Hexagram STATCOM and SV-PWM for Optimizing Power Quality in PMSG based WES

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Abstract: This paper proposes the integration of a Three-Phase Hexagram Static Compensator (TPH-STATCOM) using Space Vector-Pulse Width Modulation (SV-PWM) methods to optimize power quality in Permanent Magnet-Synchronous Generator (PMSG)-based Wind Energy Systems (WES). The study investigates the performance of the WES under varying wind velocities and nonlinear load conditions. The proposed compensator's efficacy is evaluated through a power quality optimization model for a microgrid using an Enhanced Pelican Optimization Algorithm (EPOA). Simulation results show significant improvements in power quality metrics, validating the effectiveness of the TPH-STATCOM-SV-PWM system in enhancing the stability and reliability of PMSG-based WES across various operational scenarios. The study's implications extend to the broader renewable energy sector, particularly in the context of grid integration and renewable energy penetration. The proposed TPH-STATCOM-SV-PWM system facilitates the smooth flow of wind energy into the electrical grid, promoting a more robust and sustainable energy infrastructure. The study underscores the importance of advanced control and compensation techniques in maximizing the reliability and efficiency of renewable energy systems and accelerating the adoption of clean energy technologies.

Keywords: Wind Energy Systems, Permanent Magnet Synchronous Generator, Three-Phase Hexagram Static Compensator, Space Vector Pulse Width Modulation, Enhanced Pelican Optimization Algorithm, and Power Quality Optimization.

1. INTRODUCTION

Wind power plants based on PMSG have emerged as a prominent source of renewable energy due to their environmental sustainability and economic viability (Chen and Ran, 2018). However, ensuring high power quality is crucial for the effective integration of wind energy into the power grid. Power quality encompasses various parameters such as voltage stability, frequency stability, harmonic distortion, and transient response. Enhanced power quality not only improves the reliability of the electrical grid but also facilitates the seamless integration of renewable energy sources like wind power (Yamin and Natarajan, 2018). In PMSG-based WES, maintaining optimal power quality becomes challenging due to the intermittent nature of wind energy and the inherent characteristics of PMSGs. Variations in wind speed and direction can lead to fluctuations in power output, affecting voltage and frequency stability. Therefore, there is a pressing need to develop effective techniques for power quality enhancement in PMSG-based WES to ensure grid stability and reliability.

Conventional compensation techniques, such as passive filters and reactive power compensation devices, have been widely employed to mitigate power quality issues in electrical systems. Passive filters, consisting of capacitors and inductors, are commonly used to reduce harmonic distortion and improve power factor (Saeed et al., 2016). However, passive filters have limitations in terms of their effectiveness in handling dynamic and nonlinear loads, as well as their inability to adapt to changing grid conditions. Reactive power compensation devices, including Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), are deployed to regulate voltage and reactive power exchange with the grid (Li et al., 2017). While these devices offer improved voltage stability and transient response, they may not be sufficiently agile to address rapid changes in wind power generation and load variations. Despite their utility, conventional compensation techniques may fall short in meeting the stringent power quality requirements of modern electrical grids, especially in the context of PMSG-based WES (Guerrero et al., 2013). Therefore, there is a need for advanced compensation strategies that can effectively mitigate power quality issues while accommodating the dynamic nature of wind energy systems.

The Three-Phase Hexagram Static Compensator (TPH-STATCOM) represents a sophisticated voltage-source converter-based compensator designed to enhance power quality in electrical systems. By dynamically injecting or absorbing reactive power, the TPH-STATCOM can regulate voltage, improve transient response, and mitigate harmonic distortion. SV-PWM techniques are employed to regulate the switching of voltage-source converters in the TPH-STATCOM. SV-PWM offers precise control over the amplitude and phase of the output voltage, enabling efficient and accurate compensation of reactive power and harmonic currents. Compared to traditional pulse width modulation techniques, SV-PWM results in reduced switching losses and improved harmonic performance (Chen and Ran, 2018). By integrating the TPH-STATCOM with SV-PWM techniques, PMSG-based WES can achieve enhanced power quality while effectively managing grid integration challenges. Additionally, a power quality optimization model for a microgrid is constructed using an Enhanced pelican optimization algorithm (EPOA) by introducing Levy-flight distribution to enhance the power quality. The combination of advanced compensation technologies and control strategies offers a promising solution for addressing power feature issues and optimizing the performance of renewable energy models in modern electrical grids.

2. LITERATURE REVIEW

Several studies have investigated power quality enhancement techniques in WES to deal with the difficulties in incorporating green energy sources that fluctuate into the electrical grid. A study initiated by (Ahn et al., 2015), the authors investigated the application of energy storage systems (ESS) in conjunction with wind energy systems to enhance power quality. Their research focused on the coordination of ESS operation with wind turbine control strategies to mitigate voltage fluctuations and improve grid stability. (Wang et al., 2018; Muisyo et al., 2022) conducted a comparative analysis of different control strategies for Dual-Fed Induction Generator (D-FIG)-based wind turbines to address power quality issues. Their study evaluated the performance of vector control, direct power control, and model predictive control techniques in mitigating grid disturbances and improving overall power quality. Research by (Patel and Narang, 2017; Liu et al., 2021) explored the use of hybrid compensators, combining STATCOMs with other compensation devices, to enhance power quality in WES. Their study proposed novel control algorithms and optimization techniques to maximize the effectiveness of hybrid compensator configurations under varying wind conditions and grid disturbances. A study by (Sharma et al., 2019) investigated the impact of wind farm clustering on power quality and grid integration challenges. The authors analyzed the collective behavior of multiple wind farms connected to the grid and proposed coordination strategies to mitigate voltage fluctuations and harmonic distortion at the system level. (Khan et al., 2016) conducted research on the application of advanced signal processing techniques for fault detection and diagnosis in wind turbine systems. Their study focused on the development of machine learning algorithms and fault detection methods to identify and mitigate potential reliability issues affecting power quality in WES. For instance, (Redfern et al., 2002; Bhattacharyya et al., 2010) explored the use of Static Compensators (STATCOMs) to mitigate power quality issues in wind turbine systems. Their research demonstrated the effectiveness of STATCOMs in improving voltage stability and mitigating voltage fluctuations caused by wind variability. Similarly, (Bevrani et al., 2009) conducted a comprehensive survey on the role of renewable energy sources, including wind power, in frequency regulation. Their study highlighted the importance of advanced control strategies and grid integration techniques for maintaining grid stability and frequency control in WES.

Recent advancements in compensator technologies have focused on enhancing the performance of WES by addressing power quality concerns. (Babazadeh et al., 2020) provided an overview of grid-connected voltage-source converters and their applications in wind farm integration. Their research emphasized the importance of advanced control algorithms and grid synchronization techniques for optimizing power quality in WES. Moreover, (Noroozi et al., 2023) proposed a novel electrical performance enhancement for off-grid PV systems using one-phase transformerless partial-quasi-Z-source inverters. Their study demonstrated the effectiveness of advanced control strategies in improving power quality and grid stability in WES.

Despite significant progress in power quality improvement techniques for WES, several research gaps and challenges remain to be addressed. Existing compensator technologies and control strategies not fully address the dynamic nature of wind power generation and the intricate way in which wind blades and the grid interact. Furthermore, there is a need for novel solutions that can effectively mitigate transient disturbances, harmonics, and voltage fluctuations in WES while ensuring grid stability and reliability. Current research efforts focus on developing adaptive control strategies, advanced modeling techniques, and integrated power management systems to address these challenges.

3. SYSTEM ARCHITECTURE AND CONTROL STRATEGY

This section provides a detailed description of the system architecture of the PM-SG-based WES and outlines the design and implementation of the Three-Phase Hexagram Static Compensator (TPH-STATCOM) along with an overview of SV-PWM methods for control. The proposed control strategy integrates the Three-Phase Hexagram Static Compensator (TPH-STATCOM) employing SV-PWM methods with an Enhanced pelican optimization algorithm (EPOA) using Lévy flight distribution. This integration aims to enhance the power quality of the microgrid and verify the effectiveness of the proposed model.

3.1 PMSG-based WES Setup

The PMSG-based WES consists of several key components, including the wind turbine rotor, the PMSG unit, power electronics converters, grid connection interface, and control system. The wind turbine rotor converts kinetic dynamism from the wind into mechanical energy, which is then transmitted to the PMSG unit.

The PMSG unit converts mechanical energy into electrical energy and feeds it into the power electronics converters. The power electronics converters, including rectifiers and inverters, play a crucial role in converting the variable frequency AC output from the PMSG unit into a stable DC bus voltage and then back into AC voltage synchronized with the grid frequency (Luo et al., 2020). The grid connection interface ensures seamless integration of the WES with the electrical grid, allowing for bidirectional power flow and synchronization with grid voltage and frequency. The control system of the PMSG-based WES comprises various control algorithms and strategies aimed at maximizing energy capture, optimizing power quality, and ensuring grid stability (Li et al., 2017). These control algorithms govern the operation of the wind turbine, the PMSG unit, and the power electronics converters, enabling efficient and reliable operation of the WES under varying wind conditions and grid disturbances. The proposed system is shown in Figure 1.

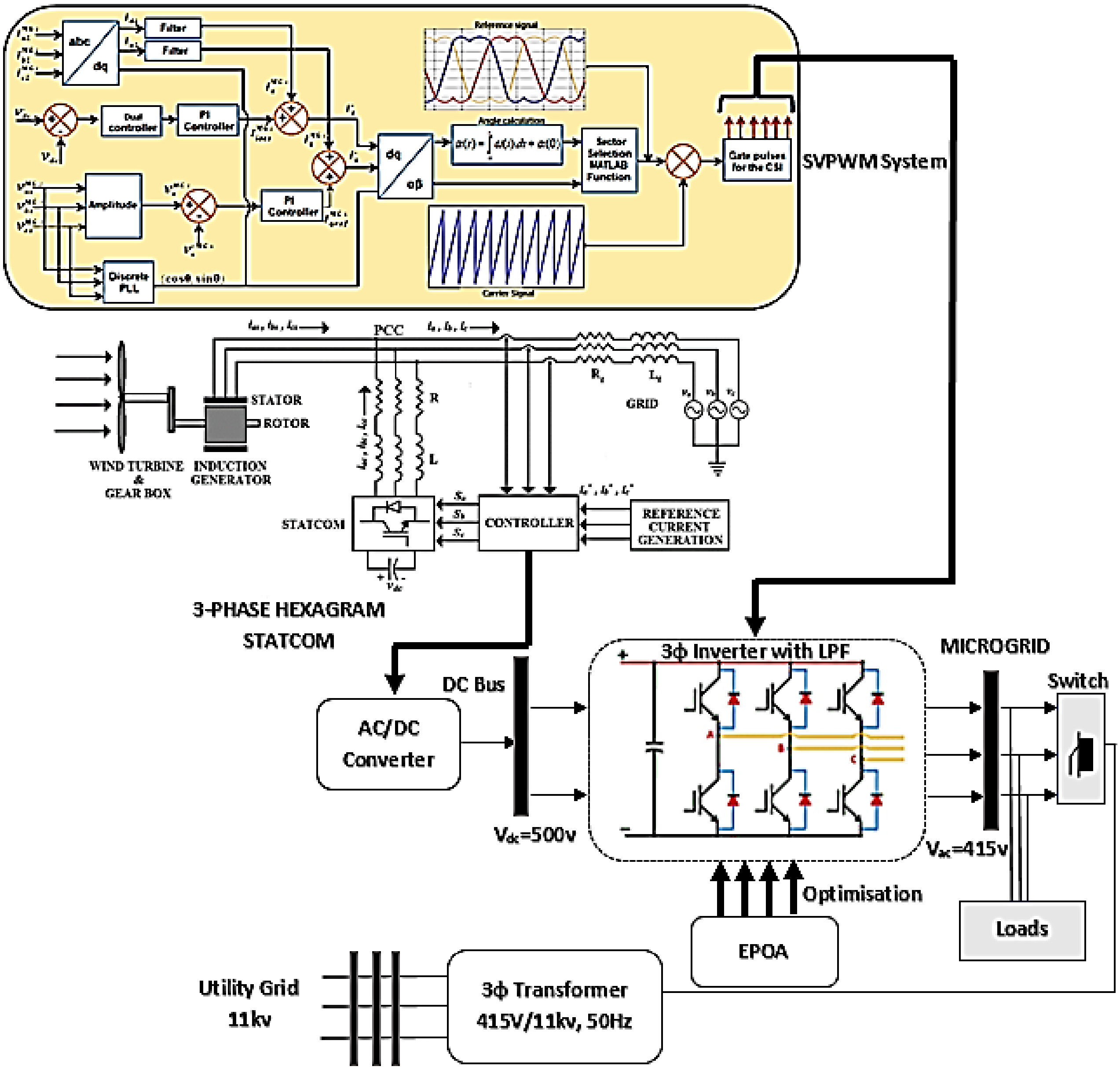


Fig. 1. Proposed PMSG-based WES system with 3-phase HEXA-STATCOM & SV-PWM.

3.2 Design and Implementation of TPH-STATCOM

The Three-Phase Hexagram Static Compensator (TPH-STATCOM) is a key component of the WES setup designed to enhance power quality by compensating reactive power, regulating voltage, and mitigating harmonic distortion (Saeed et al., 2016). The TPH-STATCOM consists of voltage-source converters (VSCs) connected in a hexagram configuration, allowing for precise control of the injected or absorbed reactive power.

The design and implementation of the TPH-STATCOM involve selecting appropriate VSC components, designing control algorithms for reactive power compensation, and integrating the TPH-STATCOM into the WES control system. Advanced control strategies, such as proportional-integral-derivative (PID) control and model predictive control (MPC), are employed to regulate the output voltage of the TPH-STATCOM and maintain grid stability under varying operating conditions. The control system of a TPH based STATCOM is shown in Figure 2.

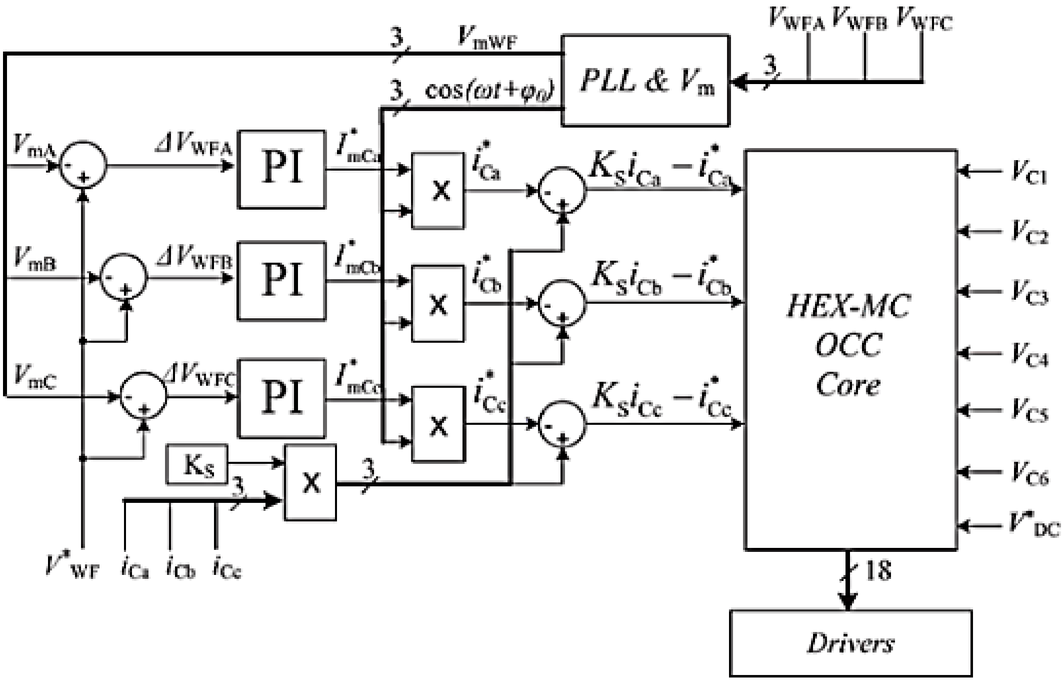


Fig. 2. Control system of a TPH based STATCOM.

3.3 SV-PWM Techniques for Control

SV-PWM methods are utilized to control the switching of the VSCs in the TPH-STATCOM, enabling precise regulation of the output voltage waveform and reactive power compensation (Saeed et al., 2016). SV-PWM techniques offer superior harmonic performance and switching efficiency compared to traditional pulse width modulation methods, making them well-suited for power quality enhancement applications. The implementation of SV-PWM involves generating space vector representations of the desired output voltage waveform and determining the switching states of the VSCs to achieve the desired voltage levels and phase angles (Paulo et al., 2023). By adjusting the modulation index and switching frequency, SV-PWM techniques enable accurate control of the output voltage, minimizing harmonic distortion and ensuring compliance with grid voltage and frequency requirements. Figure 3 displays a schematic depiction of the control circuit used to generate switching pulses for the gates that are applied to the microgrid's inverter.

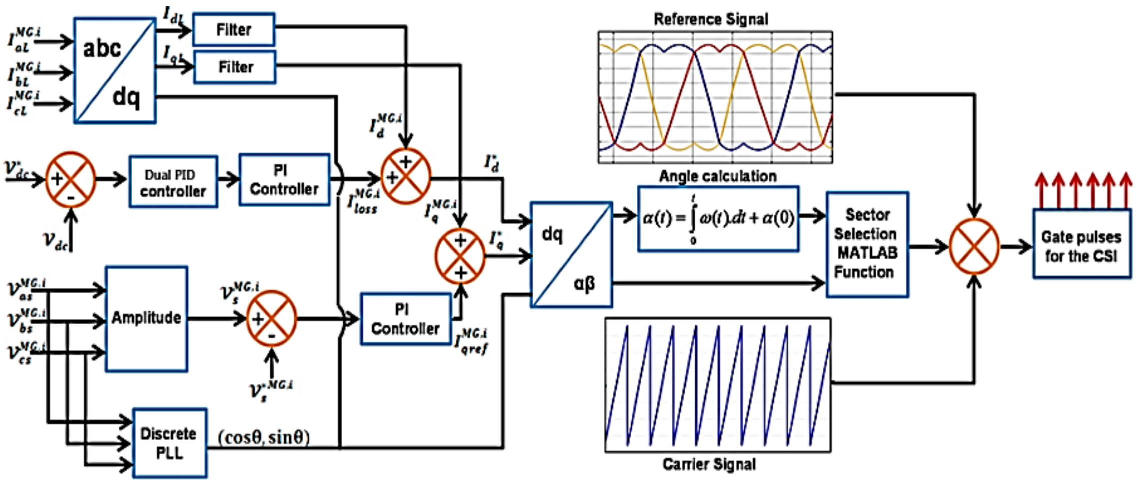


Fig. 3. Proposed Control Strategy with SV-PWM.

3.4. Enhanced Pelican Optimisation Algorithm (EPOA)

The Enhanced Pelican Optimisation Algorithm (EPOA) is an advanced metaheuristic optimization technique inspired by the foraging behavior of pelicans. In this enhanced version, the algorithm incorporates the Lévy flight distribution to efficiently explore the search space, particularly for optimization problems related to power quality at microgrids.

3.4.1. Initialization phase of the Population Using Stochastic Resistance Training

The population initialization phase aims to generate an initial set of candidate solutions by leveraging Stochastic Opposition Learning (SOL). SOL enhances the exploration capability of the algorithm by exploiting the opposite solutions in the search space. The initialization process involves the following steps:

- Randomly generate an initial population of pelicans, represented as positions in the search space.
- Apply SOL to each pelican position to generate its reactive solution.
- Evaluate the fitness of both the original and reactive solutions.
- Select the better solution as the initial position of the pelican.

SOL: Reactive $Solution = Best\ Solution - (Current\ Solution - Best\ Solution)$

3.4.2. Disturbance Suppressor

To prevent premature convergence and enhance the diversity of solutions, a disturbance suppressor mechanism is introduced. This mechanism periodically perturbs the positions of pelicans to escape local optima. The disturbance suppressor operates as follows:

- At predefined intervals, randomly select a subset of pelicans from the population.
- Perturb the positions of selected pelicans by applying a random disturbance.
- Evaluate the fitness of perturbed solutions and update the population if improvements are observed.

$$Perturbed\ Position = Current\ Position + Random\ Vector \times Random\ Factor$$

3.4.3. Lévy Flight Strategy

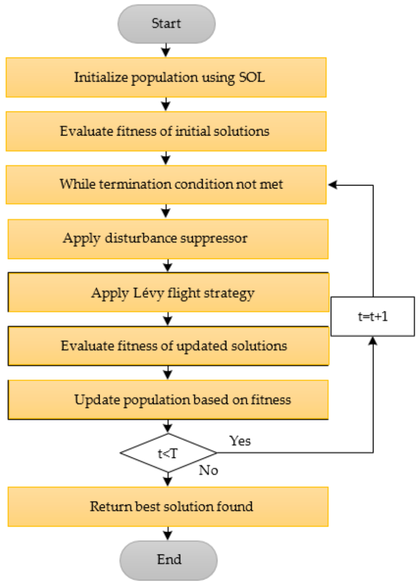
The incorporation of the Lévy flight strategy enhances the exploration capability of EPOA by introducing long-range jumps in the search space. The Lévy flight strategy is implemented as follows:

- At each iteration, randomly select a subset of pelicans.
- Generate a random step length from the Lévy flight distribution.
- Update the positions of selected pelicans by taking a step in the direction of the random vector multiplied by the step length.

$$Step\ Length = \alpha \times Levy\ Distribution$$

Where, Step Length represents the distance traveled by the pelican in each dimension during the Lévy flight, α is the scaling parameter that adjusts the magnitude of the step, and Lévy Distribution refers to the random step length generated from the Lévy flight distribution.

3.4.4. EPOA Algorithm Flow Chart and Pseudo-Code



EPOA Algorithm

Begin EPOA
1. Input the details of the optimization assignment..
2. Calculate the multitude of iterations (T) and the maximum dimension of EPOA (N)..
3. Set the pelican's initial location and determine the objective functionality.
4. Compute the objective function and update the position of the pelican.
5. Locate the pelican.
6. Aimed at t = 1:T
7. Generate prey positions randomly.
8. For i = 1:N
9. The beginning: Approaching the prey (stage of exploration).
10. For j = 1:m
11. Compute the j-th dimension's new state.
End
13. Update the ith population member.
14. The second stage: Water-based flight (development stage).
15. For j = 1:m.
16. Compute the j-th dimension's new state.
End
18. Revise the member of the i-th population.
19. Compute the j-th dimension's new state.
20. Revise the member of the i-th population.
End
22. Revise the top contender solutions.
End.
24. Deliver the top contender solution found using EPOA.
End EPOA.

4. PERFORMANCE ANALYSIS

The research aims to comprehensively investigate the effectiveness of the PMSG-based WES by simulating various operating scenarios and assessing key power quality parameters. The analysis encompasses a thorough investigation of system behavior under different wind velocities, nonlinear load conditions, and unbalanced load conditions.

4.1 Simulation Setup and Parameters

The simulation setup involves constructing a detailed model of the PMSG-based WES using simulation software such as MATLAB/Simulink or PSCAD/EMTDC. The model incorporates the dynamics of each component, including the wind turbine, PMSG unit, power electronics converters, grid connection interface, and control system. Parameters such as wind velocity profiles, turbine characteristics, electrical parameters of the PMSG and converters, grid voltage and frequency profiles, and load characteristics are carefully defined to accurately represent real-world conditions. The switching parameter with SV-PWM and its phasor diagram is shown in Figure 4 (a), (b).

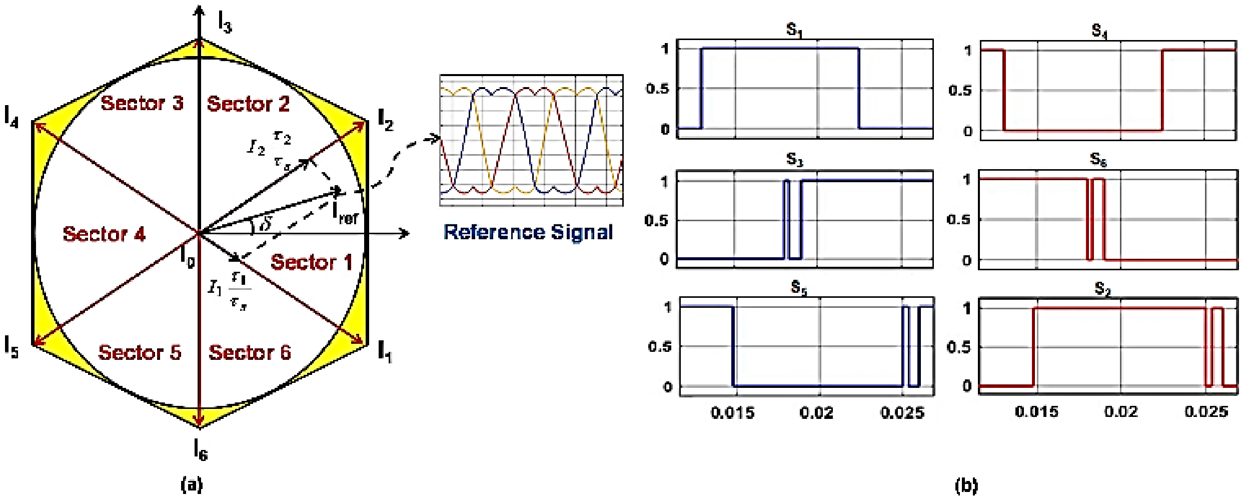


Fig. 4. (a) SV-PWM phasor representations (b) pulses at switching gates.

4.2 Power Quality Parameters Investigation under Varying Wind Velocities

The analysis begins by simulating the performance of the WES under different wind velocity profiles. By varying wind speeds, ranging from low to high velocities, the impact on power feature parameters such as voltage stability, frequency regulation, and harmonic distortions is evaluated. The simulation results provide insights into how changes in wind velocity affect the output voltage and frequency stability of the system, as well as the level of harmonic distortion introduced into the grid. Reference Current (Iref) is computed using SV-PWM technique. The voltages and currents collection parameters are improved to the λ-µ structure via Equations (1) and (2) [21].

$$\begin{bmatrix} V \\ V_\lambda \\ V_\mu \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I \\ I_\lambda \\ I_\mu \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

Here, V_a, V_b, V_c and I_a, I_b, I_c are the source voltages and currents corresponding to the a-b-c structure, and V_λ,V_μ, I_λ, $I_\mu$are the source voltages and currents corresponding to λ-µ structure. The conversion of the λ-µ structure to the m-n-o structure is specified in Equation (3). The orientation current corresponding to the X-axis (I_X^*) is attained as specified in Equation (4), where I_X is the X-axis current, and the lossy constituent rate at rth sampling time $I_{loss(r)}$ for convention the loss happened in the microgrid is acquired as given in Equation (5). In a similar manner, the current that serves as a reference relative to the Y-axis is provided by (I_Y^*).

$$\begin{bmatrix} I \\ I_m \\ I_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\phi & sin\phi \\ 0 & -sin\phi & -cos\phi \end{bmatrix} \begin{bmatrix} I \\ I_\lambda \\ I_\mu \end{bmatrix} \tag{3}$$

$$I_X^* = I_X \pm I_{loss} \tag{4}$$

$$I_{loss(r)} = I_{loss(r-1)} + K_p((V_x^* - V_x)_r - (V_x^* - V_x)_{r-1}) + K_i(V_x^* - V_x)_r \tag{5}$$

Where K_p, K_i denotes PI controller's gains and are updated by SV-PWM method procedures. Equation (6) provides the means to obtain the reference current vector..

$$I_{ref} = \frac{2}{\sqrt{3}}(\sqrt{(I_X^*)^2 + (I_Y^*)^2} \tag{6}$$

Equation (7) provides the quantitative formula for the dynamic geometry $\hat{I}_t$ of the current compiled inverter spatial component, where "t" is the segment value of the current component location.

$$\hat{I}_t = 1.17 I_{ref} e^{j(\frac{\pi}{6}-(k-1)\frac{\pi}{3})} \tag{7}$$

The dwell duration of stationary vectors is a measure of how long space vectors stay in a sector throughout τs. Estimates of dwell duration are based on the referred to ampere-second balance principle. Fundamentally, the outcome of the sampling duration τs and the referencing vector I_{ref}, is equal to the sum of the current component multiplication by the period interlude of selected spatial component. If τs is small enough, this product can be considered constant across time.

4.3 Analysis of Output Voltage, Frequency, and THD Levels during Nonlinear and Unbalanced Load Conditions

In addition to wind velocity variations, the performance analysis extends to assessing system behavior under nonlinear and unbalanced load conditions. Nonlinear loads, such as power electronic converters or variable-speed drives, are introduced into the system to evaluate their effect on power quality. The analysis includes quantifying deviations in output voltage and frequency, as well as the level of Total Harmonic Distortion (THD), under varying load conditions. Furthermore, unbalanced loads are simulated to investigate their impact on voltage and frequency deviations, highlighting potential challenges in grid integration and power quality management.

By conducting a comprehensive performance analysis, insights are gained into the dynamic behavior of the PMSG-based WES under different operating conditions. This knowledge facilitates the optimization of system parameters and control strategies to enhance power quality, grid stability, and overall performance, thereby promoting the effective integration of renewable energy into the electrical grid.

5. RESULTS AND DISCUSSION

The findings of the simulation study, focusing on a comparative analysis of power quality metrics with and without the Three-Phase Hexagram Static Compensator (TPH-STATCOM) and Space Vector Pulse Width Modulation (SV-PWM) system integrated with EPOA optimisation is presented. Additionally, the section evaluates the functionality of the equipment in various wind and load settings, followed by a discussion on the effectiveness of the proposed solution and its advantages over existing methods.

5.1 Comparative Analysis of Power Quality Metrics

The simulation results provide a comparative analysis of power feature quality metrics, such as voltage stability, wavelength regulation, and harmonic distortion, with and without the TPH-STATCOM-SV-PWM system.

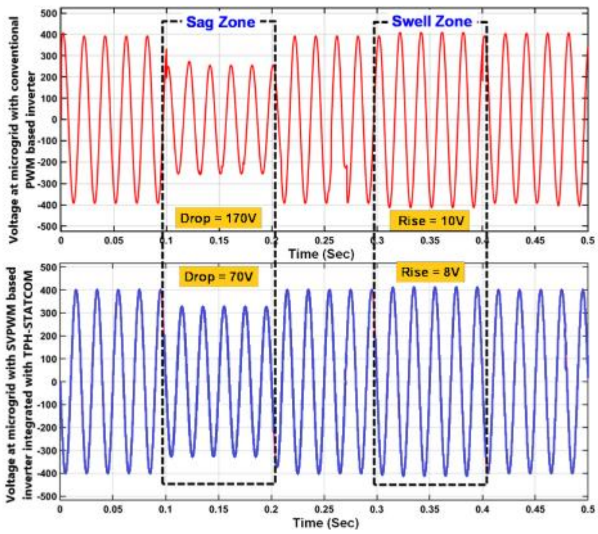


Fig. 5. Comparative analysis of voltage dip/surge at microgrid with traditional PWM and proposed TPH-STATCOM integrated SV-PWM with EPOA optimisation-based inverters.

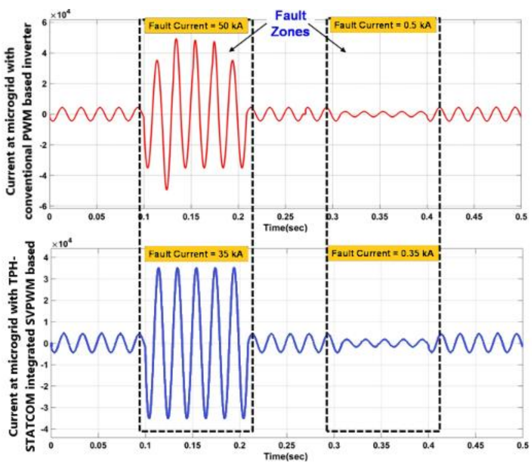


Fig. 6. Comparative analysis of current during voltage dip/surge at microgrid with traditional PWM and proposed TPH-STATCOM integrated SV-PWM with EPOA optimisation based inverters.

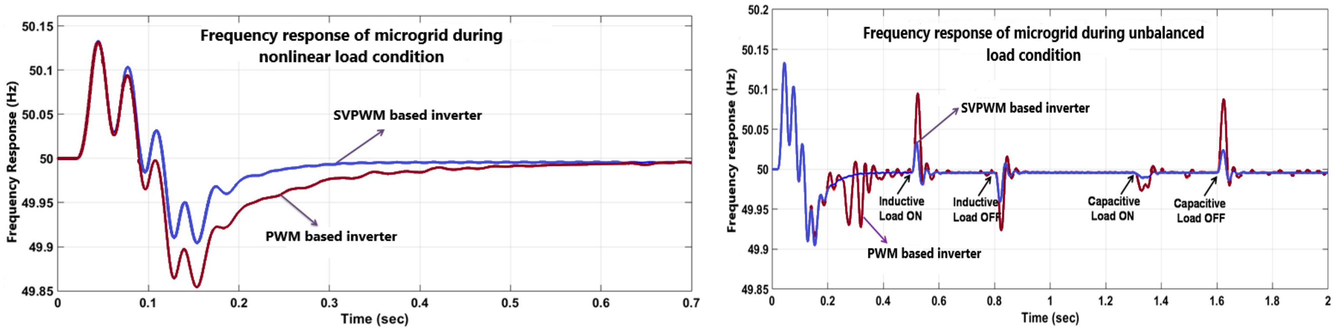


Fig. 7. Comparative analysis of frequency features of grid using traditional PWM and suggested TPH-STATCOM integrated SV-PWM with EPOA optimisation-based inverters.

By contrasting the system's performance with and without the compensator and modulation techniques, insights are gained into the efficacy of the proposed solution in improving power quality. The analysis includes assessing parameters such as voltage sag/swell mitigation, frequency deviation reduction, and harmonic distortion suppression achieved by the TPH-STATCOM-SV-PWM system. Figures 5-9 display the outcomes of the simulations that were simulated. Table 1 presents the combined quantitative statistics.

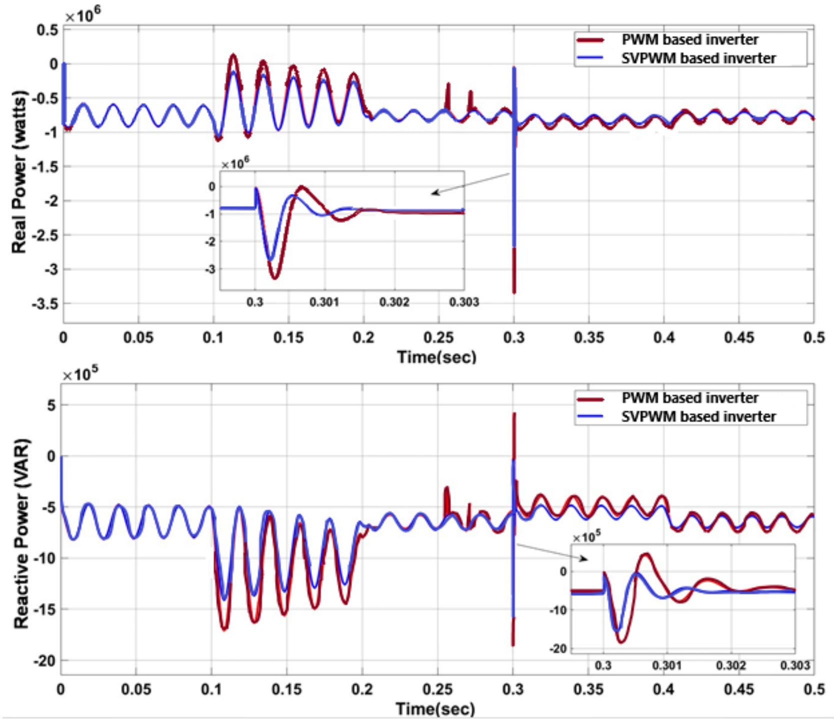


Fig. 8. Comparative analysis of power features of grid with traditional PWM and suggested TPH-STATCOM integrated SV-PWM with EPOA optimisation-based inverters.

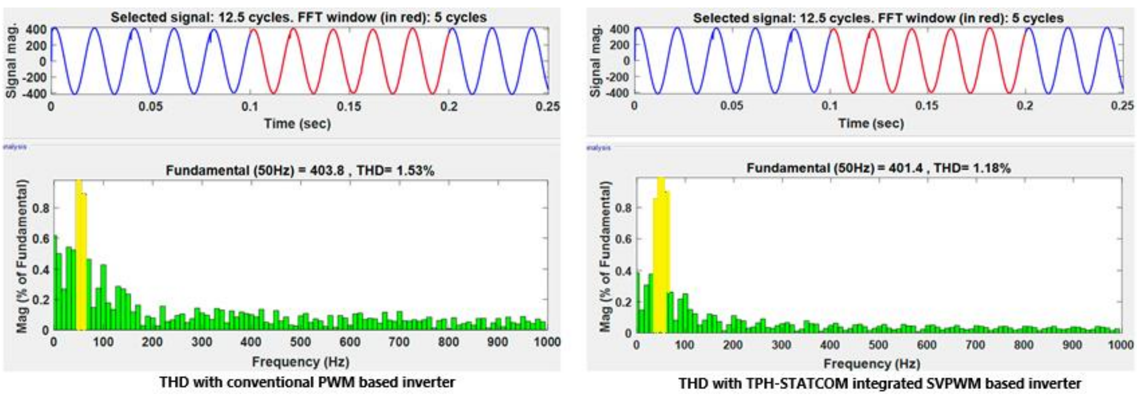


Fig. 9. Comparative analysis of THD features of microgrid with traditional PWM and proposed TPH-STATCOM integrated SV-PWM with EPOA optimisation-based inverters.

5.2 System performance Evaluation under Different Operating Conditions

Furthermore, the section evaluates the performance of the system under various wind conditions and load scenarios. Different wind velocity profiles and load variations are simulated to assess the robustness and adaptability of the TPH-STATCOM-SV-PWM system. The evaluation considers factors such as wind power output fluctuations, grid voltage disturbances, and load variations, highlighting the system's ability to maintain power quality and grid stability under dynamic operating conditions.

Table 1. Comparative analysis of power quality measures with traditional and proposed methods.

Measures		Traditional System	Proposed SV-PWM System with HSTATCOM+EPOA
Voltage Characteristics	Sag	39.7%	15.7%
	Swell	2.7%	2.79%
	Imbalance	3.05%	1.255%
Frequency Characteristics	Settling time	0.47 s	0.4 s
	Deviation (dynamic load)	1	0.27
Power Features	Settling duartion of Real power outage	2 millisec	1.2 millisec
	Settling duartion of Reactive power outage	3 millisec	1.1 millisec
Total Harmonic Distortion		7.49%	3.75%

5.3 Efficacy of the Proposed Method

The effectiveness of the proposed TPH-STATCOM-SV-PWM system with EPOA optimisation in enhancing power quality and its advantages over existing methods includes:

i. The TPH-STATCOM-SV-PWM+EPOA system's ability to mitigate voltage fluctuations and maintain voltage stability, particularly during transient grid disturbances and sudden changes in wind power output.

ii. The effectiveness of SV-PWM techniques in reducing THD and improving the feature of the yield voltage waveform, resulting in cleaner power delivery to the grid.

iii. The advantages of the TPH-STATCOM-SV-PWM+EPOA system over conventional compensation techniques, such as its faster response time, higher efficiency, and improved dynamic performance.

iv. The potential economic and environmental benefits of deploying the TPH-STATCOM-SV-PWM+EPOA system, including reduced grid losses, enhanced grid reliability, and increased renewable energy penetration.

6. CONCLUSION AND FUTURE WORK

The Three-Phase Hexagram Static Compensator (TPH-STATCOM) with SV-PWM methods has emerged as a promising solution for enhancing power quality in PMSG-based wind power plants. Through comprehensive analysis, this study underscores the pivotal role of TPH-STATCOM-SV-PWM in mitigating voltage instability, regulating frequency fluctuations, and suppressing harmonic distortions, thus addressing critical challenges in renewable energy integration. The findings provide valuable insights into the design and operation of PMSG-based WES, advancing the understanding of power quality enhancement techniques and contributing to the renewable energy sector's sustainability. Moreover, the introduction of the Enhanced Pelican Optimization Algorithm (EPOA), integrating the Lévy flight distribution, signifies a significant advancement in optimizing power quality at microgrids. By enhancing the initial population and global search ability of the algorithm, EPOA demonstrates its potential to further improve the efficiency and performance of microgrid power quality optimization. This innovation highlights the importance of leveraging advanced optimization techniques to address complex challenges in renewable energy systems effectively.

Looking ahead, the study identifies several promising avenues for future research and development. These include refining control algorithms and parameters to enhance the dynamic performance and efficiency of TPH-STATCOM-SV-PWM systems, exploring advanced energy storage solutions such as battery energy storage systems (BESS) and supercapacitors for auxiliary support and energy management, and integrating predictive maintenance techniques to enhance system reliability. Additionally, the investigation of hybrid renewable energy systems and microgrid configurations presents opportunities for enhancing resilience, flexibility, and energy independence, especially in remote or islanded regions. Collaboration with industry stakeholders and policymakers will be crucial to facilitating technology transfer and commercialization, ensuring widespread adoption, and accelerating the transition towards a sustainable and renewable energy future. Through concerted efforts in these areas, the proposed TPH-STATCOM-SV-PWM system and EPOA algorithm can lead the way in advancing power quality enhancement for PMSG-based WES, driving positive change in the renewable energy landscape.

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