excess energy generated during periods of high renewable output or low electricity demand, enabling its utilization during periods of low generation or peak load conditions [49].

Beyond mitigating output variability, energy storage plays a crucial role in grid stability by providing power and voltage regulation, ensuring a smooth and reliable energy supply. Furthermore, ESS contributes to critical grid-support functionalities such as energy management, frequency regulation, peak demand shaving, load levelling, seasonal energy storage, and emergency power supply during grid contingencies or faults. Given the escalating penetration of renewable energy into modern power systems, energy storage technologies have garnered significant research attention and are now recognized as indispensable components for ensuring grid resilience and operational efficiency [50].

The Proportional-Integral-Derivative (PID) controllers within photovoltaic systems have become a critical factor affecting the efficiency and stability of power output. PID-induced degradation significantly influences PV module performance, particularly in humid environments where system components are prone to insulation deterioration [51]. The PID control approach is implemented at two hierarchical levels: the initial-level controller and the device-level controller. The high-level controller determines the reference power setpoints, whereas the device-level controller dynamically adjusts operational parameters to maintain system stability and optimize performance. Further elaborate on comprehensive control strategies, ensuring that energy flow is balanced between supply and demand over different time frames, thereby enhancing system reliability [52].

Microgrid system optimization for renewable energy integration has garnered significant research interest. To investigate both technical and economic performance metrics of MGS under two operational paradigms: stand-alone (off-grid) and grid-connected (upper grid) configurations [53]. The study proposes a hybrid system architecture comprising PV panels, wind turbines, inverters, and advanced control units for grid integration. In the stand-alone mode, additional components such as diesel generators and short-term energy storage solutions are incorporated to enhance system resilience. Performance evaluation is conducted by analyzing various energy generation profiles and their impact on system efficiency. Furthermore, the study assesses the economic viability of MGS deployment by computing the Net Present Cost and Levelized Cost of Electricity for both operational scenarios.

The deployment of hybrid renewable energy systems incorporating both solar and wind power, supplemented with battery-based energy storage systems, has been shown to enhance microgrid efficiency.

In [54], emphasizes the critical role of an optimized Energy Management System (EMS) in maximizing renewable energy utilization within localized microgrids. Their research presents a prototype PV generation system integrated with BESS to provide energy compensation during peak demand periods. The implemented control strategy within the Building Energy Management System is designed to dynamically allocate energy resources, ensuring optimal system performance. Preliminary experimental results validate the effectiveness of this energy management approach in stabilizing microgrid operations.

Microgrid systems represent a transformative approach to achieving reliable and sustainable power distribution. They hold significant potential for integrating renewable energy sources such as wind and hydroelectric power, thereby facilitating the development of zero-emission power plants.

2.5.1 Batteries

Batteries are the most widely utilized and technologically advanced energy storage systems, classified as long-duration storage solutions. They can be configured in series and/or parallel topologies to enhance their voltage and current ratings, thereby optimizing their power capacity for various applications. Batteries are broadly categorized into two primary types: electrochemical batteries and redox flow batteries. Electrochemical batteries store energy through ion migration facilitated by electrochemical reactions occurring between the anode (negative electrode) and cathode (positive electrode) within an electrolyte medium. During the charging process, electrical energy in the form of direct current (DC) is converted into chemical potential energy through redox reactions. Conversely, during the discharging phase, the stored chemical energy is reconverted into electrical energy, enabling the movement of electrons through an external circuit in DC form [55]. These characteristics make electrochemical batteries a pivotal component in modern energy storage applications, including grid stabilization, renewable energy integration, and electric mobility.

2.5.1.1 Lithium-ion batteries

Lithium-ion (Li-ion) battery energy storage has emerged as one of the most widely adopted energy storage technologies due to its high technological maturity, cost-effectiveness, and superior energy density [56]. With its high energy density, Li-ion batteries effectively address peak power demands by storing and delivering substantial amounts of energy. However, their relatively low power density limits their ability to sustain high charge and discharge currents, making them less effective in rapidly mitigating power and voltage fluctuations or suppressing transient instabilities in the electrical grid [57]. Consequently, while Li-ion batteries are well-suited for energy-intensive applications, their performance in high-power applications requires rapid charge-discharge cycling.

The operational lifespan of lithium-ion batteries is highly temperature-dependent, making them less suitable for backup power applications where prolonged inactivity or deep discharge may occur. One of the primary limitations of Li-ion batteries is their inherent safety risk due to the use of thermally unstable metal oxide electrodes. Under elevated temperatures, these electrodes can undergo decomposition, leading to the release of oxygen and thermal energy, which may trigger thermal runaway and pose significant fire and explosion hazards.

To mitigate these safety concerns, Li-ion battery systems are integrated with advanced battery management systems that continuously monitor key parameters such as voltage, temperature, and State of Charge (SOC) to prevent overcharging and over-discharging. Additionally, most Li-ion battery packs are designed with stringent charge and discharge current limitations to enhance operational safety and prolong battery lifespan[58]–[60].

2.5.1.2 Nickel-metal hydride batteries

Nickel-metal hydride (NiMH) batteries serve as a key energy storage solution, ensuring stable integration of renewable energy sources and enhancing grid reliability in microgrids[61] . Their high energy density and extended cycle life make them ideal for managing energy fluctuations and maintaining power supply in off-grid or islanded configurations. NiMH batteries are particularly well-suited for DC microgrids due to their compatibility with the direct current nature of these systems. Despite their advantages, challenges such as temperature sensitivity, self-discharge, and the need for optimized battery management systems continue to be important areas for further research and enhancement [62].

2.5.2 Supercapacitor

Supercapacitors like electrochemical double-layer capacitors (EDLCs) or ultracapacitors, are advanced energy storage devices that store energy through electrostatic charge accumulation rather than electrochemical reactions. Unlike conventional batteries, supercapacitors achieve energy storage by forming an electric double layer at the interface between the electrode and electrolyte, eliminating the need for chemical transformations [63].

A key distinction between supercapacitors and traditional capacitors lies in their significantly higher energy density, which results from a substantially larger electrode surface area combined with an ultra-thin dielectric layer. This enhanced architecture enables greater charge accumulation and rapid energy discharge. While both conventional capacitors and supercapacitors operate on the same fundamental electrostatic principles, supercapacitors utilize an electrolyte as an ionic conductor instead of an insulating dielectric. This configuration facilitates ion migration along the high-surface-area electrode, thereby improving charge storage efficiency and power delivery capabilities [64],[65].

2.6 Modeling and Control of Hybrid Energy Storage System

In a DC microgrid, power generation from renewable sources, such as solar photovoltaics (PV) and wind energy, exhibits inherent fluctuations due to variations in climatic and geographical conditions. Additionally, domestic and industrial loads within the DC microgrid experience significant variations, leading to a dynamic load profile that consists of both steady-state average power demand and transient peak power surges. These peak power requirements occur periodically and need to be met efficiently [66]. The energy storage system in a DC microgrid must possess high energy density to supply the average power demand over extended durations, while also exhibiting high power density to accommodate short-duration transient power spikes effectively.

Certain DC loads, particularly motor-driven appliances, air conditioners, refrigeration systems, and other inductive loads, require a high inrush current, typically ranging between 7 to 10 times their nominal operating current. This surge current is required only for a few seconds, making the exclusive use of batteries for peak power management inefficient and economically unviable due to excessive oversizing requirements. Moreover, applications such as electric vehicles (EVs), spacecraft power systems, portable electronic devices, and telecommunication infrastructure share a common characteristic in their load profiles, demanding relatively low average power but exhibiting high pulse power requirements. These pulse durations typically range from a few milliseconds to seconds, depending on the application and power levels.

At present, no single energy storage technology provides both high power and high energy density to comprehensively meet the storage requirements of a DC microgrid. Consequently, hybrid energy storage systems are being investigated to enhance energy management and improve system reliability. Various energy storage devices, including batteries, flywheels, superconducting magnetic energy storage, and double-layer capacitors (ultracapacitors), are available for integration into DC microgrids. The performance of these storage technologies is influenced by several parameters, including state of charge, State of Health (SOH), charge/discharge efficiency, and response time [67]. Selecting an optimal energy storage topology tailored to the specific DC microgrid application is crucial for maximizing efficiency.

Standalone energy storage systems in DC microgrids have demonstrated limited efficiency in mitigating power imbalances, thereby necessitating the adoption of hybrid energy storage solutions. Battery technologies, such as lithium-ion and nickel-metal hydride batteries, occupy a specific region in the plot, indicating that relying solely on battery storage necessitates significant oversizing to handle transient peak power demands. Thus, the integration of high-power-density storage technologies like ultracapacitors alongside batteries presents a more efficient and cost-effective solution for DC microgrid energy management.

2.6.1 Hybrid Energy Storage System Architectures

Hybrid energy storage systems combine two or more storage devices with complementary characteristics, enabling optimized power and energy management. The key motivation behind HESS integration in DC microgrids is to decouple the energy and power requirements, thereby extending the lifespan of individual storage elements and improving system stability.

The commonly used storage technologies in HESS include [68]–[71]:

- Batteries (Li-Ion, Lead-Acid, NiMH): These are high-energy-density storage devices used for supplying continuous and steady power over long durations. However, their low power density and slow response time make them inefficient for handling transient power spikes.

- Supercapacitors (Double-Layer Capacitors, Ultracapacitors): These devices exhibit high power density, rapid charge-discharge capabilities, and low energy density, making them ideal for managing short-duration high-power transients while protecting the battery from excessive stress.
- Flywheels: Mechanical energy storage systems with high cycling capability that provide short-term energy buffering, reducing battery cycling stress.
- Superconducting Magnetic Energy Storage (SMES): Though still under research, SMES offers ultra-fast response times and high efficiency but suffers from high costs and cryogenic cooling requirements.

2.6.2 Battery and supercapacitor energy storage system

specific energy, defined as the energy stored per unit mass of an energy storage device, is a fundamental parameter that determines the storage capacity and operational endurance of the system. Energy storage devices with higher energy density can sustain a prolonged energy supply, making them essential for applications that require long-duration power support [72]. Among various energy storage technologies, batteries, particularly lithium-ion and nickel-metal hydride types, exhibit superior energy density. Their ability to store large amounts of energy makes them suitable for microgrid applications where continuous power supply is required. However, despite their high energy density, batteries have limitations in terms of charge/discharge rates, response time, and degradation under frequent high-current demand, making them less efficient for applications requiring rapid energy transfer.

In contrast, specific power, which defines the power delivered per unit mass of a storage device, determines the rate at which energy can be absorbed or discharged. Supercapacitors, also known as electrochemical double-layer capacitors, store energy through electrostatic charge accumulation instead of chemical reactions [73]. This allows them to exhibit exceptionally high charge/discharge rates, making them highly effective for instantaneous power delivery. Since no electrochemical conversion occurs during operation, supercapacitors have low internal resistance, leading to high power density, longer cycle life, and minimal energy losses [74]. The ability of supercapacitors to supply power instantaneously makes them suitable for handling transient peak loads in microgrid applications, where high-power demand occurs over short durations. However, their low energy density limits their ability to sustain power supply for extended periods, necessitating their integration with batteries in hybrid energy storage systems.

Given the complementary characteristics of batteries and supercapacitors, hybrid energy storage systems have been widely adopted for microgrid applications. By integrating both storage technologies, the system can leverage the high energy density of batteries for long-term energy supply and the high-power density of supercapacitors for instantaneous power delivery. The combination of these energy storage devices optimizes performance by reducing battery stress, enhancing power efficiency, and improving overall system longevity. A comparative analysis of batteries and supercapacitors highlights their respective strengths and weaknesses. Batteries provide high energy density but lower power density and limited charge/discharge rates, making them prone to performance degradation under high-load fluctuations. On the other hand, supercapacitors exhibit high power density, high charge/discharge rates, and rapid response capabilities but suffer from lower energy storage capacity. Integrating batteries with supercapacitors in a hybrid energy storage system addresses these challenges by ensuring efficient power distribution and improved load-handling capabilities in microgrids. The key advantages of a battery-supercapacitor HESS include reduced battery size and cost, mitigation of battery stress caused by high-power transients, and enhanced power balance between energy generation and load demand.

2.6.3 Power Electronics Interface for Energy Storage Management

The effective operation of a hybrid energy storage system in a microgrid environment requires an efficient power management interface facilitated by power electronic converters [75]. These converters play a crucial role in regulating energy exchange between storage devices and the microgrid, ensuring seamless energy transfer and stable voltage levels. Bidirectional DC-DC converters, such as buck-boost converters, are widely employed in battery-supercapacitor HESS configurations to enable dynamic voltage regulation and energy flow control. These converters allow energy to be efficiently transferred between the battery and supercapacitor based on real-time power demand, optimizing overall system efficiency [76]. Additionally, multi-input DC-DC converters have been developed to integrate multiple energy storage devices within a single converter architecture, reducing component complexity and improving energy conversion efficiency [77].

Several advanced power-sharing control strategies have been explored in the literature to optimize energy distribution in battery-supercapacitor hybrid energy storage systems. Rule-based control strategies define predefined thresholds for energy allocation, ensuring that supercapacitors handle transient peak loads while batteries provide long-term energy supply. More sophisticated model predictive control and fuzzy logic control techniques dynamically adjust power-sharing mechanisms based on real-time system behavior, allowing for adaptive and intelligent energy management. Recent advancements in artificial intelligence and machine learning have also been leveraged to enhance energy management in HESS. AI-driven control algorithms can analyze load demand patterns, predict energy fluctuations, and autonomously allocate power between batteries and supercapacitors, further improving microgrid stability and efficiency.

The integration of advanced power electronic converters and intelligent control methodologies significantly enhances the performance of hybrid energy storage systems in DC microgrid applications. By efficiently managing energy flow between storage sources and load demand, these systems ensure stable voltage regulation, minimize energy losses, and extend the lifespan of energy storage devices. As the demand for resilient and efficient microgrid energy storage solutions continue to grow, the implementation of battery-supercapacitor HESS, combined with smart power management techniques, will play a critical role in the future of sustainable energy systems.

2.7 Converter for DC Microgrid

Power electronic converters play a crucial role as interfaces in DC microgrids, facilitating efficient power management and control. Based on converter topologies, power electronic converters can be categorized into the Two-Level Converter, Neutral Point Clamped Converter, and Cascaded H-Bridge Converter. Additionally, conventional buck-boost converters, two-phase interleaved converters, multi-input converters, and multilevel converters are widely utilized as interface solutions in microgrid applications.

Energy storage systems are integral components of microgrids due to the intermittent nature of renewable energy sources. The selection of power electronic converters is based on their ability to meet the dynamic operational requirements of energy storage devices, ensuring efficient charging and discharging processes.

In conventional power generation systems, power flow is typically unidirectional. However, microgrids necessitate bidirectional power flow to enable energy exchange between storage devices and loads. This bidirectional capability ensures a continuous and stable power supply, even in the absence of renewable energy generation. Bidirectional converters facilitate this operation by enabling controlled energy transfer while dynamically regulating voltage levels to match the requirements of the system. Bidirectional converters play a crucial role in DC microgrids, enabling efficient energy exchange between distributed energy resources, energy storage systems, and loads. Based on the presence or absence of galvanic isolation, these converters are classified into Isolated Bidirectional Converters and Non-Isolated Bidirectional Converters.

1. Isolated Bidirectional Converters

Isolated bidirectional converters incorporate a high-frequency transformer to provide galvanic isolation between the input and output stages. The key topologies of isolated converters include flyback, forward-flyback, half-bridge, and full-bridge configurations. These converters offer several advantages, such as ease of design and low maintenance requirements. The presence of a transformer ensures uniform voltage stress distribution across both the primary and secondary windings, enhancing reliability. However, under high-voltage operating conditions, these converters are sensitive to power fluctuations, which can impact performance and stability.

2. Non-Isolated Bidirectional Converters

Non-isolated bidirectional converters do not utilize a transformer for isolation, resulting in a more compact and lightweight design. Common non-isolated converter topologies include Cuk, coupled inductor, conventional buck-boost, three-level multilevel, and switched capacitor converters. These converters exhibit higher efficiency due to reduced energy losses associated with the absence of isolation components. Additionally, their simplified structure minimizes design complexity and cost. However, one major drawback is the lack of sufficient galvanic isolation between the input and output, which may pose safety concerns in certain applications. To address the limitations of conventional bidirectional converters, a novel topology is proposed by integrating the features of a two-phase interleaved bidirectional DC-DC converter and a bidirectional three-level DC-DC converter**.**

A detailed review of bidirectional converters for DC microgrid applications with energy storage was presented in [78]. The study highlights the significance of power electronic interfaces between renewable energy sources and storage units, which play a crucial role in power transfer, system stability, and performance enhancement. These converters enable efficient charging and discharging of storage systems and ensure seamless power transfer [79]. The study provides an overview of isolated, non-isolated, and interleaved DC-DC converter topologies, along with a review of various control techniques such as power control, voltage mode control, current mode control, and sliding mode control to facilitate effective energy transfer between storage units and the DC bus [80]–[82][83].

An isolated three-port bidirectional DC-DC converter, specifically designed for managing power across multiple energy resources [84]. The proposed topology operates with a reduced number of switches, improving efficiency and reliability. The implementation of soft switching for the main switch, utilizing an LCL resonant circuit, significantly enhances performance. The converter acts as an interface between multiple voltage sources and loads, ensuring continuous power management between the photovoltaic system, energy storage devices, and load.

In [85], a current-fed non-isolated switched bidirectional DC-DC converter as a power electronic interface. This topology includes a half-bridge boost converter that is current-fed and utilizes an LCL resonant circuit to achieve soft switching. To enhance voltage gain, a voltage doubler is incorporated at the output side, eliminating the need for external multiplexer circuits. By operating at a high switching frequency, the converter reduces filter requirements and achieves soft switching in both buck and boost operations, improving overall efficiency.

A non-isolated symmetrical interleaved multilevel boost converter for DC microgrid applications [86]. This converter exhibits improved voltage gain while maintaining a low input current ripple, enhancing efficiency. The topology ensures identical voltage distribution across capacitors, with the output being the sum of capacitor voltages. The converter is analyzed in both continuous and discontinuous conduction modes, proving to be an efficient solution for low-to-high voltage conversion in microgrids. The continuous nature of input current reduces voltage stress on capacitors, minimizing converter cost while improving performance [87].

Soft-switched multiport bidirectional DC-DC converter for hybrid energy storage applications, integrating batteries and supercapacitors [88]. The soft-switching technique is effectively applied across all operating load conditions, improving system efficiency. The use of interleaved control significantly reduces current ripples, benefiting energy storage applications. The study elaborates on converter topology, operating principles, and control strategies for bus voltage regulation and energy storage device management. A 380V DC microgrid prototype was developed in the laboratory, and performance was validated through simulations and experimental results.

A multiport bidirectional DC-DC converter for renewable energy integration employs dual bidirectional ports, reducing the number of switching components while improving efficiency [89]. The soft-switching mechanism further enhances the converter’s performance. The design is tailored based on power ratings and soft-switching conditions, ensuring stable operation in both steady-state and transient conditions. The converter effectively transitions between islanded and grid-connected modes, supporting applications involving wind turbines, PV panels, and battery banks in DC microgrids.

In [90], bidirectional dual-active bridge converter for Vehicle-to-Grid applications in DC microgrids. The study presents the converter's design and control strategies, focusing on battery modeling and dynamic performance simulation. By implementing Zero Voltage Switching (ZVS), the converter achieves high efficiency, with optimal utilization of the ZVS region. The topology facilitates bidirectional power flow between batteries, electric vehicles, and the DC microgrid, using the Single-Phase Shift control method. The galvanic isolation provided by the converter enhances ZVS characteristics, ensuring efficient energy exchange in V2G applications.

In [91], an interleaved hybrid converter with continuous DC and AC outputs for DC microgrid applications. This topology integrates two conventional boost converters, where the active switch of the second boost converter is replaced by an H-bridge voltage source inverter. Unlike traditional converters, this topology achieves a combined duty ratio and modulation index greater than one, resulting in higher voltage gain and reduced harmonic distortion. The interleaved technique enhances input current sharing between converters, reducing the ratings of switching devices and inductors. The converter operates with low power losses and improved efficiency, while a modified unipolar sinusoidal pulse width modulation strategy ensures optimal power flow control [92], [93]. A universal active power converter for DC microgrid applications [94] introduces a power flow controller to interconnect multiple DC microgrids, ensuring efficient load management and energy storage integration. The system leverages advanced control algorithms to facilitate microgrid interconnection, enhancing the utilization of renewable energy sources while minimizing transmission losses. The power flow between DC grids and storage systems is managed through a three-port decoupled operation. The implementation of common energy storage optimizes renewable energy utilization, reducing power losses and enhancing microgrid efficiency. A 380V DC microgrid prototype was developed, with system validation conducted through simulations and experimental results.These studies collectively emphasize the advancements in bidirectional DC-DC converters for DC microgrid applications, highlighting innovations in topologies, soft-switching techniques, interleaved control strategies, and multiport configurations. These developments significantly enhance power flow management [95], efficiency [96], voltage gain, and system stability making bidirectional converters a crucial component in next-generation DC microgrids.

2.8 Power Management of DC Microgrid

Power management in DC microgrids is a critical aspect that ensures stable and efficient operation by regulating power flow between distributed energy sources, storage systems, and loads. Unlike conventional power systems, a DC microgrid comprises multiple renewable energy sources such as photovoltaic systems, wind turbines, and fuel cells, along with energy storage devices (batteries and supercapacitors) and diverse loads. The intermittent nature of renewable energy sources, coupled with fluctuating load demand, necessitates an advanced power management strategy to maintain system stability, reliability, and efficiency under varying operating conditions. The Power Management System has to regulate the DC bus voltage during source and load variations. In addition to this, the reference current generation for PV, Battery, and SC Converter control during source and load fluctuations. Also, proposed PMSs have power converter tracking speed constraints with a faster dynamic response as well as a lesser stressed battery charge/discharge rate [97].

A well-designed power management algorithm ensures that power is distributed optimally while maintaining DC bus voltage regulation in both grid-connected and stand-alone modes [98]. The system continuously monitors the power generation, storage capacity, and load demand to determine whether the microgrid is operating in excess power mode, deficit power mode, or balanced power mode. Based on the identified mode, the power management system controls energy storage charging and discharging, coordinates load sharing, and ensures smooth power exchange with the main grid or other interconnected microgrids when available [99].

In [100], excess power mode, where power generation exceeds load demand, the surplus energy is managed effectively by storing it in battery banks or supercapacitors. If the storage devices are fully charged, excess power can be diverted to auxiliary loads or exported to the main grid in a grid-connected scenario. Proper management prevents overvoltage conditions, enhances the utilization of available renewable resources, and improves overall system efficiency. Conversely, in deficit power mode, when power generation is insufficient to meet the load demand, the power management system prioritizes the discharging of energy storage devices to maintain DC bus voltage stability. If the stored energy is insufficient, load-shedding strategies may be implemented to maintain critical loads while reducing non-essential loads. In grid-connected operations, the power deficit can be compensated by importing power from the main grid or other microgrid networks, ensuring an uninterrupted energy supply. In the balanced power mode, where the generated power precisely meets the load demand, the microgrid operates in an optimal state without excessive reliance on storage devices or external sources [101]. This mode ensures minimal power losses, improves system efficiency, and maintains a stable DC bus voltage. However, continuous monitoring and adaptive control are essential to ensure that small fluctuations in power generation or load demand do not lead to instability.

The control strategies used for power management in DC microgrids include droop control [102], hierarchical control [103], model predictive control [104], [105], and fuzzy logic-based control [106]. Droop control is widely employed in decentralized microgrid architectures, where power-sharing among multiple Distributed Generation (DG) units is achieved without direct communication between them. Hierarchical control consists of primary, secondary, and tertiary levels, where each level is responsible for different aspects of power regulation, from instantaneous voltage and current regulation to economic dispatch and grid coordination. Model predictive control offers an intelligent and adaptive power management strategy by predicting system behavior based on historical data and adjusting control parameters accordingly. Fuzzy logic-based control enables real-time decision-making in uncertain and dynamic operating conditions, improving microgrid performance in the presence of intermittent renewable energy sources.

Additionally, power electronic converters play a vital role in implementing power management strategies by facilitating efficient energy conversion, voltage regulation, and power flow control. Bidirectional DC-DC converters are used to manage the charging and discharging of battery energy storage systems, ensuring smooth energy exchange between the DC bus and storage units. Multiport DC-DC converters enable flexible integration of multiple energy sources, optimizing power distribution among renewable sources, storage systems, and loads. The integration of smart controllers with power electronic interfaces enhances microgrid performance by providing real-time adaptability to changing power conditions.

Overall, an effective power management strategy in DC microgrids ensures efficient energy utilization, improved system stability, enhanced reliability, and optimal integration of renewable energy sources. DC microgrids can achieve a sustainable, resilient, and cost-effective energy supply solution by incorporating advanced control techniques, intelligent decision-making systems, and real-time monitoring.

2.9 Modeling and Control of Standalone DC Microgrid with HESS

A stand-alone DC microgrid comprises a PV module that supplies power to DC loads, while a hybrid energy storage system regulates the DC bus voltage. Hybrid Energy Storage Systems in DC microgrids represent a key innovation in modern energy systems, particularly in enabling the integration of renewable energy sources and enhancing the efficiency and reliability of the power grid [107]. The development of these systems has been driven by the need to address various challenges associated with renewable energy generation, such as variability, intermittency, and the need for energy storage to ensure a constant power supply. DC microgrids, which operate on direct current, offer an ideal environment for incorporating HESS, as many renewable energy sources, including solar panels and wind turbines, also produce direct current [108]. This compatibility allows for more efficient energy conversion and storage within the microgrid.

One of the main functions of HESS in DC microgrids is to smooth out the fluctuations in power generation and demand [109]. Solar and wind power generation are highly variable, depending on environmental conditions, and this variability can lead to supply-demand imbalances. HESS solves this problem by storing excess energy during times of high renewable generation and releasing it when generation is low. Batteries, such as lithium-ion and flow batteries, are widely used in HESS due to their ability to provide long-term storage and deliver energy over extended periods. These batteries help store excess renewable energy during the day [110]–[112].

In addition to batteries, supercapacitors and flywheels are integral to HESS, providing complementary benefits. Supercapacitors are capable of storing energy for short periods but are particularly useful in delivering rapid bursts of power when required [113]. They have high efficiency, charge, and discharge quickly, and endure many more cycles than conventional batteries. This makes them ideal for handling transient loads or sudden spikes in demand, ensuring the microgrid can meet immediate energy needs without causing instability [114]. Flywheels, while less commonly used than batteries and supercapacitors, offer advantages in stabilizing the frequency of the microgrid by providing rapid responses to fluctuations in energy supply and demand [115]. Flywheels can release stored energy almost instantaneously, which helps maintain the stability and reliability of the microgrid during short-term disturbances.

An important challenge in deploying HESS is determining the optimal combination of storage technologies to meet the microgrid's specific energy requirements. This involves designing a hybrid system that takes advantage of the strengths of each storage type while mitigating their weaknesses. Optimization techniques, such as mathematical models and computational algorithms, have been extensively studied to determine the best configuration of energy storage technologies for various microgrid scenarios. These models typically take into account factors such as the energy load profile, the generation patterns of renewable energy, the cost of different storage technologies, and the required level of reliability [116]. Additionally, various control strategies are employed to ensure the seamless operation of the different storage devices. For example, advanced control algorithms, such as model predictive control (MPC) and fuzzy logic control, have been used to manage the charging and discharging cycles of storage devices based on real-time power generation and demand forecasts.

Despite the benefits, several challenges remain in the integration of HESS in DC microgrids. One of the most significant barriers is the high initial cost of installing a hybrid storage system. The cost of batteries, in particular, can be substantial, and although their prices have been decreasing, they still represent a significant upfront investment. However, the long-term operational savings that result from increased efficiency, reduced reliance on external power grids, and decreased operational costs associated with fossil fuels help offset the initial expenditure [117]. Another challenge is the complexity of managing the operation and maintenance of a hybrid energy storage system. Since different energy storage technologies have different lifespans, efficiencies, and performance characteristics, managing the lifecycle and degradation of each component can be complex [118], [119]. Regular monitoring and advanced diagnostic tools are necessary to ensure the system operates at peak efficiency throughout its life. The integration of HESS into DC microgrids is also supported by advancements in power electronics and grid management systems. Power converters are essential for facilitating the interaction between DC and AC systems, enabling the integration of different energy sources and storage technologies [120].

Additionally, the development of smart grids and advanced communication networks has facilitated the real-time monitoring and control of energy flow within the microgrid [121]. These technologies improve the overall performance and reliability of the microgrid by enabling more precise control of energy generation, storage, and consumption. Smart meters, sensors, and distributed control systems allow operators to remotely monitor and manage the operation of HESS, ensuring that the system can respond quickly to changing conditions.

Furthermore, HESS in DC microgrids, showcases how these systems are used in real-world settings. In remote locations, such as islands or rural areas [122], [123], where access to traditional power grids is limited or unavailable, HESS has proven to be a valuable solution. These microgrids enable communities to become energy self-sufficient by harnessing local renewable resources and storing excess energy for times when generation is low. HESS can help manage the power consumption of multiple buildings, smooth out peak demand periods, and ensure a continuous supply of electricity [124].

The military sector has also shown interest in DC microgrids with HESS due to their ability to provide secure and reliable power for critical operations [125]. These microgrids are designed to operate independently of the main grid, ensuring that vital equipment and infrastructure remain operational in remote or hostile environments. The integration of HESS in such applications ensures that energy demands are met without reliance on fossil fuels, improving energy security and reducing operational costs [126], [127].

Advanced energy storage technologies, such as solid-state batteries and superconducting magnetic energy storage, have the potential to enhance the performance of HESS by providing higher energy densities, longer lifespans, and greater efficiency. Hybrid Energy Storage Systems in DC microgrids represent a transformative approach to energy storage and grid management, offering improved efficiency, enhanced reliability, and greater integration of renewable energy sources.

2.10 Optimization Techniques

The optimal planning of a photovoltaic wind-biomass hybrid energy system incorporating battery storage and a diesel generator is a complex multi-objective optimization problem aimed at achieving cost-effectiveness, reliability, and environmental sustainability [128]. In this study, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are employed to minimize the Cost of Electricity (COE), which serves as the primary objective function. By systematically evaluating various system configurations, the optimal hybrid energy system architecture is identified based on the least COE. The optimal configuration strikes a balance between system reliability, renewable energy penetration, emissions reduction, and economic feasibility. The reliability index of the system is quantified using the Loss of Power Supply Probability, a key metric that ensures the system can meet energy demand under varying operating conditions. In this research, the LPSP is constrained to a maximum threshold of 2%, ensuring a highly reliable energy supply. The hybrid energy system integrates dispatchable and non-dispatchable renewable energy sources, with battery energy storage systems playing a critical role in mitigating power fluctuations and enhancing grid stability.

Through the implementation of GA and PSO, the optimization process explores a wide search space to identify the Pareto-optimal solution that minimizes COE while maximizing the renewable energy fraction and reducing the dependency on fossil fuels. The optimal solution incorporates a well-balanced energy mix, ensuring an efficient trade-off between system costs, environmental impact, and energy reliability. By leveraging heuristic optimization techniques, the study demonstrates an advanced approach to designing cost-efficient and sustainable hybrid renewable energy systems, paving the way for enhanced integration of renewables in off-grid and grid-connected applications.

A simulation model has been developed to design a PV/Diesel/Wind hybrid microgrid system integrated with a battery bank storage to ensure optimal energy management [129]. The primary objective of the proposed system is to achieve optimal sizing that minimizes the Cost of Energy while enhancing the system's reliability and efficiency. This is accomplished by considering the Loss of Power Supply Probability as a key reliability metric, ensuring a stable and uninterrupted power supply.

To achieve an efficient and cost-effective microgrid design, advanced metaheuristic optimization algorithms have been employed, including the Whale Optimization Algorithm, Hybrid Particle Swarm-Gravitational Search Algorithm, Water Cycle Algorithm, and Moth-Flame Optimizer. These nature-inspired optimization techniques enable the identification of the most effective hybrid system configuration by exploring a vast search space and converging toward an optimal solution. The proposed methodology ensures a well-balanced trade-off between economic feasibility, energy security, and environmental sustainability, making the hybrid microgrid system highly suitable for both grid-connected and off-grid applications.

In [130], presents an optimization approach for sizing a hybrid renewable energy system that integrates wind turbines, photovoltaic panels, and a hydroelectric pumped storage system in a grid-connected framework. The study explores the application of various metaheuristic optimization techniques to determine the optimal sizing of system components, ensuring an efficient, cost-effective, and reliable hybrid energy solution.

To achieve the optimal configuration, a comparative analysis was conducted between four advanced optimization algorithms: Grey Wolf Optimizer, Water Cycle Algorithm, Whale Optimization Algorithm, and Salp Swarm Algorithm. These algorithms were evaluated based on their performance in minimizing the Cost of Energy while simultaneously meeting key operational constraints. The optimization methodology takes into account real-time meteorological data from Egypt's Ataka region, ensuring that system sizing reflects actual environmental conditions and energy demand profiles.

The primary objective of this optimization process is to achieve a low-cost, high-reliability hybrid energy system by maximizing renewable energy utilization and minimizing fluctuations in the energy injected into the grid. Special emphasis is placed on leveraging the complementary characteristics of wind and solar energy sources to enhance overall system efficiency. By integrating a hydroelectric pumped storage system, surplus renewable energy can be efficiently stored and dispatched during periods of low generation, improving the system's stability and grid interaction. This study provides a robust framework for hybrid energy system design, contributing to the development of sustainable and resilient power generation solutions.

In [131], presents a comprehensive approach to optimizing the operation of a DC microgrid, focusing on economic efficiency and minimizing transmission losses. This study identifies significant challenges in traditional AC power networks, particularly regarding power flow and efficiency. It emphasizes the advantages of DC microgrids, which utilize power electronics for more precise control over power flow, leading to improved efficiency and economic potential. To propose a dual-solver framework to address the complexities of optimizing economic costs while minimizing transmission losses. A real-time scheme is proposed that incorporates prediction implementations alongside the dual-solver optimization. This approach aims to enhance the responsiveness of the microgrid to changing conditions, such as electricity prices and load demands.

The economic and environmental benefits of stand-alone and grid-integrated hybrid energy systems with different configurations of PV/Wind/Diesel/Battery across five distinct climatic regions using the Hybrid Optimization Model for Electric Renewables [132]. The investigation evaluates the feasibility of both stand-alone and grid-connected hybrid systems, particularly PV-based options, by assessing their techno-economic and environmental impacts. This research aims to identify the optimal HESS configuration that ensures cost-effective solutions with high reliability, leveraging renewable energy resources such as solar and wind power. The design aspects of hybrid energy systems, focus on the economic and operational interdependence between various energy storage devices and charge/discharge control systems

[133]. Equality constraint of periodic system behavior, the maximum and minimum storable energy levels of storage installations, peak power requirements, and the impact of evolving fuel prices and weather conditions. The proposed optimization methodology is based on the Shark Bay Seascape Optimization algorithm, which classifies energy storage system power and energy capacities to explore the global optimal solution under varying conditions. Simulation results demonstrate that the optimal sizing, selection, and arrangement of ESS components can be effectively determined, maximizing the total net present value over the system's operational lifetime. Furthermore, a comparative evaluation between two battery technologies Vanadium Redox Battery and Lead-Acid Battery was conducted to assess their performance, cost-effectiveness, and suitability for integration into hybrid energy systems [134].

A Direct Current Microgrid has been analyzed using an Events-Based Control System, which consists of two decentralized control mechanisms: Voltage Event Control and State of Charge Event Control [135]. These mechanisms serve as the foundation for evaluating two optimization strategies aimed at enhancing the efficiency of the microgrid’s converters.The underlying nonlinear optimization problems are formulated based on small-signal averaged deterministic loss models of the converters. The two proposed strategies operate independently but can be implemented simultaneously while remaining compatible with broader economic optimization frameworks.

Additionally, the Battery Voltage Optimization Combined with the Battery Energy Storage System and Optimal Operational Setpoint Function optimization strategies are identified as suitable for microgrid applications. These strategies are particularly effective in scenarios where power flow remains low compared to the nominal power of the converters or where all converters within the microgrid converge toward a single optimal bus voltage value.

Particle swarm optimization is employed to fine-tune the fuzzy membership function. Various operational scenarios are designed to showcase the DC microgrid’s functionality under different conditions, including scenarios where production exceeds and falls below consumption. The study demonstrates the improved performance and efficiency achieved by integrating a PSO-based fuzzy controller to minimize voltage ripple in a DC microgrid and reduce battery efficiency [136]. supercapacitors are able to maintain the performance of the battery in the microgrid system [137].

In [138], explores the intelligent fuzzy logic controller tuning using the Firefly Algorithm and Particle Swarm Optimization for a semi-active suspension system equipped with a magnetorheological (MR) damper. The MR damper consists of a magnetically polarizable particle suspension in a liquid medium, enabling real-time adjustable damping characteristics. The Bouc Wen model is employed to characterize the MR damper's behavior, determining the required damping force based on force-displacement and force-velocity relationships. The performance of the controller, optimized using the Firefly Algorithm and PSO, is evaluated for its effectiveness in enhancing the semi-active suspension system’s response and stability. Effective voltage regulation is critical to ensure the reliable operation of microgrids, and optimization techniques have proven to be instrumental in addressing this challenge. Numerous optimization-based control strategies have been explored in the literature to maintain voltage stability in DC microgrids, including convex optimization, genetic algorithms [139], particle swarm optimization [140], model predictive control [141], and fuzzy logic control [142], [143].

The dynamic performance of these microgrids, specifically in terms of settling time and peak overshoot, plays a crucial role in determining system reliability, performance, and user satisfaction [144]. Settling time refers to the time required for the system's voltage or power output to remain within a specified range after a disturbance, while peak overshoot denotes the maximum deviation of the system's response from the desired steady-state value before it eventually stabilizes. The use of energy storage systems such as batteries and supercapacitors. Energy storage devices can be strategically employed to smooth out the fluctuations in voltage and power caused by renewable energy generation and sudden load changes [145]. Studies have explored the optimization of ESS dispatch schedules using various techniques like linear programming, dynamic programming, and multi-objective optimization. These methods focus on minimizing energy loss and balancing power generation and consumption, thus reducing voltage fluctuations and improving settling time and peak overshoot. Imperialist Competitive Algorithm for the robust optimization of a hybrid PV/WT/Batt system proves to be an effective approach for minimizing power losses, controlling voltage deviations, and enhancing the reliability of the network [146]. This technique provides a systematic method for addressing the challenges posed by intermittent renewable energy sources, ensuring the efficient and reliable operation of hybrid energy systems in real-world scenarios.

A Hybrid Energy Storage System combines Portable Energy Storage Systems and Stationary Energy Storage Systems to optimize energy management in grids [147]. It handles short-term fluctuations and provides long-term energy storage for stable grid operation [148]. Effective coordination between these two types of storage ensures efficient power flow and minimal losses. A key challenge is minimizing response time to rapidly adjust to load changes and renewable energy fluctuations. Using optimization techniques like model predictive control, fuzzy logic control, and algorithms like genetic algorithms, and particle swarm optimization, the system can reduce response times and ensure grid stability, enhancing overall reliability and efficiency in renewable energy integration.

2.11 Hybrid Optimization Model

Hybrid optimization in DC microgrids is a significant area of research, as it addresses the challenges associated with the integration of various energy sources and loads in a microgrid. DC microgrids are often favored due to their efficiency in distributing power, especially for systems with renewable energy sources (such as solar, wind, and storage), which naturally generate DC power. The main objective of hybrid optimization techniques is to enhance the performance, efficiency, and reliability of these systems by optimizing the operation of both energy generation and storage components. Hybrid optimization in DC microgrids combines multiple optimization techniques to enhance the efficiency and performance of energy management systems.

The DC microgrid based on the hybrid Particle Swarm Optimization/Grey Wolf Optimizer (HPSO–GWO) algorithm addresses challenges in the local control layer under various load interruptions and power production fluctuations, such as inaccurate power-sharing among sources, unregulated DC-bus voltage, and high ripple in battery current [149]. This hybrid algorithm is designed to enhance the performance of the local control layer and is evaluated under different load and photovoltaic generation scenarios. Despite load changes of 50%, 38%, and 32% at different time intervals, coupled with fluctuations in PV generation, the system achieves precise power transfer among distributed generators and effective voltage regulation. The proposed technique ensures fast voltage recovery with minimal settling time, overshoot/undershoot, and rise time. As a result, the system operation becomes more reliable and stable under critical operating conditions, demonstrating the robustness of this control technique.

Variation in system loads leads to differences in the Single Network Breakdown points, which can result in delayed voltage collapse, especially when loads are sensitive to voltage fluctuations [150]. The novelty of the hybrid ABC-PSO (Artificial Bee Colony-Particle Swarm Optimization) algorithm lies in its ability [151] to compute multi-objective functions, providing a broader perspective on the Under-Voltage load-shedding problem. This approach demonstrates that Computational Intelligence Techniques are highly effective in optimizing power system solutions and enhancing system stability and efficiency in the face of varying load conditions.

In [152], an innovative model aimed at enhancing power quality in electrical networks interconnected with photovoltaic sources. The main focus is on addressing the impact of PV power quality on local electrical networks. A hybrid Particle Swarm Optimization-Gray Wolf Optimization (PSO-GWO) algorithm is proposed to find optimal solutions. The research highlights the significant role of Unified Power Quality Conditioners in improving social welfare, with localized price reductions being the primary driver for this improvement. The study concludes that the hybrid PSO-GWO algorithm significantly enhances power quality in electrical networks linked to solar systems, resulting in substantial reductions in Total Harmonic Distortion, voltage sags, and voltage swells.

In [153], focuses on microgrid systems that integrate hybrid renewable energy sources and battery energy storage to ensure reliable operation in off-grid environments. The proposed system includes solar and wind energy with a synchronous turbine, alongside BES. A hybrid optimization approach combining Particle Swarm Optimization and Genetic Algorithm with Active Disturbance Rejection Control is developed to regulate AC bus voltage frequency and amplitude through a load-side converter. Additionally, the system efficiently manages generation and consumption using a bidirectional battery-side converter and enhances power quality by utilizing the photovoltaic inverter as a shunt active power filter. The hybrid PSO-GA-ADRC, with an extended state observer, compensates for disturbances like modeling errors and parameter fluctuations. Hardware-in-the-loop experiments confirm the effectiveness and robustness of this strategy in maintaining stable voltage and current in real-world scenarios.

The optimal solution for managing microgrids with hybrid renewable energy sources, while accounting for microgrid reserve margins, the Particle Swarm Optimization technique demonstrates strong performance in efficiently managing the charging and discharging cycles of Battery Energy Storage Systems, while ensuring the maintenance of adequate reserve margins to supply critical loads during grid outages or fluctuations in renewable energy generation [154]. BESS during off-peak hours or when excess renewable energy is available, and procuring power during low-cost off-peak periods, thereby optimizing both energy usage and cost-efficiency. The integration of PSO ensures precise coordination between generation, storage, and consumption, enhancing the overall reliability and economic viability of the microgrid system.

2.12 Research Gaps

After doing an intensive literature review, the following gap has been identified [155]–[158]:

1. Slow Response and Voltage Instability: Existing HESS configurations, such as Li-ion batteries combined with supercapacitors, struggle with slow response times and inconsistent voltage regulation during rapid load variations.
2. Battery Degradation: Li-ion batteries experience accelerated degradation due to frequent charging and high discharge rates, limiting their lifespan and efficiency.
3. Supercapacitor Limitations: Li-ion supercapacitors, while faster, have limited power density and shorter cycle life, making them less suitable for long-term storage in dynamic environments.

This study proposes a novel HESS configuration combining Ni-MH batteries and EDLC supercapacitors to address these challenges, offering better performance, stability, and longevity.

2.13 Proposed Research Methodology

The proposed research methodology focuses on [159] enhancing the performance of the Hybrid Energy Storage System in a DC microgrid by optimizing key operational parameters. The primary objectives of this study include minimizing the response time of HESS, reducing voltage fluctuations in the DC bus, maximizing battery efficiency, and minimizing the charge-discharge period of the battery. Achieving these objectives will ensure improved system stability, enhanced energy management, and prolonged battery lifespan.

To address these challenges, the research utilizes MATLAB-based simulations incorporating various optimization techniques. Particle Swarm Optimization (PSO) is employed due to its effectiveness in solving nonlinear optimization problems, while Artificial Bee Colony (ABC) is considered for its capability to enhance energy management strategies. Gray Wolf Optimization (GWO) is also integrated into the study to balance exploration and exploitation in optimization processes. Additionally, hybrid approaches such as ABC-GWO and GWO-PSO are explored [160] the combined strengths of these algorithms, aiming to further improve system response and stability. Through the implementation of these optimization strategies, this research seeks to develop a robust control framework for HESS, ensuring efficient and reliable operation within the DC microgrid.

Summary

This chapter presents a detailed review of research methodology and basic control schemes in the field of hybrid solar/wind energy-based energy management systems and optimization techniques. It is evident from the discussions that, there is a need for an effective algorithm that reduces cost, minimizes the DC voltage, and enhances the efficiency of the system.

The next chapter presents the development of a Power management model to balance the supply-demand ratio.