IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.021 ⁙ Peer-reviewed & Refereed journal ⁙ Vol. 14, Issue 7, July 2026

DOI: 10.17148/IJIREEICE.2026.14705

# Comparative Review of Wind Turbine Generators and Power Electronic Converters for Grid Integration

**Hedra Saleeb[1], Ahmed M. Kassem[2], Farid N. Abdelbar[3], Aml E. Rofaeel[1], Heba A. Mahmoud[1]**

Electrical Department, Faculty of Technology and Education, Sohag University, Sohag, 82524, Egypt[1]

Electrical Engineering Department, Faculty of Engineering, Sohag University, Sohag, 82524, Egypt[2]

Electrical Engineering Department, Faculty of Engineering, Assiut University, Assiut, 71516, Egypt[3]

**Abstract:** Coal-fired power plants (PPs) are one of the biggest causes of today's catastrophic climate crisis. To deal with this problem, there is a need to completely decarbonize the energy segment using zero-emission renewable energy sources (RES). Wind turbine (WT) farms are one of the fastest-growing energy solutions globally. These massive complexes consist of huge WT that harness wind energy, convert it into electricity, and send it to the utility grid (UG) for use alongside traditional energy sources. Integration of WT energy into the UG is interesting and could be a valuable solution for dealing with future energy challenges. Given the challenges faced regarding the connection between large WT farms and the UG using induction and synchronous generators (I&SGs), it is necessary to study and compare varying WT generator systems. This research analyzes and compares the connections of varying WT generators and their control using varying power electronics converters (PECs). This paper also discusses the current status of generators and PEC in WT concepts. He showed that a double-fed induction generator (DFIG) driving a variable-speed WT is more efficient compared to other generators.

**Keywords:** Renewable Energy, Wind Energy, Wind Turbines, Wind Generator System, Grid Connection.

## 1. INTRODUCTION

WTs produce electricity by using wind energy to power an electric generator. As the wind blows across the blades, it creates lift and rotates the force [1, 2]. The rotating blades rotate a shaft inside the nacelle, which enters a gearbox. The gearbox increases the rotational speed to what is suitable for the generator [3, 4]. The power output goes to a power transformer (PT), which converts electricity from the generator at about 700V to the appropriate voltage for the power collection system, usually 33kV [5, 6]. WTs have 2 types. One is an FSWT, and the other is a VSWT. The most common type of WT is an FSWT with an IG connected directly to the UG [7, 8]. However, this system has several disadvantages. The RP and hence the UG voltage level cannot be controlled [9, 10]. Most of the disadvantages of FSWTs are avoided when using VSWTs. These turbines improve the dynamic behavior of the turbine and reduce noise at low WS [11, 12]. However, in the case of VSWTs, a PEC is needed to make VS operation possible. WTs can be equipped with any type of 3-ph generator, such as synchronous and asynchronous generators [13, 14]. Due to its numerous benefits, the DFIG, a particular kind of asynchronous generator, is the greatest of them all [15, 16]. With DFIG technology, wind energy can be harnessed to the fullest for low wind speed (WS) by maximizing turbine speed and minimizing mechanical strains on the wind turbine during gusts. For a particular WS, the ideal turbine speed that generates the most mechanical power is proportionate to the WS [17, 18]. Another advantage of DFIG technology is the ability of PEC to generate or absorb RP, thus eliminating the need to install a CB, as in the case of a SCIG [19, 20]. Some researchers believe that DFIG should only be used for the purpose for which it was installed, i.e., providing AP only [21, 22]. The paper describes the current situation regarding generators and PECs for WTs.

The novelty and contributions of this work lie in several key aspects that contribute to advancing the integration of wind energy into UGs:

1. This study offers a comparative analysis of I&SGs used in large-scale wind farms. By systematically comparing these systems, particularly focusing on their connection and interaction with the UG.

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Impact Factor 8.021 ⁘ Peer-reviewed & Refereed journal ⁘ Vol. 14, Issue 7, July 2026
DOI: 10.17148/IJIREEICE.2026.14705

2. The study emphasizes the role of PECs in controlling and optimizing the performance of WT connected to the grid.

3. This research highlights the superior efficiency of DFIG in VSWT compared to other generator types. The study's findings contribute to ongoing discussions on the most effective generator systems for modern wind farms, particularly as renewable energy adoption scales globally.

4. The study addresses the growing issue of large-scale WT farm integration with UG, especially considering the variability and intermittent nature of wind energy. Also proposes potential pathways to overcome grid connection challenges, which are critical for achieving higher RE penetration in modern power systems.

The remainder of this paper is organized as follows: Section 2 presents an overview of WT systems and discusses the challenges and potential solutions for integrating large-scale WT farms into the UG. Also, Section 2 delves into the role of PECs in WT systems, comparing various configurations and their impact on performance and grid integration. Section 3 presents the types of WT generators, focusing on the different generator types used in wind energy conversion, specifically I&SGs. Section 4 provides a comparative analysis of the varying generator systems, highlighting the DFIG advantages in VSWT applications. Finally, Section 5 concludes the paper by summarizing the key findings and suggesting future research directions in Section 6, aimed at improving wind turbine efficiency and grid compatibility.

## 2. RELATED WORKS

Research [23] compares the performance of PMSGs with DFIGs, emphasizing the advantages of PMSGs in offshore applications due to their higher efficiency and reduced maintenance. Studies [24] have proposed hybrid generator systems that combine the benefits of DFIG and PMSG technologies, optimizing energy capture under varying wind conditions. Modern PECs, such as modular multilevel converters (MMCs), have demonstrated improved efficiency and scalability for large-scale wind farms [25]. Research [26] focuses on PECs' ability to ensure grid stability during faults, a key requirement for grid-code compliance. The study [27] addresses strategies for improving voltage stability and managing RP through advanced control algorithms, such as model predictive control (MPC). Study [28] explores the integration of wind energy with other renewables (e.g., solar PV) and storage systems, enhancing reliability and grid compatibility. Innovative approaches, such as coupling wind farms with hydrogen production and storage, have been shown to mitigate the intermittency of wind energy and enhance grid reliability [29].

## 3. OVERVIEW OF WTs AND PECs SYSTEMS

### 3.1 Overview of WTs Systems

Integrating large-scale WT farms into the UG presents several challenges, each of which requires innovative solutions to ensure a reliable, efficient, and stable energy supply [30]. Here's Table 1 summarizing the challenges and potential solutions for integrating large-scale WT farms into the UG. This table provides a concise overview of each challenge and its corresponding solution for better integration of large-scale WT farms into the UG.

### 3.2 Overview of the PECs System

PECs are a critical component of modern WT systems. They play a key role in optimizing the performance of WTs, improving their efficiency, and ensuring smooth integration with the UG [31]. As WT technology has evolved, PECs have become essential for handling the variability of wind energy and managing the interaction between WTs and the UG. Here's Table 2 summarizing the role of PECs in WT systems. This table provides a concise overview of the key roles of PECs in wind turbine systems, along with their functions and impacts on performance and grid integration. Choosing the appropriate PEC configuration is critical for optimizing the performance of WT systems and enhancing their integration into the utility grid [32]. Effective use of PECs is essential for maximizing the contribution of wind energy to a sustainable and resilient energy future. Table 3 provides a detailed comparison of various configurations of PECs used in WT systems.

Table 1. The challenges and potential solutions for integrating large-scale WT farms into the UG.

| Challenge | Description | Potential Solution |
|---|---|---|
| Intermittency of Wind Energy | Variability in WS causes fluctuations in power output, leading to grid imbalances. | Energy storage systems (ESS) such as batteries or hydrogen storage.<br>Hybrid systems (WT + PV). |

DOI: 10.17148/IJIREEICE.2026.14705

| | | |
|---|---|---|
| Grid Stability and Frequency Regulation | WTs lack inherent inertia, making it difficult to maintain frequency stability in the grid. | Grid-forming inverters and advanced PECs.<br>Improved forecasting and grid support functions (e.g., synthetic inertia). |
| Voltage Fluctuations and RP Management | Voltage variations due to remote wind farms affect power quality and efficiency. | Use of FACTS and STATCOMs for voltage regulation.<br>RP compensation and voltage support. |
| Transmission Constraints and Grid Congestion | Remote wind farms lead to transmission bottlenecks and congestion. | Upgrading grid infrastructure.<br>High-voltage direct current (HVDC) systems for efficient power transmission. |
| Grid Code Compliance | Wind farms need to meet grid code requirements for fault-ride-through, voltage support, and frequency response. | Advanced control algorithms for grid compliance.<br>WTs with enhanced PECs for grid support functions. |
| Economic and Market Integration | Fluctuations in wind energy can lead to curtailments and pricing challenges in energy markets. | Flexible market structures and policies (e.g., time-of-use pricing, demand-side management).<br>Energy storage incentives and ancillary service markets. |

Table 2. The role of PECs in WT systems.

| **Role of PECs** | **Function** | **Impact** |
|---|---|---|
| VS Operation | Enable WTs to adjust rotor speed to match changing wind conditions. | Maximizes energy capture across varying wind speeds, improving overall efficiency. |
| Grid Synchronization | Convert VF and the voltage generated by WTs into grid-compatible output. | Ensures seamless integration of wind power into the UG without disrupting stability. |
| Power Flow Control | Provide precise control over A&RP flow. | Enhances the turbine's contribution to grid stability and voltage management. |
| Fault Ride-Through (FRT) Capability | Allow WTs to remain connected during grid disturbances. | Prevents large-scale outages and supports grid resilience during short-term faults. |
| Enhanced Control Over Generator Types | Enable various generator types (IG, SG, and DFIG) to operate efficiently with variable speeds. | Makes DFIG-based turbines more efficient and suitable for large-scale wind farms compared to older technologies. |
| Grid Code Compliance | Help WTs meet regulatory requirements for grid support services. | Facilitates the integration of wind energy into the grid and ensures a higher renewable energy share. |
| Energy Storage and Hybrid System Integration | Allow integration with ESS for storing excess wind energy. | Enhances grid flexibility and reliability, contributing to energy supply during low wind or peak demand. |

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.021 ※ Peer-reviewed & Refereed journal ※ Vol. 14, Issue 7, July 2026

DOI: 10.17148/IJIREEICE.2026.14705

Table 3. The comparison of various configurations of PECs used in WT systems.

| PEC Configuration | Description | Performance Impact | Grid Integration Impact |
|---|---|---|---|
| Full-Scale Converter (FSC) | Converts the output of the generator to grid-compatible frequency and voltage directly. | Allows for VF operation, high efficiency at all speeds, and excellent power quality. | Strong grid support provides RP control and enhances grid stability and reliability. |
| Partial-Scale Converter (PSC) | Converts only a portion of the generated power (typically used in DFIG systems). | More cost-effective than FSC; efficient at variable speeds, but may have limitations in efficiency. | Good grid integration; can provide RP but with less capability than FSC systems. |
| Matrix Converter (MC) | Directly converts AC power to AC power without needing a DC link. | Can reduce losses and improve efficiency; however, complex control systems are required. | Provides excellent grid support with low harmonics; challenges with control under disturbances. |
| Back-to-Back Converter (B2BC) | Used in systems with energy storage or hybrid configurations. | Enables effective energy management and storage integration; enhances overall system efficiency. | Improves flexibility in power dispatch and grid interaction and can assist with peak load management. |
| Multi-Level Converter (MLC) | Uses multiple levels of voltage to reduce harmonics and improve efficiency. | High efficiency and low harmonic distortion; suitable for large-scale wind applications. | Excellent performance in grid support enhances the quality of power delivered to the grid. |
| Superconducting Fault Current Limiter (SFCL) | A protective device that limits fault currents in the grid. | Enhances system reliability; minimizes disruptions during fault conditions. | Significantly improves grid resilience; can protect wind farms from disturbances. |

This table provides a detailed comparison of various configurations of PECs used in WT systems, along with their impact on performance and grid integration:

- FSCs provide the best performance due to their ability to handle the entire output of the turbine, making them ideal for VS operation and improving overall energy efficiency.
- PSCs offer a more cost-effective solution while still delivering reasonable performance. They are particularly advantageous for existing DFIG configurations.
- FSCs and MLCs enhance grid stability and provide essential support services, including RP control, which is crucial for integrating RES.
- DC-DC converters and energy storage integration allow for better energy management and flexibility in power delivery, particularly important in hybrid systems where wind energy is complemented by other RES or energy storage.
- MLCs are particularly beneficial in reducing harmonics, contributing to better power quality, which is vital for sensitive grid applications.

### 3.3 WT Systems

A feature of FSWT is that they are equipped with an IG connected directly to the UG, with a soft start, and a CB to reduce RP recompense. They are designed to achieve maximum efficiency at a given WS. To increase power output, the generator of some FSWTs has two sets of coils [43]. FSWTs are simple, robust, reliable, and well-proven [33]. Its disadvantages are uncontrollable RP recompense, mechanical stress, and limited power quality control [43]. Since it runs at a constant speed, all instabilities in WS are also transmitted as instabilities in mechanical torque and then as instabilities in electrical power on the UG.

VSWTs are designed to maximize aerodynamic efficiency over a wide range of WS. It has a more complex electrical system than an FSWT. They are usually equipped with an IG or SG that is connected to the UG through a PT. The PT controls the speed of the generator. Increased energy capture, enhanced power quality, and decreased mechanical stress on the WT are the benefits of VSWTs [34]. The drawbacks of PEC include PEC losses, increased component usage,

Impact Factor 8.021 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 7, July 2026
DOI: 10.17148/IJIREEICE.2026.14705

and elevated equipment expenses. The number of feasible generator types has increased with the introduction of VSWT kinds, which also offer numerous combinations of generator and PEC types.

## 4. TYPES OF GENERATORS USED IN WTs

A WT can be equipped with any type of 3-ph generator. Today, the demand for UG-compatible electric current can be met by connecting frequency converters, even if the generator supplies AC or DC [35]. There are two types of generators used in WTs, which are:

IGs:

- SCIGs
- WRIGs
- OSIGs
- DFIGs are the most widespread.

SGs:

- WRSGs
- PMSGs

### 4.1 Type (A) WT concept: FSWT directly

As shown in Fig. 1, this architecture is equivalent to the constant or FS-controlled WT, with an asynchronous SCIG directly connected to the electric UG via a step-up PT [40]. This design calls for an RP compensator, like a CB, to lessen or possibly eliminate the RP demand from these turbine generators for the UG because the SCIG always pulls RP from the AC network. Usually, to do this, CBs are regularly switched (5–25 steps) by the AP created. If a gentle start is used, the UG connection will go more smoothly. Wind instabilities are transformed into mechanical instabilities, which are then transformed into electrical power instabilities in an FS machine, regardless of the power control principle used. When the network is poor, this can result in voltage instability at the WT's PCC to the electric UG. When a CB is not used, these voltage instabilities force the FSWT to pull instability RP from the UG, increasing the line losses as well as the voltage instabilities [36]. Because their components and construction are simple, FS systems have the benefit of being inexpensive. The concept's primary shortcomings. However, its incapacity to accommodate speed control, the need for a stiff UG (fixed voltage and frequency), and the demand for a sturdy mechanical structure to withstand the significant mechanical stress brought on by wind gusts [40].

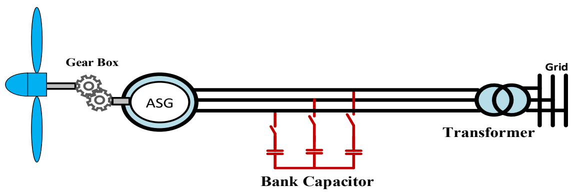


Fig. 1. Type (A) WT concept: FSWT directly connected to the UG via an SCIG.

### 4.2 Type (B) WT concept: partial VSWT with VRR

This architecture, as shown in Fig. 2, is equivalent to the partial VS-controlled WT with VRR, also known as Opti-Slip by the Danish manufacturer VestasTM wind systems [37]. It has been in operation since the mid-1990s and employs a WRIG. With a generator attached directly to the UG, this arrangement is comparable to the type (A) WT idea. On the other hand, the generator's rotor windings are linked in series with a regulated resistance, the magnitude of which determines the VS's range (usually 0–10% above the synchronous speed). A soft beginning is included to achieve a smoother UG connection, and a CB handles RP compensation. This design stands out due to its added VRR, which is adjusted by an optically controlled converter that is fixed to the rotor shaft. With the help of the innovative optical coupling system, the rotor resistance is thus controlled while removing the requirement for expensive slip rings that require brushes and maintenance. The slip and subsequently the WT's power output can be adjusted using VRR. The VRR's size affects the dynamic speed control range, which typically extends up to 10% above the synchronous speed. Heat loss results from the external power conversion unit's energy dump [40].

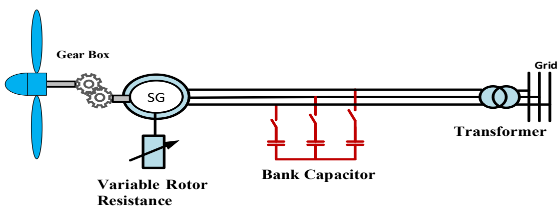


Fig. 2. Type (B) WT concept: partial VSWT directly connected to the UG via a WRIG with VRR.

 

DOI: 10.17148/IJIREEICE.2026.14705

### 4.3 Type (C) WT concept: VSWT directly

This concept corresponds to the most popular and widely used type, also well-known as DFIG [38]. It was given this name because both the stator and rotor coils are connected to the main network, according to Fig. 3. As we also see in Fig. 3, the rotor coils are connected to the network through PEC and transformers of the partial PT type, by which we mean that part of the power resulting from the process [44]. WT rotation will be passed to the PECs, which is approximately 30% of the nominal power generated. The use of PEC enables WTs to operate at varying (or changeable) speeds, and they can harvest power more effectively than their FS counterparts. A decrease in mechanical loss, which makes it possible to create lighter mechanical designs, more controllable power output (less dependent on variations in the wind), cost-effectiveness, easy pitch control, enhanced power quality, system efficiency, decreased acoustic noise, and island-operation capability are additional noteworthy advantages of using VS systems [42]. The stator and rotor coils are directly linked to the UG, as shown in Fig. 3, and the rotor frequency and speed are controlled by a partial-scale PEC. A back-to-back 4-quadrant AC/DC/AC converter design based on IGBTs makes up the partial-scale PEC [40]. The speed range of the converter is defined by its power rating, which is usually approximately ±30% of the synchronous speed [40]. Additionally, this converter enables a seamless UG connection and management of the RP reimbursement. When compared to the type C concept (Vestas's Opti-Slip), the rotor speed control range is wider. Furthermore, it recovers the energy lost in the Type C concept's variable rotor resistance, which makes it possible to raise the system's total efficiency. From an economic perspective, this notion is appealing due to the smaller PEC. But its primary shortcomings are the usage of slip rings, which require upkeep and brushes, and the intricate protective systems in the case of UG faults [40].

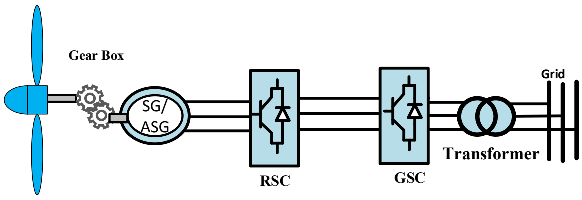


Fig. 3. Type (C) WT concept: VSWT directly connected to the UG via a DFIG controlled with a partial-scale PEC.

### 4.4 Type (D) WT concept: direct-in-line VSWT

This arrangement works with VS, in-line WTs, and a large-scale PEC connecting the generator to the UG [39]. PMSG is the kind of WT generator that is utilized to generate VF/AC electricity. This VF/AC power is converted to fixed-frequency AC power by the PEC that is linked in series (or in-line) with the WT generator [40]. Additionally, a smooth UG connection across the whole speed range and local control over the RP compensation are made possible by this PEC. The generator may be of the permanent magnet-excited type, PMSG, or the electrically excited WRSG type. Lately, as a result of PEC's technological progress. The SCIG has also started to be used for this concept [40]. As displayed in Figure 4, the generator stator is connected to the UG through PECs; that is, the energy generated by the rotation of the WT will be passed to full-scale PECs, which consist of a back/back 4-quadrant AC/DC/AC converter design based on IGBTs [40]. It also regulates the resulting frequency at varying speeds, thus often eliminating the need for a gearbox (As illustrated in the dotted lines in Figure 4). This type is the only type of WT generation system that does not have a gearbox.

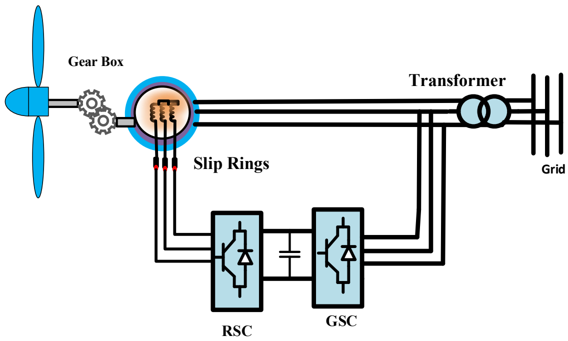


Fig. 4. Type (D) WT concept: direct-in-line VSWT connected to the UG through a full-scale PEC.

## 5. COMPARISON BETWEEN VARIOUS TYPES OF GENERATORS

This research mainly deals with 3 types of WT generators, namely SCIGs, DFIGs, and PMSGs. Table 4 below illustrates their disparities from one another.

  

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Impact Factor 8.021 ⵘ Peer-reviewed & Refereed journal ⵘ Vol. 14, Issue 7, July 2026
DOI: 10.17148/IJIREEICE.2026.14705

### 5.1 Comparison of I&SGs

The IG and SG stator constructions are the same. The structure and design of the rotors are the primary differences. IG rotor damper windings must be short-circuited for the rotor to generate a magnetic field; DC must activate the SG rotor winding for the rotor to generate a magnetic field. The comparison of I&SGs is displayed in Table 5.

### 5.2 DFIGs

DFIG is one of the generators that uses the VS principle in WTs. Reasons for using VSWTs include higher power output, temperature control, lower mechanical loads, active and RP control, reduced noise, and less variation in power output. The DFIG can precisely control the motor rotation speed and magnetic field current by introducing an electric current to the magnetic field coils of the generator through a control system called a frequency converter. This allows the generator to generate better-performing electricity at varying loads, which is one of the latest technologies used by RES plants. The DFIG supplies power to the UG through a set of electrical coils wrapped around the rotor and stator. The UG is directly connected to the stator coils, while a PEC connects the rotor coils to the UG. The PEC is an AC/DC/AC-based PWM converter. The stator coils are connected directly to the UG (50 Hz), while the rotor coils are fed through a VF AC/DC/AC converter [45].

The DFIG is considered one of the most widely used generators in RES generation plants, such as wind PPs and hydroelectric PPs, for several reasons, including:

1. Higher efficiency: The DFIG provides higher energy conversion efficiency when operating in varying conditions. The motor speed and magnetic field current can be adjusted to achieve maximum energy conversion efficiency.
2. Precise speed control: DFIG can achieve precise control of motor speed, allowing the system to generate electrical power with better performance under wind or load changes.
3. Cost saving: DFIG technology can provide lower costs in some cases, as DFIG generators can be used in a smaller size compared to generators used in other power generation technologies.
4. Safe operation: DFIG technology provides safe work under varying operating conditions, which helps maintain the safety of equipment and workers. In general, the DFIG is an advanced electric power generation technology that is widely used in renewable PPs to achieve high performance and better efficiency.

### 5.3 Simulation Data

Simulation data involves the expected WT-PEC performance under real-world wind conditions.

Table 4. Comparison of different WT generator types.

| Particulars | SCIGs | DFIGs | PMSGs |
|---|---|---|---|
| Aerodynamically efficiency | Fewer efficient | Efficient | Efficient |
| Noise problem | Noisy | Fewer noisy | Fewer noisy |
| Electrical efficiency | Efficient | Fewer efficient | Less efficient |
| Contribution to fault current | Since they are directly connected to the UG (without a converter), they depend on the standard protection scheme and add to the fault current. | Also, they add to the fault current, but the presence of the control system of the PEC detects the fault fast, and the duration of the contribution is less. | The PEC through which the turbine is connected cannot carry any current, so there is no contribution to the fault current, and the generator is isolated at the time of the fault. |
| Gearbox | Available | Available | Not available |
| Mechanical stress | More | Fewer | Fewer |
| Cost | Fewer expensive. | Expensive, although less so than PMSG driven directly. | Expensive |
| Converter | No converter | Small converter | Large converter |
| Rotor speed | Constant at any WS. | Rotates over a broad range of WS at any speed. | Rotates over a broad range of WS at any speed. |
| Harmonics problem | Present | Almost not present | Almost not present |

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.021 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 7, July 2026

DOI: 10.17148/IJIREEICE.2026.14705

Table 5. The comparison between I&SGs.

| Items | Induction Generators | Synchronous Generators |
|---|---|---|
| Stator Structure | 3-phase winding. | 3-phase winding. |
| Rotor Structure | It has a cage rotor; the winding does not need to be connected to DC [41]. | It has evidence and a controlled pole rotor winding that needs to be connected to the DC source [41]. |
| Speed | Operating at the over-synchronous speed. | Operating at a synchronized speed. |
| RP Recompense | From the system or connected to the capacitor. | Not needed |
| End Voltage Control | Can't control it. | Cause exciting system control. |
| Converter Device | Not needed | Needed |
| Maintenance | Simple and easy. | Complicated. |
| Cost | Cheap | Expensive |

Table 6. Simulation data for WT-PEC performance.

| Time (h) | Wind Speed (m/s) | Turbine Speed (rpm) | Active Power (kW) | Reactive Power (kVAR) | Converter Efficiency (%) | Grid Voltage (kV) |
|---|---|---|---|---|---|---|
| 00:00 AM | 4.5 | 12 | 350 | 0 | 98 | 33.1 |
| 02:00 AM | 8.0 | 18 | 950 | -50 | 98.2 | 33.0 |
| 04:00 AM | 12.0 | 20 | 2000 | 100 | 98.4 | 33.2 |
| 06:00 AM | 10.5 | 19 | 1700 | 50 | 98.3 | 33.1 |
| 08:00 AM | 14.0 | 22 | 2000 | -75 | 98.5 | 33.3 |
| 10:00 AM | 6.0 | 15 | 650 | 25 | 98.1 | 33.0 |
| 12:00 PM | 10.0 | 19 | 1600 | 0 | 98.3 | 33.1 |
| 2:00 PM | 14.0 | 22 | 2000 | -100 | 98.5 | 33.2 |
| 4:00 PM | 5.0 | 13 | 450 | 50 | 98 | 33.0 |
| 6:00 PM | 7.5 | 16 | 850 | -25 | 98.2 | 33.1 |
| 8:00 PM | 9.5 | 18 | 1450 | 0 | 98.3 | 33.1 |
| 10:00 PM | 4.0 | 10 | 200 | 25 | 97.8 | 33.0 |

Table 7. Summary numerical efficiency comparison.

| Generator Type | Efficiency (%) | Noise Level (dB) | Maintenance Cost ($/kWh) |
|---|---|---|---|
| DFIG | 98 | 65 | 0.01 |
| PMSG | 95 | 60 | 0.02 |
| SCIG | 92 | 75 | 0.008 |

Table 8. Comparison of power electronic converters.

| PECs Type | Efficiency (%) | Harmonics (%) | Fault Tolerance |
|---|---|---|---|
| FSC | 98 | <2 | High |
| PSC | 95 | <3 | Medium |
| MLC | 98.5 | <1.5 | Very High |

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Impact Factor 8.021 ∺ Peer-reviewed & Refereed journal ∺ Vol. 14, Issue 7, July 2026
DOI: 10.17148/IJIREEICE.2026.14705

Table 9. Comparison of economic impacts and cost-effectiveness of different types of WT generators.

| Generator Type | Capital Cost ($/kW) | Maintenance Cost ($/kWh) | Operational Lifetime (years) | Energy Yield (MWh /year) | Levelized Cost of Energy (LCOE) ($/MWh) | Payback Period (years) | Advantages | Limitations |
|---|---|---|---|---|---|---|---|---|
| SCIG | 1,200 | 0.008 | 20 | 3,000 | 45 | 8 | Low capital cost; simple design | High mechanical stress; low efficiency |
| DFIG | 1,600 | 0.01 | 25 | 4,200 | 40 | 6.5 | High efficiency; grid compatibility | Moderate maintenance cost; complex PEC |
| PMSG | 2,000 | 0.02 | 30 | 5,000 | 38 | 6 | High reliability; low noise; no gearbox | High capital cost; complex maintenance |

## 6. CONCLUSION

The various generator types and PEC utilized in modern WTs are summarized in this study. After a brief introduction outlining fundamental WT topologies and control techniques, the state of the art in WTs from an electrical perspective is examined. The principal design and attributes of varying wind power generation systems, grounded in modern WT concepts, along with their respective benefits and drawbacks, are also described. The new and old, possibly promising concepts for generators and PEC are presented based on technical aspects and market trends. There are now more generator types that are feasible because of the addition of VS options in WTs, which also give combination options for PEC and generator types a great deal of flexibility. Developing into PPs, big wind farms should function as integrated components of the electrical grid and follow this crucial trend for wind turbines. To give wind generation facilities the ability to control the power system and enhance their influence on power system stability, PECs represent a promising technological option. Here's a summary of the key findings:

1. The research highlights the superior efficiency of DFIG, especially when used in VSWTs. DFIGs allow better energy capture by adjusting rotor speed to wind conditions, maximizing output while minimizing mechanical strain.
2. PECs are critical in controlling and optimizing WT performance, enabling grid synchronization, variable speed operation, and RP management. This improves the efficiency and stability of integrating wind energy into UGs.
3. The study compares IG and SG systems, focusing on their connection to the UG and grid interaction challenges. SG generally offers better control, while IG is simpler and less expensive but contributes more to grid disturbances.
4. The integration of large-scale WT farms into the UG presents challenges such as intermittency, voltage fluctuations, and grid stability issues. Solutions such as ESS, advanced PECs, and grid-supporting technologies like STATCOMs are proposed to address these challenges.
5. The study underscores the growing role of DFIGs and PECs in improving wind farms' operational flexibility, grid stability, and economic viability. It also outlines potential pathways for overcoming grid integration barriers, crucial for scaling renewable energy adoption.

These findings provide valuable insights into optimizing WT generator systems and their integration into modern energy grids.

## 7. FUTURE WORK

1. Explore more sophisticated control strategies for WT systems, focusing on improving the performance of DFIG and SG in different wind conditions. This can include implementing machine learning algorithms for predictive maintenance and optimized power output.

DOI: 10.17148/IJIREEICE.2026.14705

2. Investigate the impact of higher penetration of wind energy on the UG, including issues such as voltage stability, power quality, and frequency regulation. This could lead to the development of more advanced grid-support features in WT systems to handle variable wind output.
3. Improving the efficiency and durability of PEC used in wind energy systems. This may include exploring new materials, such as wide-bandgap semiconductors, which could enhance converter performance, reduce energy losses, and improve system lifespan.
4. Study the integration of WT with other RES, such as solar PV systems or energy storage technologies like batteries and hydrogen. Hybrid systems could enhance energy stability and reduce reliance on traditional power plants.
5. Conduct simulations and case studies of large-scale wind farms under varying environmental conditions and grid demands. These models would help understand the long-term behavior of different generator and converter systems and inform decision-making for real-world deployments.
6. Further, assess the environmental benefits and cost-effectiveness of different WT systems. This can include lifecycle analysis of materials used in PECs and generators, as well as assessing the potential for recycling or repurposing components in decommissioned systems.

By addressing these topics, future research can build upon the findings of this study, further optimizing wind energy integration and contributing to the transition toward decarbonized power systems.

## REFERENCES

[1] Johnson, G., Wind Energy Systems, Prentice Hall, 2016.
[2] Dani, A., Mekrini, Z., El Mrabet, M., Boulaala, M. (2023). A review of different structure generators and control strategies applied to the wind turbine. International Conference on Advanced Intelligent Systems for Sustainable Development. AI2SD 2022. Lecture Notes in Networks and Systems, vol 714. Springer, Cham. https://doi.org/10.1007/978-3-031-35245-4_18
[3] Burton, T., Jenkins, N., Sharpe, D., Bossanyi, E., Wind Energy Handbook, 2nd ed., John Wiley & Sons, 2011.
[4] Tiwari, R., Babu, N.R.: Artificial neural network-based control strategies for PMSG-based grid-connected wind energy conversion system. Int. J. Mater. Prod. Technol. 58(4), 323 (2019). https://doi.org/10.1504/ijmpt.2019.100009
[5] Ackermann, T., Söder, L., "An Overview of Wind Energy Integration into Electrical Power Systems," Wind Energy, vol. 6, no. 3, pp. 229–240, 2003.
[6] Wollz, D.H., da Silva, S.A.O., Sampaio, L.P.: Real-time monitoring of an electronic wind turbine emulator based on the dynamic PMSG model using a graphical interface. Renew. Energy 155, 296–308 (2020). https://doi.org/10.1016/j.renene.2020.03.096
[7] Heier, S., Grid Integration of Wind Energy Conversion Systems, 3rd ed., John Wiley & Sons, 2014.
[8] Hossain, M.M., Ali, M.H.: Future research directions for the wind turbine generator system. Renew. Sustain. Energy Rev. 49, 481–489 (2015). https://doi.org/10.1016/j.rser.2015.04.126
[9] Ekanayake, J., Jenkins, N., "Comparison of Fixed-Speed and Variable-Speed Wind Turbines," IEEE Transactions on Energy Conversion, vol. 12, no. 2, pp. 181–186, 1997.
[10] Tawfiq, K.B., Mansour, A.S., Ramadan, H.S., Becherif, M., El-Kholy, E.E.: Wind energy conversion system topologies and converters: comparative review. Energy Procedia 162, 38–47 (2019). https://doi.org/10.1016/j.egypro.2019.04.005
[11] Muljadi, E., "Variable-Speed Wind Turbines with Synchronous Generators," IEEE Transactions on Industry Applications, vol. 35, no. 2, pp. 288–296, 1999.
[12] Abdullah, M.A., Yatim, A.H.M., Tan, C.W., Saidur, R.: A review of maximum power point tracking algorithms for wind energy systems. Renew. Sustain. Energy Rev. 16(5), 3220–3227 (2012). https://doi.org/10.1016/j.rser.2012.02.016
[13] Hansen, A. D., Sørensen, P., Iov, F., Blaabjerg, F., "Centralised Power Control of Wind Farm with Doubly Fed Induction Generators," Renewable Energy, vol. 31, no. 7, pp. 935–951, 2006.
[14] Zhang, X., Huang, C., Hao, S., Chen, F., Zhai, J.: An improved adaptive-torque-gain MPPT control for direct-driven PMSG wind turbines considering wind farm turbulences. Energies 9(11), 977 (2016). https://doi.org/10.3390/en9110977
[15] Muller, S., Deicke, M., Doncker, R. W., "Doubly Fed Induction Generator Systems for Wind Turbines," IEEE Industry Applications Magazine, vol. 8, no. 3, pp. 26–33, 2002.
[16] Mousa, H.H.H., Youssef, A.-R., Mohamed, E.E.M.: State of the art perturb and observe MPPT algorithms based wind energy conversion systems: a technology review. Int. J. Electr. Power Energy Syst. 126, 106598 (2021). https://doi.org/10.1016/j.ijepes.2020.106598

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526
International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Impact Factor 8.021 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 7, July 2026
DOI: 10.17148/IJIREEICE.2026.14705

[17] Datta, R., Ranganathan, V. T., "Variable-Speed Wind Power Generation Using Doubly Fed Wound Rotor Induction Machine," IEEE Transactions on Energy Conversion, vol. 17, no. 3, pp. 414–421, 2002.
[18] Son, J.-Y., Ma, K.: Wind energy systems. Proc. IEEE 105(11), 2116–2131 (2017). https://doi.org/10.1109/jproc.2017.2695485
[19] Smith, P., "Reactive Power Management in Wind Farms," Renewable and Sustainable Energy Reviews, vol. 14, no. 3, pp. 1082–1089, 2010.
[20] Tjiu, W., Marnoto, T., Mat, S., Ruslan, M.H., Sopian, K.: Darrieus vertical axis wind turbine for power generation II: challenges in HAWT and the opportunity of multi-megawatt Darrieus VAWT development. Renew. Energy 75, 560–571 (2015). https://doi.org/10.1016/j.renene.2014.10.039
[21] Zhou, E., "Application of DFIG in Modern Wind Energy Systems," Energy Reports, vol. 6, no. 4, pp. 255–267, 2020.
[22] Alnasir, Z., Kazerani, M.: An analytical literature review of stand-alone wind energy conversion systems from a generator viewpoint. Renew. Sustain. Energy Rev. 28, 597–615 (2013). https://doi.org/10.1016/j.rser.2013.08.027
[23] Cheng, Y., Wu, J., "Performance Comparison of PMSG and DFIG-Based Wind Farms," Renewable Energy, vol. 157, pp. 345–358, 2020.
[24] Sharma, A., Kumar, N., "Hybrid Generator Systems in Wind Energy," Journal of Renewable and Sustainable Energy, vol. 12, no. 1, pp. 101–110, 2019.
[25] Mei, S., et al., "Advances in Modular Multilevel Converters for Wind Energy Systems," IEEE Transactions on Power Electronics, vol. 35, no. 3, pp. 255–267, 2020.
[26] Rashed, M., Morcos, M., "Fault Ride-Through Capability in Wind Energy Systems," IEEE Transactions on Energy Conversion, vol. 25, no. 2, pp. 495–503, 2018.
[27] Li, X., Zhang, Y., "Voltage Stability Analysis in Wind Power Systems," Energy Systems, vol. 11, pp. 399–412, 2021.
[28] Ahn, S., "Hybrid Renewable Energy Systems: Wind and Solar Integration," Renewable Energy and Environmental Sustainability, vol. 6, no. 2, pp. 45–52, 2021.
[29] Tsiropoulos, I., Tarvydas, D., Zucker, A., "Coupling Hydrogen Storage with Wind Farms for Grid Support," International Journal of Hydrogen Energy, vol. 46, no. 7, pp. 3287–3300, 2021.
[30] Marques, J., Pinheiro, H., Grundling, H., Pinheiro, J., Hey, H.: A survey on variable-speed wind turbine systems. In: Proceedings of Brazilian Conference of Electronics of Power, vol. 1, pp. 732–738 (2003).
[31] Polinder, H., Van Der Pijl, F.F.A., De Vilder, G.-J., Tavner, P.J.: Comparison of direct-drive and geared generator concepts for wind turbines. IEEE Trans. Energy Convers. 21(3), 725–733 (2006). https://doi.org/10.1109/tec.2006.875476
[32] Cheng, M., Zhu, Y.: The state of the art of wind energy conversion systems and technologies: a review. Energy Convers. Manag. 88, 332–347 (2014). https://doi.org/10.1016/j.enconman.2014.08.03
[33] Mousa, H.H.H., Youssef, A.-R., Mohamed, E.E.M.: Variable step size P&O MPPT algorithm for optimal power extraction of multi-phase PMSG-based wind generation system. Int. J. Electr. Power Energy Syst. 108, 218–231 (2019). https://doi.org/10.1016/j.ijepes.2018.12.044
[34] Chen, J., Yao, W., Zhang, C.-K., Ren, Y., Jiang, L.: Design of robust MPPT controller for grid-connected PMSG-based wind turbine via perturbation observation-based nonlinear adaptive control. Renew. Energy (2018). https://doi.org/10.1016/j.renene.2018.11.048
[35] Matayoshi, H., Howlader, A.M., Datta, M., Senjyu, T.: Control strategy of PMSG-based wind energy conversion system under strong wind conditions. Energy Sustain. Dev. 45, 211–218 (2018). https://doi.org/10.1016/j.esd.2018.07.001
[36] Berrada, Y., Boumhidi, I.: New structure of sliding mode control for variable speed wind turbine. IFAC J. Syst. Control 14, 100113 (2020). https://doi.org/10.1016/j.ifacsc.2020.100113
[37] Tiwari, R., Babu, N.R.: Recent developments of control strategies for wind energy conversion systems. Renew. Sustain. Energy Rev. 66, 268–285 (2016). https://doi.org/10.1016/j.rser.2016.08.005
[38] Minh, H.Q., Frédéric, N., Najib, E., Abdelaziz, H.: Control of permanent magnet synchronous generator wind turbine for a stand-alone system using fuzzy logic. In: Proceedings of the 7th Conference of the European Society for Fuzzy Logic and Technology, Aix-les-Bains, France, 18–22 July 2011, pp. 720–727 (2011).
[39] Lahfaoui, B., Zouggar, S., Mohammed, B., Elhafyani, M.L.: Real-time study of P&O MPPT control for small wind PMSG turbine systems using Arduino microcontroller. Energy Procedia 111, 1000–1009 (2017). https://doi.org/10.1016/j.egypro.2017.03.263
[40] Zambroni de Souza, A.C., Castilla, M.: Microgrids Design and Implementation. Springer Science and Business Media LLC, Springer Nature Switzerland AG (2019). https://doi.org/10.1007/978-3-319-986876_1
[41] Sue, D.-C.: High-efficiency double-fed induction generator applied to wind power generator technical analyses. Energy Power Eng. 3(3), 253–261 (2011). https://doi.org/ 10.4236/epe.2011.33032.

[42] Molina, M.G., Mercado, P.E.: Modelling and Control Design of Pitch-Controlled Variable Speed Wind Turbines. Wind Turbines (2011). InTech, Available from: https://www.intechopen.com/chapters/14810

[43] Rao, K.R.: Wind Energy for Power Generation: Meeting the Challenge of Practical Implementation. Springer Science and Business Media LLC, Springer International Publishing, pp.1–1443 (2019). https://www.scribd.com/document/636452989

[44] Bizhani, H., Noroozian, R., Muyeen, S., Blaabjerg, F.: Grid integration of multiple wind turbines using a multi-port converter –a novel simultaneous space vector modulation. Renew Sustain Energy Rev. 157, 111940 (2022). https://doi.org/10.1016/j.rser.2021.111940

[45] Abadi, M.B.: Fault Diagnosis in AC Drives and Wind Turbine Doubly-Fed Induction Generators Based on Three-Level NPC Converters. PhD Thesis in Electrical and Computer Engineering, specialization in Energy, submitted to the Faculty of Sciences and Technology of the University of Coimbra, pp.1–246 (2022). https://hdl.handle.net/10316/90560