DEVELOPMENT OF EFFICIENT POWER ELECTRONICS CONVERTER FOR INTEGRATING RENEWABLE ENERGY INTO GRID

P. K. Dhal[1], Dakyrmen Kongri[1], Nongthombam Aditya Luwang[1], Chandra Bhusan[1], Vempalle Rafi[2] and Steevenson Sohtun[1]
[1]Department of Electrical and Electronics Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India
[2]Department of Electrical and Electronics Engineering, JNTUA College of Engineering Pulivendula, Pulivendula, India
E-Mail: pradyumna.dhal@rediffmail.com

ABSTRACT

The increasing demand for renewable energy sources, driven by environmental concerns and energy sustainability, has necessitated the development of efficient and reliable power electronics converters for integrating renewable energy into the grid. This research paper presents a comprehensive review, design, and analysis of power electronics converters for renewable energy integration. It explores various converter topologies, control strategies, and performance assessment methods to optimize the integration of renewable energy sources into the existing electrical grid.

Keywords: renewable energy, power electronics converters, integration, control strategies, converter topologies.

Manuscript Received 2 September 2024; Revised 15 November 2024; Published 27 December 2024

1. INTRODUCTION

The worldwide energy scene is going through a significant change driven by natural worries, energy maintainability, and the quest for a low-carbon future. This change is described by a critical shift towards environmentally friendly power sources, for example, sunlight based, wind, hydro, and geothermal power. These natural resources have the potential to produce a lot of clean energy [1]. Be that as it may, their combination into the current electrical matrix presents a special arrangement of difficulties. By making it easier to convert renewable energy into a form that is compatible with the grid and is both effective and dependable, power electronics converters play a crucial role in making this integration possible. A global shift toward renewable energy sources has been prompted by the growing dangers posed by climate change and the depletion of fossil fuel reserves. This change is basic to relieve ozone-depleting substance outflows and decrease the world's dependence on limited petroleum products. Photovoltaic (PV) solar panels and wind turbines are two examples of renewable energy technologies that have made significant advancements in recent years, increasing their affordability and accessibility [2].

Power electronics converters are a necessary component to take advantage of the potential of renewable energy sources. These converters change the variable and frequently the flighty result of sustainable power frameworks into a stable and network-viable structure. The effective coordination of sustainable power into the matrix diminishes ozone-harming substance outflows as well as upgrades the framework's unwavering quality and flexibility [3]. The urgent requirement to address the technical and operational difficulties associated with the integration of renewable energy into the electrical grid is the impetus for this research paper. The grid requires a stable and consistent power supply, even though renewable energy sources are naturally variable and intermittent. Power hardware converters act as the extension between these two unique energy sources, making their proficient plan and activity fundamental. Besides, as sustainable power limit keeps on developing, the improvement of force gadgets converters turns out to be progressively essential to guarantee the financial suitability and execution of environmentally friendly power frameworks [4]. This paper tries to investigate the most recent progressions in converter advancements and control methodologies, revealing insight into the possible answers to these difficulties.

- To give a complete survey of force hardware converters for sustainable power combinations, including their geographies, control procedures, and plan contemplations.
- To examine the exhibition measurements and assessment techniques for power gadgets converters with regards to environmentally friendly power mix.
- To deal with the difficulties and complexities of incorporating renewable energy sources into the electrical grid.
- To investigate new technologies and trends in power electronics converters and how they might affect the integration of renewable energy.

A wide range of topics related to power electronics converters and their use in the integration of renewable energy will be covered in this research paper [5]. It will concentrate on a variety of converter topologies, control strategies, design considerations, and techniques for performance evaluation. In addition to providing a comprehensive overview, it will focus on specific case studies and examples to demonstrate applications in the real world. In addition, the paper will focus on future trends and emerging technologies in the field as well as challenges associated with grid integration. The multifaceted and pressing problem of incorporating renewable energy sources into the electrical grid necessitates creative solutions. This research paper aims to provide valuable insights into the design, analysis, and optimization of power electronics converters for the effective and dependable integration of renewable energy in this endeavor. Power electronics converters are a crucial component of this endeavor.

The writing survey part of this exploration paper gives an exhaustive outline of the key ideas, improvements, and examination in the field of force gadgets converters for environmentally friendly power mix [6]. Power electronics converters, a variety of converter topologies, control strategies, performance metrics, and the existing body of research in this field are all examined in detail. Solar- panels known as photovoltaic (PV) convert sunlight into electrical energy. Research has zeroed in on working on the proficiency and unwavering quality of PV frameworks, with progress in materials, global positioning frameworks, and most extreme PowerPoint following strategies [7]. Wind turbines saddle dynamic energy from wind to produce power. Research has investigated the plan of productive breeze turbine generators and network mix strategies, including matrix codes and issue ride-through capacities.

Hydroelectric plants convert the possible energy of water into power. Late examinations have zeroed in on upgrading the adaptability and effectiveness of hydroelectric frameworks, including the improvement of variable-speed generators and high-level control techniques. To generate electricity, geothermal power plants make use of heat from the core of the Earth. The development of Organic Rankine Cycle (ORC) systems for low-temperature geothermal sources and the improvement of drilling methods for geothermal wells have been the primary focus of research. To convert DC power from batteries and solar panels into AC power that is compatible with the grid, inverters are used. Late exploration has zeroed in on improving the proficiency and dependability of inverters utilizing wide bandgap semiconductors, for example, SiC and GaN. Rectifiers convert AC power from wind turbines or the lattice into DC power for energy capacity or use. Grid-connected rectifiers with improved power quality and grid support functions have been the subject of research [8]. Energy storage and grid support are made possible by bi-directional converters, which enable energy flow in both directions. Bidirectional converter topologies and control strategies for grid energy storage and electric vehicle charging have been the subject of research. VSIs are generally utilized in sun-powered PV frameworks. MPPT control, grid synchronization, and the reduction of harmonic distortion are among the subjects of research. CSIs track down applications in matrix-tied breeze turbines. Control strategies to improve grid compliance and fault tolerance have been the subject of research [9]. Staggered converters work on the nature of result waveforms and decrease exchanging misfortunes. Research has investigated flowed H-extension and flying capacitor geographies.

The output of renewable energy sources is maximized by MPPT algorithms. Advanced MPPT methods, such as algorithms for machine learning and artificial intelligence, have been used in recent research. To keep the grid stable, grid-tied converters require precise control. Studies have zeroed in on network synchronization, voltage and recurrence guidelines, and receptive power control. Grid compliance necessitates the reduction of harmonics in the output waveform. Research has investigated the utilization of aloof channels and high-level balance methods. Converter effectiveness is a basic boundary for environmentally friendly power frameworks to boost energy yield. Methods for increasing efficiency and cutting-edge semiconductor devices have been the subject of research. Total harmonic distortion, voltage regulation, and frequency stability are power quality metrics. Grid codes and standards have been the focus of research. This writing survey features the multi-layered nature of force hardware converters for environmentally friendly power combinations [10]. It lays the groundwork for the subsequent sections of this research paper, which will examine specific converter topologies, control strategies, design considerations, and grid integration challenges. In addition, it prepares the ground for discussing emerging trends and technologies in the field that promise to advance the integration of renewable energy into the electrical grid in the future [11].

2. PROWER ELECTRONIC CONVERTER TOPOLOGIES

Power gadget converters act as the pivotal connection point between sustainable power sources and the electrical framework, guaranteeing the productive and solid exchange of energy. An extensive variety of converter geographies has been created to address the prerequisites of various sustainable power frameworks [12]. Voltage Source Inverters are broadly utilized in environmentally friendly power frameworks, especially in photovoltaic sunlight-based establishments. Two-level inverters and three-level inverters are two common VSI topologies. Harmonic distortion can be reduced, and efficiency can be increased with three-level inverters. In VSIs, MPPT algorithms are essential to maximizing power extraction from the solar panels. For seamless grid integration, voltage control and grid synchronization are also necessary. Higher power density and efficiency are now possible thanks to the use of wide-bandgap semiconductors like Silicon Carbide and Gallium Nitride in VSIs.

Current Source Inverters are normally utilized in matrix-associated breeze turbines. Normal CSI geographies incorporate two-level and staggered inverters. Waveform quality and fault tolerance are enhanced by multilevel CSIs. To manage grid synchronization and guarantee a stable connection, particularly in varying wind conditions, CSIs require sophisticated control algorithms. Grid-tied CSIs must adhere to grid codes and standards, which necessitates the development of advanced control methods. Staggered converters have acquired conspicuousness in sustainable power frameworks because of their capacity to decrease symphonious contortion and further develop general framework execution. The cascaded H-bridge and flying capacitor topologies are two typical topologies for multilevel converters [13]. The quality of the voltage waveform is improved and switching losses are reduced with these topologies. High-level regulation procedures, for example, Stage Moved PWM and Specific Consonant End, are utilized to productively control staggered converters. Staggered converters are leaned toward for their capacity to give improved matrix support capabilities, including low-voltage ride-through and issue ride-through abilities.

In a variety of renewable energy applications, matrix converters represent a compact and adaptable converter topology. Network converters comprise bidirectional switches organized in a lattice structure. Because there is no intermediate DC stage, matrix converters have the potential to be very efficient. To maximize performance, however, they require sophisticated control strategies. When direct AC conversion is preferable, matrix converters are used in renewable energy systems like ocean wave energy converters and small-scale wind turbines. Bidirectional converters are fundamental for energy capacity frameworks (ESS) generally coordinated with environmentally friendly power sources. Bidirectional converters can take different geographies, including help buck converters and full-span inverters. The decision is made based on the application and voltage levels [14]. To control the bidirectional flow of power, ensure energy efficiency, and maintain system stability, advanced control strategies are required. Bidirectional converters work with the joining of energy stockpiling innovations like batteries, supercapacitors, and flywheels, upgrading the general unwavering quality and matrix support abilities of environmentally friendly power frameworks.

Choosing the proper converter geography for a given sustainable power framework includes considering elements, for example, power rating, effectiveness, voltage levels, network prerequisites, and cost. It is frequently necessary to conduct a comparative analysis of these topologies to choose the best solution [15]. The topologies of power electronics converters are crucial for making it possible to incorporate renewable energy sources into the electrical grid. The specific characteristics of the renewable energy system, its power requirements, and the technical constraints of the grid influence the choice of topology [16]. The efficiency and dependability of renewable energy systems are continuing to be enhanced by advancements in converter design and control strategies, which contribute to the global shift toward a future based on sustainable energy as shown in Figure-1.

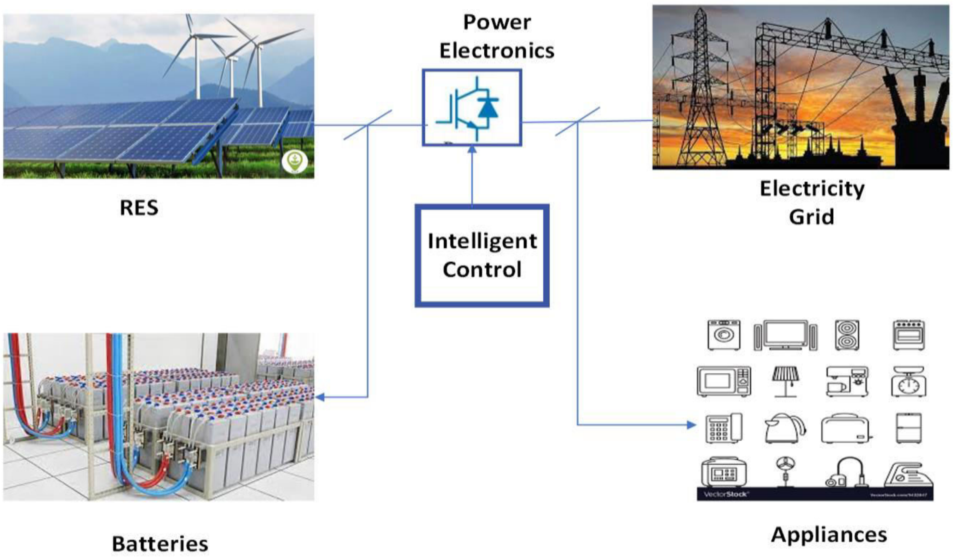


Figure-1. Configuration of RESs and power electronics with intelligent controller.

2.1 Control Strategies

Control procedures are crucial in guaranteeing the productive and solid activity of force gadget converters for sustainable power combinations. Power flow, voltage regulation, and synchronization with the electrical grid are managed by these strategies. MPPT is a fundamental control strategy utilized in photovoltaic and wind power applications of renewable energy systems. Its essential objective is to enhance the result of the sustainable power source by consistently changing the working point to follow the greatest power that anyone could hope to find. P&O changes the operating point and watches the power output change. Until the maximum point is reached, it adjusts the operating point in a way that maximizes power. Income compares the voltage and current product with the instantaneous change in power. It changes the working point to follow where dP/dV rises to the negative of I/V. HC is an advancement-based MPPT technique that changes the working point iteratively, looking for the greatest power point by climbing the slope of the power-voltage bend. For improved accuracy and adaptability, particularly in dynamic and partially shaded conditions, MPPT has been applied to advanced AI and machine learning algorithms like genetic algorithms and neural networks [17].

For converters that are connected to the electrical grid, Grid-Interfacing Control is essential for ensuring grid compatibility and stability. To allow for seamless energy injection, converters must synchronize their output with the voltage and frequency of the grid. Stage-locked circle and synchronization calculations guarantee exact network coupling. Lattice-associated converters keep up with the framework's voltage and recurrence inside satisfactory cutoff points. Relative Essential regulators are regularly used to manage voltage and recurrence. To maintain grid stability, grid-tied converters frequently take part in active power control, adjusting their power output in response to grid signals or market conditions.

Voltage regulation and grid stability depend on reactive power control. By adjusting the phase angle between the converter output voltage and the grid voltage, VSIs can control both active and reactive power. This control is critical for voltage backing and power factor adjustment. Due to their current-source nature, CSIs automatically provide reactive power support. Control procedures center around managing the size and period of the result current. Hang control is utilized in equal associated inverters to disperse the heap relatively founded on yield voltage or current, guaranteeing equivalent sharing of receptive power support. To reduce harmonic content, pulse-width modulation (PWM) techniques shape the converter's output voltage waveform. Space vector modulation and sinusoidal PWM are frequently utilized. The converter's harmonic currents can be canceled out with active filters. They infuse equivalent and inverse consonant flows to relieve framework twisting [18]. LCL channels are coordinated into the converter plan to constrict consonant substance in the resulting voltage while keeping a low-impedance way for power.

It is of the utmost importance to shield power electronics converters from faults and guarantee grid stability during fault conditions. When overcurrent or overvoltage conditions are detected, converters are equipped with protection mechanisms that trigger shutdown or fault-clearing actions. Converters are frequently required to remain connected and provide grid support during grid faults by grid codes. Converters use algorithms that detect disturbances to the grid and disconnect when necessary to prevent unintentional islanding (isolation from the grid). During grid faults, advanced protection systems can use communication networks to coordinate the actions of multiple converters. For power electronics converters in renewable energy systems to function properly, control strategies are necessary. Contributing to the reliable and effective integration of renewable energy sources into the electrical grid, these strategies ensure maximum energy capture, grid compatibility, and fault protection. Progresses in charge of calculations and computerized advancements keep on improving the exhibition and adaptability of converters in sustainable power applications.

3. DESIGN CONSIDERATIONS

The process of designing power electronics converters for the integration of renewable energy is intricate and crucial, necessitating careful consideration of numerous aspects. The converter's performance, effectiveness, and dependability are affected by these elements. To avoid bottlenecks, the converter's power rating should match the maximum power output of the renewable energy source (such as a PV array or wind turbine). To ensure seamless integration without overloading or harming the grid, the converter's power rating should be by grid standards and regulations. Scalability in design makes it simple to expand the renewable energy system to accommodate capacity expansion in the future. The efficiency, electromagnetic interference, and thermal management of the converter are all affected by the switching frequency that is chosen. Higher frequencies lessen channel measures yet increment exchanging misfortunes. Power electronics converters are drawn to devices made of Silicon Carbide and Gallium Nitride due to their higher efficiency and quicker switching speeds [19]. To guarantee long-term dependability, semiconductor devices' ratings for voltage and current should match those of the converter. It is essential to choose the right capacitors and inductors based on the voltage, current, and frequency requirements.

To reduce power losses, low-ESR capacitors are frequently utilized. Latent parts should be intended to deal with the normal temperature climb. To keep components reliable, they need adequate cooling and thermal management solutions. Make sure that the converter's passive components are rated to withstand voltage and current stresses. To effectively dissipate heat, heat sinks, and thermal interfaces should be designed in the best possible way. Air cooling, fluid cooling, or a blend of both can be utilized depending on the converter's size and warm prerequisites. When modeling the distribution of temperature, thermal simulation software aids in the identification of hotspots and the optimization of cooling strategies. Basic parts can be copied or needlessly arranged to guarantee framework uptime in the event of disappointments. Configuration of shortcoming lenient elements into the converter, for example, the capacity to work in corrupted modes during part disappointments. Predictive maintenance strategies should consider the long-term effects of aging and wear on components, particularly in harsh environments. During disturbances, check to see that the converter can withstand and support voltage and frequency variations within the limits set by the grid. Plan the converter to limit sounds and keep up with power quality as per network guidelines. To meet the requirements of the grid code, implement communication interfaces for real-time monitoring and control.

Consider the converter's impact on the environment, including the materials used, recycling options, and how it will be disposed of at its end. The importance of eco-friendly and sustainable design practices is growing. Assess the expense viability of the converter configuration, including forthright expenses, support, and anticipated life expectancy. Money-saving advantage investigation ought to consider factors like energy reserve funds, motivators, and sponsorships for environmentally friendly power frameworks. The planning of power gadget converters for environmentally friendly power coordination requires a comprehensive methodology that thinks about power evaluations, semiconductor gadgets, latent parts, warm administration, unwavering quality, lattice guidelines, ecological effect, and cost viability [20]. When developing converters that effectively and reliably bridge the gap between renewable energy sources and the electrical grid and contribute to the sustainable expansion of renewable energy systems, careful consideration of these aspects is essential as shown in Figure-2.

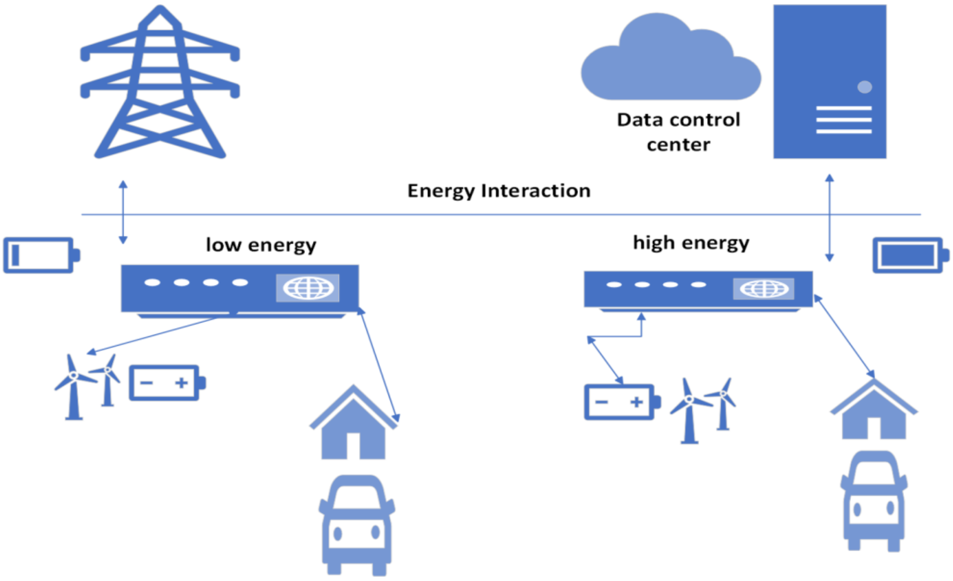


Figure-2. Connection between low and high levels of renewable energy.

4. SIMULATION ANALYSIS

Reenactment and examination are pivotal strides in the plan and streamlining of force hardware converters for sustainable power coordination. Through demonstrating and testing in a virtual climate, specialists and scientists can evaluate the presentation, effectiveness, and dependability of converters before sending. Sunlight-based charger models ought to catch the electrical qualities, including the flow voltage and power-voltage bends, temperature impacts, and concealing impacts. Mechanical and electrical properties, wind speed profiles, and dynamic responses to varying wind conditions should all be considered in wind turbine models [21]. Models for geothermal and hydroenergy sources ought to consider temperature profiles, asset accessibility, and varieties in water stream rates. The utilization of certifiable information and environmental conditions improves the precision of sustainable source demonstrating. Make an itemized model of the chosen converter geography, including semiconductor gadgets, detached parts, control calculations, and security instruments.

Assess switching losses, voltage spikes, and current waveforms by modeling the switching behavior of semiconductor devices. Analyze the converter's dynamic response to various operating conditions by implementing control strategies and algorithms in the simulation environment. Perform thermal simulations to determine whether cooling systems are adequate and to forecast converter temperature distributions. Decide the converter's effectiveness under various burden conditions, considering exchanging misfortunes, conduction misfortunes, and warm impacts.

Survey the consistent state conduct, including voltage and current waveforms, power variables, and bending levels. Dissect transient reactions to changes in load, framework conditions, and sustainable source varieties. Ascertain and assess consonant substance in the converter's result to guarantee consistency with matrix codes and power quality norms. Examine aspects of power quality like reactive power control, voltage sag and swell tolerance, and flicker. Foresee the converter's dependability and interim between disappointments through pressure testing and issue recreations. Investigate the effects of changing component parameters on the converter's behavior. To ensure safe and stable operation, simulate and analyze transient events like grid faults, load changes, and intermittent renewable source power. Research shortcoming conditions and assess the converter's issue reaction, insurance instruments, and issue recuperation systems.

Examine the converter's interaction with the grid, looking for fault ride-through capabilities, voltage and frequency regulation, and grid synchronization. Think about the presentation of various converter geographies, control methodologies, and semiconductor gadgets to decide the most appropriate plan. Experimentation should be used to verify the simulation results, preferably with hardware-in-the-loop setups. Iterative plans given recreation and trial discoveries, consider refinements and advancements to meet execution and dependability targets. The reproduction and examination are fundamental to the plan and streamlining of force hardware converters for environmentally friendly power reconciliation. They give significant bits of knowledge into the converter's conduct under different circumstances, empowering architects, and analysts to calibrate the plan, upgrade productivity, and guarantee solid and consistent activity while interfacing sustainable power sources to the electrical framework as shown in Figure-3 and Figure-4.

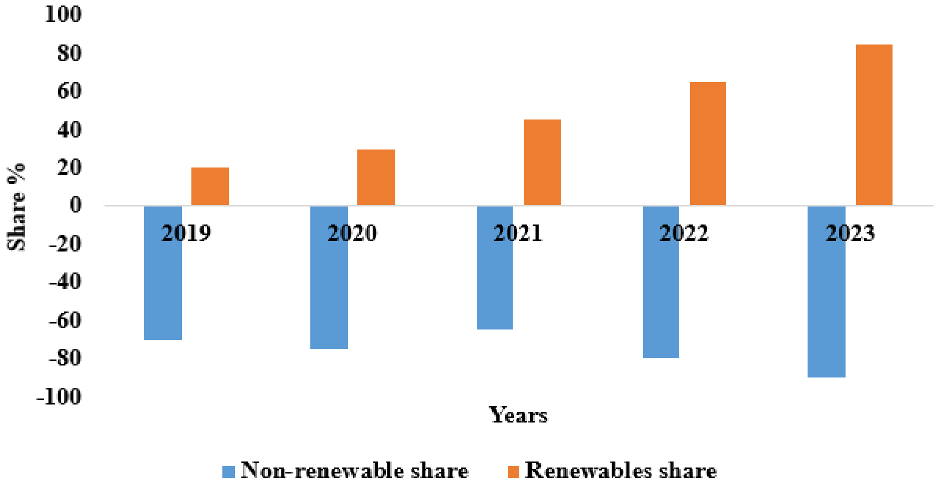


Figure-3. Comparison of RESs and non-RESs between 2019 and 2023.

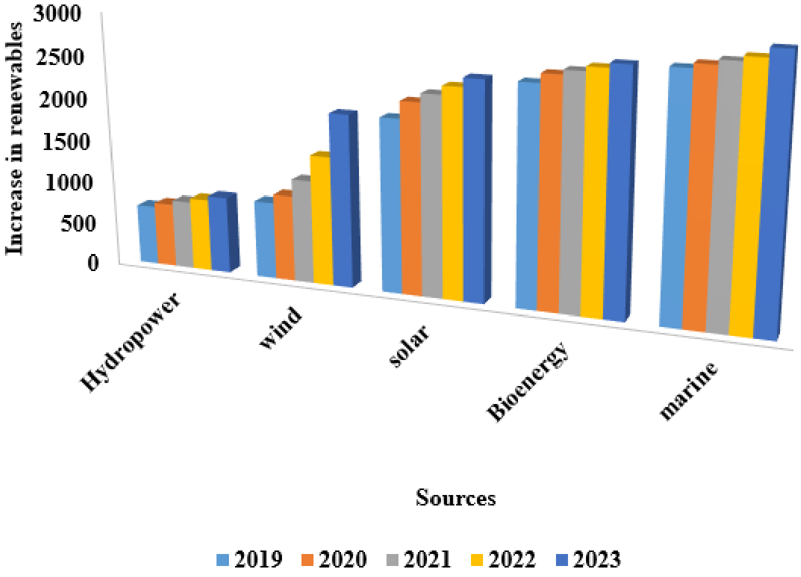


Figure-4. Global accumulated capacity of RESs from 2019–2023.

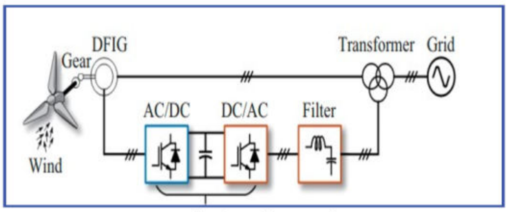
4.1 Integration challenges

The mix of environmentally friendly power sources in the electrical network represents a few specialized and functional difficulties. Beating these difficulties is vital to guarantee the solid and effective working of force gadget converters and the general progress of environmentally friendly power incorporation. Network synchronization is fundamental for converters to associate flawlessly with the framework. During startup or grid disturbances, it can be challenging to ensure that the converter's output voltage and frequency match the grid's parameters [22].

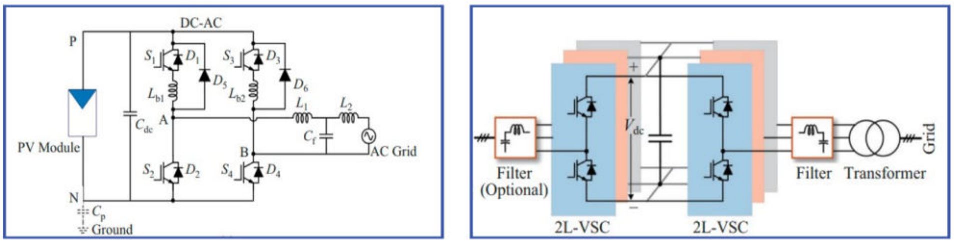
To achieve accurate synchronization even in adverse grid conditions, employ sophisticated synchronization algorithms like grid-synchronized controllers and phase-locked loops. Plan converters with fast reaction times follow framework voltage, and recurrence changes, guaranteeing smooth and speedy synchronization. The stability of the grid depends on keeping the voltage and frequency of the grid within certain limits. Voltage and frequency can be affected by fluctuations in the output of renewable energy. Integrate framework support capabilities into converters, empowering them to direct voltage and recurrence on a case-by-case basis. Active power control and reactive power compensation are two examples of this. Join converters with energy capacity frameworks (ESS) to give network settling administrations, for example, recurrence guidelines and voltage support, during environmentally friendly power changes. During a grid outage, islanding occurs when a portion of the electrical system continues to function independently of the main grid. Islanded operations can pose a threat to grid stability and utility workers. Execute dynamic islanding discovery techniques in converters, which screen network boundaries and detach from the lattice on the off chance that islanding is recognized. These strategies frequently incorporate the pace of progress of recurrence and voltage/recurrence edges. Allow converters and the grid operator to communicate with one another to speed up the detection and disconnection of the grid during islanding events. Compliance with grid codes and regulations can be difficult and costly for renewable energy systems due to regional differences.

Construct converters by grid code requirements, such as the capacity to ride through voltage and frequency, harmonic limits, and reactive power support. Create converters with adaptable control features that enable them to operate in various regions and conform to various grid codes. Incorporating sustainable power frameworks into the matrix frequently requires interconnection with existing foundations, which might be obsolete or not intended for irregular energy sources. Team up with framework administrators to recognize essential lattice overhauls, for example, voltage support hardware and matrix support, to oblige expanded environmentally friendly power joining. In regions with questionable frameworks, consider executing microgrid arrangements that consider more independent activity during lattice aggravations. As sustainable power frameworks become more carefully interconnected, they become likely focuses for cyber-attacks.

Carry out strong network safety conventions and instruments to safeguard correspondence organizations and control frameworks from digital dangers. Consistently screen the security of the environmentally friendly power framework's computerized foundation and update network safety measures on a case-by-case basis. Coordinating irregular sustainable power sources requires a tough lattice fit for dealing with variable age and potential matrix unsettling influences. To improve the resilience and adaptability of the grid, encourage the use of DERs like demand response, energy storage, and smart grid technologies. To anticipate fluctuations in renewable energy and plan grid operations in accordance, make use of predictive analytics and advanced forecasting. Even though integrating renewable energy is good for the environment, the production and disposal of power electronics converters can hurt the environment. Consider recycling and disposal options for used converters, as well as environmentally friendly materials for converter production. Advance a round economy approach, where parts and materials are reused, remanufactured, or reused to limit squandering. Grid operators, developers of renewable energy systems, policymakers, and technology providers all need to work together to find solutions to these integration problems. By creating and executing imaginative arrangements, the consistent incorporation of environmentally friendly power sources into the framework can be accomplished while guaranteeing lattice soundness, dependability, and maintainability as shown in Figure-5.



power electronics scale



Power converters for PV systems

wind Generator

Figure-5. Control structure for grid-connected PV systems: power electronics scale, power converters, and wind generators.

5. CONCLUSIONS

In conclusion, power electronics converters play a pivotal role in the successful integration of renewable energy sources into the electrical grid. Through advanced topologies, efficient control strategies, and ongoing innovations, converters are enabling a cleaner and more sustainable energy landscape. As we move forward, addressing grid integration challenges, embracing emerging technologies, and focusing on environmental sustainability will be critical to accelerating the adoption of renewable energy and achieving a resilient and eco-friendly energy future.

REFERENCES

[1] Y. K. Wu, J. H. Lin and H. J. Lin. 2017. Standards and guidelines for grid-connected photovoltaic generation systems: a review and comparison.IEEE Transactions on Industry Applications. 53(4): 3205-3216.

[2] Y. K. Wu, S. M. Chang and P. Mandal. 2019. Grid-connected wind power plants: a survey on the integration requirements in modern grid codes. IEEE Transactions on Industry Applications. 55(6): 5584-5593.

[3] F. Blaabjerg, Y. H. Yang, D. S. Yang and X. F. Wang. 2017. Distributed power-generation systems and protection. Proceedings of the IEEE. 105(7): 1311-1331.

[4] K. Alluhaybi, I. Batarseh and H. B. Hu. 2020. Comprehensive review and comparison of single-phase grid-tied photovoltaic microinverters. IEEE Journal of Emerging and Selected Topics in Power Electronics. 8(2): 1310-1329.

[5] A. K. Bhattacharjee, N. Kutkut, and I. Batarseh. 2019. “Review of multiport converters for solar and energy storage integration. IEEE Transactions on Power Electronics. 34(2): 1431-1445.

[6] B. Enayati, N. Grid, J. C. Boemer, R. Bravo, M. Higginson, T. Key, R. Quint, J. R. Aguero, M. Siira, C. Vartanian and L. X. Zhang. 2020. Impact of IEEE 1547 standard on smart inverters and the applications in power systems. IEEE PES-TR67.r1.

[7] J. Y. Fang, H. C. Li, Y. Tang and F. Blaabjerg. 2019. On the inertia of future more-electronics power systems. IEEE Journal of Emerging and Selected Topics in Power Electronics. 7(4): 2130-2146.

[8] N. H. Khan, M. Forouzesh, Y. P. Siwakoti, L. Li, T. Kerekes and F.Blaabjerg. 2020. Transformerless inverter topologies for single-phase photovoltaic systems: A comparative review. IEEE Journal of Emerging and Selected Topics in Power Electronics. 8(1): 805-835.

[9] Y. H. Yang, K. A. Kim, F. Blaabjerg and A. Sangwongwanich. 2018. Advances in Grid-Connected Photovoltaic Power Conversion Systems, Duxford, UK: Woodhead Publishing.

[10] Y. H. Gui, Q. W. Xu, F. Blaabjerg and H. Gong. 2019. Sliding mode control with grid voltage modulated DPC for voltage source inverters under

distorted grid voltage. CPSS Transactions on Power Electronics and Applications. 4(3): 244-254.

[11] S. A. Khajehoddin, M. Karimi-Ghartemani, and M. Ebrahimi. 2018. Optimal and systematic design of current controller for grid-connected inverters. IEEE Journal of Emerging and Selected Topics in Power Electronics. 6(2): 812-824.

[12] M. Mahzarnia, M. P. Moghaddam, P. T. Baboli and P. Siano. 2020. A review of the measures to enhance power systems resilience. IEEE Systems Journal. 14(3): 4059-4070.

[13] S. S. Ma, S. Y. Li, Z. Y. Wang and F. Qiu. 2019. Resilience-oriented design of distribution systems. IEEE Transactions on Power Systems. 34(4): 2880-2891.

[14] X. Zhang, T. Zhao, W. Mao, D. Tan, and L. C. Chang. 2018. Multilevel inverters for grid-connected photovoltaic applications: examining emerging trends. IEEE Power Electronics Magazine. 5(4): 32-41.

[15] A. Sangwongwanich, Y. H. Yang and F. Blaabjerg. 2017. A sensorless power reserve control strategy for two-stage grid-connected PV systems. IEEE Transactions on Power Electronics. 32(11): 8559-8569.

[16] E. Rakhshani and P. Rodriguez. 2017. Inertia emulation in AC/DC interconnected power systems using derivative technique considering frequency measurement effects. IEEE Transactions on Power Systems. 32(5): 3338-3351.

[17] M. Andresen, K. Ma, G. Buticchi, J. Falck, F. Blaabjerg and M. Liserre. 2018. Junction temperature control for more reliable power electronics. IEEE Transactions on Power Electronics. 33(1): 765-776.

[18] U. M. Choi and F. Blaabjerg. 2018. Separation of wear-out failure modes of IGBT modules in grid-connected inverter systems. IEEE Transactions on Power Electronics. 33(7): 6217-6223.

[19] Y. Chang, H. Z. Luo, F. Iannuzzo, A. S. Bahman, W. H. Li, X. N. He and F. Blaabjerg. 2020. Compact sandwiched press-pack SiC power module with low stray inductance and balanced thermal stress. IEEE Transactions on Power Electronics. 35(3): 2237-2241.

[20] Z. Ni, X. F. Lyu, O. P. Yadav, B. N. Singh, S. Zheng and D. Cao. 2020. Overview of real-time lifetime prediction and extension for SiC power converters. IEEE Transactions on Power Electronics. 35(8): 7765-7794.

[21] S. Zhao, F. Blaabjerg and H. Wang. 2021. An overview of artificial intelligence applications for power electronics. IEEE Transactions on Power Electronics. 36(4): 4633-4658.

[22] X. Li and S. Wang. 2021. Energy management and operational control methods for grid battery energy storage systems. CSEE Journal of Power and Energy Systems. 7(5): 1026-1040.