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Adaptive Control and Energy Management in Hybrid AC/DC Microgrids for Future Smart Grid Applications

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Abstract - The rapid integration of renewable energy resources, distributed generation systems, electric vehicles, and smart electronic loads has significantly accelerated the development of Hybrid AC/DC Microgrids (HMGs). These microgrids provide improved operational flexibility, enhanced reliability, and efficient integration of AC and DC energy systems within modern smart grid infrastructures. However, maintaining stable bidirectional power exchange, voltage regulation, power quality, and dynamic energy management between interconnected AC and DC microgrids remains a major technical challenge. This paper presents an intelligent AI-assisted adaptive control framework for Hybrid AC/DC Microgrids based on Bidirectional Interlink Power Converters (BILPCs), adaptive droop control, and optimization-driven energy management. The proposed methodology integrates machine learning-based renewable energy forecasting, IoT-assisted monitoring, and intelligent converter coordination to improve system stability and energy efficiency. Furthermore, advanced control strategies such as adaptive power-sharing, fault-tolerant energy routing, and dynamic voltage stabilization are incorporated to address operational uncertainties caused by renewable energy intermittency and varying load conditions. Comparative performance analysis demonstrates that the proposed approach significantly improves power quality, converter efficiency, voltage stability, and overall reliability of hybrid microgrid systems.

Keywords – Microgrid, Converter, Stability, Optimization, Forecasting.

1. Introduction

The increasing global demand for sustainable and reliable electrical energy has accelerated the transformation of traditional power systems into intelligent smart grid infrastructures. Rapid urbanization, environmental concerns, depletion of fossil fuels, and the growing penetration of

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renewable energy resources such as solar photovoltaic (PV) systems and wind energy systems have motivated researchers and industries to develop efficient distributed energy architectures. In this context, microgrids have emerged as an effective solution for integrating renewable energy sources, energy storage systems, and distributed generation units within localized power networks.

Hybrid AC/DC Microgrids (HMGs) have recently attracted substantial attention due to their ability to combine the advantages of both AC and DC distribution systems simultaneously. According to the attached review article, hybrid microgrids simplify the implementation of future smart grids by enabling flexible plug-and-play integration of renewable energy resources and distributed loads . These systems typically consist of interconnected AC and DC subgrids linked through Bidirectional Interlink Power Converters (BILPCs), which facilitate controlled bidirectional power transfer between AC and DC networks.

The review article identifies several important advantages of HMGs, including improved utilization of renewable energy resources, enhanced reliability, optimized energy storage usage, flexible power flow control, and better system stability . However, despite these benefits, hybrid microgrids still face numerous operational challenges. The AC and DC microgrids possess fundamentally different dynamic characteristics such as voltage levels, frequency regulation, phase synchronization, and power oscillations. Furthermore, renewable energy sources introduce uncertainties due to fluctuating power generation patterns, which complicates real-time energy balancing and converter coordination.

The attached article extensively discusses multiple interconnection methods for HMGs, including single BILPCs, parallel-connected BILPCs, Solid-State Transformers (SSTs), Energy Routers (ERs), and small-scale FACTS devices such as UPFC, UPQC, and UIPC . Among these, Bidirectional Interlink Power Converters remain the most widely adopted solution because they provide flexible active and reactive power exchange between AC and DC subsystems while supporting voltage and frequency regulation.

Traditional converter control techniques mainly rely on fixed droop control, centralized architectures, or rule-based energy management systems. Although these methods provide acceptable performance under normal operating conditions, they exhibit limited adaptability under dynamic load variation, renewable intermittency, harmonics, communication delays, and

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fault conditions. Additionally, centralized control approaches suffer from communication dependency, scalability limitations, and increased computational burden.

To overcome these limitations, this paper proposes an AI-assisted adaptive control and energy management framework for Hybrid AC/DC Microgrids. The proposed methodology combines machine learning-based renewable energy forecasting, adaptive converter control, IoT-enabled monitoring, and optimization-driven energy scheduling. The framework aims to improve voltage stability, reduce power loss, enhance converter coordination, and provide fault-tolerant operation under uncertain environmental and load conditions.

The remainder of this paper is organized as follows. Section 2 presents a detailed literature review on hybrid AC/DC microgrid interconnection strategies and intelligent control techniques. Section 3 discusses the major challenges in existing systems and formulates the objectives of the proposed research. Section 4 describes the proposed AI-assisted methodology in detail. Section 5 presents the discussion and performance analysis. Finally, Section 6 concludes the paper and highlights future research directions.

2. Literature Review

The integration of Hybrid AC/DC Microgrids into smart grid infrastructures has become one of the most rapidly evolving research areas in modern power systems. The attached review article comprehensively explains various interconnection techniques and control strategies used for Hybrid Microgrids, particularly emphasizing the role of Bidirectional Interlink Power Converters (BILPCs) in facilitating flexible power transfer between AC and DC subgrids .

Early research on hybrid microgrids mainly concentrated on conventional AC and DC microgrid architectures independently. AC microgrids primarily included AC sources and loads connected through a common AC bus, whereas DC microgrids incorporated DC renewable energy sources and storage systems connected through a common DC bus. However, due to the increasing use of mixed AC/DC loads and renewable energy systems, researchers gradually shifted toward hybrid architectures capable of simultaneously supporting both AC and DC networks.

The attached article explains that hybrid microgrids are generally categorized into three types: AC-coupled HMGs, DC-coupled HMGs, and fully hybrid AC/DC coupled microgrids . Among

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these, fully hybrid coupled microgrids received significant attention because they offer greater flexibility, improved reliability, and efficient renewable energy integration.

One of the earliest and most commonly adopted interconnection methods involved the use of a single Bidirectional Interlink Power Converter. These converters enabled controlled bidirectional power flow between AC and DC microgrids while supporting voltage and frequency regulation. The attached article highlights that single BILPC systems provide simple control structures and lower implementation costs but suffer from limited power transfer capability and reduced reliability under fault conditions .

To improve reliability and power-sharing capability, researchers introduced parallel-connected BILPC architectures. According to the review article, parallel-connected converters increase exchanged power capacity and provide modularity and redundancy for hybrid microgrid systems . However, several technical challenges emerge in such configurations, including circulating current problems, unequal power sharing, synchronization complexity, and DC-link instability.

The literature also explores the use of Solid-State Transformers (SSTs) for hybrid microgrid interconnection. SSTs provide multiple operational advantages such as voltage regulation, reactive power compensation, harmonic filtering, and intelligent protection capabilities . In addition, SST-based architectures facilitate integration between medium-voltage and low-voltage microgrids while improving overall system flexibility. Despite these benefits, SSTs require highly coordinated control systems and sophisticated converter synchronization mechanisms.

Another important interconnection strategy discussed in the attached paper is the Energy Router (ER)-based architecture. Energy Routers utilize multiple DC/DC and DC/AC converters to interconnect several AC and DC microgrids with different operating characteristics . These systems improve energy routing flexibility and support intelligent power balancing; however, they increase implementation cost and converter complexity due to the involvement of multiple conversion stages.

Furthermore, the attached review article discusses small-scale FACTS-based interconnection methods such as UPFC, UPQC, and UIPC for hybrid microgrid applications . These systems significantly improve power quality, harmonic suppression, voltage regulation, and active/reactive power flow control. Nevertheless, their implementation requires sophisticated controller coordination and high computational capability.

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Recent research trends have shifted toward integrating Artificial Intelligence, Machine Learning, IoT, and optimization algorithms into hybrid microgrid control systems. Machine learning-based forecasting techniques are increasingly used to predict renewable energy generation and load demand patterns. Deep learning models such as Long Short-Term Memory (LSTM) networks improve forecasting accuracy by learning temporal dependencies in power generation data. Similarly, reinforcement learning and adaptive optimization algorithms are being explored for dynamic energy scheduling and real-time converter coordination.

In addition to intelligent control, IoT-enabled monitoring systems have gained popularity for real-time data acquisition, remote supervision, and predictive maintenance in smart microgrid environments. These technologies enhance operational visibility and enable proactive fault detection and energy management.

Although significant progress has been achieved in hybrid microgrid research, the attached article indicates that several challenges still remain unresolved. These include dynamic stability issues, converter synchronization problems, renewable energy intermittency, communication dependency, DC-link instability, harmonics, fault management, and computational complexity . Therefore, there is a strong need for intelligent, adaptive, and fault-tolerant energy management frameworks capable of addressing these limitations in future smart grid systems.

Table No 1 : Literature Review Analysis

Ref	**Methodology**	**Major Contribution**	**Limitation**
[1]	Single BILPC	Simple interconnection architecture	Limited power transfer
[2]	Parallel BILPC	Improved reliability and modularity	Circulating current issues
[3]	Droop Control	Effective decentralized operation	Poor adaptability
[4]	SST-Based HMG	Voltage regulation and harmonic reduction	Complex converter coordination
[5]	Energy Router	Flexible energy routing	High converter complexity
[6]	UPQC-Based HMG	Improved power quality	Computational burden
[7]	UIPC-Based HMG	Flexible active/reactive power flow	Control complexity
[8]	IoT Monitoring	Real-time system visibility	Cybersecurity issues

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[9]	ML Forecasting	Renewable energy prediction	Limited generalization
[10]	Reinforcement Learning	Dynamic energy scheduling	Training complexity
[11]	Fault-Tolerant Control	Enhanced reliability	High implementation cost
[12]	Optimization EMS	Reduced operational cost	Slow convergence
[13]	Deep Learning Forecasting	Improved prediction accuracy	Data dependency
[14]	Distributed Control	Reduced communication dependency	Lower global optimization
[15]	FACTS-Based Interconnection	Enhanced voltage stability	Expensive infrastructure

3. Challenges in Existing Systems and Research Objectives

Despite the significant advancement of Hybrid AC/DC Microgrids, several technical and operational limitations continue to affect their large-scale deployment and practical implementation. The attached review article highlights multiple challenges associated with converter coordination, power sharing, voltage stability, and renewable energy integration within hybrid microgrid environments .

One of the major challenges is the dynamic mismatch between AC and DC microgrids. AC microgrids operate based on frequency synchronization and phase control, whereas DC microgrids depend on voltage regulation mechanisms. Maintaining stable bidirectional power transfer between these fundamentally different systems requires highly coordinated converter control strategies.

Another significant issue is renewable energy intermittency. Solar photovoltaic systems and wind turbines produce fluctuating output power due to environmental variations. These fluctuations introduce instability in DC-link voltage and negatively affect the power-sharing capability of Bidirectional Interlink Power Converters.

Parallel-connected BILPC architectures, although beneficial for reliability enhancement, introduce additional problems such as circulating currents, unequal load sharing, harmonics, and synchronization complexity. Fault conditions further complicate system operation because sudden disturbances may overload converters and destabilize the interconnected microgrids.

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Communication dependency in centralized control systems also remains a critical limitation. Centralized architectures require continuous communication among controllers, which increases latency, computational burden, and vulnerability to communication failures or cyberattacks.

Furthermore, existing control approaches often lack intelligent adaptability under uncertain operating conditions. Traditional droop control and rule-based systems are insufficient for handling dynamic load variation, renewable intermittency, and fault scenarios in real-time smart grid environments.

To address these limitations, the proposed research aims to achieve the following objectives:

1. To develop an intelligent AI-assisted adaptive control framework for Hybrid AC/DC Microgrids.
2. To improve voltage stability and dynamic power balancing between AC and DC subgrids.
3. To integrate machine learning-based renewable energy forecasting for proactive energy management.
4. To minimize power losses and improve converter coordination using optimization-driven control strategies.
5. To enhance fault tolerance, harmonic suppression, and system reliability under uncertain operating conditions.
6. To implement IoT-assisted monitoring for real-time data acquisition and intelligent decision-making.
7. To design a scalable and communication-efficient microgrid architecture suitable for future smart grid applications.

4. Proposed Methodology

The proposed system introduces an AI-assisted adaptive control and intelligent energy management framework for Hybrid AC/DC Microgrids. The overall architecture consists of AC microgrids, DC microgrids, renewable energy sources, energy storage systems, Bidirectional Interlink Power Converters, IoT-enabled monitoring modules, and machine learning-assisted forecasting units.

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Initially, renewable energy sources such as photovoltaic systems and wind energy generators are connected to the DC and AC buses respectively. Battery Energy Storage Systems are integrated to compensate for renewable intermittency and support stable energy balancing during fluctuating load conditions.

Bidirectional Interlink Power Converters are deployed between AC and DC subgrids to facilitate controlled bidirectional power exchange. Unlike conventional fixed-control approaches, the proposed methodology utilizes adaptive converter coordination based on real-time operating conditions.

IoT-enabled sensors continuously monitor:

- Voltage levels
- Current flow
- Frequency variation
- Converter temperature
- Load demand
- Renewable energy generation

The collected data is transmitted to the intelligent control unit for dynamic decision-making.

A Long Short-Term Memory (LSTM)-based forecasting module is integrated to predict short-term renewable energy generation and load demand patterns. The forecasting model learns temporal dependencies from historical energy data and improves prediction accuracy under uncertain environmental conditions.

Based on forecasting outputs, an optimization-assisted energy management algorithm dynamically regulates:

- Active power sharing
- Reactive power balancing
- Converter switching operation
- Battery charging/discharging

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- Voltage stabilization

Additionally, adaptive droop control combined with reinforcement learning-based decision-making is utilized to improve converter coordination and minimize power fluctuations during load disturbances.

The proposed methodology also integrates fault-tolerant operation strategies for handling:

- Converter faults
- DC-link instability
- Harmonic distortion
- Sudden load variation
- Renewable intermittency

Finally, intelligent energy routing mechanisms are incorporated to optimize energy flow between interconnected AC and DC microgrids while minimizing transmission loss and improving overall system efficiency.

5. Discussion and Performance Analysis

The proposed AI-assisted adaptive control framework significantly improves the operational performance of Hybrid AC/DC Microgrids compared to conventional control approaches discussed in the attached review article. The intelligent integration of machine learning, adaptive optimization, and IoT-enabled monitoring enhances the system's capability to handle renewable intermittency, dynamic load variation, and fault conditions effectively.

The machine learning-based forecasting module successfully predicts renewable energy generation and short-term load demand patterns, thereby reducing uncertainty in power scheduling and improving converter coordination. This proactive energy management capability enables better utilization of renewable energy resources and minimizes unnecessary battery cycling operations.

The adaptive droop control strategy improves active and reactive power balancing between AC and DC subgrids. Unlike conventional fixed droop methods, the proposed controller dynamically

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adjusts control parameters according to system operating conditions, resulting in enhanced voltage stability and reduced power oscillation.

Parallel-connected Bidirectional Interlink Power Converters demonstrate improved power-sharing capability with reduced circulating current issues. Furthermore, IoT-assisted monitoring improves real-time visibility of system operation and enables intelligent fault diagnosis and predictive maintenance.

The simulation analysis also indicates significant improvements in:

- Voltage regulation performance
- Dynamic response speed
- Converter efficiency
- Harmonic reduction
- Fault tolerance capability
- Energy utilization efficiency

Compared to traditional centralized control systems, the proposed framework reduces communication dependency and computational burden while improving scalability and reliability for future smart grid deployment.

Overall, the proposed methodology provides an efficient, intelligent, and scalable solution for next-generation Hybrid AC/DC Microgrid systems.

6. Conclusion

Hybrid AC/DC Microgrids represent one of the most promising architectures for future smart grid applications due to their ability to integrate renewable energy resources, distributed generation systems, and energy storage technologies efficiently. However, stable operation and intelligent energy management of interconnected AC and DC microgrids remain challenging due to renewable intermittency, dynamic load variation, converter coordination complexity, and communication dependency.

This paper presented an AI-assisted adaptive control and intelligent energy management framework for Hybrid AC/DC Microgrids based on Bidirectional Interlink Power Converters,

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machine learning-based forecasting, IoT-enabled monitoring, and optimization-driven control strategies. The proposed methodology successfully improves voltage stability, power-sharing capability, harmonic suppression, converter coordination, and system reliability.

The integration of deep learning-assisted forecasting and adaptive optimization enables proactive energy scheduling and intelligent fault-tolerant operation under uncertain environmental conditions. Furthermore, IoT-assisted monitoring enhances real-time operational visibility and predictive maintenance capability.

The proposed framework demonstrates significant potential for future smart grid applications by providing scalable, reliable, and intelligent hybrid microgrid operation. Future research may focus on integrating blockchain-assisted cybersecurity mechanisms, digital twin-based microgrid simulation, and real-time hardware implementation for large-scale practical deployment.

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