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Modular Converters in Renewable Energy Systems: A Review

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Abstract

This extensive review paper carefully examines the function of modular converters in renewable energy systems. In light of the rapidly evolving energy landscape, modular converters have emerged as crucial elements for achieving efficient and adaptable power conversion. In this essay, we cover the benefits and drawbacks of modular converters, as well as the various applications for them in various renewable energy systems and the most recent advancements in this area. In addition, we investigate the effects of modular converters on grid integration, energy storage, and the general sustainability of renewable energy sources. This review paper synthesizes existing literature and highlights key points to provide insightful information on the current situation and potential future of modular converters in renewable energy systems.

Keywords: *Modular converters, power conversion, renewable energy, grid integration, sustainability, energy storage,*

I. INTRODUCTION

Global demand for electricity has increased significantly in recent decades. Many nations are using environmentally friendly power generation, such as solar photovoltaic (PV) energy and wind energy, to meet these demands. The advantages of renewable energy sources (RES), such as their affordability, energy effectiveness, and sustainability, make them the preferred choice. The enormous growth of RES is pulling the modern power grid away from the traditional synchronous generator (SG) rotational generator-dominated power system and toward the inverter-dominated power system.

Applications for VI-based inverters and their control strategy include flexible loads, modular multilevel converter (MMC)-based direct current (DC) system electronic appliances, static synchronous compensator (STATCOM), virtual inertia machine (VIM), and STATCOM. These applications include flexible loads to support frequency stabilities, high voltage direct current (HVDC) transmission energy storage systems (ESS), microgrid electric vehicle (EV) chargers, STATCOM, and grid-connected wind and solar power plants. Fig. 1 depicts how VI is used and implemented in the modern power system.

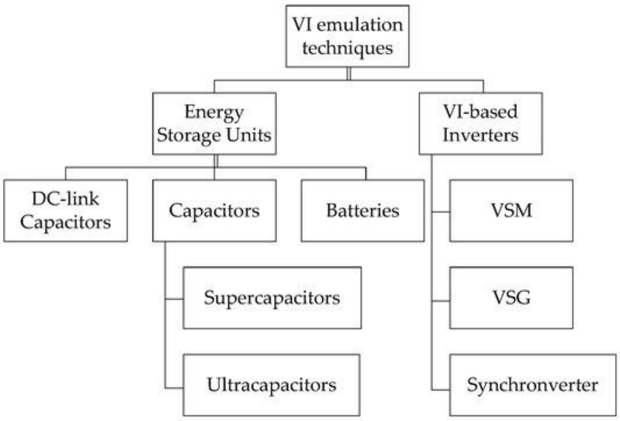

Figure 1. The implementations of VI emulation technique [1]

The development of a comprehensive network is required for the seamless integration of Photovoltaic (PV) power into the national utility grid, which is what solar-grid integration entails. This is a sizable technological advance with numerous advantages because it improves building energy balance, increases the economic viability of PV systems, lowers operational costs, and adds value for both utility companies and consumers. Solar-grid integration is now a common practice on a global scale, thanks to the growing demand for eco-friendly energy sources in contrast to the depleting supply of fossil fuels [2].

Renewable energy sources have become more and more important in the twenty-first century as a result of the growing environmental consciousness and the depletion of fossil fuel reserves. Researchers are diligently striving to foster a pollution-free environment by proposing carbon-free technologies across various sectors, including automobiles, apparel, household appliances, and other facets of energy consumption [3]. According to recent research, the majority of low- and intermediate-mass stars are born with large circumstellar disks of gas and dust. The majority of young pre-main-sequence stars with ages of less than ∼1 Myr have gaseous disks that are 100 AU in size or larger and have masses of less than ∼0.01 M. A lot of older main-sequence stars have dusty debris disks that are 100–1000 AU in size. According to recent source data, the proportion of stars with observable disks decreases from approximately ∼100% for the youngest stars to less than 10% for stars older than one Gyr [4].

Low-voltage grids are advancing steadily to provide the cutting-edge services needed in the upcoming energy scenario. Flexible power control, which enables participation in transactive energy markets and resilience to variable power demand, is one example of a crucial feature. Other features include optimal power quality, which considers power factor and balanced power absorption, and islanded operation, which responds to unfavorable localized events that disrupt the main electricity supply. Usually, hierarchical control systems, with the droop control as the top layer, are used to manage the diverse requirements. EPCs are frequently used in ac microgrids for droop control under control as voltage sources. Automatic power sharing in isolated grids is made possible by utilizing its capacity to adjust inverter voltage references as well as its ability to support grid voltage. Since their combined input controls the grid voltage, these droop-controlled Energy Power Converters (EPCs) are frequently thought of as playing a grid-forming role. The concept of "zero-level control," which includes voltage and current controllers that receive reference signals from the primary controller, is also shown in Figure 2. Numerous options are available for implementing zero-level control in this situation, including using the natural reference frame ABC with linear voltage and current regulators. Nevertheless, regulating output power presents some difficulties. These difficulties involve balancing two conflicting requirements: 1) maintaining a constant and grid-independent output power to enable precise power control, which is especially useful during grid-tied operation, and 2) maintaining grid voltage stability through the adjustment of inverter output power in keeping with droop laws, an essential consideration during islanded operation [5].

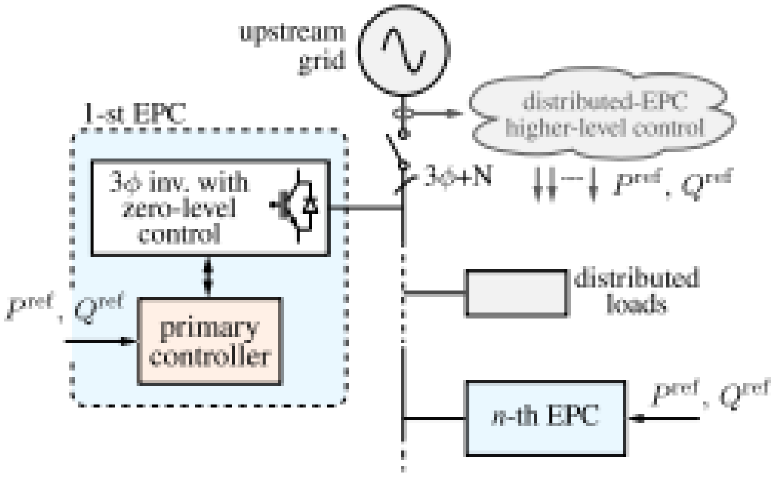

Figure 2 Islanded Microgrid with Distributed EPCs and Power Reference Acceptance

The use of voltage source converters (VSCs) for high-voltage direct current (HVDC) transmission has made it possible to connect remote renewable energy sources to extensive AC networks. Traditionally, conventional VSC-HVDC systems mainly relied on two- or three-level converters incorporating series-connected Insulated Gate Bipolar Transistors (IGBTs) in order to achieve both high voltage and reliable power conversion. But these converters struggled with problems like uneven distribution of high voltage among all power semiconductor devices and poor power quality. Multilevel converters, which have topologies with more than three levels, have drawn a lot of attention over the past few decades for a number of compelling reasons. They include the ability to handle high-voltage operations without the need for switching devices connected in series, a decrease in common-mode voltages, improved power quality and efficiency, and the built-in redundancy. The modular multilevel converter (MMC), which Marquardt first proposed, has maintained its position as the top possibility for HVDC systems among these multilevel converter designs. It is currently being actively used in HVDC projects of a commercial scale.

MMC provides higher modularity and scalability than other topologies, transformer-free operation, a decrease in switching power losses, and fewer output filtering requirements [6].

II. LITERATURE REVIEW

Maximum power point tracking (MPPT) for photovoltaic (PV) power systems was thoroughly reviewed by **Ishaque and Salam [7]** in their study. The Perturb and Observe, Incremental Conductance, and Hill Climbing strategies were the main topics of their investigation, along with discussions of their various adaptations and adaptive iterations. They also explored the more recent MPPT techniques for PV power system applications that use evolutionary algorithms, artificial neural networks, and fuzzy logic control. Despite covering MPPT in great detail under normal (uniform) insolation, the paper's emphasis will be on applications of the aforementioned techniques in partial shading. This review work is anticipated to be a useful tool for PV professionals to stay current on this field's most recent advancements as well as for new researchers to get started on MPPT.

Al-Shahri, et. al. [8] The use of renewable energy has a number of advantages, including reduced costs for power transmission and a reduction in the effects of global warming. The investigation of operational parameters that have an impact as well as the optimization of the solar energy system are crucial components to increasing power conversion efficiency. The various optimization methods have been used to improve solar energy application performance. How to create the best strategies, however, given the intermittent nature of solar energy resources, is one of the most crucial problems that needs to be researched. Additionally, this study introduces the newest intelligent optimization techniques used in solar energy systems, along with their functions, limitations, research gaps, and contributions. According to this review, the main purposes of optimization techniques are to increase system reliability while reducing emissions, investment, and operating and maintenance costs. A brief discussion of the various challenges and issues related to solar energy optimization is also included in their article. The review offers some useful future directions for developing a reliable and efficient solar PV system.

Gržanić, M., et. al. [9] Consumers are changing from passive participants to active contributors within power systems that are characterized by a significant share of renewable energy sources as a result of the emergence of on-site production and adaptable consumption. The implementation of real-time pricing, easy and quick supplier switching, the encouragement of aggregation opportunities, the facilitation of local energy production and exchange, and the offering of ancillary services are just a few of the opportunities brought about by this prosumer-centric paradigm. The paper conducts a thorough analysis of the variety of options available to prosumers, allowing them to realize their full potential. It starts this investigation by carefully examining potential scenarios and models for a specific end-user who has made the decision to invest in flexible electronics, electric vehicles, and photovoltaic (PV) technology. The possibility of meeting the needs of both transmission and distribution system operators is also discussed in the paper. It delves into the complex issues of coordination when utilizing prosumers or resources connected to the distribution network for flexibility services. For each of the scenarios under consideration—individual prosumer flexibility, the combination of several flexible prosumers, and energy communities with the possibility of peer-to-peer trading—the paper provides straightforward models and results. The paper carefully examines and discusses these scenarios.

S. Rivera, et. al. [10] An innovative design for a photovoltaic energy conversion system for large-scale power plants is presented in this paper. hooked up to the grid. Utilizing these cells, the grid-tied converter is based on a modular multilevel converter with voltage source H-bridge cells. The proposed converter is more efficient and capable of concentrating a multi-megawatt PV plant with distributed string MPPT tracking capability, high power quality, and compared to conventional two-level voltage source converters. The main difficulty is addressing any potential power imbalances between the converter's three phases as well as among the various cells in one phase. In their paper, they examine the control strategy to address these imbalances. The simulation results for an eight-level MMC with 18 H-bridge cells and PV strings are presented to support the proposed topology and control method.

M. Barnes, et. al. [11] In contemporary smart grids, direct current (dc) power networks—either at high voltage or at medium voltage—are used more frequently. This is a result of the flexible control offered by direct current (dc) and its capacity to transmit and distribute power in situations where alternating current (ac) networks are either unable to do so or do so at a lower cost. The history of high-voltage direct current (HVDC) transmission is outlined in this paper, from the earliest Thury systems to current multiterminal voltage-source converter systems and ultrahigh-voltage dc systems. We also discuss the modeling requirements and the operation of both current-source and voltage-source systems. In-depth reading is made possible by the paper's extensive references and snapshot of the state of the art in HVDC. Highlighted are significant developments from the past 20 years. Drivers in economics and policy, as well as problems with multiterminal operation and dc protection, are discussed. Incorporating HVDC into smart grids will be impacted due to this.

III. ROLE OF MODULAR CONVERTERS

The modular multilevel converter (MMC) was initially proposed as a new member of the multilevel converter family. In San Francisco's 2010 Trans Bay project, Siemens used this ground-breaking converter for the first time on a commercial scale. Since its first application, the MMC has attracted a lot of interest and development because of its promising advantages, which include outstanding output performance, high modularity, simple scalability, and reduced voltage and current rating requirements for power switches. It is still clear that the MMC has advantages over traditional two-level and multilevel converters. The MMC excels particularly well in a variety of medium and high-voltage power conversion applications, such as high-voltage direct current (HVDC) transmission systems, renewable energy setups, static synchronous compensators (STATCOM), battery storage systems (BESS), medium-voltage motor drives, power interface applications, as well as (hybrid) electric vehicle chargers and drivetrains [12].

A. Advantages

Customized System Sizing: Modular converters allow for the design of customized power systems by adding or removing converter modules as needed. This adaptability is especially valuable in renewable energy systems where power generation can vary.

Optimized Energy Harvesting: Scalability enables better utilization of available energy sources. In solar systems, for example, additional converter modules can be added to harness more sunlight in response to increased energy demands.

Redundancy and Reliability: Modular converters can offer redundancy, which enhances system reliability. If one module fails, others can continue operating, reducing downtime and ensuring continuous power supply.

Ease of Maintenance: The modular design simplifies maintenance and troubleshooting. Technicians can isolate and replace faulty modules without affecting the entire system, reducing maintenance costs and downtime.

Future Expansion: Modular converters facilitate future system expansion. As energy needs grow, additional modules can be seamlessly integrated, extending the lifespan and capabilities of the energy system.

B. Disadvantage

Complex System Integration: It can be challenging to integrate various converter modules into a single system. It necessitates careful engineering because it requires meticulous coordination of the operation of each module and the assurance of compatibility with other system components.

Specialized Knowledge: To work with modular converters, those in charge of installation and maintenance may need advanced training. Increased labor costs and a need for technicians with higher levels of training may result from this.

Higher Initial Costs: When compared to non-modular converter solutions, multiple converter modules may incur higher initial costs due to the procurement, installation, and control system requirements.

Challenges with interconnection: Especially in large-scale installations, ensuring effective interconnection between modules can be difficult. Power losses and decreased system efficiency can result from poorly designed interconnections.

Space requirements and physical footprint: Modular converters may have a larger installation footprint than non-modular alternatives, making them less suitable for all locations.

Component Reliability: The reliability of individual converter modules can vary, and the failure of a single module can impact overall system performance. Quality control and component selection are critical considerations.

IV. CHALLENGES IN SOLAR POWER DISTRIBUTION

Over the last decade, the cost of producing electricity from solar power has reduced substantially, yet the usage of solar power has not increased proportionately. This Note analyses the constraints in power transmission and distribution, including infrastructural constraints and demand-side factors. It goes on to propose strategies for policy makers to increase the diffusion of solar power. Solar power distribution faces several challenges, including the intermittent nature of solar energy generation, which is heavily influenced by weather conditions and daylight hours. Efficiently storing excess solar energy for use during periods of low or no sunlight presents another significant hurdle. Integrating solar power into existing electrical grids often requires costly infrastructure upgrades and advanced grid management systems. Moreover, aligning the variable solar output with fluctuating energy demand demands precise load forecasting and effective demand management. Ensuring equitable access to solar energy across diverse communities and addressing potential environmental impacts further complicate the distribution process. Additionally, staying at the forefront of evolving solar technology and seamlessly integrating innovations into existing systems is an ongoing challenge in the field of solar power distribution.

Intermittent Energy Generation: Solar power generation is highly dependent on weather conditions and the time of day, resulting in intermittent energy production. This makes it challenging to ensure a consistent and reliable power supply.

Energy Transmission and Efficiency: When solar energy is transported over great distances, from isolated solar farms to populated areas, there may be energy losses along the way. To ensure the highest level of solar power distribution efficiency, it is essential to reduce these losses.

Energy Storage and Grid Integration: It is essential to store excess solar energy efficiently so that it can be used when there is little or no sunlight. It may be difficult to integrate these storage systems with the grid due to both technical and financial issues.

Variable Load Demand: Balancing the varying energy demands of consumers with the fluctuating solar generation output is a challenging task. The management of this variability requires sophisticated grid management techniques and advanced load forecasting.

V. CONCLUSION

This review emphasizes how crucially important modular converters are in the context of renewable energy systems. These converters are necessary for efficient power conversion, seamless grid integration, and effective energy storage as the focus of the world shifts to renewable energy sources. Based on their advantages, which include adaptability and scalability, renewable resources can be used in the most effective manners. Yet there are still problems that need to be solved, such as the high cost and complex design. For modular converters to reach their full potential and enable dependable and effective renewable energy systems, it is crucial to successfully address these issues. Positive developments in the field of modular converter technology, particularly in the areas of HVDC transmission and energy storage, show great promise. Modular converters are in a prime position to be the driving force behind the development of a sustainable, reliable, and eco-friendly energy future due to ongoing innovation by scientists and engineers. This review not only provides insightful information, but it also lays the foundation for future research in this dynamic area.

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