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Recent Advances in Power Electronics for Renewable Energy Systems

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Abstract

Since mid-twentieth century, pioneer work in power electronics has led to its widespread application in other areas. Power electronics is a field that has undergone rapid evolution over the past thirty years, both in technology and in its use in renewable energy. The three-node model of photovoltaic (PV) energy conversion systems has been extensively used in academic and industrial design, analysis, and control. The modular multilevel converter (MMC) topology has been accepted and used in the offshore wind and solar energy industries. Power electronics have been integrated into wind power systems and wind energy generation is typically based on doubly fed induction generator (DFIG), which features a back-to-back converter as its power-electronic interface (Banerjee, 2019).

Keywords: *Power electronics, renewable energy, photovoltaic PV, wind power, modular multilevel converter (MMC), silicon carbide (SiC), gallium nitride (GaN), doubly fed induction generator (DFIG).*

1. Introduction

Renewable energy is important for future power generation, given environmental issues, diminishing fossil fuel reserves, and current urbanisation. The main sources of renewable energy are solar power, wind power, hydroelectricity and bioenergy. However, photovoltaic systems and solar energy in general are growing at a very high rate. Such systems of renewable power generation rely on numerous power converters, which directly affect conversion efficiency, footprint, reliability, and feasibility of distributed generation solutions. Power converters used in renewable energy systems are available in broad spectrum of topologies, control methods, and technologies. A general overview of recent developments in this field can help with the correct selection, design, and implementation of renewable energy systems.

Power electronic converters for renewable energy systems are divided on following basis: conversion method and interfacing strategy. Both the topology options (isolated, non-isolated, single-stage, two-stage) and the implementation techniques (control strategies, modulation techniques) are included in the conversion category. The interfacing category includes grid-code requirements, international grid-connected system, grid-following control of synchronous energy sources, and grid-forming control of non-synchronous generation and storage control.

2. Principles of Power Electronics in Renewable Systems

The basic elements of renewable systems include power electronics for efficient energy conversion and integration (Banerjee, 2019). These systems are designed to integrate renewable energy generators and storage systems into electrical networks. Conventionally, the renewable sources have been linked to the utility grid via power converters. The widespread deployment of distributed energy resources has spurred the development of smart grids capable of integrating with various regulatory schemes. Renewable energy generation or conversion systems usually use power conditioners to ensure the energy's value is preserved amid fluctuating demand. There are many studies devoted to the modelling and control of renewable generation units, such as wind farms with energy storage, as well as to power conditioning systems that optimise the operation of the entire network. The integration of electrical networks, sources, and storage systems has attracted considerable attention to the control and management of energy systems. When distributed generator interfaces are installed, coordination and management of energy sold and purchased, as well as locally injected power, are handled. The problems of compatibility, stability, and efficiency of renewable energy sources, as well as the corresponding power conditioning systems, are of foremost importance in the context of energy systems. The grid codes' compliance with modelling means that numerous pieces of equipment installed in the network are not compatible with them. Power-conditioning systems are also involved in the interconnection of offshore energy systems and the power supplies allocated to the oil industry located in remote areas. Depending on the system size and technology, power-electronic converters are used to interface renewable generation and storage, employing different topologies and control techniques. The interconnection of DFIGs or direct-drive wind systems and the coupling of battery energy storage in medium- and large-scale photovoltaic systems exemplify how renewable energy and storage rely on power conditioners. The electronic power converters must meet grid connection requirements, and their topologies and configurations vary significantly with the generation technology and converter demand.

2.1 Energy conversion converter topologies

Energy-conversion converter topologies are key elements of power electronics, enabling efficient connections between generation systems and the grid (or storage units). These designs primarily consist of isolated and non-isolated converters, as well as single-stage and two-stage converters. The choice of the right configuration depends on application-related parameters such as efficiency, compatibility with the target technology, and the desired level of simplicity (Essakiappan, 2015). Table 1 classifies other topologies based on these properties for three popular renewable energy technologies: photovoltaic systems, wind generation systems, and storage units. Topological data on energy sources are also provided to show similarities among generation-technology interfaces.

Table 1:

Isolated converter topologies incur a quantifiable efficiency cost but are commonly employed to provide high levels of galvanic isolation. The realisation of global maximum power point tracking in PV setups, such as isolated setups, is frequently dependent on their use. Isolated solutions are also required in battery-storage systems that use series-parallel interconnect combinations. Non-isolated topologies, conversely, are used when the input and output entity references can be matched exactly, as in storage systems using buck-boost configurations or fly-back topologies that support operation at minimal energy levels (Juan Sandoval, 2017).

Technology	Isolated Topologies	Non-Isolated Topologies	Single-Stage	Two-Stage
PV Systems	Flyback, Forward, Push-Pull (galvanic isolation for MPPT)	Buck-Boost, SEPIC (voltage matching)	✓	✓
Wind Systems	Full-Bridge, Phase-Shifted (DFIG back-to-back)	NPC, T-Type (medium voltage)	✓	✓
Storage Units	Dual-Active Bridge (battery isolation)	Buck-Boost, Interleaved (series-parallel)	✓	✓

2.2 Modulation techniques and control methods

The power converters serve as the interface between the power systems and renewable energy sources. A wide range of control strategies and modulation techniques have been applied to enhance the stability and quality of the interconnection between renewable sources and energy-storage systems; a list of these techniques is presented below. They can include PID controllers, predictive control, hysteresis control, and other modulation strategies using PWM and space-vector modulation (Ngancha et al., 2017). In addition to ensuring proper power flow direction, grid-connected converters should comply with grid codes prescribed by various authorities. A range of methods has been used to ensure grid voltage synchronisation during parallel operation or upon reconnection to the grid following a fault (Trimurtulu, 2018).

2.3 Interfacing and standards of grids

The concept of grid interfacing is important for integrating renewable energy sources into power systems and ensuring their stable operation. Grid codes are technical specifications for how interconnection will be made, which affect converter design, control methods, and switch-on procedures. Standardisation is grounded in technical exigencies and supports coherent, consistent interconnections. Specifically, the IEEE Power Electronics Society (IEEE PELS), the System Integration of Renewable Energy Committee (IEEE, 2018), and IEC 61727 provide guidelines that place greater emphasis on grid-connected operation. There are significant engineering implications of the difference between grid-following and grid-forming controls (SARKAR & Odyuo, 2019).

The grid-following control operates based on the grid voltage, and the grid-forming control produces a voltage reference at the same frequency and phase. The basic algorithm for grid-following control is defined in the Renewable Energy Standard (IEEE 1547; IEC 62116) (Ravi et al., 2023). A three-step synchronous reference frame, used in all converter systems connected to a grid, separates frequency and voltage feed-forward to construct control formulations. It has both active and reactive power loops within the control structure, which provide droop characteristics based on feedback from grid voltages.

3. Wide-Bandgap Semiconductors in Renewable Applications

Devices of interest for renewable power applications are based on wide-bandgap semiconductors such as SiC and GaN, due to their favourable characteristics compared to silicon. SiC is better suited for high-voltage applications and has higher breakdown field strength, thermal conductivity, thermal stability, and electron mobility (Almasoudi, 2018). GaN devices benefit from high switching frequencies due to low parasitic capacitance and inductance, and can therefore be used with smaller filters. Other benefits include reduced on-resistance, a smaller die size than other circuits, and desirable reverse recovery (Dargahi, 2012).

Multi-level converter topologies are frequently used in photovoltaic systems because of their low-voltage and high-switching-frequency operation. SiC switches simplify converter design by reducing the number of devices required due to their conduction characteristics. GaN devices are employed in applications that demand switching frequencies over 100 kHz, such as inverters. In the process of doubling induction generators, SiC and GaN are utilised to convert wind energy. In energy-storage systems, SiC allows for more efficient modular multi-level converters, while GaN is used in high-frequency, compact bidirectional converters.

3.1 Silicon carbide products and users

SiC devices can operate at higher temperatures and frequencies than commercial silicon devices, enabling energy savings and other benefits when used in renewable energy systems. The other advantages comprise reduced heat sinks, reduced output and input filters, increased power densities and permanent fault isolation. Nevertheless, SiC devices have yet to reach a dominant market position.

SiC devices also enable higher switching frequencies, thereby reducing the size of passive components. SiC-based power converters typically achieve a 5- to 10-fold increase in switching frequency without requiring additional equipment or circuit modifications compared to Si-based converters. The commercial market, primarily dominated by Si technology, is gradually shifting toward DC-DC converters with zero-voltage-switching (ZVS) and zero-current-switching (ZCS) capabilities, which typically operate at several hundred kHz. These trends align with new international requirements for distributed energy resources (DER), which also call for increased operating frequency as a means of safety isolation where applicable (G. Neudeck, 1998; Murtala Aliyu et al., 2017; KIMOTO, 2022).

3.2 Gallium nitride devices and applications

GaN devices are efficient, high-frequency, and lighter and less bulky. GaN-on-Si enhancement-mode is the leading technology for both high- and low-voltage applications, with configurations tailored to each. The switching loss includes overlap, gate, and output-charge losses, with the former being most prevalent at low frequencies (Amano et al., 2018). Major sectors have begun operations in automotive applications, including E-Motor drives, OBCs, and DCDC converters (Dargahi, 2012). The operating frequencies may also be raised to 30-300 kHz to minimise PCB size and optimise EMI performance. The trade-off among switching frequency, PCB area, and EMI performance is common and a key issue in the automotive market.

3.3 Reliability and thermal management issues

The power converters of renewable energy systems should be designed to reduce stresses on components, ensuring reliable operation throughout their entire lifespan. Thermal management is also a major consideration in this and among the most crucial reliability factors in power electronic systems (Andresen & Liserre, 2014). Several thermal modelling methods can be used to describe the thermal behaviour of a converter and to design reliable systems, at both the circuit and system modelling levels (Falck et al., 2018). Along with thermal modelling, reliability testing is also used to determine the predicted life of components under actual operating conditions and various aggregated engineering conditions. Measures of reliability, based on empirical knowledge of the failure phenomena a system is experiencing, can be used to direct systems to the actual areas where their design margins lie.

Thermal paths and the power dissipated must be properly identified to establish the highest possible junction temperature for each component. This, along with the highest anticipated ambient temperature, normally suffices to model the system's thermal behaviour and determine component reliability. Some components might prove critical due to their high switching frequency and direct connection to the power loop, contrary to perceptions based on total dissipated power. To avoid the sea-of-samples approach in cycling reliability analysis, it is suggested to adopt a set of specific parameters to enhance reliability or reduce cumulative thermal fatigue.

Lastly, derating methods extend component life and enhance system reliability. Derating allows one to simplify the design of the thermal management system and reduce the system's sensitivity to changes in environmental conditions. Thermal control of the thermal management system, per se, and the specific concern of thermal cycling can also help extend reliability.

4. Power Interfaces Efficiency, Size and Cost Trends

Recent advancements in renewable energy systems have led to growing interest in modular multilevel converters as a potential solution for grid integration. This idea leverages the fact that multiple smaller converters can benefit from lower voltages while still offering scalability and fault tolerance. Modular multilevel converters are inherently different from conventional technologies and can offer significant reductions in volume and weight, achieving up to 98 per cent efficiency (Eldeen Hafez, 2015).

Selection between gallium nitride or silicon carbide devices is a critical issue for photovoltaic and wind energy converters. Gallium nitride devices would make it easier to reduce size, since they operate at high frequencies; silicon carbide offers greater thermal and electrical stability and greater resistance to moisture and corrosion. The decisions to be made, involving trade-offs in costs, performance, switching losses, electromagnetic interference, packaging, and module design, are summarised to provide an idea of the technology choice based on the activity (Almasoudi, 2018).

The combination of energy storage and power electronics expands the energy management strategies and enables firming of the renewable generation.

Power and energy balancing methods may be applied when selecting bidirectional converter topologies. These combinations enhance conversion when energy is collected over varying time periods, address the specific degradation of storage elements, augment grid- and building-level features, improve the life-cycle impact of the entire system, and constrain grid services to particular time intervals.

4.1 Scalability and modular multilevel converters

The Modular Multilevel Converter is a scalable power converter with high-voltage ratings and a flexible design, suitable for projects ranging from small to large renewable energy sources (solar and wind) and their storage. They are used to transmit High Voltage Direct Current (HVDC) power, and are appropriate in other applications including drive systems and Smart Grid (Khanal, 2019). They are also suitable for grid integration, photovoltaic energy conversion, and other industrial applications due to their dynamic performance and scalability.

The MMC topology that uses distributed energy storage (sub-module capacitors) improves the quality of power conversion in two ways: it enables soft-switching and it can generate more output voltage levels. These configurations have achieved efficiency improvement of 2.5-5 percent and improvement in overall volume (20-50-80 percent lower than a corresponding conventional converter). Also, lower switching frequency (= 50 kHz, normal = 20 kHz) and temperature increase (= 30 degrees Celsius, normal = 20 degrees Celsius) give additional benefits in the long run (S. et al., 2019).

4.2 PV and wind converter trade-offs between GaN and SiC

In energy conversion using photovoltaic and wind, both GaN and SiC device-based packages are significantly more cost-effective in terms of performance. The low-frequency dead times cause losses in the main switching devices, which are limiting factors. The dead times in GaN transistors can be reduced relative to Si IGBTs, and this can be further improved in applications using a three-level topology rather than a two-level topology. At typical grid voltages, e.g., 400 V_{dc} or 800 V_{dc}, the system's concept and topology may differ considerably, leading to different choices of GaN and SiC devices. At voltages of 1500V or more, both technologies can still be used, though overall estimated costs vary considerably with switching frequency.

At the inverter level in PV applications, where the current is generally much lower than in wind applications, the potential cost advantage of GaN devices is even greater at inverter frequencies above a few hundred Hz. Nevertheless, switching frequencies in PV applications remain relatively low, often below 1 kHz, resulting in an insignificant economic benefit from transitioning away from IGBTs. GaN transistors can match the efficiency of IGBTs with a tighter efficiency margin, enabling operation at higher switching frequencies due to their favourable thermal properties (Gurpinar et al., 2016). To conclude, GaN devices minimise switching losses and enable the adoption of three-level topologies with voltages down to 1500 V. In contrast, GaN or SiC devices offer greater flexibility for PV or wind applications, respectively.

4.3 Combining energy storage with power electronics

There has been an increase in integration of renewable energy systems into contemporary power grids, particularly solar and wind. In 2010, solar energy capacity was approximately 17.3 GW, and wind energy generation was approximately 340 TWh worldwide. Wind energy provided approximately 6 per cent of the world's total electricity. The nature of renewable sources makes them intermittent, thus generating an uneven power supply and necessitating a storage system to balance voltage and provide on-demand power. Traditionally, standard sources of power, such as diesel generators, have been stable. However, with the Kyoto Protocol, there has been an increased need for flexible renewable energy storage sources. Storage systems play a significant role in balancing fluctuations in renewable energy production and enabling integration into the grid.

As a result, power electronics are used to regulate such storage systems in contemporary power systems to balance energy (Yunus et al., 2012). As sSupercapacitors provide power within minutes to hours, and batteries address intermittency, these energy storage systems help solve the issue together. This energy or power balance is achieved by connecting two control strategies: hierarchical management and energy/power balancing, using an additional follow-power control loop connected to a grid-forming converter.

Energy storage plays a significant role in smoothing out the intermittency of renewable power generation. Several power electronics are interrelated to regulate the energy or power flow to/from the energy storage into the grid. The bidirectional in/out flow to the storage is useful for achieving a certain cycle life of the energy storage without compromising system performance.

5. Digitalisation and Control of Renewable Power Electronics

In modern renewable energy systems, electronic power converters are increasingly used, which is why research and development of converter architectures and control mechanisms that optimise efficiency and performance without compromising reliability and size are under intense focus (Mohebbi, 2017). Model Predictive Control (MPC) is the most advanced control strategy, which enables effective utilisation of battery energy storage by leveraging Physics-Informed Data-Driven (PIDD) modelling that responds to users' optimisation needs in real-time and accounts for changing conditions. Although high-dimensional state-trajectory PIDD-metric-based control systems entail a considerable computational load, current model-prevention techniques reduce system complexity and enhance robustness to uncertainty, enabling their application in higher-power RES. Capacity converters with Energy Storage (ES) and RES have high capacity and offer more ancillary service options. Techniques of communication, such as the Industrial Internet of Things (IIoT), and cloud-based Digital Twin modelling, allow the correct monitoring of the status of large photovoltaic installations and distributed generating systems, making it possible to use Condition-Monitoring (CM), predictive diagnostics, maintenance planning, early identification of interference mechanisms, and involvement in Local Flexibility Markets (LFM). The standards for protection against emergent threats and accidental Internal Quality (IQ) degradation in Cyber-Physical Security (CPS) will provide continuous support for the changing requirements of the dynamic RES in future generations of converter, ES, and ACS technologies. Managerial capabilities arising from Converter-Equipment-Sensor (C-S-E) integration provide processors with modern digital resource specifications.

5.1 Model predictive control and real-time optimisation

Generalised formulations of control strategies for specific applications are available in the literature. However, their application is generally limited by computational burden or by the ability to satisfy control objectives under uncertainty. Controllers capable of addressing the specific features of system dynamics and constraints in a computationally tractable way are therefore of considerable interest (Tarisciotti et al., 2016). The track-plate example presented later is a third-order system that can be reduced to a second-order one. In its static formulation, the distributed control architecture ensures performance only under operating-point variations, at the expense of robustness to disturbances. A Time-Critical-MPC approach, based on the same control architecture, has been proposed that enables maintaining a simplified model over shorter periods and, therefore, upgrading the distributed controller with an alternative observer. The approach aims to improve the ability to cope with disturbances and parameter uncertainty without significantly increasing the overall computational burden. Where dynamic performance is the primary objective in MHMPS principles, specifying derivatives of control inputs makes the pursued constraints less stringent and allows quantification and comparison of the benefits of faster control action in terms of attainable disturbance rejection (Gulbudak, 2016).

5.2 Digital twins and condition monitoring

Digital twins and condition monitoring provide critical enablers for the reliability and maintenance of electronic systems interfacing with renewable energy. A digital twin represents a physical system in a virtual environment, enabling data analysis to inform monitoring and predictive maintenance throughout the entire life cycle. Digital twinning is increasingly relevant to renewable energy applications, and predictive maintenance strategies continue to evolve. There are opportunities to develop and improve digital-twin modelling for power converters and to monitor a wider set of components, including the cooling system, better to estimate the state of health of individual elements. Prognostics and health management (PHM) approaches are increasingly being integrated with digital twins to improve estimation accuracy and enable more effective maintenance planning (Matania et al., 2023).

Digital twins are being investigated for industrial Internet-of-Things applications, including a case study on wind-turbine predictive maintenance using condition monitoring via a distributed fog-computing architecture. This concept can improve asset utilisation and management by providing real-time monitoring, predictive analytics, and early health management diagnosis for mechanical and electronic components (Abdullahi et al., 2024). Further work could couple condition-monitoring data with digital models to provide a more accurate digital twin of the system and to support more sophisticated maintenance strategies.

5.3 High-speed communication and cyber-physical security

Emerging converters in renewable energy systems are increasingly global in scale, spanning vast distances on multiple physical layers. Such international communication for grid control, command, monitoring, and protection must comply with national/regional communication standards, posing challenges for compatibility, integrity, performance, and privacy (Cui et al., 2018). Power-level communication architectures must satisfy stringent real-time constraints, as platform and module communications largely determine overall converter latency (Sahu et al., 2020). To protect against cyber-physical attacks that undermine these critical signals, tampering intrusion detection becomes essential, yet existing cyber-physical system (CPS) cyber-resilience approaches target data-level rather than signal-level integrity.

Internationalisation multiplies cyber-physical risk across energy communities of consumers and prosumers. Cyber attacks may shut down renewable generation or storage, degrading power quality. Given their particular vulnerability to command-and-control data malware, such as false data injection, renewable systems require robust wide-area protection. As converter activity becomes subject to critical command signing/wiring, effective cyber-physical protection confirms that data-transfer capability does not imply unmonitored alteration of power-quality/monitoring signals or renewable enabling/disabling commands.

Communication throughput and speed remain pivotal in large-scale power-electronics converter systems for distribution, storage, and drives in grid-connected, grid-forming, and full-storage situations. Digital interfacing bridges information, modulation control, condition monitoring, and telecommunication. Cyber-physical vulnerabilities affect both public and tightly secured networks in the usual converter structure. Governance dimensions concern not only standards, systems, equipment, and protocols but also the "who" and the "how", which affect the character of communication and interaction and determine broader accessibility. Finally, intervention must remain narrowly targeted to preserve stable performance.

6. Applications in Specific Renewable Domains

Photovoltaic energy conversion systems convert solar energy into electricity through photovoltaic cells. Renowned for their simplicity, reliability, long life, and silent operation, they have gained traction in distributed energy generation (Almasoudi, 2018). Improving the efficiency of PV grid-tied inverters remains vital for enabling sustainable energy production on a global scale.

Conventional grid-tied PV systems employ either a central inverter or a micro-inverter configuration. An extensive literature review of multiple maximum power point tracking (MPPT) and grid-support techniques for central inverters, particularly in the low-voltage PV range, has been conducted. Reliability issues arising from partial-shading conditions in PV systems equipped with a central inverter have been an important consideration (Juan Sandoval, 2017).

Modern wind turbine conversion systems have evolved from primitive doubly-fed induction generators with partial-scale converters to fully-fledged systems without brushes or slip rings. A comprehensive investigation of electrical architectural alternatives has been conducted for both DFIG and DFIG-less configurations. Fellow researchers value advancements in grid-supporting, fault-ride-through, and reliability strategy studies.

Marine energy arises from the movement of ocean water and is converted into electricity by marine energy converters. An extensive literature review of diverse ocean energy sources, energy conversion systems, grid connections, and benefits/developments of marine energy has been conducted. Case studies involving a particle-orbital-motion water-wave-ocean-energy converter and an oscillating-water-column wave-energy converter have also been presented, drawing on prior knowledge. Addressing key sea-water-cable-mooring problems has emphasised the need for ongoing research to tackle present-day constraints and maximise future output.

6.1 Photovoltaic energy conversion systems

Maximising energy capture and optimising converter control in photovoltaic systems are essential to improving the performance of grid-connected PV systems. In distributed PV generation systems, edge power converters are affected by partial shading of PV panels due to certain array layout configurations, which can significantly degrade overall system performance.

Many array configurations may lead to partial shading of PV panels, caused by buildings, tree shadows, and dust covering only part of the panels. Based on the extracted maximum power point (MPP) data under different irradiance levels of partially shaded PV panels, the common shading patterns of PV panels are summarised. To maximise energy capture in PV generation systems, an energy-oriented optimal switching strategy that considers only the extracted MPP under different shading scenarios, rather than the extracted voltage information, is proposed (Almasoudi, 2018).

6.2 Wind turbine power electronics

Wind turbine generators (WTGs) remain the leading contributor, with a total capacity of over 329 GW worldwide in 2020. The majority of converters operate at an AC generator. To enable low-speed operations of the generator, converters are designed with a stub circuit such that only high-frequency components are processed. The supply of synthetic inertia during shortages enhances system stability and reliability.

Wind turbine power electronics comprise matrix converters, gearless topologies, back-to-back converters with generators relying on squirrel cage rotors, and converter- and turbine configurations facilitating grid-forming control, WTG generating fluctuated power appropriately integrated with energy storage systems, and modeling approaches like coupled mathematical model guaranteeing complete operational specification under arbitrary high-performance grid-code compliance (Thomas Daniel, 2016) (Hassanzadeh et al., 2017). Wind turbine converters can operate in grid-forming or grid-following modes, providing inertial response, primary frequency restoration, active/reactive power sharing, and various ancillary services. A higher DC-link voltage is further needed, increasing active belt converter switching losses. At the same time, an optimised tool ensures power converters' dl-curves coincide with the simulated environment level, enabling a parity premium when appraising control advantages.

6.3 Marine and tidal energy converters

Marine and tidal energy converters harness energy from ocean currents, tides, and waves. Various ocean energy extraction devices are developed, assessed, and modelled. Generator requirements for efficient power transmission and grid integration technologies for offshore projects hold particular significance. Overtopping systems and wave interaction arrays have been studied. The Islay LIMPET Wave Power Plant demonstrates the practical implementation of wave energy systems.

Tidal turbines and marine current generators are modelled to improve stability and efficiency. Research includes the design of converter control systems, the potential for power acquisition, and turbine blade load effects. Lake Sihwa tidal power plant exemplifies practical application. Performance evaluation of different turbine configurations, including pitch and stall regulation, optimises energy output. Advanced modelling, comprising hydrodynamic characterisation and simulation, supports the development of reliable marine energy devices. Overall, research emphasises enhanced energy extraction, stability, and control of marine and tidal energy systems (Ghefiri et al., 2017) (Song Ngu, 2013).

6.4 Energy storage-interfaced power electronics

Energy storage-interfaced power electronics represent an essential component of modern energy systems.

Many renewable energy sources, such as wind and solar power, remain intermittent, slowing their adoption and deployment (Essakiappan, 2015). Energy storage helps to smooth power fluctuations, increases stability within the electricity grid, and facilitates efficient dispatch of renewable generation. The integration of storage technologies at generation sites or within distribution networks further enhances local utility and effectiveness (Yunus et al., 2012). Applications of energy storage systems (ESS), such as Battery Energy Storage Stations (BESS), are particularly important for capturing short-term fluctuations from photo voltaics and wind sources (Leite et al., 2014). The rapid deployment of electric vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs) has also drawn attention to the vehicle-to-grid concept, which permits energy exchange between EVs and the grid, facilitating increased penetration of intermittent generation.

7. Grid Integration and Ancillary Services

The success of renewable energy sources in tackling climate change depends on how fast they can be deployed and integrated into electricity grids. Grid integration encompasses all measures and actions taken to utilise RES generation to meet energy demand while respecting system safety norms (SARKAR & Odyuo, 2019). Active power controls enable RES generators and other distributed energy resources to provide flexibility and additional services beyond conventional energy generation throughout their operating lives (Leite et al., 2014).

Inertia emulation is a safety service that prevents the system's operational frequency from changing too quickly, which could endanger system stability; it enables RES generators to provide faster response times and to participate in primary and secondary frequency regulation. For new power systems that incorporate more RES, the remaining safety and ancillary services remain the same as for conventional BENs. These include frequency response, cascade frequency response, and energising and substitutive capacity, collectively known as tertiary regulation. Furthermore, RES can avoid under-frequency conditions that could stop existing generation units by providing standard frequency support, allocate existing limited capacity by taking care of frequency-first regulation, and limit power balance fluctuations between generation and consumption through cascade frequency response.

Moreover, RES maintain load-following performance, the ability to dynamically adjust generated power while maintaining a constant power or energy expectation over a long period. Load-following is relevant to economic trading in most electricity markets, where RES must face long-term energy and economic management. RES can also provide ramping power support, helping the system sustain longer-duration, excessively fast ramping events. By tracking the trend of variation at the planning stage, RES offers flexible ramping services that enable it to participate actively in economy- or money-based bidding and hour-difference adjustments while considering balancing reserves.

7.1 Active power support and inertia emulation

The electric power system is becoming increasingly dominated by renewable generation interfaced through power electronics. These technologies lack the natural inertia and governor damping of synchronous machines. As a result, frequency excursions may be larger, and in some cases, system instability may occur. Inertia emulation is the concept of mimicking the dynamic behaviour of synchronous machines (Kameshwar Poolla et al., 2018).

Equipment participating in inertia emulation contributes to primary, secondary, and tertiary regulation. A model of synthetic inertia closely matches the dynamic response of static inertial behaviour. High and low-frequency active power support can also be provided through droop control on such equipment (Jibji-Bukar & Anaya-Lara, 2019). A power reserve must be maintained to enable a frequency-responsive release of synthetic inertia.

Advantageous participation in regulation can occur at several time scales. Additional techniques enhance the overall frequency-support strategy. Continuous coordination of available droop and synthetic inertia enables a higher-frequency response without compromising stability.

7.2 Voltage and frequency regulation through power electronics

Distributed energy resources such as solar photovoltaic systems, wind turbines, and battery energy storage systems can generate energy near demand loads, thereby significantly reducing the transmission and distribution losses. By carefully orchestrating the DERs, active power can be freely distributed to different loads while voltage regulation may become challenging.

Several control strategies can be implemented solely for voltage control. These strategies aim to increase system stability and extend the maximum load capacity. For instance, when multiple DERs are connected to the same radial feeder, they are assumed to be less than 1200 m apart. In this scenario, the DERs employ a voltage regulation strategy that allows each DER to share a specific portion of the local voltage drop via local voltage feedback.

The overall system can maintain at least one of the following voltage stability criteria: (i) if one DER goes offline, the remaining DERs can still regulate the local voltage drop, (ii) if the local load increases, the local voltage remains above the minimum allowable level, and (iii) if the local load decreases, the local voltage would eventually converge toward an equilibrium point (Banerjee, 2019).

7.3 Participation in markets and frequency response

The challenge of integrating large amounts of non-dispatchable generation into electrical power systems has spurred the development of ancillary services markets, which create opportunities to secure additional revenue streams for wind and solar plants. In most regions, however, the telemetry and performance metrics required to participate in such markets exceed those of conventional energy products. As a consequence, companies that manufacture, deploy, or operate wind and solar electrical conversion systems face a pressing need to assess the feasibility of meeting these more stringent participation criteria (Edmunds et al., 2019).

Meeting the requirements for frequency control also introduces additional structural complexity for distributed energy resources (DERs) that aggregate renewable generation and energy storage systems in low-voltage environments. Commercially available products that enable small-scale photovoltaic systems to participate in the more accessible primary reserve markets for larger-scale plants would offer a stepwise approach to securing value-added revenue streams while minimising the additional telemetry and control burden on the overall system (Tokombayev, 2014).

Many publications have detailed the connections between a system's electrical characteristics and the frequency-response measures required for participation in active control markets.

8. Reliability, Standards and Life-Cycle Considerations

A survey by the European Centre for Power Electronics on reliability issues found that the importance of power electronics reliability has increased across wind power, photovoltaics, electric vehicles, drive systems, and energy transmission. At the same time, the complexity of power electronic systems has increased to fulfil functional demands. Consequently, the risks associated with component failures have risen. Gaps in the reliability of capacitors, power modules, and circuit boards are critical because reliability is defined as the probability that a power-electronic system will perform as specified over its intended period under specified conditions. The industry is increasingly focusing on improving the reliability of power-electronic systems (Falck et al., 2018).

In the power-electronic sector, compliance with emerging interoperability standards will be critical to advancing multi-vendor integration across various renewable applications. Shortages in components and materials also influence component lifetimes in renewable applications. Extensive access to papers, models, and tools has spurred the development of data-driven analysis techniques, and hybrid data-driven approaches have emerged alongside traditional physics-based strategies. Consequently, operators can now also implement data-driven tools that extend into real operations for both prediction and control.

8.1 Reliability testing and failure modes

Reliability of power converters remains a critical concern in the development of renewable energy systems, with many manufacturers proactively adopting stringent reliability testing. Although well-established standards exist for the automotive and aviation industries, comprehensive regulatory frameworks for power converters are still under development (Falck et al., 2018). The reliability metrics currently used for these converters originate from semiconductor chips, which are often non-integrated and generally neglect the overall converter system. With increasing system integration, there is a growing need for new reliability metrics based on the converter system itself (SMITH, 2018).

Recent progress in understanding degradation physics has led to the introduction of novel metrics that characterise the expected lifetime of power converters under various operating conditions. Commercial tools exist for reliability assessment, yet robust predictive information on converter degradation remains limited. Failure-mode analysis is essential for providing early warning of performance degradation and, ultimately, preventing functional failure. Since power converters are often subjected to multiple modes of degradation simultaneously, failure-mode analysis must capture interactions among degradation pathways.

8.2 Standards, interoperability and safety

The success of renewable generation technologies hinges on the long-term dependability of accompanying power electronic interfaces. Consequently, the provisioning of robust systems that survive challenging operating conditions is crucial. Both the field and research community exhibit significant interest in reliability of power electronic systems. Surveys reveal that industry participants deem reliability a top-three priority in photovoltaic systems, and established companies regularly assess their arrangements with a focus on this metric (Falck et al., 2018). Defining a precise specification of reliability remains challenging, yet broad agreement exists on how to characterise the associated parameters. Maintaining a low failure rate over a specified duration is essential. Such agreements do not extend to methodologies for reliability evaluation, although attempts are underway to converge on harmonised practices. Several such techniques already circulate within the renewable energy sector, reflecting a common perspective on the matter.

An interconnected and interdependent world requires the establishment of standards that ensure safety, interoperability, and compliance with grid codes (Almasoudi, 2018). Adhering to these requirements for all power converters supplying distributed energy resources–such as wind turbines, photovoltaic inverters, microturbines, and batteries–is critical to construct a new energy network. Consequently, reliability and security in power electronics with energy sources continue to gain momentum as research areas.

Safety standards and guidelines for grid-connected converters, equipment, and systems that integrate with or exchange power with the grid have emerged globally since the advent of renewable and distributed energy resources. Standards of this kind cover Australia, Japan, Europe, North America, and China. The installation of renewable generators in the grid has copied the same trend. Specific periods, set points, and metrics exist for grid-connected and renewable generators.

8.3 Maintenance strategies and predictive diagnostics

Achieving a feasible energy transition to mitigate climate change requires accelerating the deployment of energy-generation technologies that do not rely on fossil fuels. Correspondingly, the planning and operation of future energy systems will require large-scale integration of renewable energy sources such as solar photovoltaic (PV) systems, wind turbines, and marine and tidal energy converters. Integration poses significant network stability challenges, particularly for synchronous generator-based systems; and increased generation flexibility, improved operational agility, and other ancillary services (both conventional and new) that can be supplied by converter-interfaced distributed energy resources (DERs) are therefore essential. Knowledge of converter topologies and control techniques commonly used in renewable energy generation systems, energy storage systems, and hybrid energy systems is essential for both large-scale future power systems and individual renewable energy systems that must be flexible to support all system stability measures (Saleem Afridi et al., 2021).

A new era of renewable energy generation and consumption has already begun. Global energy security is becoming a top priority for an increasing number of countries. In particular, nations are becoming aware of the importance of energy security and the protection of natural resources for future generations. Power electronics plays a key role in facilitating the Energy Transition and the timely realisation of the Sustainable Development Goals. A comprehensive, perspective overview is provided, elaborating on advances in power electronics and energy converters in the domain of Renewable Energy Systems (RES) and generation. Different Renewable Energy Sources (RES) are explored, i.e., Photovoltaics (PV), Wind, and Tidal Marine Energy systems. RES configuration developments (converter circuits, control algorithms, ancillary services) are also covered. Additionally, future work is needed further to enhance the impact of RES on the Energy Transition.

9. Emerging Topics and Future Perspectives

Power electronics continues to evolve and adapt to meet the increasing demand for renewable energy. Prospects for these technologies highlight three interesting areas. Hybrid renewable generation systems comprise combinations of two or more sources. While investigating the most suitable configuration, fundamental attending criteria include topology, power-storage interface, equipment size, weight, efficiency, economy, functionality, reliability, and lifetime (SARKAR & Odyuo, 2019). The Internet of Things connects many devices and machines (Almasoudi, 2018), creating opportunities and challenges. Processing data at the edge enhances response speed and efficiency while increasing complexity. Cyberspace and physical systems also interact, posing challenges and necessitating safety considerations, thereby making cyber-physical security an emerging topic. Sustainability builds on ecological feeding or neutral consumption: material choices, production flow, and end-of-life recycling all impact sustainability.

9.1 Optimum topology selection for hybrid renewable systems

Selecting the optimal topology for hybrid renewable systems is crucial for efficient energy production (Ahangari Hassas & Pourhossein, 2017). Various topologies have been studied for integrating solar, wind, and fuel cell systems, thereby improving stability and reducing power fluctuations. The optimal design of grid-connected hybrid systems enhances distributed energy production. Topologies of high-quality rectifiers and power-factor pre-regulators are important in managing system harmonics and ensuring power quality. Effective system design considers multiple input sources and their integration to ensure reliable renewable energy generation.

Integrating different energy sources into a hybrid renewable energy system (HRES) improves overall performance, making the optimal topology selection process more complex. HRESs can include solar photovoltaics (PV), wind turbines, fuel cells, batteries, hydropower, and biogas plants, depending on local resource availability. For standalone applications, considerations may include load type, load-hour distribution, and desired quality of service, whereas for hybrid microgrids, the focus is usually on cost and environmental impact. In both cases, fluctuating renewable generation and system capacity are important factors. As a result, stringent criteria regarding efficiency, reliability, and return on investment, alongside secondary criteria such as footprint, weight, and functionality, control strategy compatibility, space availability, grid synchronisation, and energy-flow purpose, must also be addressed.

9.2. Internet-of-Things integration and edge computing in power electronics

Power systems have evolved tremendously over the last decade due to the rapid growth of renewable energy sources, the advent of electric vehicles, and the proliferation of electrical power generation, conversion, and conditioning devices. Thus, it is necessary to develop smart power systems that offer distributed intelligence, enable information sharing among devices, and provide control at points close to power generation sources or energy-consuming devices. Smart interconnected systems cannot be implemented without small, low-cost processors embedded in them (Javier Ferrández-Pastor et al., 2019). On the other hand, the Internet of Things (IoT) concept was developed to reduce the information density of control signals and to sense areas where traditional data cannot reach, at low cost. It is possible to control different energy sources without connecting or interlinking with large power systems, yet still achieve a considerable power function using IoT and the concept of control-at-the-edge.

9.3 Sustainability and recyclability considerations

Enhancing the sustainability and recyclability of power electronics components and systems could lead to more environmentally friendly product designs. Interest in sustainability has recently spurred research on design for recycling (DfR) and sustainability in the photovoltaic (PV) sector, particularly on DfR of PV modules and target recycling/recovery rates (Kim et al., 2019). Sustainability also influences component and circuit topology selection, manufacturing, and repair strategies (Almasoudi, 2018). Current sustainability trends encourage further exploration of the sustainability and recyclability of power converters, energy storage, and other auxiliary power electronic components associated with PV, wind, and grid-support systems.

Societal and industrial interest in sustainability has attracted substantial research attention over the past few decades, with initiatives often addressing interactions among the economy, environment, and society. Ambitious international efforts to establish universal sustainability indicators and incorporate sustainability into science, technology, and business decision-making have also emerged. These developments have spurred attempts to design and quantify sustainable systems and devices, including photovoltaic systems.

10. Conclusions

The drive to electrify all sectors demands urgent and sustained action. Enormous changes in the generation and consumption of electrical energy must occur to accommodate the use of trees, plants, wind, and sunlight as primary energy sources for transportation, heating, and industrial processes. Renewable energy sources account for nearly 30% of global electricity production (Almasoudi, 2018). Energy from solar photovoltaics is currently the fastest-growing and is likely to continue growing rapidly. This provides an opportunity to substantially increase demand for renewable energy, thereby securing and sustaining jobs and growth. Energy policy, technology, and partnership activities are aimed at the architecture and practices necessary for sustainable resource supply and success in energy production and use. Many of the critical advances involve integrating materials, circuits, converters, batteries, hydrogen, ammonia, and natural drafts. The strategy presented herein focuses on half-century developments in medium-voltage and power-electronic converters.

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