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Original Article

Advanced Control Techniques for Power Quality Enhancement in Off-Grid Wind Power Systems

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Abstract *- Renewable energy output, particularly from wind power, is dependent on unpredictability due to its reliance on climate conditions. Due to this fluctuation, relying only on these sources for a steady power supply is impractical. A constant power source becomes even more crucial in areas where grid electrification is difficult, such as distant locations. To address this problem, the concept of an Isolated Wind Power Generation System (IWPGS) has arisen, designed to operate under variable wind and load situations. However, IWPGS systems suffer power quality issues. Power electronic interfaces can cause harmonics and power quality degradation, nonlinear loads coupled to the system, and the reactive power consumption generated by these loads. This paper presents an Active Power Filter (APF) to solve the power quality issues related to IWPGS. The APF is a device that improves power quality by adjusting for harmonics, reactive power, and other electrical system disturbances. A thorough analysis of numerous indexes proves the APF's performance. These metrics assess the APF's performance in reducing harmonics, improving power factor, and improving the overall power output quality in the IWPGS. This research aims to demonstrate that including an APF into an IWPGS can significantly enhance its power quality, making it a more stable and sustainable energy source, especially in distant places where grid connection is not always possible.*

Keywords *- Power quality enhancement, Wind energy integration, Voltage regulation, Pulse Width Modulation, Total Harmonic Distortion.*

1. Introduction

Off-grid wind power systems gained popularity as sustainable and dependable sources of electricity in isolated and rural areas where grid connectivity was either absent or unreliable. These systems harnessed the wind's kinetic energy to generate electricity, offering a clean and environmentally friendly alternative to conventional diesel generators or expensive grid upgrades. However, integrating wind power into off-grid systems presented several challenges, with power quality emerging as a significant concern. Voltage stability, frequency regulation, and harmonic distortion were all examples of power quality issues that must be addressed.

High power quality was a critical requirement in off-grid wind power systems to ensure the efficient and stable operation of connected loads and to minimize potential damage to sensitive equipment. To achieve this, engineers and designers of these systems employed various techniques and technologies. They implemented voltage regulation mechanisms to maintain a consistent voltage level, ensuring connected devices received a reliable power supply. Frequency regulation systems were also employed to keep the electrical frequency within acceptable limits, preventing disruptions to the performance of electrical appliances. Furthermore, measures were taken to minimize harmonic distortion, which could lead to electrical noise and interference in the system. Filters and power conditioning equipment were commonly used to reduce harmonic distortion and ensure the power output met the required quality standards [1-3].

In the past, ensuring power quality in off-grid wind power systems presented many challenges that required advanced control solutions. The variable nature of wind speeds led to frequent fluctuations in power output, necessitating the implementation of complex control algorithms. These algorithms were crucial for maintaining stable voltage and frequency levels within the off-grid system. One of the significant developments in the past was integrating energy storage systems. These systems played a pivotal role in mitigating power outages caused by the inherent variability of wind power. Sophisticated control systems were developed to efficiently manage energy storage, ensuring a continuous and reliable power supply.

Off-grid wind power systems also faced issues related to harmonic distortion and voltage sags. To address these problems, complex filtering and compensation approaches were employed. These solutions helped maintain a clean and stable electrical supply for sensitive electronic equipment and appliances. Another significant challenge in the past was coordinating multiple distributed energy resources, including wind turbines, solar panels, and diesel engines. Optimizing power quality and system efficiency required intricate control strategies to balance the contribution of each energy source and ensure a reliable power supply. In retrospect, addressing these complex control challenges was of utmost importance for the reliability and performance of off-grid wind power systems in the past. These advancements paved the way for more dependable and efficient off-grid renewable energy solutions, contributing to a greener and more sustainable energy landscape [4-8].

2. Literature Review

Off-grid wind power systems have received significant attention recently as a promising way to offer clean, renewable energy to remote or isolated areas. These devices created power by harnessing the kinetic energy of the wind, providing an environmentally acceptable alternative to fossil fuels. Despite their enormous potential, off-grid wind power systems have advantages and disadvantages. One of the key benefits was their capacity to supply a dependable and sustainable source of electricity, reducing reliance on traditional grid infrastructure and lowering greenhouse gas emissions. Off-grid wind power systems were especially useful in rural and off-grid areas with limited or no connection to centralized power grids. They helped achieve energy independence and could drastically lower long-term energy bills. One significant difficulty was the intermittent nature of wind energy, which was affected by wind speed and direction. Energy storage devices, such as batteries, were critical for storing extra wind energy and releasing it when needed. Furthermore, the upfront expenses of off-grid wind power systems could be very substantial, making them less accessible to some communities. Maintenance and technical skills were also required to ensure these systems' long-term reliability [9-11].

The amount by which the electrical waveform generated by the wind turbine deviated from a pure sinusoidal waveform was referred to as Total Harmonic Distortion (THD). This distortion caused several issues with off-grid wind power systems. To begin with, high THD levels harmed sensitive electrical equipment such as inverters, appliances, and electronic devices. These devices were intended to operate on a pure sinusoidal waveform, and harmonic distortion caused overheating and premature failure.

Furthermore, THD caused system inefficiencies, lowered overall performance, and reduced energy generation. Harmonics in the electrical system caused increased energy losses, resulting in a lower wind turbine power output. These challenges were significant considerations for those managing and maintaining off-grid wind power systems in the past. The impact on the system's reliability and economic sustainability affected the off-grid area's energy demands and jeopardized its long-term viability. Mitigating THD in off-grid wind power systems has presented significant challenges. It often required the deployment of expensive harmonic filters, which proved challenging to maintain in remote locations. Additionally, ensuring these filters' correct sizing and installation was crucial for effectively addressing the issue during that time [11-15].

The charge controller was a typical type used in off-grid wind power systems. It regulated the charging and discharging of batteries to store extra energy for later use. These controllers frequently faced battery maintenance issues, such as sulfation and overcharging, which could impact battery longevity and system efficiency. Regular monitoring and maintenance were essential for mitigating these problems. The inverter, which converted Direct Current (DC) generated by wind turbines and stored in batteries into Alternating Current (AC) for household or industrial usage, was another crucial controller. Voltage fluctuations and harmonic distortions could occur in inverters, impacting the quality of power delivered to appliances.

Furthermore, in the past, off-grid wind power systems had to contend with intermittent wind conditions, necessitating the incorporation of energy storage and backup power sources. The controller algorithms of these systems had to be exceptionally clever to effectively handle the unpredictability of wind energy, all while ensuring a consistent power supply. Moreover, sizing the system and ensuring component compatibility posed significant challenges.

Diverse components had to seamlessly work together to optimize power generation and storage in these systems. This required careful consideration of various factors, including the capacity of the wind turbine, the capacity and type of energy storage, and the efficiency of the entire system. Engineers and designers of off-grid wind power systems had to grapple with these complexities to create reliable and efficient solutions in the past [16-21].

The most renowned applications of Renewable Energy Systems (RES) in the past were Photovoltaic panels (PV) and Wind Turbines (WT). A notable drawback of RES systems has historically been their intermittent nature. Speed control for WT was a crucial aspect of power generation, as it was heavily influenced by connecting the generator to loads or the grid. Options included a total converter with the generator, a wound rotor generator equipped with resistance, or a Double Feed Induction Generator (DFIG), all operated at fixed speeds.

In the past, grid-connected WT systems often featured a 12-kW variable speed asynchronous generator and a 600 V DC link. These systems utilized an AC-DC-AC converter with a back-to-back break chopper, resulting in the highest recorded power losses of 430 W. In a previous study, a 1,050 V DC link converter was employed in conjunction with a Permanent Magnet Synchronous Generator (PMSG) to enhance Power Quality (PQ) and achieve Maximum Power Point Tracking (MPPT). This control structure encompassed a fuzzy logic controller on the turbine side and a PI controller on the load side. The generator employed in this research possessed specifications of 2 KVA output capacity, operated at a speed of 1,800 rpm, and notably, did not require slip rings and brushes.

Furthermore, this generator was designed to be maintenance-free, eliminating the need for rare earth magnets. To regulate the current in the system, a hysteresis current control technique was implemented in conjunction with an AC-DC inverter, as described in [5]. This technique necessitated the incorporation of peak and valley current detectors, constructed using RC integrators and RS flip-flops to enable real-time monitoring of current values [22-25].

A novel control approach was employed for a back-to-back converter with a DC connection linked to a Permanent Magnet Synchronous Generator (PMSG) to enhance Power Quality (PQ) and Maximum Power Point Tracking (MPPT) performance. The introduced APF method reduced source current harmonics without necessitating intricate component adjustments while maintaining a power factor close to unity across a broad range of loads. The APF technique enhanced PQ in an isolated wind turbine WT system equipped with a PMSG supplying power to a nonlinear load. The outcomes were compared between the APF method and the traditional approach involving tuning inductors and capacitors [26-29].

Voltage fluctuations and frequency oscillations in isolated hybrid power systems demanded robust control strategies in the past, and these were achieved by opting for suitable soft computing algorithms like the Genetic Algorithm (GA), Particle Swarm (PS) algorithm, mine blast algorithm, and various other Artificial Intelligence (AI) applications. In the past, addressing voltage fluctuations and frequency oscillations in isolated hybrid power systems required implementing resilient control strategies. These were effectively attained through carefully selecting appropriate soft computing algorithms, including but not limited to the Genetic Algorithm (GA) and a diverse range of Artificial Intelligence (AI) applications [30].

In off-grid wind power systems, one of the primary challenges was the intermittent nature of wind energy. Wind speeds could vary dramatically, leading to fluctuations in power output. Advanced control techniques, such as predictive control and energy storage integration, were pivotal in mitigating these issues. Predictive control algorithms were employed to anticipate changes in wind conditions and adjust the operation of the wind turbines and energy storage systems accordingly, ensuring a smooth and uninterrupted power supply [31, 32].

On the other hand, on-grid wind power systems faced challenges related to grid integration and power quality. Wind turbines generated power that had to be synchronized with the grid’s frequency and voltage levels. Variations in wind speed often lead to voltage and frequency fluctuations, causing power quality issues like voltage sags and flicker. To address these problems, advanced control techniques were employed, including using grid-connected inverters equipped with active power filters. These inverters could rapidly adjust their output to compensate for fluctuations in wind power, maintaining stable grid conditions.

Another critical issue that both off-grid and on-grid systems faced in the past was the introduction of harmonics by power electronic converters. These harmonics could potentially distort voltage and current waveforms, significantly impacting overall power quality. Advanced control techniques such as model predictive and resonant controllers were applied to mitigate these effects, minimizing harmonics and ensuring clean and sinusoidal waveforms.

Moreover, cybersecurity emerged as a concern in past wind power systems. As these systems became more connected and reliant on digital control and communication networks, they became increasingly vulnerable to cyberattacks. Advanced control techniques from the past had to incorporate robust cybersecurity measures to protect against unauthorized access and tampering, safeguarding the integrity and reliability of wind power systems [33-37].

A PMSG connected with a WT, nonlinear loads, and advanced control approaches to improve power quality in off-grid wind power systems. It had been mentioned the following objectives:

Implement a closed-loop controller for the PMSG to maintain stable mechanical torque production, ensuring optimal energy extraction from varying wind conditions.

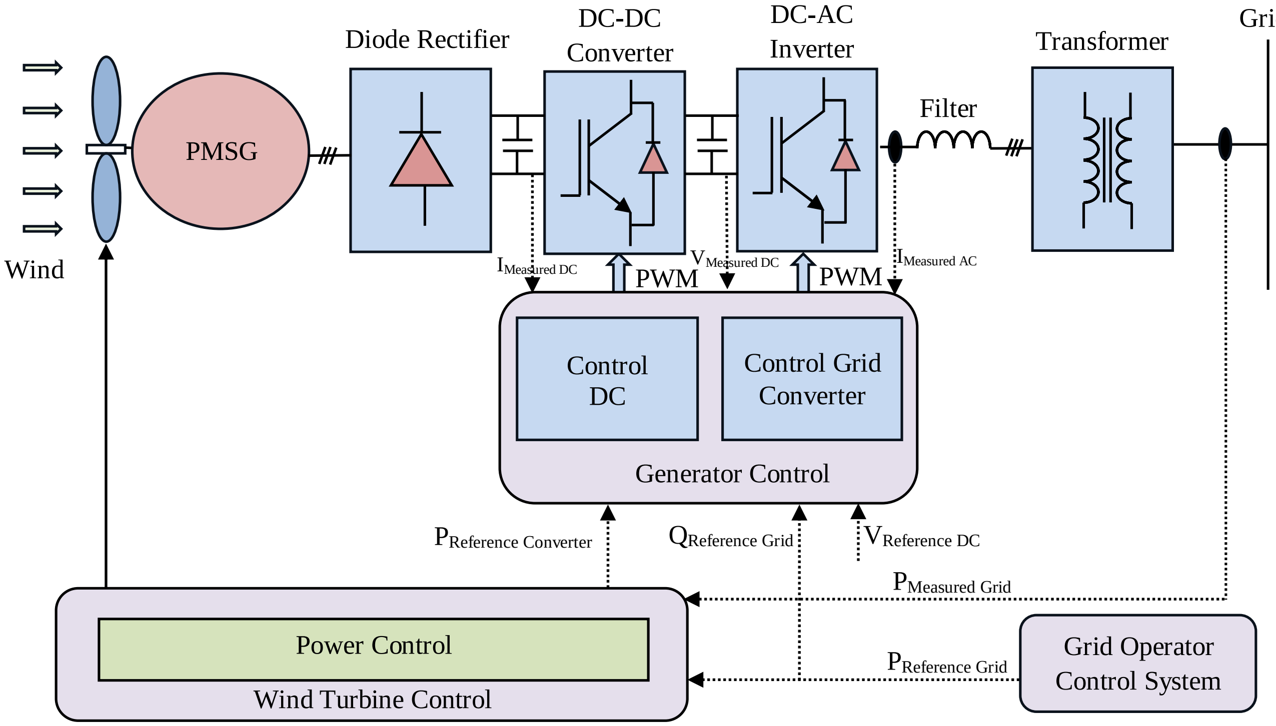

Fig. 1 Structure of isolated wind turbine conversion system

- To design an efficient controller to regulate the output voltage amplitude, maintaining it within acceptable limits to avoid voltage sag or swell during load changes.
- To employ advanced control algorithms and active filters to mitigate harmonics generated by nonlinear loads, ensuring a clean power supply to connected loads.
- To develop a robust inverter control strategy to efficiently convert the variable DC output of the PMSG into stable AC power for the load.
- To optimize the LC filter design to suppress high-frequency voltage components and filter out switching harmonics, improving the overall power quality.
- To implement an intelligent energy management system to balance power supply and demand, ensuring reliable operation and efficient energy utilization in off-grid scenarios.

3. Structure of Isolated Wind Turbine with PMSG

The isolated wind turbine conversion system, formed of several connected parts, was essential for capturing and incorporating wind energy into the grid. A Permanent Magnet Synchronous Generator (PMSG) was at the heart of the system to transform the wind's kinetic energy into electrical energy. The generated AC power was then rectified into DC electricity using a diode rectifier. A DC-DC converter adjusted the voltage levels to guarantee effective power transfer.

The DC power was subsequently transformed into AC power using a DC-AC converter, making it eligible for grid integration. In reaction to shifting wind conditions, wind turbine control systems continuously monitor and improve the turbine's performance. In addition, the grid operator control system made sure that the electrical grid and the wind turbine had constant communication, enabling effective power injection. An active power reference converter and reactive power reference grid were utilized to control the active and reactive power output to keep the system stable. The voltage levels were maintained within acceptable bounds using a voltage reference DC.

Generator control systems made sure the PMSG was running at its best. While transformers made it easier to transform voltage for grid connection, filters were used to reduce harmonics and voltage swings. In the end, this integrated system made it easier to convert wind energy into a dependable supply of electricity, which assisted in creating a sustainable and environmentally friendly energy landscape. Figure 1 illustrates the structure of the isolated wind turbine conversion system.

The kinetic energy of an object is given by in expression (1),

$$E = \frac{1}{2} m \upsilon^2 \tag{1}$$

Where, m is mass (kg) and υ (m/s) is the velocity.

The power available in wind can be defined in equation (2),

$$P = \frac{1}{2}\rho\upsilon^3 A \quad (2)$$

Where A is the cross-sectional area (m^2) of the wind turbine and ρ is the air density.

The coefficient factor Cp for the WT can be expressed in equation (3),

$$C_p = \frac{P_0}{P} \quad (3)$$

The power converted from the wind speed is expressed in equation (4),

$$P_0 = C_P \frac{1}{2}\rho A\upsilon^3 \quad (4)$$

Tip-speed ratio of wind turbine can be expressed in equation (5),

$$\lambda = \frac{R\ \omega}{\upsilon} \quad (5)$$

Where R is the radius of the wind turbine, and ω is the angular speed of the wind turbine.

Permanent Magnet Synchronous Generator *d* and *q* axis change in current, it can be expressed in equation (6) and (7) respectively,

$$\frac{dI_d}{dt} = -\left(\frac{R_a}{L_d}\right)I_d + \omega_s\frac{L_q}{L_d}I_q + \frac{1}{L_d}U_d \quad (6)$$

$$\frac{dI_q}{dt} = -\frac{R_a}{L_q}I_d - \omega_s\left(\frac{L_d}{L_q}I_d + \frac{1}{L_q}\psi_p\right) + \frac{1}{L_q}U_q \quad (7)$$

Where R_a is the resistance, L_d is the *d* axis inductance, L_q is the *q* axis inductance, ω_s is the angular speed of the rotor, ψ_p is the permanent flux, U_d is the d-axis voltage, and Uq is the q-axis voltage.

An extensive procedure was required to integrate renewable energy into the connectivity of a wind turbine generator. A three-phase full bridge diode rectifier was the first component, and its primary function was to change the alternating current produced by the wind turbine into direct current. This rectifier was essential in guaranteeing a reliable and constant DC output.

The DC boost converter came next and was in charge of increasing the DC voltage to a level appropriate for effective power transmission. This increase in voltage was required to reduce power losses during the energy transfer to the grid. The three-phase inverter, the last component of this complex system, was created to transform the amplified DC power back into grid-compatible AC.

The inverter's function was crucial in ensuring that the electricity produced by the wind turbine could integrate easily into the current grid system. In the end, this networked system enabled the clean, renewable energy produced by the wind turbine to be effectively transmitted to the grid, supplying a dependable source of electricity to power homes and businesses while lowering carbon emissions and dependence on non-renewable energy sources. Figure 2 illustrates the interconnection of three three-phase diode rectifiers, boost converter, and three-phase inverter to load and generator.

The electro-mechanical torque produced by the wind turbine can be expressed in equation (8),

$$T_e = -1.5\frac{P}{2}\left[\left(\psi_p I_q + I_d I_q\left(L_d - L_q\right)\right)\right] \quad (8)$$

The phase voltage transformation of the three-axis system can be expressed in equations (9), (10), and (11), respectively,

$$U_{ga} = U_{Ia} - L\frac{dI_a}{dt} - IR_a \quad (9)$$

$$U_{gb} = U_{Ib} - L\frac{dI_b}{dt} - IR_b \quad (10)$$

$$U_{gc} = U_{Ic} - L\frac{dI_c}{dt} - IR_c \quad (11)$$

The axis voltage transformation system can be expressed in equations (12) and (13), respectively,

$$U_d = R_a I_d - \omega_s L_q I_q + \frac{dI_d}{dt}L_d \quad (12)$$

$$U_q = R_a I_q + \omega_s L_d I_d + \frac{dI_q}{dt}L_q + E_s \quad (13)$$

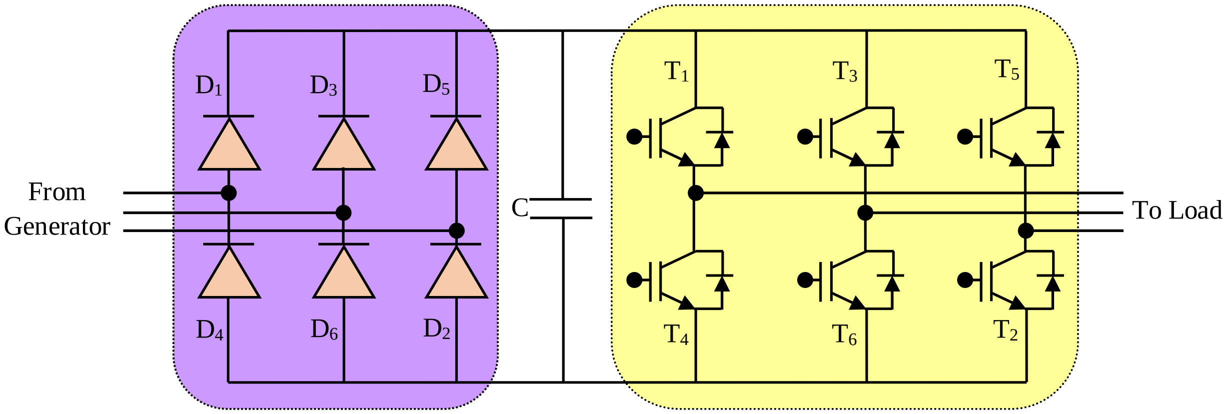

Fig. 2 Interconnection of diode rectifier-DC boost converter-three phase inverter to load

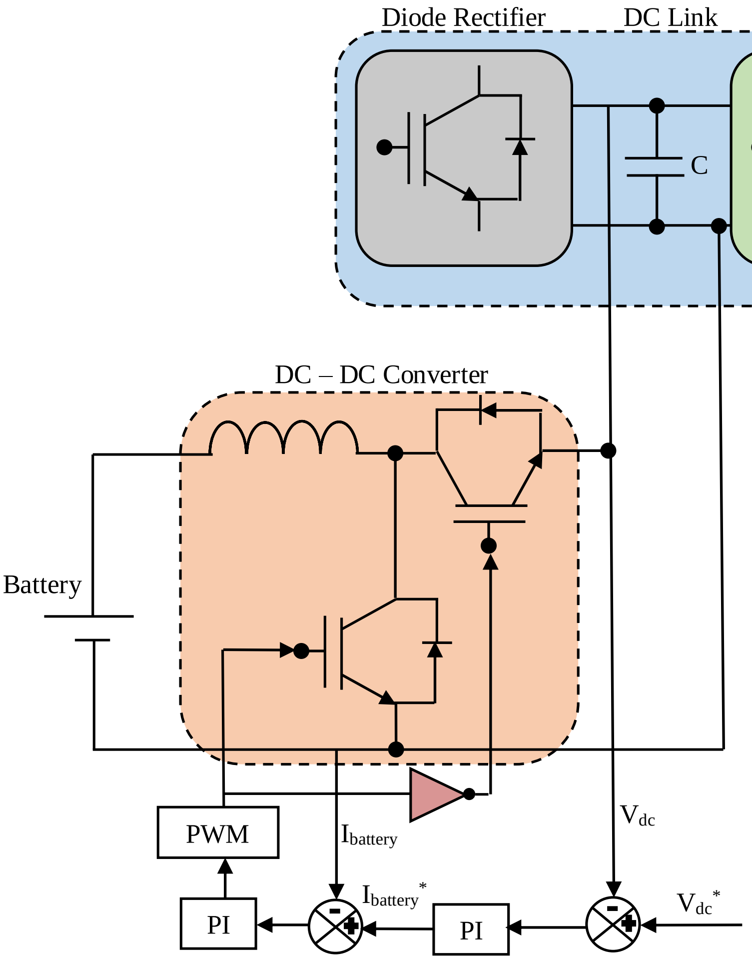

Fig. 3 Controller of DC-DC converter and diode rectifier and inverter system

Transformed d and q axis, controllers can be expressed in equations (14) and (15), respectively,

$$U_d = e_d - RI_d + \omega\ L\ I_q - L\frac{dI_d}{dt} \tag{14}$$

$$U_q = -R_a I_q - \omega\ L\ I_d - L\frac{dI_q}{dt} \tag{15}$$

Simplifying the above two equations final simplified expression can be illustrated in equation (16),

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t - \theta) \\ \sin(\omega t - \theta) \\ 0 \end{bmatrix} \tag{16}$$

θ is the Estimated angle in e a-b-c to d-q transformation.

The performance of a wind turbine is essential for producing energy efficiently, and incorporating a Proportional-Integral (PI) controller within its DC-DC converter is critical to optimizing this procedure. A typical control technique called the PI controller modifies the duty cycle of the converter's switching components to control the output voltage.

It balances the trade-off between transient reaction and steady-state precision to ensure that the wind turbine runs at its peak power for optimum energy extraction. A diode rectifier works with a DC-DC converter to change the changing AC output from the wind turbine generator into a steady DC voltage.

As a device for unidirectional current flow, the diode rectifier only permits forward current to pass from the generator to the DC connection. The DC voltage is then converted into AC by the inverter system's last component, making it eligible for grid connection. The PI controller in the inverter system makes seamless integration with the electrical grid possible, ensuring the output voltage and frequency precisely match the grid's needs.

This system, which includes a wind turbine, a DC-DC converter with a PI controller, a diode rectifier, and an inverter, guarantees effective energy conversion, grid synchronization, and overall optimal performance, promoting renewable energy sources and sustainable power generation.

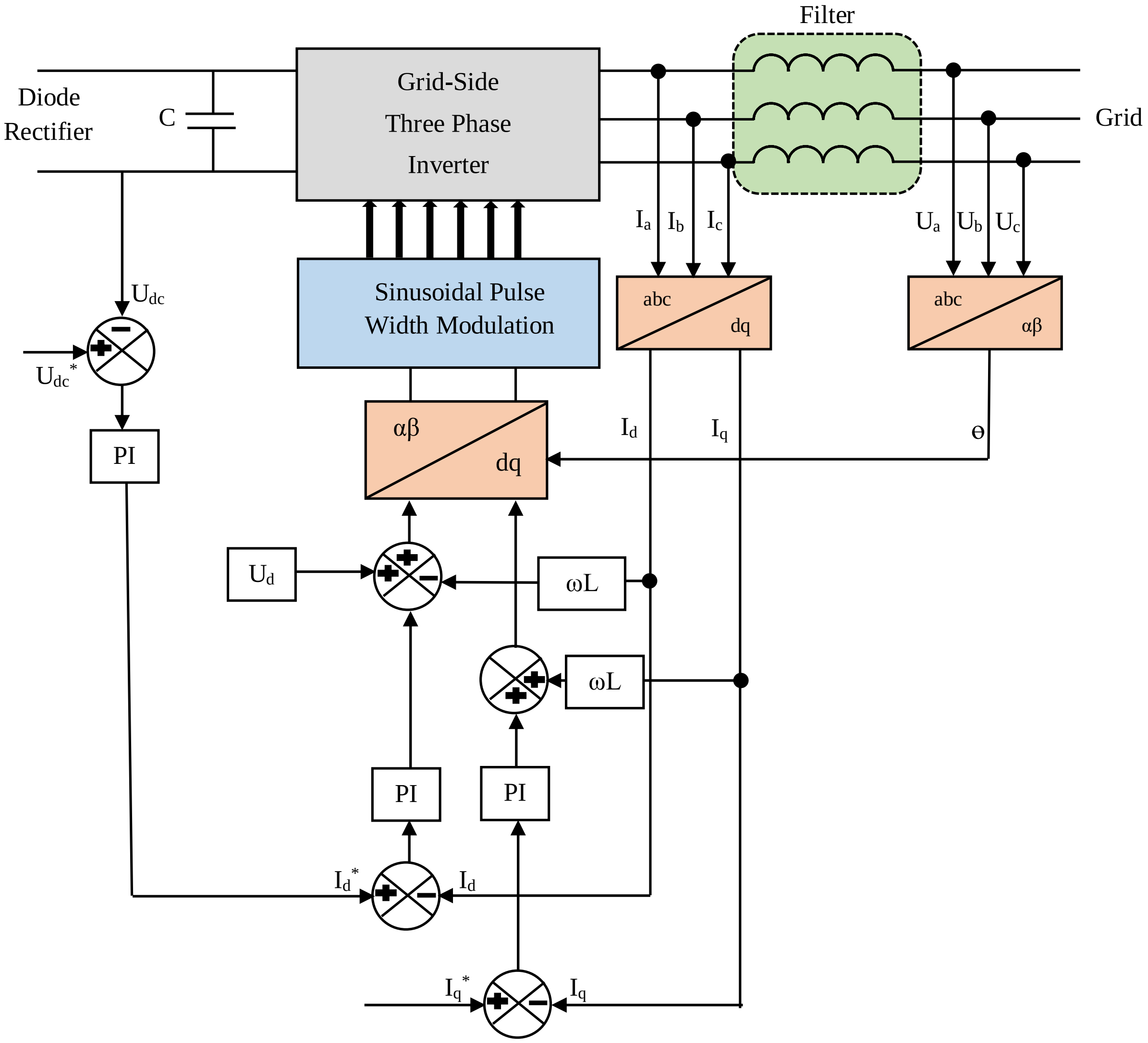

Fig. 4 Three-two axis transformation and two-three-axis transformation of controller from diode rectifier and grid

Advanced techniques such as clark/park three-axis transformation are used to improve control and effectiveness. By transforming the AC variables into a two-axis reference frame using this transformation, the analysis is made more straightforward, and the DC voltage can controlled precisely. The next stage includes using an inverter to change the DC voltage into an alternating voltage. Popular techniques include sinusoidal Pulse Width Modulation (PWM), which synthesizes the inverter’s output voltage by adjusting its power components’ switching timings.

However, this conversion process frequently includes harmonics into the output voltage, which must be filtered away to provide a clean AC waveform. To accomplish that, filters are used, assuring adherence to grid requirements and minimizing electromagnetic interference. Utilizing a PI controller to manage the output voltage and current is standard practice. This controller improves system stability and transient response by continuously adjusting the inverter’s output to maintain optimal performance. Figure 4 illustrates the Three-two-axis transformation and two-three-axis transformation of the controller from the diode rectifier and grid.

4. Results and Discussion

Figure 5 shows the Permanent Magnet Synchronous Generator’s (PMSG) speed in (a), the rotor current in (b), and the stator current in (c). The Wind Energy Conversion System’s (WECS) performance and behaviour can be examined through these crucial factors. The output voltage of the three-phase diode bridge rectifier, which is necessary for converting the alternating current produced by the PMSG into direct current for further processing, is shown in Figure 6. The boost converter’s DC link output voltage, which represents the voltage level following the rectification and boosting stages, is shown in Figure 7. Figure 8 provides a thorough overview of the power generation and use inside the system by displaying the Active and Reactive Power generated in the WECS. The pulse signal supplied to the three-phase inverter, which regulates the production of three-phase AC output, is shown in Figure 9. Figure 10 compares the three-phase output voltage with and without a filter to show how well the filter works to lower voltage aberrations.

Understanding the voltage gain of the DC Link Boost Converter, which is essential for improving the energy conversion process, is provided in Figure 11. Figure 12 examines the three-phase inverter Total Harmonic Distortion (THD), contrasting the performance with and without a filter to judge the ability of the generated three-phase output voltage. These statistics help with the investigation, control, and optimization of the WECS by forming a complete visual narrative of its different components. Table 1 illustrates the overall performance parameters of the wind energy conversion system.

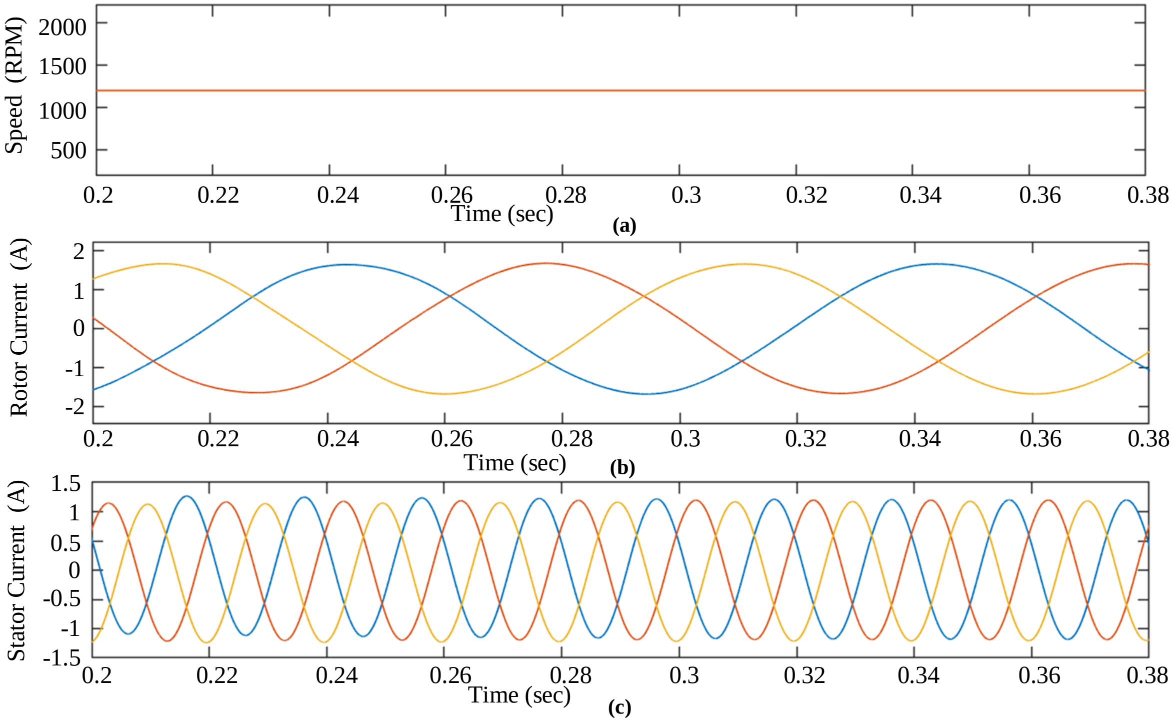

Fig. 5 (a) Speed of PMSG, (b) Rotor current, and (c) Stator current.

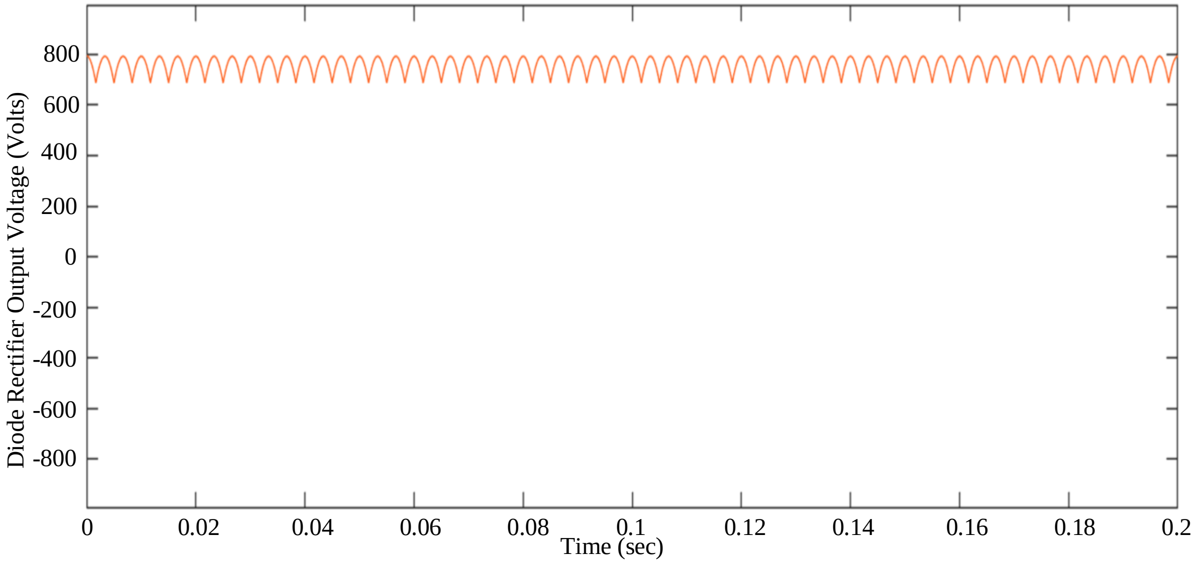

Fig. 6 Three-phase diode bridge rectifier output voltage

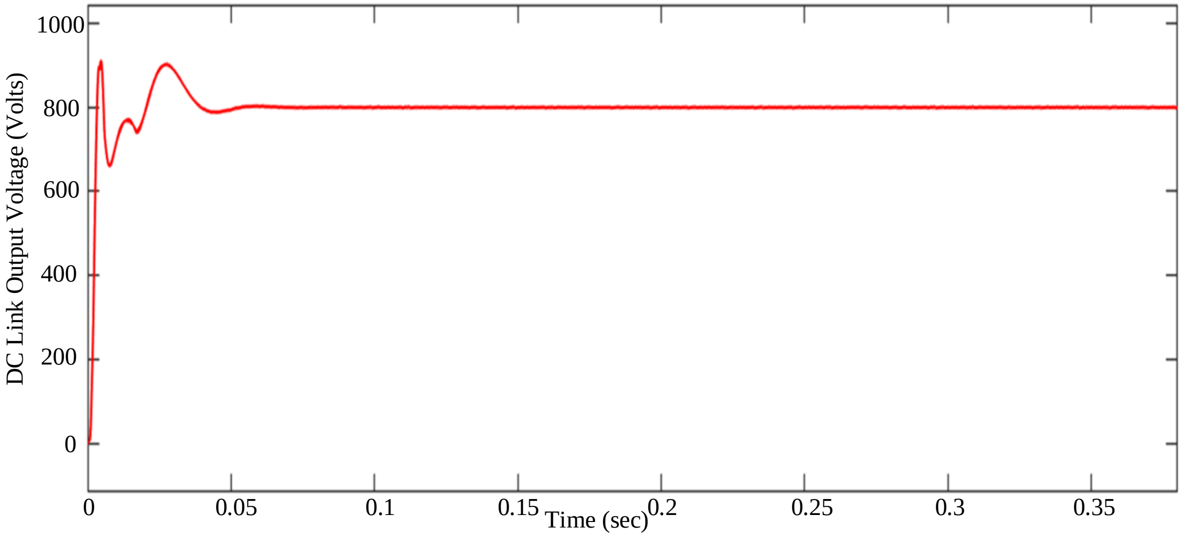

Fig. 7 DC link output voltage of boost converter

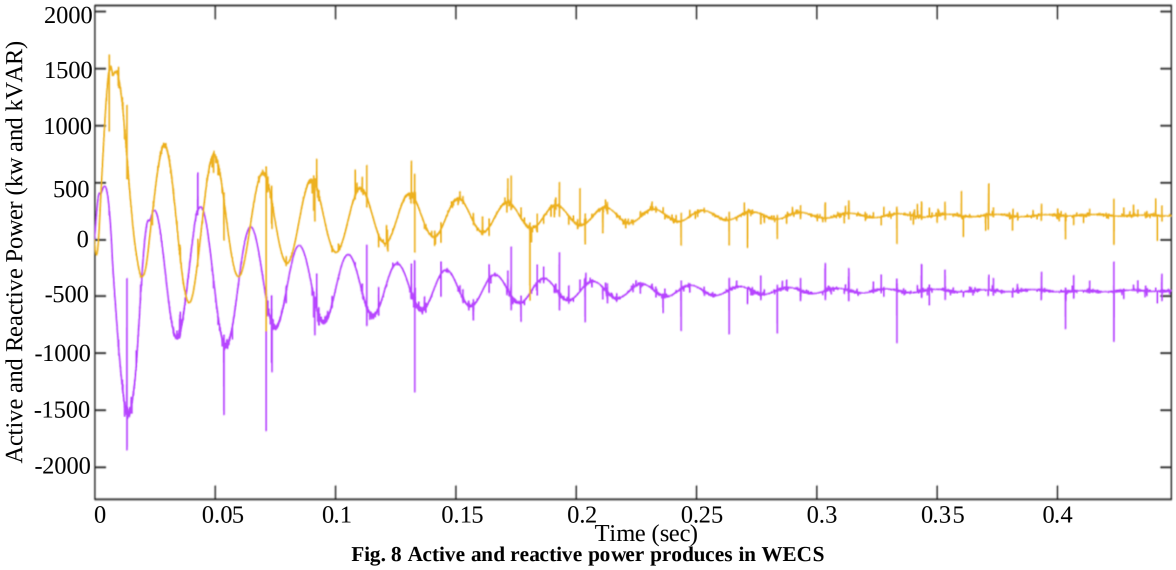

Fig. 8 Active and reactive power produces in WECS

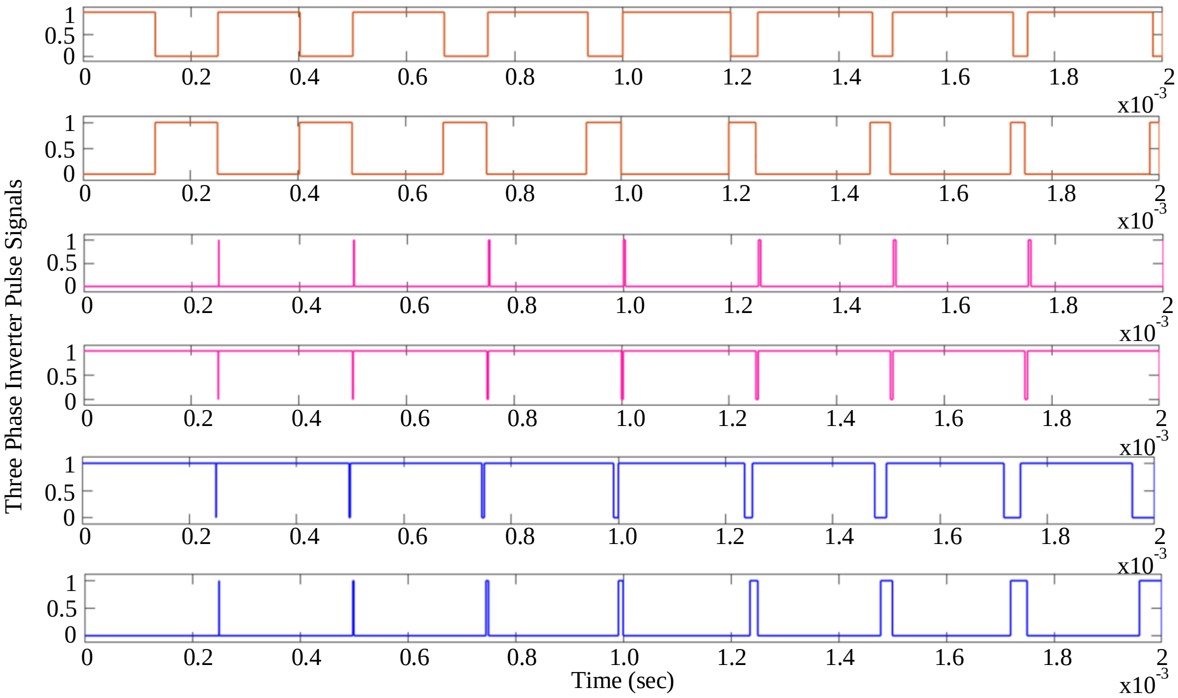

Fig. 9 Pulse signal to three-phase inverter

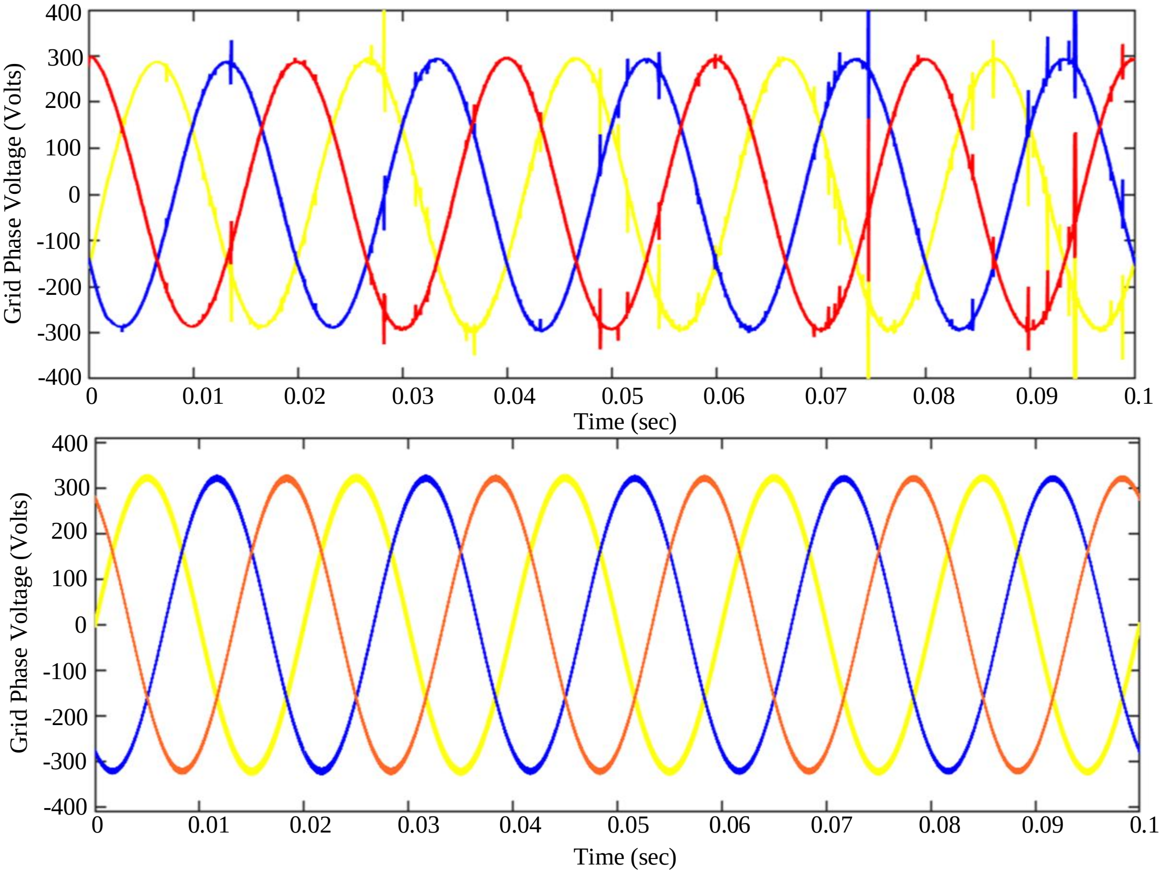

Fig. 10 Three-phase output voltage with and without filter

Table 1. Performance parameters of wind energy conversion system

Parameters	Value
PMSG	
Number of Pair Poles	2
Stator Resistance	2 Ω
Inductance on the d-Axis	0.526 H
Inductance on the q-Axis	0.243 H
Rotor Flux Linkage	1 Wb
Speed	1200 rpm
Rotor Current	1.8 A
Stator Current	1.2 A
Three-Phase Diode Rectifier Output Voltage	800 V
Boost Converter	
Internal Resistance of Inductor	0.2 Ω
Inductance	0.009 H
Capacitance	147 µF
DC Link Output Voltage	800 V
Duty Cycle	0.8
Voltage Gain	5.2
Three Phase Inverter	
Number of IGBT Switches	6
Number of Driver Circuits	6
Switching Frequency	2 kHz
Grid	
RMS Three-Phase Grid Voltage	300 V
Filter - Resistance	0.8 Ω
Filter - Inductance	0.65 H
%Total Harmonic Distortion (Current) - Without Filter	18 (RL Load)
%Total Harmonic Distortion (Current) - Filter	2.3 (RL Load)

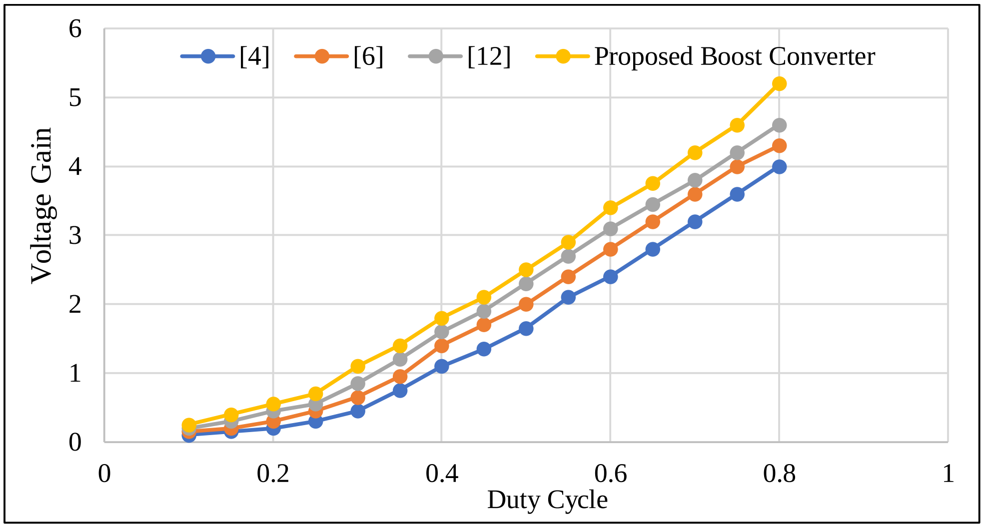

Fig. 11 Voltage gain of DC link boost converter

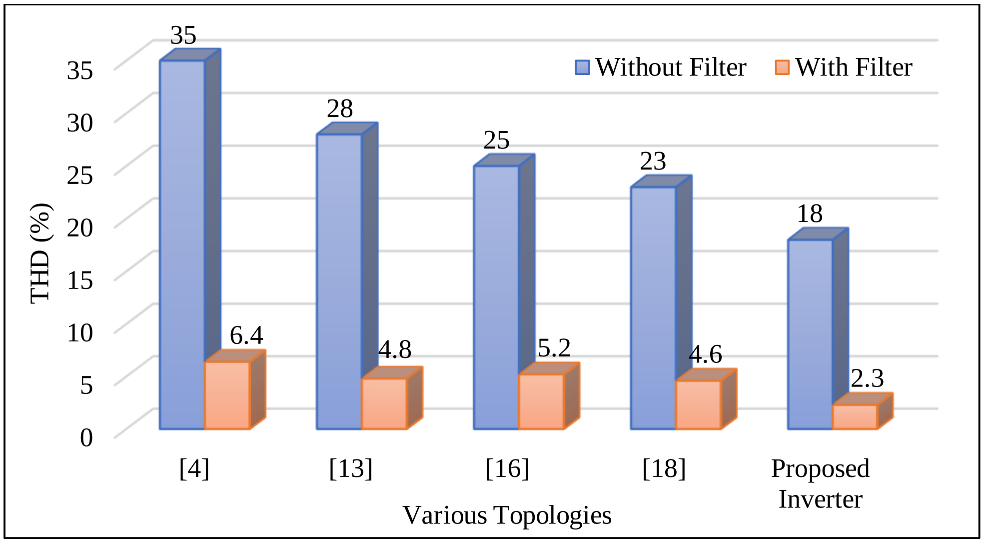

Fig. 12 Three-phase inverter THD analysis based on with and without filter

5. Conclusion

The critical issue of power quality in isolated wind power generation systems is discussed in this paper, and an effective solution in the form of an active power filter has been proposed. Despite being crucial for remote and grid-challenged areas, IWPGS systems experience power quality issues for various reasons, such as harmonics, reactive power consumption, and nonlinear loads. The APF is promoted as a workable solution to these problems, capable of strengthening system stability and improving power quality by reducing harmonics and reactive power. This research investigation proves the effectiveness of the APF in lowering harmonics, boosting power factor, and raising the general Caliber of power output in IWPGS settings by a thorough review of numerous performance measures. These results suggest that adding an APF to an IWPGS can significantly improve its dependability and sustainability, particularly in rural areas where grid access is inconsistent or insufficient. Future improvements in control methods could substantially improve the power quality of off-grid wind power installations. The creation of advanced predictive control algorithms that can foresee and immediately address power quality problems is a crucial field of investigation. These algorithms can increase system performance using updated sensor technologies and data analytics. A continuous power supply can be ensured under various wind situations by integrating energy storage solutions, such as innovative batteries, which can further stabilize power output.

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