

A COMPARATIVE STUDY OF AC AND DC MICROGRID SYSTEM WITH DISTRIBUTED ENERGY RESOURCES

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Abstract- In this paper modern systematic literature analysis of AC and DC microgrids (MG) in combination with renewable energy sources (RESs) as distributed generations units (DG), loads and battery bank to store electricity. A review on the different DG units arrangements consisting distribution networks of the low voltage AC and DC using numerous applications of microgrid systems in the perspective of current and the future customer apparatus energy market is broadly deliberated. Based on the techno-economic and ecological advantages of the renewable energy-based DG units, a detailed comparison of AC and DC microgrid systems is done. This paper also explores the possibility, controlling and energy management schemes of the both microgrid systems depending upon the most recent research findings. Eventually, the protection and the power management techniques in microgrid systems are discussed and delivered in detail. Out of this literature analysis, it could be evidenced that both type of microgrid systems consisting multiconverter gadgets are inherently conceivable for the upcoming energy systems to attain the consistency, better power supply and efficiency.

Keywords: AC microgrid, DC microgrid, Renewable energy sources (RESs), Distributed generation units (DGs).

Nomenclature

| | | | |
|------|----------------------------------|------|------------------------------------|
| MG | Micro-grid | MPPT | Maximum power point tracking |
| PV | Photovoltaic | SEMS | Smart energy management system |
| ESS | Energy storage system | MGCC | Microgrid control and coordination |
| DG | Distributed generation unit | DSM | Demand side management |
| MG | Micro-grid | DER | Distributed energy resources |
| HVDC | High voltage direct current | PED | Power electronics devices |
| HVAC | High voltage alternating current | CHP | Combined heat and power |

1. INTRODUCTION

From a historical standpoint, AC power networks have long been the preferred choice for commercial energy systems, powering everything from household lighting to industrial machinery since the late 1800s. Their ability to efficiently transmit power over vast distances, coupled with the adaptability to convert AC voltage for diverse applications, solidified AC networks as the industry standard. Over a century later, AC loads continue to dominate the market, showcasing the enduring legacy of this technology[1]. However, challenges loom in meeting the world's escalating energy needs. Limited funding and high energy costs hinder the construction of new power plants and transmission infrastructure. Additionally, mounting concerns such as global warming, aging power infrastructure, and the finite nature of energy resources underscore the urgent need to modernize the current energy landscape. The surge in energy consumption standards and the proliferation of DC loads, driven by advancements in electronics, further highlight the necessity for this transformation. In response, energy engineers and researchers have embarked on a journey to overhaul conventional power systems[2]. Leveraging modern solutions such as renewable energy-based distributed generation units, energy storage systems, and advanced control strategies rooted in information technology, they aim to usher in a new era of energy efficiency and sustainability. However, the realization of these sophisticated systems requires further research and development. In conclusion, the imperative to modernize the energy system is clear. Through ongoing innovation and collaboration, we can pave the way for a more resilient and environmentally conscious energy future[3].

Existing microgrid systems leverage established AC power system standards, including frequency, voltage levels, and protection principles, to ensure smooth operation. Conversely, the adoption of electronic devices, notably the mercury vapor rectifier in 1893, pioneered grid control, paving the way for high voltage direct current (HVDC) transmission in 1928. This innovation revolutionized power transmission with its remarkable capability for DC power inversion and correction. Despite initially limited applications, such as shipboards, tractions, and telecommunications, advancements in power electronics have spurred a resurgence of interest in DC power systems[4], [5]. Today, they find utility in various sectors, including manufacturing, automotive, aerospace, and electronics industries. DC distribution systems, or DC microgrid systems, have become integral for power distribution in these domains. Notably, DC power supplies play critical roles in cutting-edge technologies like the International Space Station, modern aircraft, and electronics loads such as computers and servers in data centres. Moreover, the liberalized electricity market has fostered an environment conducive to high penetration of DC

systems[6].

This market evolution underscores the growing demand for reliable, efficient, and diversified energy sources. Currently, a significant portion of renewable energy units generate either DC or variable frequency/voltage AC output power. Power electronics devices (PEDs) have become indispensable for realizing Microgrids (MGs). Distributed Generation (DG) units, such as fuel cells and micro-turbines, offer the advantage of combined heat and power (CHP) generation, enhancing overall efficiency by serving various types of loads, including both AC and DC[7]. To optimize energy generation, DG devices like wind turbines and PV arrays often employ maximum power point tracking (MPPT). Similarly, Energy Storage Systems (ESSs) paired with wind or PV-based DG units can regulate output power to match load demand and support dispatched power generation. This approach enables MGs to maximize the utilization of renewable energy resources while improving overall thermal and electrical efficiency. Effective placement of various DG units, considering geographical factors and available load types, is crucial for optimizing MG performance. Under such operational scenarios, microgrid systems require wide-range control systems capable of managing diverse tasks efficiently[8].

This study offers comprehensive literature reviews on mixed loads (combining AC and DC), energy storage systems (ESSs), and microgrid setups driven by renewable energy sources. It delves into the realms of mixed load integration, ESS advancements, and the dynamics of renewable energy-based microgrid systems. The impetus behind this research stems from the surging interest in renewable energy, the evolution of energy storage technologies, and the shifting consumer inclination towards DC-powered equipment over traditional AC systems[9]. Consequently, a detailed survey scrutinizing microgrid configurations, encompassing various Distributed Generation (DG) setups across low voltage AC (LVAC) and DC (LVDC) networks, is conducted to explore their current and potential applications within both energy and consumer equipment markets. Furthermore, an in-depth comparative analysis of AC and DC microgrids is provided, emphasizing their economic, technological, and ecological benefits. This comparison extends to evaluating their viability, control mechanisms, and security protocols. Through these endeavours, the study aims to provide invaluable insights into the synergies between mixed loads, energy storage solutions, and renewable energy-based microgrid systems, thus informing stakeholders about emerging trends and future trajectories in sustainable energy deployment[10]. The rest of the paper is structured as follows: Feasibility of AC microgrid and DC microgrid have been discussed in the second section. In the third section, various types of Distributed generation units based on renewable energy resources have been discussed. The various parameters such as system types, cost of energy, type of software used have been deliberated. and the conclusion is summarized in section 4.

2. AC AND DC MICROGRID SYSTEMS

This section examines the feasibility analysis of AC and DC microgrid systems based on their power management and control schemes. The primary system may operate as either a DC or AC bulk system, with connections between Distributed Generation (DG) units and Energy Storage Systems (ESSs) across the distribution network. An "AC microgrid" constitutes a compact, standalone AC power system comprising load circuits and DG units. Typically, these networks are interconnected at the Point of Common Coupling (PCC), with loads primarily sourced locally from Renewable Energy Source (RES)-based DG units and supplemented by utility power as needed. Excess power can be exported to the main system if the load demand is lower than what the DG units produce[11]. Additionally, this section presents several examples of AC microgrid systems deployed internationally or utilized as testing prototypes. Most often, AC microgrid systems adhere to traditional distribution system voltage and frequency standards, ensuring compatibility and seamless integration as depicted in Fig. 2.1.

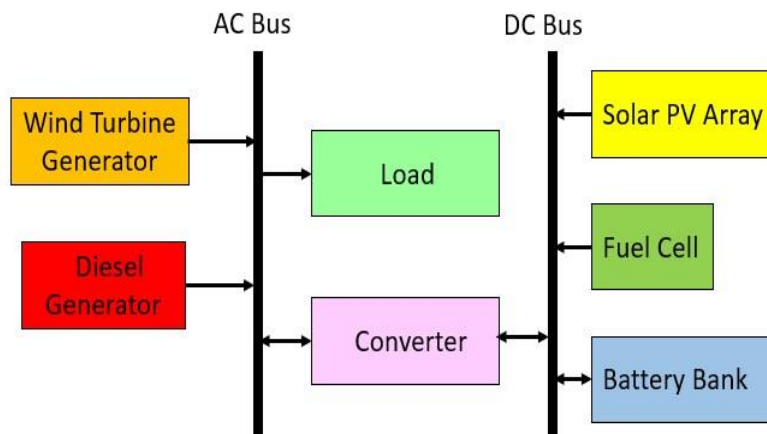


Fig. 2.1 AC Microgrid system with DG Units

Numerous countries have conducted research and implemented renewable energy-based DC microgrid systems, with their operational viability scrutinized by various investigators. Solanki et al. proposed a Smart Energy

Management System (SEMS) aimed at maximizing the microgrid's economic performance. This SEMS comprises modules for Energy Storage System (ESS) administration, optimization, and forecasting[12]. Analyzing the PV output under diverse weather conditions, a module for one-day-ahead power forecasting is introduced. Considering the complexities of energy price structures and optimizing energy storage across multiple time steps, the economics aspect is challenging. Hence, the ESS module identifies optimal operating strategies, while the SEMS integrates smart ESS management, economical load dispatch, and DGU unit operation optimization[13]. Regardless of whether the microgrid is DC- or AC-coupled, various currents are present in different proportions. The method of connecting each component differs, with a DC/DC voltage conversion being more efficient than a single AC to DC conversion. For instance, in a solar and battery microgrid, surplus solar energy is stored in batteries for later use when solar power is unavailable, such as at night or during overcast weather. In a DC-coupled system, only one inversion of AC to DC is required, whereas an AC-coupled system necessitates three inversions. In AC-coupled microgrids, a central controller connected to each unit is typically employed to balance generating sources and loads. However, this process, despite quick communication and a fast central controller, can be hindered by the speed at which electrical energy travels, posing challenges for timely response to load variations. This can lead to issues like circuit breaker trips and equipment damage, potentially causing downtime[14].

On the other hand, in DC-coupled systems, all components are connected to a single DC bus, enabling the creation of a more sophisticated control system independent of communication methods. Each device directly monitors the voltage on the system, allowing for swift response without the need for extensive communication. This common DC bus facilitates easy reconfiguration of microgrids without requiring significant modifications[15]. Components can be added or modified without hassle, with each device responsible for maintaining the DC bus voltage. Control adjustments for expansion or reconfiguration are simple with the Auto Sync DC bus, as only setpoint adjustments are needed. Conversely, coordinating various device combinations in an AC-coupled system is more complex due to independent regulation of each component[16].

DC microgrid system is a confined electricity distribution network that utilizes direct current instead of alternating current. It is typically comprising power sources, energy storage devices, loads and control systems tailored to supply power to small geographical area. DC microgrids have garnered attention due to their potential to enhance efficiency[17].

Table-2.1 Comparison analysis of AC and DC Microgrid Systems in Grid Connected and islanding Mode[1]

| Mode | AC Microgrids | DC Microgrids |
|----------------|---|--|
| Grid Connected | The monitoring system diagnoses issues by gathering data from the low voltage AC (LVAC) network, Distributed Generation (DG) units, and both AC and DC load. | The primary role of the Microgrid Control and Coordination (MGCC) system is to autonomously manage the power flow and regulate the voltage profile of the Distributed Generation (DG) units in reaction to disturbances and fluctuations in load |
| | Utilizing available data, the Microgrid Control and Coordination (MGCC) system conducts state estimation and security assessments, while also assessing economic generation scheduling, and actively controlling both active and reactive power of the DG units. Additionally, it manages demand-side management functions. | The Microgrid Control and Coordination (MGCC) system plays a role in economic generation scheduling, load tracking or management, and Demand Side Management (DSM) by overseeing the control of storage devices. |
| | The Microgrid Control and Coordination (MGCC) system ensures that each DG unit swiftly ramps up its generation to fulfill its portion of the load in standalone mode. Additionally, it facilitates the automatic transition of DG units back to grid-connected mode with the assistance of the MGCC. | The Microgrid Control and Coordination (MGCC) system ensures that each DG unit promptly ramps up its generation to meet its allocated load in standalone mode and seamlessly transitions back to grid-connected mode automatically. |
| Islanding | The Microgrid Control and Coordination (MGCC) system conducts active and reactive power control of the DGs to uphold stable voltage and frequency levels at the load terminals. | Autonomously regulate the power flow and voltage profile at the load terminals of the DG units in response to disturbances and changes in load. |
| | Utilizing Demand Side Management (DSM) techniques with Energy Storage System (ESS) support to implement load | The Microgrid Control and Coordination (MGCC) system ensures swift generation pickup by DG units to supply local loads |

| | | |
|--|--|--|
| | interruption/shedding strategies for maintaining power balance and voltage stability. | in islanding mode and facilitates automatic reconnection to the grid. |
| | Directing each DG unit to promptly increase its generation to power its designated local loads in standalone mode, and seamlessly resynchronize with the grid with assistance from the MGCC. | Guaranteeing that each DG unit swiftly ramps up its generation to supply its allocated portion of the loads in standalone mode, and seamlessly transitions back to grid-connected mode automatically under the guidance of the MGCC. |

The integration of renewable energy sources and the suitability of DC microgrids for specific applications, like data centers, telecommunications facilities, and remote communities, are notable. DC microgrids can incorporate various power sources such as solar photovoltaic (PV) panels, wind turbines, fuel cells, and batteries, as depicted in figure 2. These sources either generate DC power directly or can be converted into DC using power electronic converters. Energy storage systems (ESS) play a crucial role in DC microgrids, storing excess energy from renewable sources for later use or providing backup power during low generation periods[18]. While batteries are the most common form of energy storage in DC microgrids, other technologies like supercapacitors or flywheels can also be employed. Loads in a DC microgrid encompass a variety of electrical devices such as lighting, appliances, HVDC systems, and electronic equipment. DC loads are increasingly prevalent due to their compatibility with the DC distribution system. Unlike traditional AC microgrids, which rely on transformers and switchgears for voltage conversion and distribution, DC microgrids employ simpler distribution networks with fewer conversion losses[19].

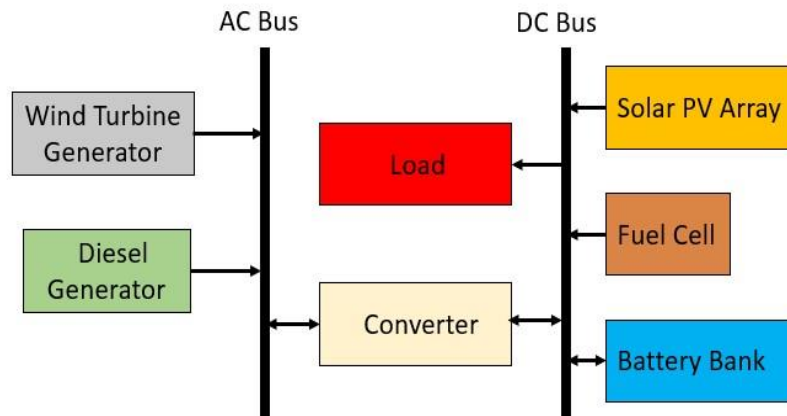


Fig. 2.2 DC Microgrid system with DG units

Power electronic converters, such as DC-DC converters and inverters, serve as vital components of DC microgrid systems. These devices play roles in voltage regulation, power conditioning, and seamless integration of diverse power sources and loads. Advanced control algorithms and supervisory systems are utilized to efficiently manage DC microgrid operations. These systems monitor energy generation, consumption, storage levels, and grid stability, optimizing power flow, prioritizing loads, and ensuring reliable operation across various conditions. DC microgrids can either connect to the main grid or operate autonomously in islanded mode. Even when disconnected from the main grid, the microgrid continues to supply power to critical loads, bolstering reliability and resilience. Compared to AC systems, DC microgrids typically offer higher efficiency due to reduced conversion losses and simpler distribution infrastructure. Moreover, they provide enhanced reliability and power quality, particularly in applications involving sensitive electronic equipment[20].

3. DISTRIBUTED GENERATION UNITS

Distributed generation units refer to small-scale power generation systems that are located close to the point of electricity consumption. These units can include a variety of technologies such as solar photovoltaic panels, wind turbines, fuel cells, micro-turbines, and diesel generators. Distributed generation units provide electricity either independently or in conjunction with the main grid, offering benefits such as improved energy efficiency, reduced transmission losses, and enhanced grid resilience. They play a crucial role in decentralized energy systems and can contribute to meeting local energy needs while reducing dependence on centralized power plants. Voltage control is crucial for distributed energy resources (DER) inverters when they lack a main network to provide voltage reference. It's beneficial to apply voltage control to specific powerful DER inverters for energy continuity[21]. While constant amplitude and frequency reference values are typical inverter control techniques for primary source inverters in single master applications, drop-based voltage control techniques are widely used in multiple main source applications like microgrids. The density of DERs with variable output in microgrids necessitates different energy management mechanisms. Separate management scenarios are established for

network-connected situations and independent operating states where the microgrid provides voltage and frequency stability. Studies have shown that the energy management mechanism for an independent droop-controlled microgrid offers an optimal solution by minimizing fuel costs and enhancing stability, energy quality, and system performance. A new double-layer control system has been developed for microgrids, usable in both island mode and grid-connected operation. The first layer utilizes renewable system estimation data, while the second provides real-time power flow and voltage regulation. In island mode, the primary objective is energy balance. A composite storage system incorporating high-energy-density batteries and ultra-power capacitors is used to optimize energy management and distribution. Energy/power management constraints and objectives are determined, and optimum solutions are introduced using particle swarm and ant colony optimization methods, providing faster solutions than traditional methods[22].

Modern loads such as LED and power electronics are widely used, and energy supplies for these products through the DC distribution system connected to the microgrid are discussed. A hybrid AC-DC microgrid minimizes transducer losses, with AC loads connected to the AC grid and DC loads to the DC grid. Excess energy from DC output sources like PV and solid fuel cells is efficiently distributed through high-quality and high-efficiency DC distribution lines as shown in figure 3.

In rural areas without access to electrical energy, instant power sharing and distributed control of network voltage are implemented in DC microgrid structures to minimize energy storage losses. Scenario-based day-ahead power scheduling models consider the stochastic nature of DERs and unpredictable energy demand, reducing reliance on conventional fuel-based units in microgrids[23].

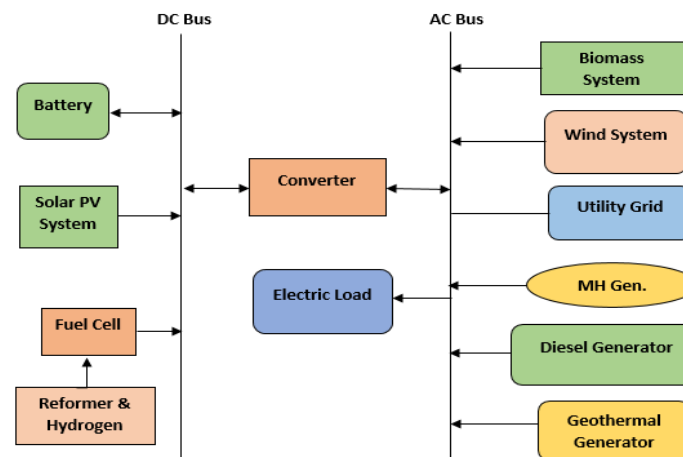


Fig. 3.1 Hybrid Grid Connected Distributed Generation System

However, none of the aforementioned energy management studies have addressed the impact of demand response and the use of electric vehicles on microgrid operation. A study has been developed and presented to optimize the design and economic conditions of a hybrid microgrid, utilizing PV from DER, wind, diesel generator as energy sources, and a fixed battery. Numerous studies aim to improve system performance, efficiency, and sustainability by integrating demand response programs into the energy management system and by integrating large-scale renewable resources into the microgrid. The hybrid distributed generation system comprises various conventional and non-conventional generating resources to meet the demand of the community[24].

CONCLUSION

In this paper, the meditative analysis of AC and DC microgrid systems with distributed generation units, battery banks as energy storage devices, loads and power converters that are presented by researchers was discussed. Considering the increasing demand of energy and interests growing in generating power from the non-conventional based distributed generating units, the need for supply of quality power, reliability and efficiency can lastly be attained. In this paper the problems related with the non-renewable distribution system and the roles renewable energy resources-based distribution system has been presented. In addition to this a complete review of configuration of AC and DC microgrids with possible distributed generated units based on their protection strategies, control schemes, and power management techniques were done.

REFERENCES

- [1] J. J. Justo, F. Mwasilu, J. Lee, and J. W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 387–405, 2013, doi: 10.1016/j.rser.2013.03.067.
- [2] B. Nabi and S. Seyedtabaai, "Fast distributed control design for DC linked microgrids," *International Journal of Electrical Power and Energy Systems*, vol. 122, no. April, p. 106221, 2020, doi: 10.1016/j.ijepes.2020.106221.
- [3] R. Gugulothu, B. Nagu, and D. Pullaguram, "Energy management strategy for standalone DC microgrid

- system with photovoltaic/fuel cell/battery storage,” *J Energy Storage*, vol. 57, no. December 2021, p. 106274, 2023, doi: 10.1016/j.est.2022.106274.
- [4] L. M. Castro, C. Ramírez-Ramos, J. H. Sánchez, and D. Guillén, “On the modelling of DC microgrids for steady-state power flow studies,” *Electric Power Systems Research*, vol. 207, no. September 2021, 2022, doi: 10.1016/j.epsr.2022.107868.
- [5] M. Nabatirad, R. Razzaghi, and B. Bahrani, “Autonomous power balance in hybrid AC/DC microgrids,” *International Journal of Electrical Power and Energy Systems*, vol. 146, no. September 2022, p. 108752, 2023, doi: 10.1016/j.ijepes.2022.108752.
- [6] Y. Kirim, H. Sadikoglu, and M. Melikoglu, “Technical and economic analysis of biogas and solar photovoltaic (PV) hybrid renewable energy system for dairy cattle barns,” *Renew Energy*, vol. 188, pp. 873–889, 2022, doi: 10.1016/j.renene.2022.02.082.
- [7] M. S. Alam, F. S. Al-Ismail, F. A. Al-Sulaiman, and M. A. Abido, “Energy management in DC microgrid with an efficient voltage compensation mechanism,” *Electric Power Systems Research*, vol. 214, no. PA, p. 108842, 2023, doi: 10.1016/j.epsr.2022.108842.
- [8] A. A. Abou El-Ela, H. A. Mosalam, and R. A. Amer, “Optimal control design and management of complete DC- renewable energy microgrid system,” *Ain Shams Engineering Journal*, vol. 14, no. 5, p. 101964, 2023, doi: 10.1016/j.asej.2022.101964.
- [9] S. Moradi, G. Zizzo, S. Favuzza, and F. Massaro, “A stochastic approach for self-healing capability evaluation in active islanded AC/DC hybrid microgrids,” *Sustainable Energy, Grids and Networks*, vol. 33, p. 100982, 2023, doi: 10.1016/j.segan.2022.100982.
- [10] I. A. Bello, M. D. McCulloch, and D. J. Rogers, “A linear regression data compression algorithm for an islanded DC microgrid,” *Sustainable Energy, Grids and Networks*, vol. 32, p. 100901, 2022, doi: 10.1016/j.segan.2022.100901.
- [11] L. Xu et al., “A Review of DC Shipboard Microgrids - Part I: Power Architectures, Energy Storage, and Power Converters,” *IEEE Trans Power Electron*, vol. 37, no. 5, pp. 5155–5172, 2022, doi: 10.1109/TPEL.2021.3128417.
- [12] M. Panda, V. B. Devara, and T. Maity, “A novel dc bus-signaling based power management strategy for dc microgrid,” *International Transactions on Electrical Energy Systems*, vol. 31, no. 2, pp. 7–10, 2021, doi: 10.1002/2050-7038.12758.
- [13] H. Lotfi and A. Khodaei, “AC versus DC microgrid planning,” *IEEE Trans Smart Grid*, vol. 8, no. 1, pp. 296–304, 2017, doi: 10.1109/TSG.2015.2457910.
- [14] A. M. Iuoras, N. C. Szekely, L. D. Vitan, M. Bojan, and P. D. Teodosescu, “AC home appliances retrofitting for DC microgrids,” *Proceedings of the 12th International Conference on Electronics, Computers and Artificial Intelligence, ECAI 2020*, pp. 3–8, 2020, doi: 10.1109/ECAI50035.2020.9223183.
- [15] M. Kim, B. Y. Choi, K. M. Kang, H. Lee, Y. S. Lee, and C. Y. Won, “Energy Monitoring System of AC/DC Hybrid Microgrid Systems using LabVIEW,” *23rd International Conference on Electrical Machines and Systems, ICEMS 2020*, pp. 489–493, 2020, doi: 10.23919/ICEMS50442.2020.9290836.
- [16] P. Yang, M. Yu, Q. Wu, P. Wang, Y. Xia, and W. Wei, “Decentralized Economic Operation Control for Hybrid AC/DC Microgrid,” *IEEE Trans Sustain Energy*, vol. 11, no. 3, pp. 1898–1910, 2020, doi: 10.1109/TSSTE.2019.2946227.
- [17] M. Manbachi and M. Ordonez, “Intelligent Agent-Based Energy Management System for Islanded AC-DC Microgrids,” *IEEE Trans Industr Inform*, vol. 16, no. 7, pp. 4603–4614, 2020, doi: 10.1109/TII.2019.2945371.
- [18] J. J. Shea, J. Hastings, and M. Liptak, “Modular DC / AC Microgrid,” 1990.
- [19] Y. Xia, Y. Peng, and W. Wei, “Triple droop control method for ac microgrids,” *IET Power Electronics*, vol. 10, no. 13, pp. 1705–1713, 2017, doi: 10.1049/iet-pel.2017.0005.
- [20] O. Husev, O. Matiushkin, D. Vinnikov, C. Roncero-Clemente, and S. Kouro, “Novel Concept of Solar Converter with Universal Applicability for DC and AC Microgrids,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 5, pp. 4329–4341, 2022, doi: 10.1109/TIE.2021.3086436.
- [21] Y. Joshi; et al., “Performance Improvement of Standalone Battery Integrated Hybrid System” *IEEE 7th International Conference on Electrical Energy Systems (ICEES)*, Organized by Sri Sivasubramaniya Nadar College of Engineering during 11-13 Feb. 2021at Chennai, India.
- [22] Vyas, Megha & Yadav, Vinod & Vyas, Shripati & Joshi, R.. (2021). Voltage Sag Mitigation Using Distribution Static Compensator. 10.1007/978-981-15-8586-9_24.
- [23] R. Jangid; J.k Maherchandani; R.R. Joshi and B.D Vairagi, “Development of Advance Energy Management Strategy for Standalone Hybrid Wind & PV System Considering Rural Application”, *IEEE 2nd International Conference on Smart Systems and Inventive Technology*, Organized by Francis Xavier Engineering College during November 27-29, 2019 at Tirunelveli, India.
- [24] P. J. D. S. Neto, T. A. D. S. Barros, J. P. C. Silveira, E. R. Filho, J. C. Vasquez, and J. M. Guerrero, “Power Management Strategy Based on Virtual Inertia for DC Microgrids,” *IEEE Trans Power Electron*, vol. 35, no. 11, pp. 12472–12485, 2020, doi: 10.1109/TPEL.2020.2986283.

- [25] T. Wang, “Hybrid Microgrid,” 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), pp. 1–6, 2018.
- [26] H. Kumawat and R. Jangid, “Using AI Techniques to Improve the Power Quality of Standalone Hybrid Renewable Energy Systems”, *Crafting a Sustainable Future Through Education and Sustainable Development*, IGI Global, Pages 219-228, 2023.
- [27] F. Nejabatkhah, Y. W. Li, and H. Tian, “Power quality control of smart hybrid AC/DC microgrids: An overview,” *IEEE Access*, vol. 7, pp. 52295–52318, 2019, doi: 10.1109/ACCESS.2019.2912376.