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A Review on Full-Scale Back-to-Back Converter Topologies for PMSG-Based Wind Energy Conversion Systems

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ABSTRACT

This article gives a general review of converter topologies used in Type 4 wind energy conversion systems with permanent magnet synchronous generators (PMSG). Type 4 systems based on full-scale back-to-back converters can be operated to maximize wind turbine performance during variable wind speed, facilitate grid decoupling and decrease maintenance. The paper compares different converter setups, such as diode rectifiers, six-switch converters, Vienna rectifiers, Z-source converters, nine-switch converters, multilevel converters and matrix converters and describes their operation principles, advantages and drawbacks. Every topology has been studied with respect to efficiency, reliability, power quality, cost, and applicability to renewable energy systems. Results underscore the pivotal role played by power electronics to bring new generations of wind energy devices to market and provide guidance for choosing the optimal converter topology to deliver dependable, efficient, and economically attractive energy conversion in contemporary wind energy conversion schemes.

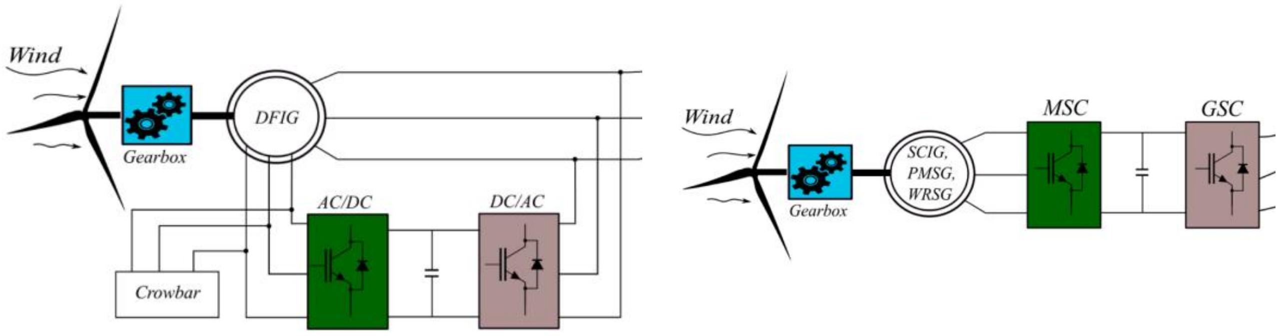
Keywords: Back-to-back Converters, Diode Rectifiers, Full Converters, Grid integration, Matrix Converters, Multilevel Converters, Nine-Switch Converters, PMSG, Six-Switch Converters, Type 4, Vienna Rectifiers, Wind Turbines, Z-Source Converters.

1. Introduction

Wind energy conversion systems are central to providing energy to the world by using the force of wind [1]. Such systems employ different generators and power electronics to produce electrical power [2][3] and variable-speed wind turbines are increasingly popular because of their high efficiency and ability to cope with wind variability. The full-rated back-to-back converter topology, often employed in Type 4 wind energy conversion systems, is one such advancement that allows for greater operational flexibility and efficiency. This article explores the different types of variable-speed wind turbine systems, with a particular focus on permanent magnet synchronous generator (PMSG)-based Type 4 systems, exploring the different full-rated back-to-back electronic converter topologies reported in the literature.

1.1 Power Converters in Variable-Speed Wind Energy Conversion Systems

Wind turbines are classified into different types according to the type of energy conversion system [3]-[5]. The two primary categories are Type 3 and Type 4 systems, shown in Fig. 1. Type 3 systems, commonly known as Doubly-Fed Induction Generators (DFIG), typically involve a wound rotor induction machine with power electronics controlling the rotor-side and grid-side converters. This configuration allows for limited speed variation, typically within ±30% of the synchronous speed, and offers several benefits, including reduced power converter ratings and improved mechanical resilience.



(a) (b)

Fig. 1 – Variable-speed energy conversion systems [(a): Type 3; (b) Type 4].

In contrast, Type 4 systems employ full-scale back-to-back frequency converters, consisting of a machine side converter (MSC) and a grid side converter (GSC). This setup decouples the generator from the grid, allowing for enhanced flexibility in speed control and operation. It enables the turbine to function at its optimal aerodynamic speed, producing a "wild" AC output from the generator that can be transformed into a grid-compatible frequency. Additionally, the full-rated converter removes the necessity for a gearbox, as the turbine can run at lower rotational speeds. The generators utilized in Type 4 systems can vary and include wound rotor synchronous machines (WRSG), permanent magnet synchronous generators (PMSG), squirrel cage induction machines (SCIG), and wound field induction machines (WFIM).

1.2 Generator Options in Type 4 Wind Energy Conversion Systems

The flexibility in design and operation of Type 4 systems arises from the variety of generator types available [1]-[5]. These include:

- Wound Rotor Synchronous Generator (WRSG): These generators are actually assimilable to the traditional synchronous machines commonly found in hydroelectric plants. They feature a field winding that allows for the regulation of the excitation current. This improves efficiency across a wide range of wind speeds. However, these machines tend to be larger and require more maintenance compared to other types.
- Permanent Magnet Synchronous Generator (PMSG): These generators are becoming increasingly popular in contemporary wind energy systems due to their high efficiency, compact design, and potential elimination of a gearbox. They utilize permanent magnets in the rotor, which removes the need for reactive power in the rotor circuit and boosts overall efficiency. PMSGs operate effectively over a wide range of speeds and are especially suitable for variable-speed wind turbines. Fig. 2 illustrates the Type 4 wind energy conversion system that utilizes PMSG.

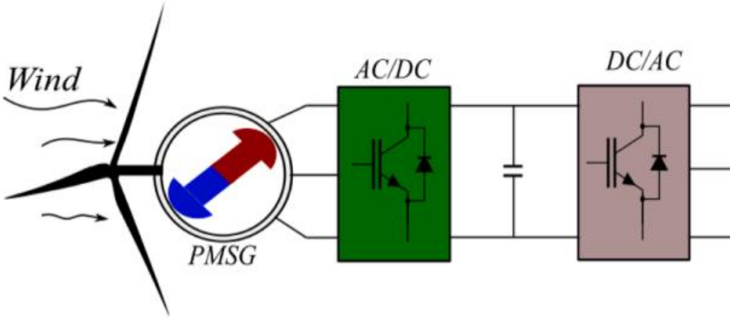


Fig. 2 – PMSG-based Type-4 wind energy conversion system.

- Squirrel Cage Induction Generator (SCIG): While SCIGs are economical, they possess reduced efficiency in comparison to PMSGs and WRSGs. Their performance is more influenced by variations in wind speed, and controlling speed is more intricate than with synchronous machines. Moreover, SCIGs encounter increased power losses at reduced rotational speeds.
- Wound Field Induction Machine (WFIM): WFIMs offer a balance between SCIGs and WRSGs. They provide a certain degree of speed regulation and deliver greater efficiency compared to SCIGs. Nevertheless, they remain less efficient than PMSG and demand more upkeep compared to wound-field synchronous machines.

1.3 Advantages and Drawbacks of PMSG

Several advantages and drawbacks of PMSG can be derived [6]-[8]:

Advantages of PMSGs:

1. High Efficiency and Reliability: The use of magnets in the rotor eliminates the requirement for additional power input, improving overall efficiency. This results in a system marked by reduced losses and enhanced reliability.
2. No Gearbox Needed: Systems based on PMSG eliminate the need for a gearbox, simplifying mechanical design and lowering maintenance requirements. Gearboxes frequently face failures, leading to energy loss in wind turbines; thus, their removal enhances both the efficiency and lifespan of the system.
3. Compact and Lightweight: Due to the incorporation of permanent magnets and multi-pole structures, PMSGs are capable of attaining high power densities. This leads to a more compact configuration relative to other types of generators, aiding in reducing the total dimensions and mass of the wind turbine.
4. Grid Decoupling: PMSGs are adequate for full-scale converters that separate the generator from the grid. This feature enables improved management of power output and enhances energy extraction from different wind speeds, guaranteeing effective performance over a wide array of conditions.

Drawbacks of PMSGs:

1. Cost of Permanent Magnets: The cost of the permanent magnets, particularly those manufactured with rare earth elements, presents a considerable obstacle for large-scale wind turbines. Despite the greater efficiency of PMSGs, their elevated upfront expenses might limit their application in specific scenarios.
2. Design Challenges: Although the multi-pole configuration of PMSGs offers enhanced power densities, it may also lead to issues such as harmonic distortion and elevated Joule losses in the stator winding. Such losses may reduce overall efficiency and accelerate wear on the system.
3. Thermal Management: PMSGs generate less heat than other generator types because of their greater efficiency. Nonetheless, efficient thermal management is crucial in high-power applications to avoid overheating, as this could jeopardize the machine's lifespan and performance.

1.4 Technical Details of PMSG-Based Type 4 Wind Energy Conversion Systems

a) Control Strategies and MPPT

An essential characteristic of Type 4 systems is their ability to optimize energy retrieval from the wind. This is typically achieved by using Maximum Power Point Tracking (MPPT) algorithms, which modify the generator speed to match the best aerodynamic conditions for maximizing power output. In Type 4 systems, MPPT is performed through the generator-side converter (MSC), which controls the generator's speed and guarantees that the wind turbine functions at optimal efficiency.

The grid-side converter (GSC) is responsible for controlling the DC bus voltage and monitoring the reactive power delivered to the grid. The GSC enables consistent performance by isolating the generator from the grid, adjusting for changes in wind speed, and ensuring the generated power aligns with the grid's voltage and frequency.

b) Power Electronics and Converter Topologies

Power converters play a crucial role in Type 4 systems, as they enable the transformation of the generator's variable-frequency output into a grid-compatible frequency. Full-scale back-to-back converters, comprising an AC/DC rectifier and a DC/AC inverter, are frequently used in systems based on PMSG. These converters provide effective and adaptable management of power output, facilitating integration with the grid.

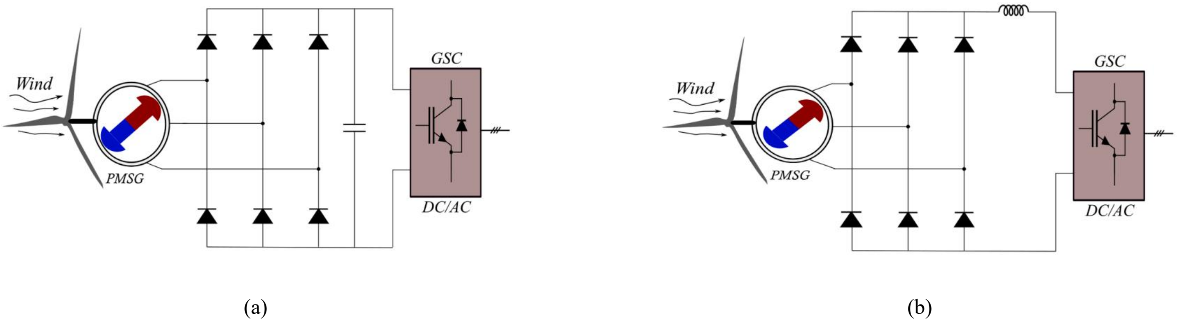
c) Efficiency and Reliability

The use of full-rated converters and PMSGs in Type 4 systems leads to increased efficiency and reduced mechanical wear, primarily because there is no gearbox involved. The efficiency of the system is enhanced by employing multi-pole PMSGs, capable of generating power at reduced speeds and in diverse wind conditions. Additionally, the modularity and scalability of power electronics improve the overall reliability and strength of the system.

2. Converters with Diode Bridge Rectifier as MSC

Diode bridge rectifiers are commonly used as AC-DC converters due to their simplicity and low cost [9]-[11]. A single-phase diode bridge rectifier is an affordable solution for converting AC to DC, but it operates efficiently only at high wind speeds. At lower wind speeds, the output DC voltage is insufficient, falling below the grid voltage, which reduces performance. Therefore, full three-phase diode bridges are used. In such configurations, the

DC-link component can either be a capacitor (in voltage source converters, VSC) or an inductance (in current source converters, CSC), as depicted in Fig. 3(a) and 3(b), respectively.



(a) (b)

Fig. 3 – Diode bridge rectifier [(a): VSC; (b) CSC].

Despite their cost-effectiveness, diode bridge rectifiers have notable limitations. These include an inability to achieve maximum power extraction from the wind and lack of control over the wind turbine's dynamics and energy quality. To address these shortcomings, a cascaded DC-DC boost converter with a diode rectifier can be introduced, as shown in Fig. 4. The DC-DC boost converter enhances system performance by enabling MPPT, allowing for better control over the DC-link voltage [12]. This provides an additional advantage by ensuring the voltage remains higher than the grid voltage amplitude, thus improving control flexibility for the GSC.

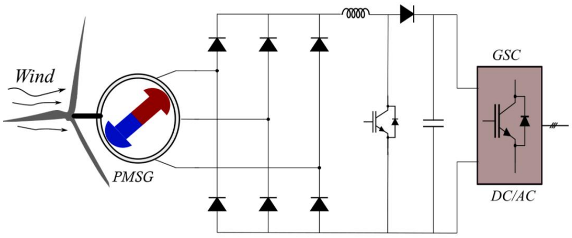


Fig. 4 – Diode bridge rectifier with chopper.

However, even with the inclusion of the cascaded boost converter, the system still faces some challenges. Specifically, controlling a variable-speed PMSG with a diode rectifier and DC chopper leads to the same issues as the basic diode rectifier setup. These issues include limited control over the generator's power factor, which can lower efficiency, as well as increased harmonic distortion in the generator windings.

3. Six-Switch Controlled Converters

The six-switch converter, commonly used as the main topology for the MSC and GSC in wind power applications [13][14], operates as either a controlled rectifier or a voltage inverter, as illustrated in Fig. 5. This topology consists of two Voltage Source Inverter with Pulse Width Modulation (VSI-PWM) converters, linked by a storage capacitor. This arrangement allows for the connection of the generator to the electrical grid and enables control over the electrical power delivered to the grid, facilitating MPPT or Active Power Point Tracking (APPT).

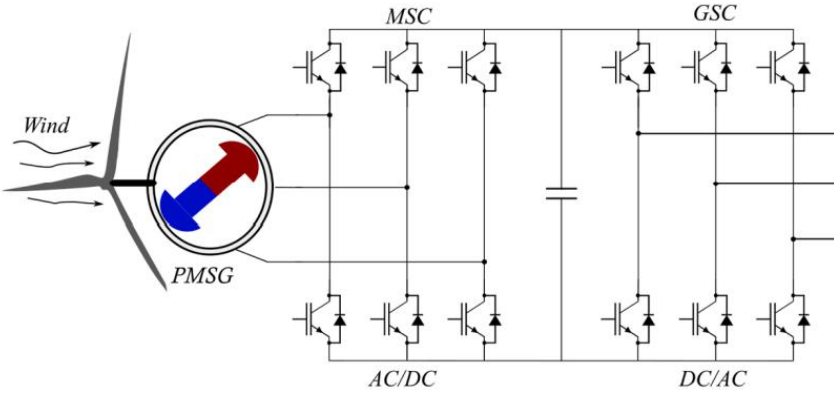


Fig. 5 – Six-switch controlled converter.

Unlike diode rectifiers, controlled rectifiers in the six-switch converter topology can adjust the DC voltage supplied to the grid by modifying the phase and amplitude of the alternating current produced by the wind turbine. This control is achieved using power switches such as thyristors, IGBTs, or MOSFETs. When integrated with a PMSG, this converter topology provides the capability to regulate critical parameters such as the generator's speed, power factor, and electromagnetic torque, all while minimizing current harmonic distortion.

The inclusion of a DC bus in the system provides a clear separation between the generator and the grid, helping to prevent transients on the generator side from affecting the grid [15]. To ensure the optimal performance of the grid-side converter, it is important to maintain a DC bus voltage that is higher than the grid peak line-to-line voltage.

4. Converters with Vienna Rectifier as MSC

The Vienna rectifier, as shown in Fig. 6, is an innovative three-level power converter topology that is gaining traction in wind power applications [16][17]. This topology is used as the MSC in permanent magnet wind turbine systems, offering several advantages over traditional two-level rectifiers, such as VSI-PWM rectifiers. One key benefit is that the Vienna rectifier requires fewer power switches, which reduces both manufacturing and maintenance costs.

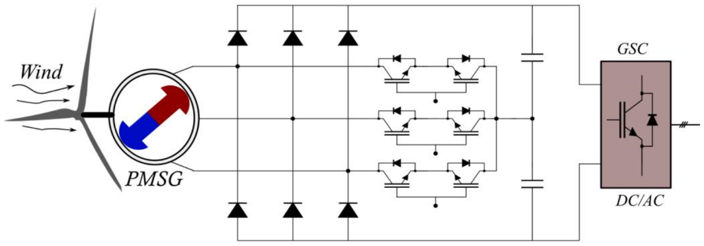


Fig. 6 – Vienna rectifier.

In addition to cost savings, the Vienna rectifier improves power quality by generating a multilevel voltage waveform, resulting in lower Total Harmonic Distortion (THD) compared to two-level rectifiers. This reduction in harmonic distortion leads to improved grid current quality and minimizes switching losses [18]. The Vienna rectifier also supports bidirectional power flow, allowing efficient control of the power exchange between the generator and the grid.

The topology offers enhanced fault tolerance and reliability due to its redundant power paths. If a switch fails, the rectifier can continue functioning with the remaining switches, ensuring system availability and reducing downtime [19]. These features make the Vienna rectifier a highly reliable and cost-effective solution for wind power systems.

Additionally, the Vienna rectifier minimizes switching and conduction losses, contributing to a longer system lifespan and better overall reliability. It enables precise control of both active and reactive power, which aids in managing power flow within electrical grids. By generating a sinusoidal current waveform that complies with grid standards, the Vienna rectifier ensures smooth integration with power networks and helps mitigate harmonics. The high-frequency operation of the Vienna rectifier further boosts system efficiency. With advancements in power semiconductors and controllers, this topology has become an effective solution for energy conversion and management in modern electrical grids.

5. Z-Source Converters

Z-source inverters, illustrated in Fig. 7, represent a family of power converters designed to facilitate energy conversion between two voltage sources [20][21]. Unlike traditional inverters that rely on full-bridge topologies to link the input source to the load, Z-source inverters utilize a unique impedance network. This network, arranged in a "Z" configuration, introduces an additional degree of freedom in the energy conversion process, making these inverters highly versatile.

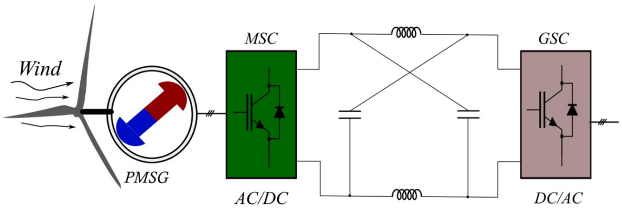


Fig. 7 – Z-source converter.

The core of the Z-source inverter topology comprises an inductor and two capacitors configured in a specific layout. The inductor is connected in series with the DC input voltage source, while the two capacitors are arranged in parallel with each other and in series with the load. This impedance network interfaces with a standard inverter bridge to complete the energy conversion.

Z-source inverters offer several advantages, particularly in renewable energy systems. They can provide a boosted output voltage, making them suitable for applications where the input voltage is variable, such as wind energy systems. Additionally, these inverters demonstrate enhanced resistance to electromagnetic interference, which improves overall efficiency.

Despite these benefits, Z-source inverters have limitations. The topology is more complex and costlier than traditional inverters, and it can suffer from reduced controllability at high power levels. Stability and reliability challenges are also notable, particularly in demanding applications. To address these issues, advanced control strategies are often required, especially for applications in wind energy conversion systems.

6. Nine-Switch Controlled AC/AC Converter

The nine-switch inverter topology, shown in Fig. 8, offers a more economical option compared to traditional back-to-back converters by minimizing the number of power switches needed [22]. In contrast to standard setups that utilize twelve switches across two distinct bridges, the nine-switch converter combines the roles of these bridges into one unit with just nine switches. This simplification leads to energy savings and reduced manufacturing expenses.

This topology features sinusoidal inputs and outputs, as well as a unity input power factor, making it particularly suitable for applications where cost and efficiency are critical. However, despite its reduced switch count, the nine-switch inverter does not reduce the total switching frequency. Its overall switching count remains comparable to that of a twelve-switch system when operated at similar frequencies.

Additionally, modulation techniques such as PWM and vector PWM do not provide a significant boost to the inverter's efficiency. Nonetheless, the cost advantages offered by the nine-switch topology make it an attractive choice for applications prioritizing economic efficiency over advanced operational capabilities [23][24].

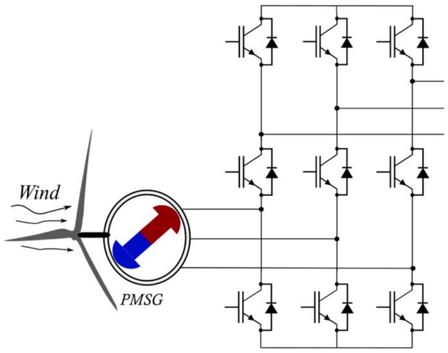


Fig. 8 – Nine-switch controlled converter.

7. Multilevel Converters

Multilevel converters represent a sophisticated technology for producing multi-level output voltages, which reduces the need for bulky output filters. They are especially suitable for high-power and large-scale wind energy applications [25]-[28]. The most prevalent multilevel converter topologies consist of the Neutral-Point-Clamped (NPC) converter (Fig. 9), the Flying Capacitor (FC) converter (Fig. 10), and the H-Bridge Modular Multilevel Converter (HB-MMC) (Fig. 11).

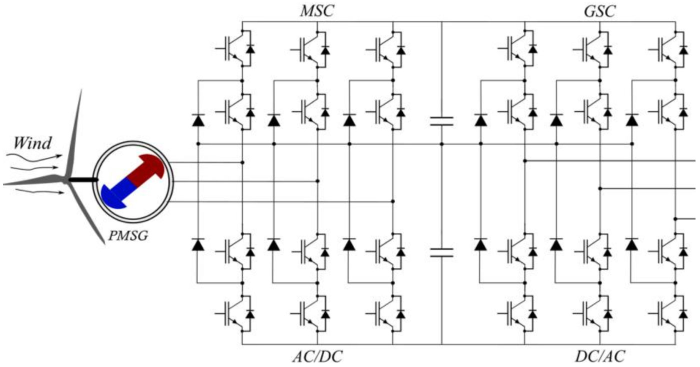


Fig. 9 – NPC converter.

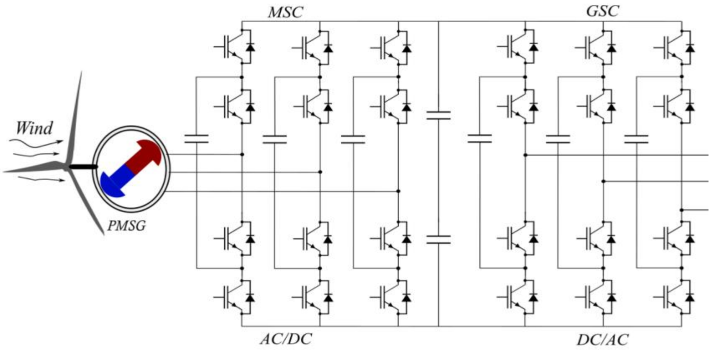


Fig. 10 – FC converter.

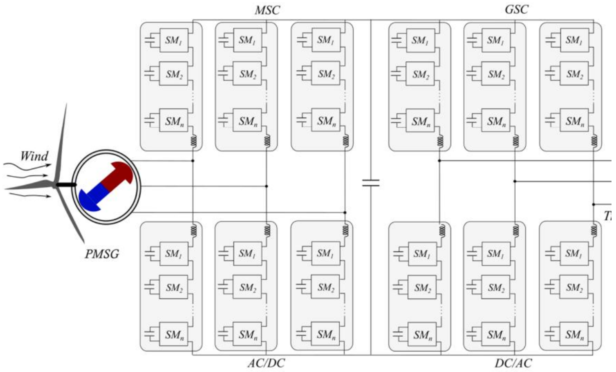


Fig. 11 – HB-MMC.

The standout topology within this category is the Modular Multilevel Converter (MMC), which has garnered significant research interest due to its ability to meet high-power and high-voltage demands in various industrial settings [29]-[32]. MMCs operate at elevated voltage levels without relying on line frequency transformers, instead using numerous half-bridge converter submodules. This modular approach improves reliability by incorporating redundancy and significantly lowers the average switching frequency, which helps maintain high energy quality. Modular Multilevel Converters (MMCs) are becoming more common in applications like medium-voltage drives, high-voltage direct current (HVDC) transmission, and flexible power transmission systems.

The advantages of multilevel converters include:

- Modular structure and fault tolerance.
- Increased reliability and reduced switch stress.
- Quasi-sinusoidal output waveforms, which reduce harmonics.
- High efficiency, even at high voltage levels.

Despite these benefits, multilevel converters come with challenges, such as complex control strategies and the need for extensive measurements to maintain system stability.

Individual submodules (SM) within MMCs can be implemented using either a half-bridge configuration, which includes two Insulated Gate Bipolar Transistors (IGBTs) and a DC-link capacitor, or an H-bridge configuration, which uses four IGBTs. The modular design enables scalability, but the overall cost depends on factors like the power rating, voltage level, number of submodules, type of semiconductor devices, and control features. Advanced features and customizations, along with manufacturer reputation and regional factors, can further influence the cost.

Multilevel converters' unique combination of efficiency, modularity, and scalability makes them a promising solution for modern high-power wind energy systems.

8. Matrix AC/AC Converters

Matrix converters (MCs), illustrated in Fig. 12, are an innovative alternative to traditional back-to-back converters in wind energy conversion systems. A key advantage is the elimination of a DC-link capacitor, resulting in reduced system size, cost, and complexity. These converters provide direct AC/AC conversion, enabling simultaneous control of parameters on both the generator and grid sides [33][34]. This configuration is associated with high reliability and lower harmonic distortion in the output current.

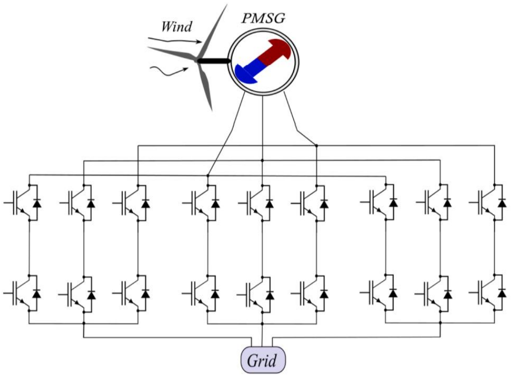


Fig. 12 – Matrix converter.

Matrix converters offer several advantages [35], including high power density, reduced size and weight, and improved efficiency compared to traditional AC/AC converters with intermediate DC links. They enable direct control of output frequency and voltage magnitude without requiring additional modulation techniques, contributing to streamlined operation. Furthermore, matrix converters eliminate the need for energy storage components like DC-link capacitors, reducing system cost and complexity. They also provide simultaneous control of generator- and grid-side parameters, ensuring reliable operation and lower harmonic distortion, which enhances power quality and integration into electrical grids.

However, MCs have limitations [36][37]. They require advanced control algorithms to manage the switching of bidirectional switches effectively, which must handle both positive and negative voltage and current. Additionally, MCs typically deliver a lower output voltage than traditional AC-to-AC converters due to their voltage gain being less than one, inherently operating in buck mode [38].

Several variants of matrix converters exist:

a) Direct Matrix Converter (DMC):

DMCs omit energy storage components, leading to greater energy efficiency and reduced switching losses [39]-[41]. However, they have a high level of control complexity, particularly in variable wind conditions. DMCs also produce substantial harmonic distortion in the output current, necessitating advanced filtering solutions [42].

b) Indirect Matrix Converter (IMC):

IMCs incorporate energy storage elements, which facilitate smoother power regulation in variable wind scenarios [43]. While this makes IMCs suitable for certain applications, the energy storage elements introduce minor efficiency losses.

c) Indirect Matrix Converter with Unity Power Factor (IMC-UPF):

IMC-UPF enhances power quality by achieving unity power factor, minimizing current distortion and improving grid integration [44]. However, achieving this level of performance requires sophisticated control strategies [45].

Efficient matrix converter operation depends on advanced control strategies, including:

1. Space Vector Modulation (SVM): Reduces harmonic distortion in output currents.
2. Direct Duty Ratio Control (DDRC): Simplifies implementation.
3. Predictive Control: Optimizes performance by considering nonlinearities and constraints.
4. Hysteresis Control: Offers simple and straightforward regulation.
5. Space Vector Hysteresis Control (SVHC): Combines the benefits of SVM and hysteresis for enhanced performance.
6. Model Predictive Control (MPC): Uses advanced optimization to address system dynamics and achieve specific objectives.

The choice of control strategy is highly application-dependent and should align with the desired performance outcomes and operational constraints. MCs represent a compelling solution for AC/AC energy conversion, balancing compactness, reliability, and efficiency while addressing the complexities of advanced control and harmonics management [46].

9. Conclusions

The development and optimization of converter topologies play a vital role in enhancing the performance and efficiency of Type 4 wind energy conversion systems. Among the analyzed configurations, diode rectifiers are cost-effective but limited by power quality issues, while six-switch converters dominate due to their versatility and control capabilities. Vienna rectifiers and multilevel converters stand out for their superior power quality and efficiency, making them suitable for high-power applications. Z-source converters provide flexibility with voltage boosting but face challenges in cost and complexity. Matrix converters emerge as a promising alternative, offering high power density and compactness but requiring sophisticated control algorithms. Each topology presents unique trade-offs in terms of cost, reliability, harmonic distortion, and control complexity. The selection of an appropriate converter depends on specific application requirements, including power rating, operational environment, and economic considerations. The advancements in semiconductor technology and control strategies continue to drive innovations in converter design, paving the way for more efficient and sustainable wind energy systems. These findings underscore the importance of tailored solutions to optimize energy conversion in PMSG-based wind energy conversion systems and contribute to the global shift toward renewable energy.

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