Microgrid and Its Architecture

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The world today is plagued with problems of increased transmission and distribution (T&D) losses leading to poor reliability due to power outages and an increase in the expenditure on electrical infrastructure. To address these concerns, technology has evolved to enable the integration of renewable energy sources (RESs) like solar, wind, diesel and biomass energy into small scale self-governing power system zones which are known as micro-grids (MGs). A de-centralised approach for modern power grid systems has led to an increased focus on distributed energy resources and demand response. MGs act as complete power system units albeit on a small scale. However, this does not prevent them from large operational sophistication allowing their independent functioning in both grid-connected and stand-alone modes. MGs provide greater reliability as compared to the entire system owing to the large amount of information secured from the bulk system. They comprise numerous sources like solar, wind, diesel along with storage devices and converters. Several modeling schemes have been devised to reduce the handling burden of large scale systems.

state-space representation | distributed energy sources | penetration ratio | relief factor | power management | prosumer

1. Introduction

The critical dependence of today's society on a secure supply of energy is well known. The heightening worries for the accessibility of primary energy and the ever mellowing infrastructure of the present transmission and distribution (T&D) networks pose a continuous threat to security, reliability and standard of power supplied. Conventional generation sources (CGSs) like diesel and natural gas–based generation plants steadily add to greenhouse gas emissions (GHGs) resulting in increased global warming and sudden climate changes. Hence, the generating capacity of CGSs to meet the growing global demand for energy is severely limited. This has given a massive push to alternatives called as renewable energy sources (RES) which include energy from solar, wind and biomass sources. The setup of RES integrated in a distribution system is commonly referred to as distributed generation (DG). DG is typically installed at medium voltage (MV) and high voltage (HV) levels and power flow is uni-directional keeping in mind the passive nature of consumer loads. Due to this, extensive research has been carried out on the linkage of DG within distribution networks. This includes topics stretching from control and protection of DG integrated distribution networks to the quality of power supplied by them. A number of RES including photovoltaics (PV), wind energy conversion systems (WECS), micro-turbines (MT) and fuel cells (FC) have come up as encouraging alternatives to meet the ever increasing load demands without compromising on power quality besides addressing different economic and environmental concerns. Out of different RES, solar PV systems and WECS are the most utilised ones owing to their high energy potential and easy availability [1]. DG has led to massive improvement in power quality besides engineering a remarkable decrease in T&D losses by meeting the load demands locally. Furthermore, it has improved service quality by decreasing the distance between load and point of generation.

The most efficient way to meet the growing energy needs is to include novel technologies in DG systems and grid architectures. Power electronic converters (PECs) interfaced with DGs have led to tenable structures called (MGs) [2][3][4][5][6]. A MG is defined as a network that can inventively combine the activities of all entities linked to it—generators, consumers and loads to competently provide tenable, profitable and fixed power supply. It utilizes intelligent monitoring, control and communication technologies to achieve these objectives. Until very recently, AC MG used to be the main electrical architecture for supplying power to remote and inaccessible networks [5][7][8]. Eventually, it has been replaced by the concept of a DC MG owing to increased use of DC loads over the years and also due to the fact that DC power is generated by a bulk of DG sources. The major benefits of a DC MG include absence of AC-DC or DC-AC conversion stages leading to increased efficiency and reliability [9][10][11][12][13]. However, AC MGs are still presiding due to the use of AC based DG and loads. An AC MG can also be directly linked with the traditional distribution systems with least adjustments. Hence, it is profitable to design a new architecture to merge these two types of MGs by means of a bidirectional interlinking converter (ILC) to extricate the advantages of both these categories [14][15][16][17]. This notion of merging DC and AC MGs is referred to as a hybrid MG. This type of architecture can accommodate both types of DG sources and loads to warrant trouble-free transfer of power between two sub-grids. It can operate in both grid connected and stand-alone modes while regulating power flow by means of the ILC. However, the stand-alone mode of a hybrid MG is relatively way more perilous due to demand-generation regulation and the intermittent nature of DG sources.

Power sharing in a hybrid MG is an emerging topic and has been extensively researched about in this decade. An AC MG employs active power-frequency and reactive power-frequency droop characteristics for power sharing while as current-voltage and active power-voltage droop characteristics are employed in a DC MG. As a result, control algorithms of both the individual MGs should be synchronised with the ILC to warrant supply of quality power to the end users. The control techniques of a MG are mainly categorised into three sections namely primary control, secondary control and tertiary control. The primary control stablises voltage and frequency without the need of communication links. The voltage and frequency deviations then are recompensed by the secondary controller which regulates power quality and energy management of MGs. It is further sub-categorised into centralized and decentralized control. In the former, a central controller optimises the control decisions by acquiring pertinent data from the network. In the latter, all DG sources operate in parallel to regulate energy management by employing the information acquired from neighboring sources. The tertiary control improves the power quality by regulating energy management between various MGs and the utility grid and it is administered by collaboration between a MG and the utility grid. The non-dispatchable and intermittent nature of electric power produced by DG sources requires a MG system for their trouble-free working and productive integration with the power system [5][17][18][19][20]. Energy Storage Systems (ESS) and CGS are employed to address the sporadic nature of DG power [21][22]. However, ESS alone can't alleviate the problem of balancing and keeping in mind the environmental constraints, alternative substitutes are required due to high GHG emissions of CGS. Demand response and prosumers are the finest alternatives unfolding that could assist in stabilising power demand locally [23][24].

2. Microgrid and Its Architecture

Numerous definitions of MG have been put forward over the years taking into consideration various characteristics associated with its applications [25][26][27][28]. MG has been defined as “the idea of nomadic DG sources like PV, wind, storage devices and different loads in the prevailing power system which can be controlled either in grid-connected or in stand-alone modes” in [25]. The authors in [26] have explained MG as “a scaled-down power system which comprises DG sources, controllers and loads”. MGs consist of low voltage (LV) distribution systems and they work in grid-connected or stand-alone modes.

2.1. MG Architectures

Hybrid MGs work on the concept of both AC and DC power and their architectures are dictated by the character of loads, DG sources involved, the room to adjust ESS and their energy needs. MG architectures can be divided into three classes depending on architecture of the system and its voltage characteristics. These are AC MG, DC MG and hybrid MG [29][30][31]. Additionally, MGs can be categorised as per their utilisation areas like utility MGs, institutional MGs, commercial and industrial MGs, transportation MGs and remote-area MGs [32]. **Figure 1** illustrates the classification of a MG into different categories. A flexible MG has to be able to import/ export energy from/to the grid, while controlling active and reactive-power flow by managing energy storage. Based on operating modes, MGs are categorised into grid-connected, transited, or island, and reconnection modes, which increase their reliability by disconnecting them from the grid in case of network failures. In terms of power or voltage characteristics, MGs are categorized into AC power system, DC power system, hybrid system networks or simply as AC, DC and hybrid MGs. In addition, MGs can be categorised based on their application areas like utility MGs, institutional MGs, commercial and industrial MGs, transportation MGs and remote-area MGs. In addition to this, campus MGs support multiple loads situated in a constrained geographical location, community MGs which support penetration of local energy and millitary base MGs which focus on physical and cyber security for military facilities. A tabular comparison of AC, DC and hybrid MGs is given in **Table 1**.

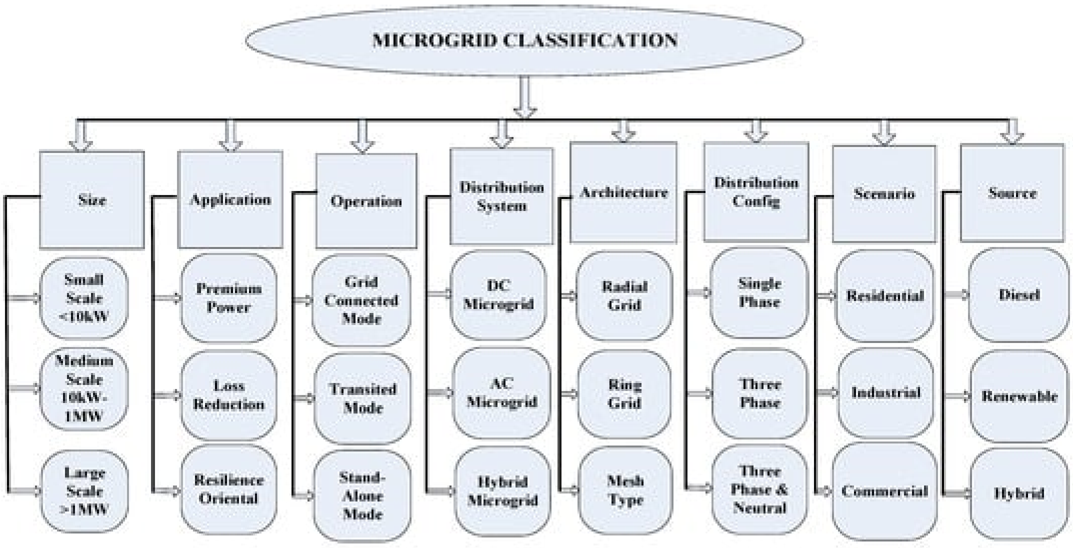

Figure 1. Classification of a MG.

Table 1. Comparison of AC, DC and hybrid microgrids.

AC Microgrids	DC Microgrids	Hybrid Microgrids
Multiple energy conversions.	Less conversion processes.	Less conversion stages.
Presence of continuous reactive current loss component.	Absence of reactive components.	Presence of circulating reactive currents.
Reduced efficiency.	Greater efficiency.	Improved efficiency.
Affected by external disturbances.	Free from external disturbances.	Increased robustness.
Synchronisation issues.	No synchronisation issues.	No synchronisation issues.
Supply may be compromised during seamless transfer.	Power supply generally reliable.	Highest reliability.
Complex control process due to frequency.	Simpler control approach.	Complex control.
Simple, cheap and mature protection schemes.	Complex and costly protection components.	Adaptive intelligent protection schemes

2.2. Microgrid Toplogies

Different architectures are required to regulate the flow of energy from various sources into the utility grid. MGs are largely categorised into AC, DC and hybrid MGs.

2.2.1. AC Microgrids

This is the most traditional form of MG where PECs are employed to integrate DG sources with electrical networks [33] and needs minimum modifications for its integration. These MGs are integrated with MV and LV distribution networks to increase power flow and decrease transmission line losses in distribution networks. Here, power moves directly from/to the grid sans any converter. The connected loads, DG sources and ESS must be grid-adaptable as the feeder voltage and frequency matches with the grid conditions. This gives rise to the main advantage of AC MGs which is their affinity with the conventional grid which can be recomposed to an AC MG strategy. However, the presence of complex PEC interfaces to synchronize DERs with the utility grid and to supply good quality AC currents which is devoid of harmonics presents one of the major drawbacks of AC MGs which reduces the efficiency and reliability of the system. Also, certain issues crop up upon their integration like system stability, power quality and shortage of reactive power. These are addressed by applying advanced control techniques [34][35]. The MG is able to adjust power generation and load demand to any working condition by switching its topology by means of circuit breakers. The inter-connection of the MG with the distribution grid is governed by the static switch. It can disengage the MG when the quality of power being supplied to the distribution grid is below par making it to operate in is-landed mode. At times of a grid fault, the static switch as well as the circuit breaker open to disengage the non-critical loads from the grid to elude their impairment [36]. This sustains good quality and reliable power supply to delicate loads that are catered from DG sources and ESS.

2.2.2. DC Microgrids

A majority of the current consumer loads work on DC. Hence, their integration with DC MGs is a smart choice due to increased efficiency and power quality independence from the distribution grid. Around 35% of the generated AC power is fed to a PEC before its utilization [37]. Majority of DC loads, DC-based DG sources and PECs are employed for varied applications due to the technological prowess of the latter [38]. This has created a sea of new opportunities in the field of DC MGs due to reduced losses during power conversion and absence of reactive current circulation [39][40]. An AC/DC bi-directional interface called as the interlinking converter (IC) is the primary architect in a DC MG which links it to the AC grid after providing the necessary voltage shift and galvanic isolation. All DG sources and storage devices are linked with the DC bus via a PE interface (DC/DC or AC/DC).

DC MGs possess a plethora of advantages as there are relatively lower transmission losses owing to the non-existence of reactive current circulation. They possess simple architecture and control requirements as grid synchronization, harmonics and reactive power do not bother them. Additionally, they possess fault-ride-through ability and are least influenced by blackouts or voltage sags due to the presence of capacitors. However, they have their own shortcomings which include the need to construct DC distribution systems and the need to address their incompatibility with traditional electrical systems. Also, they face challenges in protection schemes due to immature guidelines and constrained practical involvements. As such, they need special protection mechanisms to address DC short-circuit current interruption due to the absence of zero-point crossing of the current waveform. Also, DC MGs need additional converters as they are not feasible for direct connection of AC loads. However, the biggest drawback of this architecture is the presence of series-connected IC which handles power flow with the utility grid as it decreases system reliability [41].

2.2.3. Hybrid MGs

Hybrid MGs are a combination of AC and DC MGs and are gaining attention because they facilitate the direct integration of DGs, loads and storage devices with the traditional distribution system [36][42]. They possess the advantages of both MGs like increased reliability and efficient economic operation. Hybrid MGs cater to all types of loads and reduce inverter and rectifier power losses. However, they demand a robust coordinated control and increased investigation due to the intermittency of DG sources and reactive power compensation. Hybrid MGs are further classified as coupled and decoupled AC configurations on the basis of the interfacing device and the grid connection. The AC bus of the MG is directly integrated with the grid by means of a transformer and an AC/DC converter is employed for the DC link in the former while as the latter comprise an AC/DC and a DC/AC stage with no direct linkage between the grid and the bus.

Figure 2 depicts the architecture of a typical hybrid MG. It clearly distinguishes between the AC and DC grids and interlinks them by means of a bidirectional AC-DC converter [36]. The AC bus caters to the AC loads while as the DC bus caters to the DC loads while as the DG sources and storage units are connected at either of the buses. A PE converter is employed for maintaining the necessary voltage levels. This architecture lets the installation of critical loads onto the DC feeder while as more robust loads are installed onto the AC feeder [34][36]. It decreases conversion phases and consequently the energy wastage. It is straightforward to limit harmonics into the AC side from the DC side thus improving the quality of power in the grid. Voltage transformations in the AC side can be carried out in a simple manner by means of conventional transformers while as DC-DC converters do the job in the DC side of the network. Although the initial investment of a hybrid MG is higher due to the inclusion of a principal AC-DC converter and a communication system for device interconnections, it is beneficial in the long run as it reduces the number of interfacing converters as number of attached devices increases. However, the DC side of a hybrid MG is still under study as far as protection problems of the MG are concerned. Also, the reliability of a hybrid MG takes a hit owing to the main interface PE converter. The power flow management is relatively complex because appropriate control strategies need to be applied for the connected devices to ensure a stable and reliable power flow. Power balance between the AC and DC side of a hybrid MG is a major challenge and it is still under study.

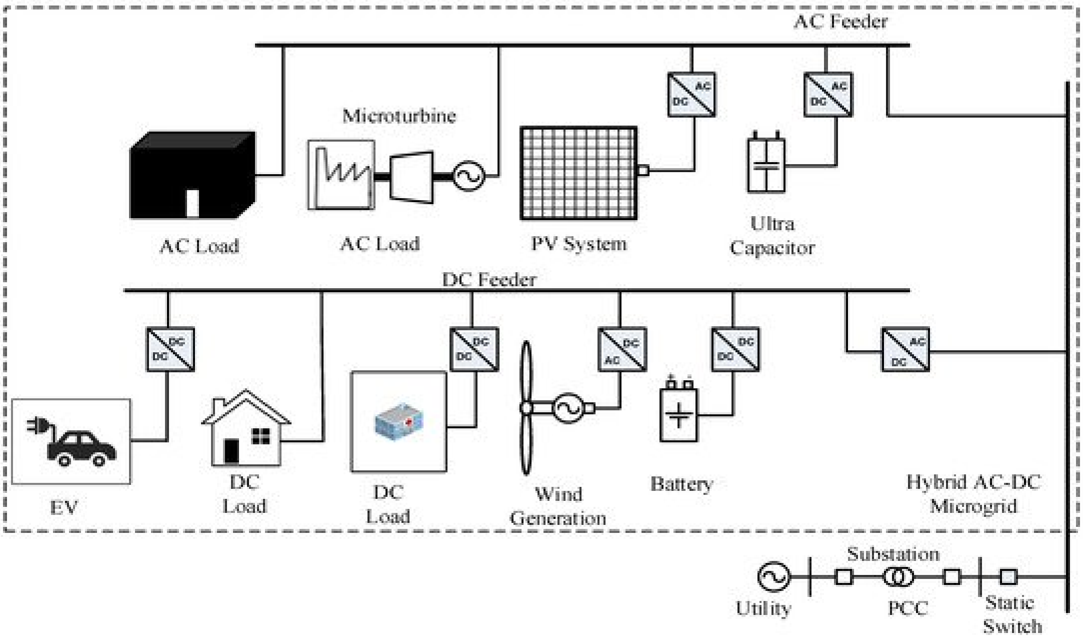

Figure 2. Architecture of a basic MG.

References

1. Aguero, J.R.; Takayesu, E.; Novosel, D.; Masiello, R. Modernizing the Grid: Challenges and Opportunities for a Sustainable Future. IEEE Power Energy Mag. 2017, 15, 74–83.
2. Katiraei, F.; Iravani, R.; Hatziargyriou, N.; Dimeas, A. Microgrids management. IEEE Power Energy Mag. 2008, 6, 54–65.
3. Lasseter, R.; Paigi, P. Microgrid: A conceptual solution. In Proceedings of the 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551), Aachen, Germany, 20–25 June 2004; Volume 6, pp. 4285–4290.
4. Nikkhajoei, H.; Lasseter, R.H. Distributed Generation Interface to the CERTS Microgrid. IEEE Trans. Power Deliv. 2009, 24, 1598–1608.
5. Hatziargyriou, N. Microgrids: Architectures and Control; John Wiley & Sons: Hoboken, NJ, USA, 2014.
6. Marchand, S.; Monsalve, C.; Reimann, T.; Heckmann, W.; Ungerland, J.; Lauer, H.; Ruhe, S.; Krauß, C. Microgrid Systems: Towards a Technical Performance Assessment Frame. Energies 2021, 14, 2161.
7. Farrokhabadi, M.; Cañizares, C.A.; Simpson-Porco, J.W.; Nasr, E.; Fan, L.; Mendoza-Araya, P.A.; Tonkoski, R.; Tamrakar, U.; Hatziargyriou, N.; Lagos, D.; et al. Microgrid Stability Definitions, Analysis, and Examples. IEEE Trans. Power Syst. 2020, 35, 13–29.

8. Espín-Sarzosa, D.; Palma-Behnke, R.; Núñez-Mata, O. Energy Management Systems for Microgrids: Main Existing Trends in Centralized Control Architectures. Energies 2020, 13, 547.
9. Baran, M.; Mahajan, N. DC distribution for industrial systems: Opportunities and challenges. IEEE Trans. Ind. Appl. 2003, 39, 1596–1601.
10. Eghtedarpour, N.; Farjah, E. Control strategy for distributed integration of photovoltaic and energy storage systems in DC micro-grids. Renew. Energy 2012, 45, 96–110.
11. Xu, L.; Chen, D. Control and Operation of a DC Microgrid with Variable Generation and Energy Storage. IEEE Trans. Power Deliv. 2011, 26, 2513–2522.
12. Eghtedarpour, N.; Farjah, E. Distributed charge/discharge control of energy storages in a renewable-energy-based DC micro-grid. IET Renew. Power Gener. 2013, 8, 45–57.
13. Zhu, B.; Hu, H.; Wang, H.; Li, Y. A Multi-Input-Port Bidirectional DC/DC Converter for DC Microgrid Energy Storage System Applications. Energies 2020, 13, 2810.
14. Dong, B.; Li, Y.; Zheng, Z.; Xu, L. Control strategies of microgrid with Hybrid DC and AC Buses. In Proceedings of the 2011 14th European Conference on Power Electronics and Applications, Birmingham, UK, 30 August–1 September 2011; pp. 1–8.
15. Karabiber, A.; Keles, C.; Kaygusuz, A.; Alagoz, B. An approach for the integration of renewable distributed generation in hybrid DC/AC microgrids. Renew. Energy 2013, 52, 251–259.
16. Kurohane, K.; Senjyu, T.; Yona, A.; Urasaki, N.; Goya, T.; Funabashi, T. A Hybrid Smart AC/DC Power System. IEEE Trans. Smart Grid 2010, 1, 199–204.
17. Aryani, D.R.; Song, H. Coordination Control Strategy for AC/DC Hybrid Microgrids in Stand-Alone Mode. Energies 2016, 9, 469.
18. Zia, M.F.; Elbouchikhi, E.; Benbouzid, M. Microgrids energy management systems: A critical review on methods, solutions, and prospects. Appl. Energy 2018, 222, 1033–1055.
19. Guerrero, J.M.; Chandorkar, M.; Lee, T.L.; Loh, P.C. Advanced Control Architectures for Intelligent Microgrids—Part I: Decentralized and Hierarchical Control. IEEE Trans. Ind. Electron. 2013, 60, 1254–1262.
20. Khosa, F.K.; Zia, M.F.; Bhatti, A.A. Genetic algorithm based optimization of economic load dispatch constrained by stochastic wind power. In Proceedings of the 2015 International Conference on Open Source Systems Technologies (ICOSST), Lahore, Pakistan, 17–19 December 2015; pp. 36–40.
21. Zia, M.F.; Elbouchikhi, E.; Benbouzid, M. An Energy Management System for Hybrid Energy Sources-based Stand-alone Marine Microgrid. IOP Conf. Ser. Earth Environ. Sci. 2019, 322, 012001.

22. El Amin, I.; Zia, M.F.; Shafiullah, M. Selecting energy storage systems with wind power in distribution network. In Proceedings of the IECON 2016—42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 23–26 October 2016; pp. 4229–4234.
23. Liu, N.; Yu, X.; Wang, C.; Li, C.; Ma, L.; Lei, J. Energy-Sharing Model With Price-Based Demand Response for Microgrids of Peer-to-Peer Prosumers. IEEE Trans. Power Syst. 2017, 32, 3569–3583.
24. Zia, M.F.; Elbouchikhi, E.; Benbouzid, M.; Guerrero, J.M. Energy Management System for an Islanded Microgrid with Convex Relaxation. IEEE Trans. Ind. Appl. 2019, 55, 7175–7185.
25. Olivares, D.E.; Mehrizi-Sani, A.; Etemadi, A.H.; Cañizares, C.A.; Iravani, R.; Kazerani, M.; Hajimiragha, A.H.; Gomis-Bellmunt, O.; Saeedifard, M.; Palma-Behnke, R.; et al. Trends in Microgrid Control. IEEE Trans. Smart Grid 2014, 5, 1905–1919.
26. Mohammed, A.; Refaat, S.S.; Bayhan, S.; Abu-Rub, H. AC Microgrid Control and Management Strategies: Evaluation and Review. IEEE Power Electron. Mag. 2019, 6, 18–31.
27. Parhizi, S.; Lotfi, H.; Khodaei, A.; Bahramirad, S. State of the Art in Research on Microgrids: A Review. IEEE Access 2015, 3, 890–925.
28. Nejabatkhah, F.; Li, Y.W.; Tian, H. Power Quality Control of Smart Hybrid AC/DC Microgrids: An Overview. IEEE Access 2019, 7, 52295–52318.
29. Hossain, E.; Kabalcı, E.; Bayindir, R.; Perez, R. Microgrid testbeds around the world: State of art. Energy Convers. Manag. 2014, 86, 132–153.
30. Hammerstrom, D.J. AC Versus DC Distribution SystemsDid We Get it Right? In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–5.
31. Jiang, Z.; Yu, X. Hybrid DC- and AC-Linked Microgrids: Towards Integration of Distributed Energy Resources. In Proceedings of the 2008 IEEE Energy 2030 Conference, Atlanta, GA, USA, 17–18 November 2008; pp. 1–8.
32. Hatziargyriou, N.; Asano, H.; Iravani, R.; Marnay, C. Microgrids. IEEE Power Energy Mag. 2007, 5, 78–94.
33. Arulampalam, A.; Barnes, M.; Engler, A.; Goodwin, A.; Jenkins, N. Control of Power Electronic Interfaces in Distributed Generation Microgrids. Int. J. Electron. 2004, 91, 503–523.
34. Unamuno, E.; Barrena, J.A. Hybrid ac/dc microgrids—Part I: Review and classification of topologies. Renew. Sustain. Energy Rev. 2015, 52, 1251–1259.
35. Vasantharaj, S.; Indragandhi, V.; Subramaniyaswamy, V.; Teekaraman, Y.; Kuppusamy, R.; Nikolovski, S. Efficient Control of DC Microgrid with Hybrid PV—Fuel Cell and Energy Storage Systems. Energies 2021, 14, 3234.

36. Patrao, I.; Figueres, E.; Garcera, G.; González-Medina, R. Microgrid architectures for low voltage distributed generation. Renew. Sustain. Energy Rev. 2015, 43, 415–424.
37. Reed, G. DC Technologies: Solutions to Electric Power System Advancements . IEEE Power Energy Mag. 2012, 10, 10–17.
38. Rashid, M. Power Electronics Handbook: Devices, Circuits, and Applications; Elsevier: Amsterdam, The Netherlands, 2011; p. 1389.
39. Arnold, G.W. Challenges and Opportunities in Smart Grid: A Position Article. Proc. IEEE 2011, 99, 922–927.
40. Battaglini, A.; Lilliestam, J.; Haas, A.; Patt, A. Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources. J. Clean. Prod. 2009, 17, 911–918.
41. Planas, E.; Andreu, J.; Gárate, J.; Martinez de Alegria, I.; Ibarra, E. AC and DC technology in microgrids: A review. Renew. Sustain. Energy Rev. 2015, 43, 726–749.
42. Wang, P.; Goel, L.; Liu, X.; Choo, F.H. Harmonizing AC and DC: A Hybrid AC/DC Future Grid Solution. IEEE Power Energy Mag. 2013, 11, 76–83.