A Comprehensive Review of Techno-Economic Perspective of AC/DC Hybrid Microgrid

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***Abstract*—The main objective of this research is to review the techno-economic aspects of AC/DC hybrid microgrid. This review has been done by scrutinizing the essential constituents of both AC and DC microgrids, accentuating their corresponding benefits and constraints. The benefits and reasons for integrating AC and DC technology in a hybrid microgrid setting are then covered. From a technological standpoint, the study addresses Renewable Energy Integration, Power Electronic Converters, Energy Storage Systems, Control and Energy Management system and Grid Synchronization. This can lead to a reduction in the overall operational expenses of the microgrid, making it more economically viable in the long run. Initial Investment, Life cycle costs, Payback period, Operational and Maintenance Costs, Regulatory Incentives and Policies and energy savings cost regarding the financial aspect has been reviewed in this paper. complexity to design, operation, and control is a big challenge of AC/DC Hybrid Microgrid. Challenges in the smooth integration of AC and DC components have also been reviewed. The study also investigates how different regulations, laws, and incentives affect the financial sustainability of AC/DC hybrid microgrid projects. Real-world examples and case studies are included to offer useful insights into the effectiveness and viability of current AC/DC hybrid microgrid systems from an economic standpoint. In addition, the review points out areas of current research deficiency and makes recommendations for future directions in this area of study. Researchers, practitioners, and policymakers interested in the design and implementation of resilient and sustainable energy systems will find great value in the thorough review that presents the current level of knowledge on the techno-economic aspects of AC/DC hybrid microgrids. The review's conclusions can be used by legislators to create well-informed rules and policies that encourage the installation of AC/DC hybrid microgrids and their integration with the current energy infrastructure. When designing, developing, and implementing AC/DC hybrid microgrid systems, researchers and technology developers can recognize important obstacles as well as opportunities.**

Keywords*—Technical Perspective, Economical Perspective, Hybrid Microgrid, AC/DC, Energy Storage System

I. Introduction

Microgrids are emerging as major system in the future energy landscape due to the paradigm shift in power systems brought about by the world's fast shift to sustainable energy solutions [1]. Among these, hybrid microgrids which effectively combine DC (direct current) and AC (alternating current) components have drawn a lot of interest. The goal of this integration is to maximize energy management, capitalize on the complementary qualities of AC and DC systems, and improve the general effectiveness, dependability, and resilience of microgrid operations. Given this, a thorough evaluation of AC/DC hybrid microgrids from a techno-economic standpoint is conducted in this research. The demand for a hybrid microgrid, which combines the advantages of both AC and DC microgrids, has increased due to the depletion of natural resources and the intermittent nature of renewable energy sources. This hybrid microgrid will minimize overall deficiency inadequacies and boost system reliability [2]. The growing proportion of renewable energy sources in the mix of power generation highlights the need for sustainable energy solutions [3]. Renewable energy sources are numerous and clean, but because they are intermittent, integrating them effectively requires modern grid systems. The benefits of both AC and DC systems are combined in AC/DC hybrid microgrids, which offer a comprehensive solution to the problems of grid resilience, energy efficiency, and the integration of renewable energy sources [4].

In order to understand the reasons behind the integration of AC and DC technology, a review begins with a framework for the emergence of hybrid microgrids [5]. Distinctive features of AC and DC systems are discussed, with an emphasis on how well-suited they are for various applications in microgrid environments. The role that hybrid microgrids play in overcoming the shortcomings of single AC or DC microgrid configurations is highlighted [6]. The review explores converter technologies, control tactics, and interoperability challenges as it digs into the essential elements of AC/DC hybrid microgrids from a technological depth [7]. Moving on to achieve smooth integration and effective operation of AC and DC systems within a hybrid microgrid framework, the section attempts to provide a basic grasp of the technical nuances involved [8]. The report then shifts its focus to the economic side and discusses the costs involved in AC/DC hybrid microgrids. AC/DC hybrid microgrids can lessen dependency on conventional fossil fuels by incorporating renewable energy sources like solar and wind, which will eventually result in cheaper energy costs. The initial financial outlay required to establish AC/DC hybrid microgrids can be substantial and include grid infrastructure, energy storage, and renewable energy production. Even though these expenses are frequently offset by long-term gains, funding the initial expenditure is still a barrier for many enterprises. A study of life cycle costs, payback times, and financial models relevant to the installation and upkeep of hybrid microgrid systems are included in this. The review also looks at how incentives, regulations, and regulatory frameworks affect the financial sustainability of AC/DC hybrid microgrid projects [9].

Real-world case studies and examples are used throughout the review to highlight the usefulness of implementing AC/DC hybrid microgrids [10]. These illustrations support theoretical ideas and offer insightful information about the difficulties and performance of ongoing projects. This thorough analysis essentially seeks to compile the body of information regarding the techno-economic elements of AC/DC hybrid microgrids [11]. The purpose of this study is to increase the understanding of researchers, practitioners, and policymakers who are involved in the design, implementation, and progress of resilient and sustainable energy systems by combining information from both technological and economic viewpoints. The key motivations for conducting this research paper are:

- To show the importance of AC/DC hybrid Microgrid in power system.
- For enhancing AC/DC hybrid microgrid performance, which is essential for reaching the energy to all levels of consumers.
- For understanding the technological and financial aspect related to the installation and upkeep of AC/DC hybrid microgrids.
- To analyze the essential constituents of both AC and DC microgrids, accentuating their corresponding benefits and constraints.

The main contribution of this review is understanding the integration of DC and AC technology in hybrid microgrids [12]. This entails being aware of the benefits and technical compatibility of mixing both AC and DC components. The evaluation may concentrate on how AC/DC hybrid microgrids enable the integration of diverse renewable energy technologies, given the growing significance of renewable energy sources [13]. Recommendations for further study and advancement in the area of AC/DC hybrid microgrids may be included in the review's conclusion. This could serve as a guide for scientists, decision-makers, and business experts as they develop and use these technologies further.

II. Methods

The alignment of an AC/DC hybrid microgrid's technical and financial aspects is essential to the system's effective setup and functioning [14]. When direct current (DC) and alternating current (AC) components are combined, energy management can be optimized, and flexibility enhanced in hybrid microgrids [15]. From the original design and execution to continuous operation and maintenance, the technical and financial aspects of an AC/DC hybrid microgrid are intricately linked. For the hybrid microgrid to be resilient, efficient, and sustainable, technological optimization and economic factors must be integrated in a well-balanced manner. Technically speaking, the hybrid microgrid combines AC and DC components in the best possible way, taking into account the unique energy requirements and features of the connected loads [16]. This integration enables smooth energy flow throughout the system and permits the effective use of both AC and DC sources. Advanced control and management systems that keep an eye on energy supply, storage, and consumption are essential to technical optimization [17]. These systems use algorithms to automatically regulate the operation of DC and AC equipment, guaranteeing energy balance and optimal performance. An essential part of powering the microgrid is provided by renewable energy sources like wind turbines, solar photovoltaic (PV) panels, and energy storage systems (ESS). These innovations assist maintain a balance between supply and demand inside the microgrid by producing power from renewable sources and storing extra energy for later use. Complex control systems are used to keep an eye on and regulate the electricity flow in the microgrid. SCADA systems, or supervisory control and data acquisition, are examples of these control systems. Taking into consideration variables like energy demand, renewable energy output, energy storage capacity, and grid constraints, energy management algorithms can be utilized to improve the scheduling and dispatch of energy resources.

An AC/DC hybrid microgrid's implementation costs are related to the purchase and installation of several parts, such as converters, energy storage, AC and DC generators, and control systems [18]. The decisions made during the planning phase of technical design are influenced by the initial capital investment. Technical design decisions are directly influenced by economic factors, such as the expenses of continuous operation and maintenance. Economizing can be achieved by selecting parts that require less maintenance and have longer lifespans. Tariffs and energy costs have an impact on the economic feasibility of an AC/DC hybrid microgrid [19]. Technical choices, including energy source and storage technology selection, are made with consideration for how they will affect overall energy costs. The capacity to function independently or seamlessly integrate into the main grid affects both the technical and financial elements [20]. The capacity to sell excess energy back to the grid through grid connectivity promotes revenue creation and long-term economic viability. The entire energy usage and, thus, the microgrid's economic efficiency are directly impacted by technical factors, such as the integration of energy-efficient devices and technology [21]. The economic viability is increased if the AC/DC hybrid microgrid is built to produce excess energy that can be sold back to the grid or nearby customers. The microgrid's technical features, like its effective energy conversion and storage, help to generate income. Through the use of sophisticated algorithms, real-time monitoring, and coordinated control techniques, modern control and management systems enable AC/DC hybrid microgrids to balance loads, maximize energy flow, and guarantee stability.

III. AC/DC Microgrids

Two varieties of power distribution systems that use various electrical currents for energy transmission and distribution are AC (Alternating Current) and DC (Direct Current) microgrids [22]. To maximize the benefits of each technology, a hybrid AC/DC microgrid combines different parts from AC (alternating current) and DC (direct current) systems. An example of an AC source for a microgrid would be a distributed generator, a traditional grid link, or renewable energy sources that produce AC electricity. It also includes DC sources, which effectively produce or store DC electricity. Systems for storing extra energy produced by renewable sources or during times of low demand are known as energy storage systems, or ESS. Power conversion between AC and DC is accomplished through the use of DC/AC inverters and AC/DC converters. The schematic diagram of hybrid AC/DC microgrid has been shown in Fig. 1.

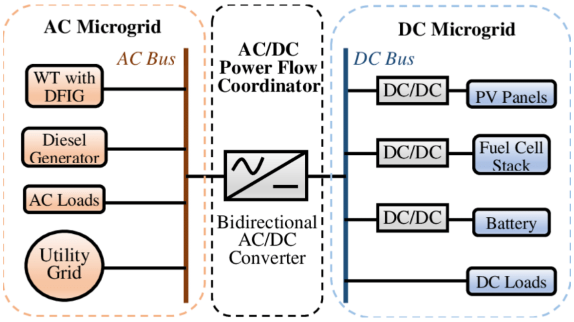

Fig. 1. Schematic diagram of hybrid AC/DC microgrid [23]

Both AC and DC have benefits and drawbacks, and the decision between them is influenced by a number of variables, such as the particular application, the needed level of efficiency, and the incorporation of renewable energy sources [24]. The unique application, the infrastructure that already exists, the need for efficiency, and the incorporation of renewable energy sources all influence the decision between an AC, DC, or hybrid microgrid [25]. There are advantages and disadvantages to each type, and the best approach frequently entails a thorough examination of the particulars and objectives of the particular microgrid project. The microgrid's central nervous system (EMS) is in charge of coordinating the actions of different parts to maximize energy production, storage, and consumption. To efficiently dispatch power, it makes use of real-time data from sensors, weather forecasts, and energy storage systems. In Fig. 2, power management and control of hybrid AC/DC microgrids is shown.

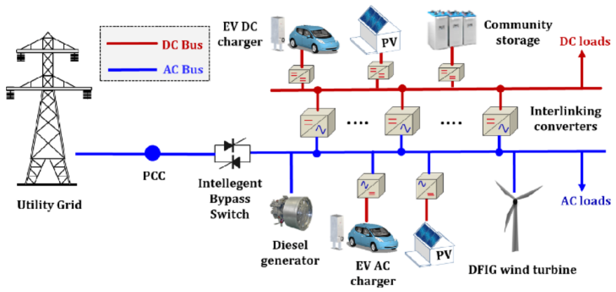

Fig. 2. Power management and control of hybrid AC/DC microgrids [26]

IV. Technical Perspective of AC/DC Hybrid Microgrid

A hybrid microgrid that combines direct current (DC) and alternating current (AC) components into a single energy distribution system is examined from an engineering and technology standpoint from the technical point of view. By combining the best features of both AC and DC technology, this integration aims to improve power distribution by making it more adaptable, reliable, and efficient [27]. In conclusion, power conversion, integration of renewable energy, control systems, safety features, and communication infrastructure are among the technical issues that must be resolved in an AC/DC hybrid microgrid. Utilizing developments in power electronics, control engineering, and communication technologies, a comprehensive and multidisciplinary strategy is necessary for successful implementation.

A. Renewable Energy Integration

Solar and wind power are two examples of renewable energy sources that are frequently included in hybrid microgrids [28]. These sources provide DC power and integrating them seamlessly with AC and DC loads is a significant technical problem that requires the development of cutting-edge power electronic converters.

B. Power Electronic Converters

By allowing the conversion of AC to DC or vice versa, bidirectional power electronic converters are essential to the operation of the AC/DC hybrid microgrid [29]. These converters assist in controlling the fluctuating nature of renewable energy sources and offer the flexibility required for energy transfer between the AC and DC subsystems.

C. Energy Storage Systems

Batteries-based energy storage devices are essential to an AC/DC hybrid microgrid's technical operation [30]. In order to maintain grid stability, these systems store excess energy during times of high generation and release it when demand exceeds supply.

D. Control and Management Systems

Modern control and management systems are necessary for the hybrid microgrid's component parts to be coordinated and monitored in real time [31]. These systems balance loads, maximize energy flow, and guarantee the stability and dependability of the microgrid as a whole.

E. Grid Synchronization

Synchronizing the DC and AC subsystems is a difficult technological task that calls for exact control methods. By keeping synchronization, problems like phase mismatches are avoided and the hybrid microgrid's power quality is guaranteed to be constant [32].

V. Economic Perspective of AC/DC Hybrid Microgrid

An analysis of the financial aspects, cost-benefit analysis, and economic feasibility of integrating direct current (DC) and alternating current (AC) components into a single energy distribution system are all part of the economic viewpoint of an AC/DC hybrid microgrid. In order to fully understand the economics of AC/DC hybrid microgrids, a thorough examination of the system's lifetime costs, advantages, and financial factors must be done [33]. When assessing the viability and sustainability of putting AC/DC hybrid microgrid projects into action, decision-makers, investors, and stakeholders must have a thorough understanding of the economic ramifications.

A. Initial Investment and Deployment Costs

Reviewing the initial expenditures related to the implementation of AC/DC hybrid microgrid systems, such as the installation of energy storage systems, renewable energy sources, control systems, power electronic converters, and other infrastructure parts [34].

B. Life Cycle Costs

Taking into account the whole life cycle costs, which include not only the original investment but also expenditures associated with operation and maintenance during the anticipated lifespan of the system [35]. A thorough grasp of the financial effects of implementing an AC/DC hybrid microgrid can be obtained by evaluating life cycle costs.

C. Payback Period

Calculating the payback period, or the amount of time needed for the hybrid microgrid's total financial gains to offset the original outlay of capital [36]. A shorter payback period makes the system more appealing from an economic standpoint.

D. Operational and Maintenance Costs

Assessing the costs of continuous maintenance and operation for the hybrid microgrid, including expenses for equipment upkeep, recurring upgrades, and monitoring and control system expenditures [37].

E. Energy Cost Savings

Evaluating possible energy cost savings through the effective integration of energy storage, advanced control systems, and renewable energy sources [38]. Reduced reliance on outside power sources and grid electricity at times of high demand is one aspect of this.

F. Regulatory Incentives and Policies

Examining how regulatory incentives, guidelines, and support systems affect the financial sustainability of hybrid AC/DC microgrid initiatives [39]-[42]. The financial viability of such systems can be strongly impacted by government regulations, tax breaks, and subsidies.

VI. AC/DC Hybrid Microgrid

The techno-economic viewpoint on a community microgrid entails taking into account both the financial and technological ramifications of putting in place a decentralized energy infrastructure of this kind. An extensive examination of technology integration, control systems, resilience, economic feasibility, community involvement, and the possibility of future growth and scalability is all part of the techno-economic viewpoint of a community microgrid. A fair assessment of the technical and financial aspects of putting in place a community microgrid is ensured by this all-encompassing approach.

A. Technical Perspective

A community microgrid's technical viewpoint entails comprehending the many technologies and parts that comprise the microgrid system. Determine and incorporate renewable energy sources into the microgrid, such as biomass generators, wind turbines, and solar photovoltaic (PV) panels. Determine the possibilities for renewable energy in the area and select solutions based on what the community needs. Install energy storage systems to store extra energy during times of high generation. These systems usually use batteries. By utilizing this stored energy at times of low generation or in the event of a grid outage, the microgrid's resilience and dependability are increased. Investigate the application of systems that produce electricity and heat concurrently. Configure a microgrid controller to oversee and synchronize the functioning of different microgrid components. When necessary, configure the microgrid to work in tandem with the main power grid. This includes the capacity to transition between islanded (standalone) and grid-tied modes in response to crises or changes in the grid. Incorporate demand-side management techniques to maximize community energy use. Provide safety procedures and emergency methods to address any mishaps inside the microgrid.

B. Economical Perspective

Considering the financial effects and practicality of putting in place a decentralized energy system customized for regional requirements is the focus of a community microgrid's economic viewpoint. Energy storage, renewable energy sources, control systems, and other infrastructure expenditures are included in the initial capital investment. A thorough economic analysis should take into account operational and maintenance costs, which include regular maintenance and software updates. One important statistic is the return on investment (ROI), which takes into account things like prospective revenue streams, reduced costs, and energy savings. A thorough examination of the regulatory framework and tariff structure in the area facilitates comprehension of how the microgrid interacts with current pricing systems. The project's economic appeal is enhanced by energy cost savings, which are obtained by contrasting microgrid electricity charges with those of the regular grid. Taking into account variables like energy savings, reduced expenses, and possible revenue sources, the return on investment (ROI) is a crucial statistic. Understanding how the microgrid interacts with current pricing mechanisms requires an analysis of the regulatory framework and local tariff structure. The project is more financially appealing when energy prices are reduced when comparing microgrid electricity charges to those of the regular grid. Completing the economic analysis becomes more difficult when one considers government incentives, financing choices, and revenue-generating opportunities like selling energy back to the grid. A comprehensive risk assessment takes financial risks into account, but the economic impact on the community, including job creation and local growth, is crucial.

VII. Challenges of AC/DC Hybrid Microgrid

The successful integration and operation of AC/DC hybrid microgrids necessitates the resolution of several issues that arise during their installation [43]. These difficulties cover a wide range of operational, financial, legal, and technical issues. A multidisciplinary strategy combining cooperation between engineers, regulators, legislators, and industry stakeholders is needed to address these issues. Solutions to these issues should surface as technology develops and knowledge from pilot projects builds, which will aid in the wider adoption of AC/DC hybrid microgrid systems. The following is an overview of the main difficulties in putting AC/DC hybrid microgrids into practice. A comparative table of AC, DC, and hybrid microgrid shown in Table 1.

- In order to ensure smooth energy transfer between AC and DC subsystems, power electronic converters must achieve high efficiency.
- It is difficult to ensure that various parts and technologies in the hybrid microgrid work together.
- Combining AC and DC subsystems can be difficult to coordinate.
- A power generating profile that incorporates renewable energy sources becomes more variable and intermittent.
- Energy storage is necessary to keep the microgrid stable and store extra energy, but because energy storage systems especially batteries are expensive, there may be financial difficulties and the project's viability may be compromised.
- It can be difficult to design scalable AC/DC hybrid microgrids that can handle future expansions.

Table 1. A comparative table of AC, DC, and hybrid microgrid

Criteria	AC Microgrid	DC Microgrid	Hybrid Microgrid
Technical Perspective			
Efficiency	Losses are typically greater in AC systems.	In some cases, DC systems can be more efficient.	Through the use of both AC and DC components' advantages, hybrid systems can maximize efficiency.
Voltage Levels	It could be necessary to use multiple voltage levels.	Maintaining constant voltage levels makes things easier.	By carefully balancing the use of AC and DC components, hybrid systems may balance the voltage needs.
Power Quality	Due to frequent voltage changes, it is susceptible to problems with power quality.	Because of the steady voltage, power quality is often better.	Power quality problems can be successfully mitigated by hybrid microgrid design.
Energy Storage Compatibility	More issues with certain energy storage technologies' compatibility.	DC systems and energy storage technologies frequently work well together.	By carefully choosing the best technology for each kind of energy storage system, hybrid microgrids may maximize energy storage.
Economic Perspective			
Cost of Components	Because AC system components are generally available, expenses may be lowered.	Due to their simplicity and ease of integration, DC components might be economically advantageous.	Hybrid systems could include a variety of parts, and the total cost would depend on the particular setup and technology employed.
Maintenance Costs	Because AC systems can be sophisticated, maintenance expenses may be greater.	Less complicated systems and fewer parts translate into generally cheaper maintenance costs.	In order to ensure effective maintenance and lower costs over the system's lifecycle, hybrid systems require careful planning.
Integration with Renewable Energy	For the incorporation of renewable energy, AC systems could need extra hardware.	Integrating DC systems with renewable energy sources is a smart idea.	By utilizing the advantages of both AC and DC systems, hybrid microgrids can effectively incorporate renewable energy sources.
Grid Connection Costs	The necessity for inverters may result in higher costs when connecting to the main grid.	DC systems might be less expensive to connect to the grid.	Dependent on the local grid infrastructure, hybrid microgrids may optimize costs by providing a range of grid connection alternatives.

VIII. Discussion

The detailed analysis of the techno-economic viewpoint of AC/DC hybrid microgrids presents a complex picture of how economic factors and technology developments are closely related. It has been demonstrated that combining AC and DC technology in hybrid microgrids produces synergies that improve the overall resilience and efficiency of the system. The analyzed case studies offer insightful information by highlighting real-world applications and illuminating trends that appear in a range of implementations. A careful examination of life cycle costs, payback times, and different financial models is used to determine the economic viability of hybrid microgrid deployment, which is a crucial component. Policies and regulatory frameworks are important factors that affect the profitability and success of AC/DC hybrid microgrid projects. Although the study highlights the potential advantages, it also openly notes the difficulties in integrating, opening the door for conversations on how to get past these obstacles. The discovery of research gaps offers a path forward for further studies, implying that a more thorough comprehension of the techno-economic dynamics can greatly aid in the creation of robust and sustainable energy systems. Consequently, it concludes with a synthesis of the practical consequences, highlighting the necessity of stakeholders involved in the planning and execution of AC/DC hybrid microgrid projects making educated decisions. This thorough investigation adds to our understanding of the topic and provides insightful information for both researchers and industry practitioners. Observations from studies on AC/DC hybrid microgrids are important because they help progress technology and make resilient, sustainable energy systems a reality. Research study results are used to determine the best design arrangements, operational approaches, and control schemes to improve the dependability and efficiency of AC/DC hybrid microgrids. Research results on AC/DC hybrid microgrids are important because of what they can do for resilience, energy sustainability, and technological innovation. Research plays an essential role in propelling the development and widespread use of AC/DC hybrid microgrid technology, ultimately contributing to the change of the global energy environment by increasing knowledge, creating solutions, and influencing decision-making.

IX. Conclusion

A complete and perceptive analysis of the state-of-the-art in this quickly developing sector has been made possible by the extensive assessment on the techno-economic perspective of AC/DC hybrid microgrids. Combining DC and AC technology in hybrid microgrids appears to be a viable way to deal with the problems associated with grid resilience and the integration of renewable energy. The technologies have been found to work well together, and case studies provide empirical support for theoretical ideas. The life cycle costs and financial models that are part of the economic feasibility analysis highlight the delicate balance needed for the successful deployment of hybrid microgrids. It is acknowledged that regulatory frameworks and policies play a key role in determining project outcomes and forming the economic environment. The difficulties that come with the integration process are openly acknowledged, pointing to potential areas for further study and development despite the obvious benefits. The need for ongoing investigation and improvement of technological and economic elements is highlighted by the identification of research gaps. In the end, this thorough analysis advances our knowledge of AC/DC hybrid microgrids from an academic perspective while also providing useful information for researchers, industry experts, and legislators working to develop sustainable and resilient energy systems.

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