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**Research Article**

# Permanent Magnet Reluctance Generator: - State of the art review

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**ARTICLE INFO** **ABSTRACT**

**Objectives:** This paper reviews the latest developments in switched reluctance machines (SRMs) focusing on their use in generating electricity, known as generating mode. While the motoring mode of SRMs is well understood, generating mode requires more study due to its unique properties. SRMs are valued for their simple design, durability, ability to operate over a wide range of speeds, and the absence of permanent magnets and rotor windings, making them suitable for variable-speed applications.
**Method:** The review explains how SRMs work in generating mode and discusses different control methods for switched reluctance generators (SRGs). It also examines phase control in permanent magnet reluctance generators (PMRGs), highlighting its importance for improving power quality, stability, and overall system performance.
**Findings:** phase control is crucial for maximizing the efficiency and performance of PMRGs. By understanding and applying effective phase control techniques, researchers and engineers can enhance the use of renewable energy and better integrate these systems into the power grid.
**Significance:** This paper emphasizes the need for ongoing research to further develop SRM and PMRG technologies.

**Keywords:** Electrical Machines, Reluctance Machines, permanent magnet reluctance generators (PMRGs), Wind Energy system

## 1. Introduction

### *1.1 Research Contributions*
This study investigates the principles and techniques of phase control in permanent magnet reluctance generators (PMRGs), widely used in renewable energy systems like wind and hydropower, as well as in micro-gas turbines. PMRGs are known for their simple construction, high efficiency, and robustness, converting mechanical energy into electrical energy through the reluctance torque between the stator and rotor [1], [2]. The manuscript provides a comprehensive overview of PMRGs, examining the significance of phase control and presenting various methods and algorithms for its implementation. Additionally, it explores the impact of phase control on power quality, stability, and overall system performance, while discussing the latest developments in the field and identifying challenges and future research directions.

### *1.2 Research Gaps*
Despite the widespread use of PMRGs in renewable energy systems, there is a significant need for a deeper understanding of phase control to optimize power generation efficiency, ensure stable operation, and improve overall system performance [3], [4]. Precise control of the phase and phase angle is crucial for maximizing power output, regulating voltage and frequency, mitigating harmonics, and enhancing grid integration

capabilities. The lack of comprehensive studies on phase control in PMRGs highlights a critical research gap that this manuscript aims to address.

### *1.3 Research Questions*

To address these research gaps, the following questions are explored:

1. What are the fundamental working principles and construction aspects of PMRGs?
2. How does phase control influence the performance of PMRG systems?
3. What methods and algorithms are currently used for phase control in PMRGs?
4. What is the impact of phase control on power quality, stability, and overall system performance?
5. What are the latest developments and challenges in phase control for PMRGs?

**Table 1. Summary of some literature reviewed**

| Serial No. | Author and Year | Title of Paper | Findings | Limitations |
|---|---|---|---|---|
| 1 | Zhao, W., 2023 | Design and Optimization of an Interior Permanent-Magnet Synchronous Motor for Aircraft Drive Application | Optimization of motor structure led to improved torque density and reduced torque ripple. | Focused primarily on simulations with limited experimental validation. Future work could include real-world testing to confirm simulation results |
| 2 | Diab, H., Ait-Ahmed, Y., Bouillaut, G., 2023 | Open Circuit Performance of Axial Air Gap Flux Switching Permanent Magnet Synchronous Machine for Wind Energy Conversion: Modeling and Experimental Study | Found that the flux-switching PMSM exhibited better sinusoidal EMF waveform and lower harmonics compared to a traditional surface-mounted PMSM. | The study focused on open-circuit conditions, and further investigation is needed under load conditions to fully assess the machine's performance |
| 3 | Azarinfar, H., Aghaebrahimi, M.R., 2023 | Design, Analysis, and Fabrication of a Novel Transverse Flux Permanent Magnet Machine with Disk Rotor | Developed a novel transverse flux machine with a disk rotor, showing high power factor and efficiency, suitable for wind turbines. | Limited practical implementation and testing. The design needs more comprehensive testing in diverse operational conditions to validate the findings |
| 4 | Tao, D., Zhang, F., Li, Y., Du, G., Zhang, Y., 2024 | Electromagnetic Design of High-Power and High-Speed Permanent Magnet Synchronous Motor Considering Loss Characteristics | Analyzed loss characteristics, including core loss and eddy current loss, and optimized design for high-speed applications in energy storage systems. | The learnings focus on loss reduction may have overlooked other critical factors such as mechanical stresses and long-term reliability, which need further exploration |

To overcome the limitations in recent research on Permanent Magnet Reluctance Generators, it's important to include more real-world testing to validate simulation results. Testing under different load conditions can help ensure that the machines perform well in various situations. Additionally, using advanced optimization tools can help design these machines to be not only efficient but also reliable and durable. This approach will improve the practical application and long-term use of these generators.

#### *1.4.1 Working Principle*

Switched reluctance (SR) generator generates electric power by using magnetic saliency. The working principle of PMRGs is based on the reluctance torque generated between the permanent magnet rotor and the stator teeth (Fig.1). When the rotor rotates, the variable air gap between the rotor and stator teeth causes a change in the reluctance of the magnetic circuit. This variation in reluctance generates a torque that drives the rotor. As the rotor moves, the phase angle between the rotor and stator determines the efficiency and power output of the PMRG [5],[6],[7],[8],[9].

The phase angle between the rotor and stator significantly influences the power generation efficiency of PMRGs. By controlling the phase angle, the generator can operate at the optimum power factor, maximizing power output and minimizing losses. Additionally, phase control allows for improved power flow management and better utilization of the available renewable energy resource.

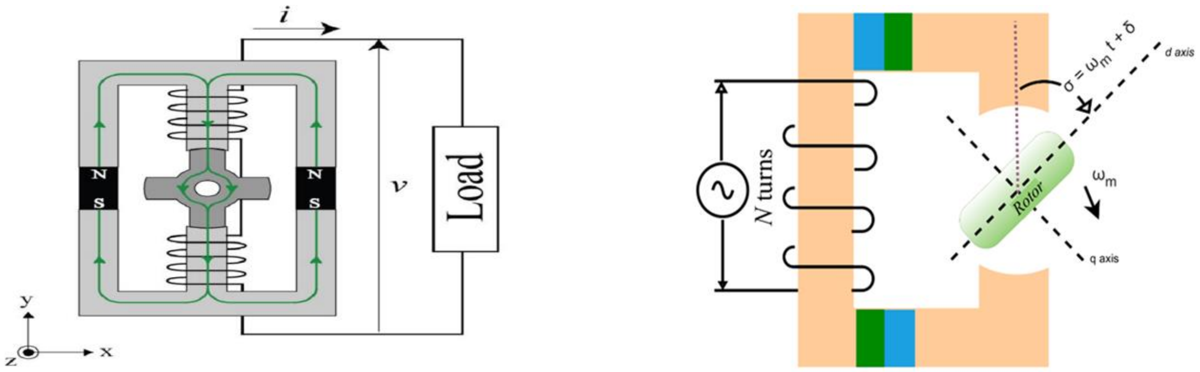


**Figure 1. Simplified diagram of a reluctance generator**

### 1.4.2 Construction and Components

PMRGs consist of a stator with teeth and windings and a rotor equipped with permanent magnets. The stator teeth create a magnetic flux path and generate the reluctance torque. The permanent magnets on the rotor create a magnetic field that interacts with the stator teeth. The windings on the stator produce the necessary magnetic fields for power generation. Fig.2 shows a schematic construction diagram of a single phase and three phase PMSRG [10],[11],[12],[13]

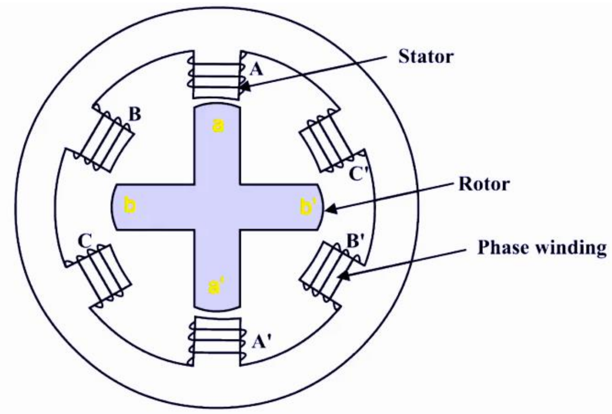


**Figure 2. Collective Stator and Rotor picture**

### 1.4.3 Classification and Design of SRGs

A Permanent Magnet Switched Reluctance machine can be classified into two categories.

### 1.4.4 Linear PMSRG [14], [15]:

Construction:

✓ Linear PMSRGs operate in a linear motion rather than rotational. They consist of a single-step stator and rotor.

Working Principle:

✓ These generators use varying magnetic reluctance to generate force along a linear path.

Applications:

✓ DSPMMs are used in various industrial and renewable energy systems.

### 1.4.5 Rotary PMSRG [16],[17],[18]:

**Construction**: Rotary PMSRGs have a more complex structure with multiple steps in both the stator and rotor.

**Working Principle**: Similar to other SRGs, rotary PMSRGs rely on varying reluctance to produce torque. The rotor position determines the magnetic flux path.

Advantages:

✓ **Permanent Magnet Assist**: Incorporating permanent magnets enhances performance by providing additional magnetic flux.

✓ **High Efficiency**: Permanent magnets contribute to higher efficiency.

✓ **Reduced Torque Ripple**: The combination of switched reluctance and permanent magnets minimizes torque fluctuations.

Challenges:

✓ Control Complexity: Managing both the switched reluctance and permanent magnet components requires sophisticated control strategies.

✓ Design Optimization: Balancing the benefits of both technologies while minimizing drawbacks.

Applications

✓ Rotary PMSRGs are suitable for wind turbines, electric vehicles, and industrial machinery.

### *1.4.6 Doubly Salient Permanent Magnet Motor (DSPMM) [19], [20]:*

Overview

✓ DSPMM is a specific type of rotary PMSRG that combines the merits of permanent magnet brushless motors and switched reluctance motors.

Structure

✓ It shares the same configuration as conventional SRMs but incorporates permanent magnet materials in the stator.

Advantages:

✓ **High Torque Density**: Permanent magnets boost torque output.

✓ **Fault Tolerance**: DSPMM retains SRM's fault-tolerant features.

**Simplicity**: The structure remains robust and straightforward.

Applications:

✓ DSPMMs are used in various industrial and renewable energy systems2.

### *1.4.7 Design Considerations*

The design of PMRG involves several critical considerations, including the selection of suitable permanent magnets, optimization of rotor and stator geometries, and efficient magnetic circuit design as shown in Table 2. Factors such as magnetic saturation, cogging torque, and windage losses must be carefully addressed to enhance the performance and efficiency of the generator. Additionally, advancements in materials science and manufacturing technologies have enabled the development of compact and lightweight PMRG systems for various applications.

**Table 2. Different designs of switched reluctance machines**

| Ref. | **Design Speciality** | **Advantages** |
|---|---|---|
| [21] | -Permanent Magnet Assisted Synchronous<br>Reluctance Motor with Asymmetric Rotor (PMA-SynRM)<br>-asymmetric rotor design with position-biased<br>Magnet | -high torque density<br>-Increased power density.<br>-Increased torque ripple |
| [6], [22] | -Control of switched reluctance generator in wind power system<br>application for variable speeds<br>- Asymmetric half bridge converter is proposed | -changes in phase cur-<br>rents were affected by selecting the turn-on and the turn-off angle. |
| [22], [23] | -Control of switched reluctance generator in wind power system<br>application for variable speeds | -These generators are used especially in wind power plants due to their ability to operate in<br>variable speed range and applications of aviation and electric cars.<br>-output voltage of the SRG is controlled by using PI voltage controller |
| [24] | Power Factor Correction and Current Harmonic Mitigation | -AC<br>Variable Reluctance Generator with DC Excitation<br>- could operate as one-phase or<br>three-phase AC generator |
| [25] | Three-Phase Full-Bridge Converter Controlled<br>Permanent Magnet Reluctance Generator for<br>Small-Scale Wind Energy Conversion Systems | -A three-phase asymmetric half-bridge<br>(AHB) converter with a torque ripple minimization-assisted maximum power point tracking (MPPT) algorithm presents an effective control for a PMRG-based WECSs<br>-The configuration employs a three-phase FB converter and a torque ripple minimization-assisted MPPT control algorithm. |
| [26] | New Design of Permanent Magnets Reluctance<br>Generator | -Rotor of the generator, designed according to<br>consists of 2 pieces and both are connected by a shaft with a different angle of 180°<br>-By this way electromagnetic torque of the two rotors are able to reduce<br>-The permanent magnets reluctance generator new models was able to produce power 167%, compared to the shaft input power. |

### *1.4.8 Advantages and Limitations*

PMRGs offer several advantages, including high power density & efficiency, simple construction, and robustness. They do not require a separate field winding or excitation system, reducing the overall complexity and cost. PMRGs are also highly reliable due to the absence of slip rings or brushes. However, they have limitations such as limited power factor control and a dependence on rotor position for optimal performance.

**Table 3. Types of Reluctance generators**

| Ref. | Type | Applications | Advantages | Challenges |
|---|---|---|---|---|
| [27], [28] | Single-phase RG | Wind energy conversion system | | -High leakage reluctance<br>-Low efficiency<br>-Non-sinusoidal output voltage waveform |
| [8], [29] | Three-phase RG | Wind energy conversion system | Low leakage reluctance<br>High efficiency | -Non-sinusoidal output voltage waveform |
| [30], [31] | DC excitation RG | Wind energy conversion system | | -Non-sinusoidal output voltage waveform |
| [32], [33] | PM Excitation RG | | | -Non-sinusoidal output voltage waveform |

### *1.5 Recent Developments.*

In recent years, researchers and engineers have focused on several developments related to the phase control of permanent magnet reluctance generators (PMRGs). Some notable advancements include:

1. Advanced Control Strategies: Researchers have been exploring advanced control strategies to enhance the performance of PMRGs. These include model predictive control (MPC), adaptive control, fuzzy logic control, and artificial intelligence-based control techniques. These strategies aim to improve dynamic response, optimize power output, and enhance fault ride-through capabilities.
2. Sensorless Control Techniques: Sensorless control methods have gained attention as they eliminate the need for additional position sensors in PMRGs. Various sensorless control algorithms, such as back-electromotive force (EMF) estimation and high-frequency signal injection methods, have been developed to estimate the rotor position accurately. These techniques reduce system complexity, cost, and potential reliability issues associated with position sensors.
3. Grid Integration and Power Quality: With the increasing integration of PMRGs into electrical grids, researchers have focused on improving grid integration capabilities and power quality. Fig. 3 Block diagram of grid integrated wind generation system. Advanced phase control algorithms have been developed to ensure seamless synchronization with the grid, voltage and frequency regulation, and compliance with grid codes and standards.

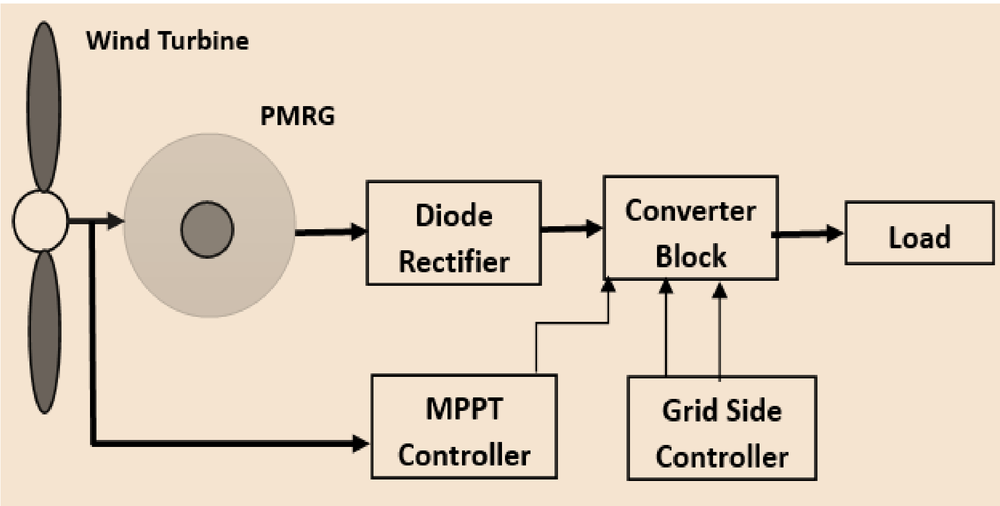


**Figure 3. Block diagram of grid integrated wind generation system.**

4. Harmonics Mitigation: Harmonics generated by PMRGs can impact the quality of the electrical power supply. Recent developments have focused on mitigating harmonics through advanced phase control strategies, such as model-based control algorithms and the use of active filters. These techniques reduce harmonic distortion and ensure compliance with power quality standards.
5. Hybrid Energy Systems: Researchers have explored the integration of PMRGs with other renewable energy sources and energy storage systems to create hybrid energy systems. The combination of PMRGs with wind turbines, solar panels, and energy storage devices allows for better utilization of available resources and improved stability of the hybrid system. Advanced phase control strategies play a crucial role in achieving efficient power flow management and optimal energy utilization.
6. Optimization Techniques: Researchers have employed optimization techniques, such as genetic algorithms, particle swarm optimization, and evolutionary algorithms, to maximize power output and efficiency in PMRG

systems. These techniques optimize the phase control strategy by considering various factors such as wind speed, load variations, and environmental conditions.
7. Hardware and Power Electronics: Advances in power electronics components, such as high-performance converters and intelligent power modules, have contributed to more efficient and reliable phase control in PMRGs. These advancements enable better integration, higher power density, and improved control capabilities, enhancing the overall performance of PMRG systems as shown in Fig. 4.

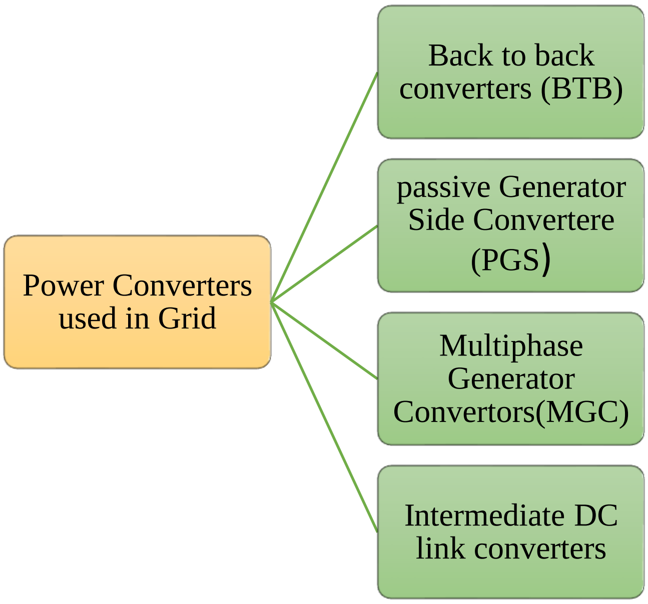


**Figure 4. Classification of power converters used in Wind energy conversion systems**

### 1.6 Power Quality Considerations
Effective phase control in PMRGs helps regulate voltage and frequency, ensuring stable power supply to the grid [17], [34]. Maintaining accurate phase relationships with the grid is crucial for maintaining power quality and avoiding disruptions in the electrical network. By actively adjusting the phase angle, PMRGs can contribute to a reliable and stable power system. Table 4 and 5 shows the factors which are responsible for power quality.

### 1.7 Grid Integration and Stability
Phase control facilitates seamless integration of PMRGs into the electrical grid. By synchronising the generator's phase with the grid, PMRGs can contribute to grid stability and provide active power support during transient events. Phase control strategies also enable PMRGs to comply with grid codes and facilitate smooth grid connection [17], [34].

## 2. Methods and Techniques for Phase Control
### 2.1 Review Methodology
### 2.2 Fixed Phase Control
Fixed phase control involves setting a specific phase angle between the rotor and stator that remains constant during operation [35], [36]. This method is relatively simple and widely used in PMRG systems where a constant power factor is desired. However, fixed phase control lacks flexibility in adapting to changing operating conditions.

### 2.3 Variable Phase Control
Variable phase control allows for dynamic adjustment of the phase angle based on operating conditions and grid requirements [35], [36]. This method optimizes power generation efficiency by continuously tracking the optimum power factor. Variable phase control can be achieved through feedback control loops that adjust the rotor position or by employing advanced algorithms and control techniques.

### 2.4 Sensorless Control
Sensorless control techniques eliminate the need for position sensors by estimating the rotor position based on measured electrical variables [36], [37]. These techniques rely on signal processing algorithms and mathematical models to estimate the rotor position, enabling accurate phase control without additional hardware. Sensorless control reduces system complexity and cost while maintaining precise control over the phase angle.

### 2.5 Model-Based Control
This techniques utilize mathematical models of the PMRG system to predict and control the phase angle [38], [39]. By considering system dynamics, load variations, and environmental conditions, model-based control algorithms can optimize phase control for improved performance. These techniques often require accurate system modelling and parameter identification.

### 2.6 Comparison and Evaluation
Different phase control methods and algorithms have specific advantages and limitations. The selection of an appropriate phase control strategy depends on the specific application, system requirements, and available resources. Comparative evaluations and simulations can help determine the most suitable approach for a given PMRG system.

### 2.7 Algorithms for Phase Control
#### 2.7.1 Synchronous Operation Algorithms
Synchronous operation algorithms ensure the synchronization of the PMRG with the grid by maintaining a constant phase relationship. These algorithms adjust the rotor position or the stator current to achieve synchronization and maximize power transfer. Examples of synchronous operation algorithms include the vector control algorithm and the direct torque control algorithm.

#### 2.7.2 Maximum Power Point Tracking (MPPT) Algorithms
MPPT algorithms aim to extract the maximum power from the PMRG under varying operating conditions [40]. These algorithms continuously adjust the phase angle to track the maximum power point, considering factors such as wind speed, load variations, and environmental conditions. Perturb and observe, incremental conductance, and particle swarm optimization are common MPPT algorithms. Some studies are found in the literarure that are aimed to track the maximum power form SRGs drived by a wind energy turbine. These studies aimed to turn ON/OFF the switches of converter to get optimized power.

#### 2.7.3 Adaptive and Predictive Control Algorithms
Adaptive and predictive control algorithms dynamically adjust the phase angle based on real-time measurements and system characteristics. These algorithms use feedback information to continuously adapt and optimize the phase control strategy. Adaptive control algorithms adjust control parameters based on system identification, while predictive control algorithms anticipate future conditions to proactively adjust the phase angle.

### 2.8 Impact of Phase Control on PMRG Performance
Power Output and Efficiency Precise phase control techniques maximize power output and improve the overall efficiency of PMRGs. By operating at the optimal power factor and adjusting the phase angle based on load and environmental conditions, PMRGs can generate more power while minimizing losses.

### 2.9 Voltage and Frequency Regulation
Accurate phase control ensures voltage and frequency regulation, which is vital for maintaining power quality. By adjusting the phase angle, PMRGs can provide voltage support and frequency stability, contributing to a reliable and consistent power supply to the grid.

**Table 4. Harmonics mitigation and fault ride capability**

| Harmonics Mitigation Phase control techniques | Fault Ride-Through Capability |
|---|---|
| 1. By adjusting the phase angle, the harmonic content can be minimized<br>2. reducing distortion and ensuring compliance with grid code<br>3. Reduces Impact on connected load | 1. PMRGs can adjust the phase angle to continue operating and contribute to grid stability during fault<br>2. Enhances the resiliency and reliability of renewable energy systems. |

### 2.10 Performance Comparison of Different Phase Control Methods
A case study can be conducted to compare the performance of fixed phase control, variable phase control, and sensorless control methods. Parameters such as power output, efficiency, voltage regulation, and harmonics can be analyzed under various operating conditions to assess the advantages and limitations of each approach. Another case study can focus on the grid integration and stability of PMRGs using different phase control techniques. The impact of phase control on grid synchronization, fault ride-through capability, and power quality can be investigated through simulations or field tests. The results can demonstrate the importance of phase control in achieving reliable and stable grid integration.

**Table 5. Performance Comparison of Different Phase Control Methods**

| Method | Description |
|---|---|
| Multi-Objective Control Strategy | - Combines turn-off angle optimization, closed-loop control, and real-time tuning.<br>- Maximizes output power range at different rotor speeds. |
| Voltage Control with PI Controller | - Maintains constant output voltage regardless of speed and load variations. |
| Pulse Width Modulated (PWM) Control | - Suitable for SRMs functioning as generators at high and low speeds. |
| Linear Active Disturbance Rejection Control | - Uses LADRC and hybrid optimization algorithm (HOA) to reduce torque ripple and enhance robustness. |
| Optimal Operating Parameters | - Determines optimal parameters based on mechanical input power. |

### *2.11 Integration with Energy Storage Systems*

Integrating PMRGs with energy storage systems, such as batteries or super capacitors, can enhance their overall performance and grid support capabilities. Future research should focus on developing control strategies that enable seamless integration and effective utilization of energy storage in conjunction with phase control.

### *2.12 Power Electronics and Control*

Advancements in power electronics and control hardware are essential for efficient and reliable phase control in PMRGs. Developing innovative power electronic converters, advanced control algorithms, and reliable sensing and measurement techniques will contribute to the optimization of phase control strategies. Fig 5 depicts the use of PMSRG with power electronics for Wind energy conversion system

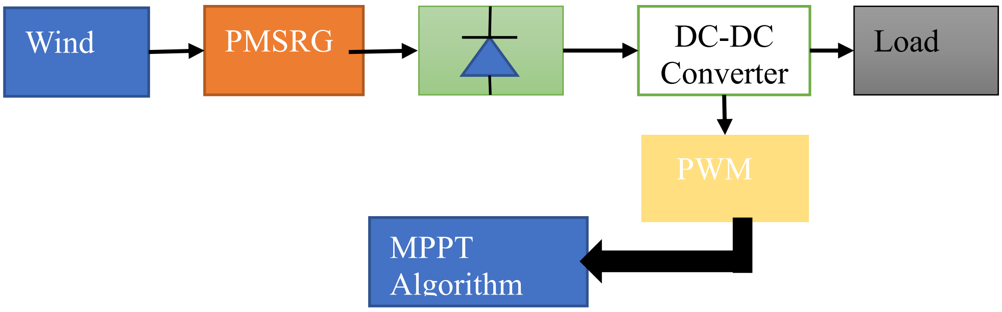


**Figure 5. Use of power electronics for Wind energy conversion system**

## 3. Overview

### *3.1 Results, Discussions, Conclusions and Recommendations:*

### *a. Results & Discussions*

It this literature survey study, it is found that

- Efficiency of Reluctance generators are generally high so RGs are the first choice in wind energy conversion system and micro-gas-turbine generation.
- Output voltage of a SRG is non-sinusoidal in nature (predominantly 3$^{rd}$ and 5$^{th}$ harmonics are prevalent).
- Non-sinusoidal output voltage waveform is not an issue as it is rectified and then inverted at suitable voltage level and frequency.
- There is a scope of research to eliminate or filter harmonics of SRG so that it can be directly used as AC.
- Large leakage flux becomes when the rotor pole is in the unaligned position relative to causes a decrease of the output and thus power and efficiency. A viable solution is to increase number of poles.

### *b. Challenges*

- Improving the accuracy and robustness of senseless control techniques is an ongoing challenge. Further research is needed to enhance estimation algorithms, reduce computational complexity, and ensure accurate rotor position estimation under varying operating conditions.
- Exploring advanced control strategies, such as predictive and adaptive control algorithms, can further optimize phase control in PMRG systems. These strategies can adapt to changing operating conditions, improve dynamic response, and enhance overall system performance.

## 4. Conclusions and Recommendations:

Phase control is crucial for optimizing the performance of permanent magnet reluctance generators (PMRGs) in renewable energy systems. It improves power generation efficiency, power quality, and grid integration. This review covered various phase control methods and their effects on power output, voltage stability, and noise reduction, supported by experimental data and case studies. However, some significant gaps remain in this field:

1. Sensorless Control: More effective sensorless control techniques are needed for different operational conditions.
2. Energy Storage Integration: Further research is required to optimize the integration of PMRGs with energy storage systems for better power output stability.
3. Material and Design Improvements: Innovations in materials and designs are necessary to reduce losses and extend the lifespan of PMRGs.
4. Long-Term Performance: More studies are needed on the long-term reliability and maintenance of PMRG systems.

This review advances understanding by detailing the role of phase control in enhancing PMRG efficiency and stability, offering new insights compared to previous studies. Addressing these gaps and further developing phase control techniques will be crucial for maximizing the benefits of PMRGs in renewable energy applications.

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