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Enhancing off-grid wind energy systems with controlled inverter integration for improved power quality

Introduction. *Off-grid wind energy systems play a pivotal role in providing clean and sustainable power to remote areas. However, the intermittent nature of wind and the absence of grid connectivity pose significant challenges to maintaining consistent power quality. The wind energy conversion system plays a central role in tapping renewable energy from wind sources. Operational parameters such as rotor and stator currents, output voltages of rectifiers and converters, and grid phase voltage variations are crucial for stable power generation and grid integration. Additionally, optimizing power conversion output through voltage gain analysis in boost converters is essential. Moreover, ensuring electricity quality via total harmonic distortion reduction in inverters is vital for grid compatibility.* ***Goal****. Enhancing the power quality of grid-integrated wind energy conversion systems.* ***Methods.*** *The proposed topology is implemented in MATLAB/Simulink with optimized control strategies for enhancing power quality in off-grid wind energy systems.* ***Results****. Control strategies with a grid-connected wind energy conversion system yields substantial improvements in power quality. This includes effectively mitigating voltage fluctuations and harmonics, resulting in smoother operation and reduced disturbances on the grid.* ***Practical value.*** *The proposed topology has proven to be extremely useful for off grid-integrated wind system.* References 18, table 1, figures 11.

Key words: **off-grid wind energy systems, power quality, optimized control strategies, voltage regulation, harmonic mitigation.**

Вступ*. Автономні вітроенергетичні системи грають ключову роль у забезпеченні екологічно чистої та сталої електроенергії віддалених районів. Однак переривчастий характер вітру та відсутність підключення до мережі створюють значні проблеми для підтримки сталої якості електроенергії. Система перетворення енергії вітру відіграє важливу роль у використанні відновлюваної енергії з джерел вітру. Робочі параметри, такі як струм ротора та статора, вихідна напруга випрямлячів і перетворювачів, а також коливання фазної напруги мережі, є вирішальними для стабільного виробництва електроенергії та інтеграції в мережу. Також важлива оптимізація вихідної потужності за допомогою аналізу посилення напруги в підвищувальних перетворювачах. Забезпечення якості електроенергії за рахунок зменшення повного гармонійного спотворення в інверторах є життєво важливим для сумісності з мережею.* ***Мета****. Підвищення якості електроенергії інтегрованих в мережу систем перетворення енергії вітру.* ***Методи****. Запропонована топологія реалізована в MATLAB/Simulink з оптимізованими стратегіями керування для підвищення якості електроенергії у автономних вітроенергетичних системах.* ***Результати****. Стратегії керування за допомогою підключеної до мережі системи перетворення енергії вітру дають суттєві покращення якості електроенергії. Це включає в себе ефективне послаблення коливань напруги та гармонік, що призводить до більш плавної роботи та зменшення завад у мережі.* ***Практична цінність****. Запропонована топологія виявилася надзвичайно корисною для автономної інтегрованої вітрової системи.* Бібл. 18, табл. 1, рис. 11.

Ключові слова: **автономні вітроенергетичні системи, якість електроенергії, оптимізовані стратегії управління, регулювання напруги, послаблення впливу гармонік.**

Abbreviations

DFIG	Doubly Fed Induction Generator	THD	Total Harmonic Distortion
ESS	Energy Storage System	VSC	Voltage Source Converter
PWM	Pulse Width Modulation	WECS	Wind Energy Conversion System
STATCOM	Static Synchronous Compensator		

1. Introduction. Off-grid wind energy systems represent a promising avenue for providing clean and sustainable power to remote areas, islands, and regions where traditional grid infrastructure is absent or unreliable. These systems harness the abundant energy of the wind to generate electricity, offering a decentralized solution to meet local energy needs. However, despite their environmental benefits and potential to promote energy independence, off-grid wind energy systems face significant challenges in maintaining consistent power quality [1, 2].

The intermittent nature of wind, coupled with the absence of grid connectivity, poses unique obstacles to ensuring stable and reliable electricity supply [3]. Fluctuations in wind speed and direction can lead to variations in power output, causing voltage and frequency instabilities within the system. Moreover, the lack of a grid connection eliminates the buffering effect typically provided by centralized power distribution networks, amplifying the impact of these fluctuations on local power quality [4].

Ensuring adequate power quality in off-grid wind energy systems is crucial for their successful operation and integration into the broader energy landscape. Poor power quality can result in voltage sags, swells, and transients, as well as harmonic distortions, which can damage equipment, disrupt operations, and compromise the performance of connected loads. Additionally, inconsistent power quality may limit the feasibility and reliability of critical applications, such as telecommunications, healthcare facilities, and industrial processes, which rely on stable electricity supply [5–7].

To address these challenges, advanced control strategies have emerged as a key solution for enhancing power quality in off-grid wind energy systems. By leveraging sophisticated control algorithms and innovative techniques, such as predictive control and adaptive filtering, these strategies aim to regulate voltage and frequency, mitigate harmonics, and improve the overall stability and reliability of the system. One of the fundamental challenges in off-grid wind power systems is the variability of wind speed and direction, which directly impacts the output power of wind turbines. To address this challenge, researchers have investigated predictive control techniques that utilize advanced algorithms to forecast wind conditions and adjust system parameters accordingly. Another area of focus in power quality enhancement is voltage regulation, which is crucial for ensuring the stability and reliability of off-grid wind power systems. Several studies have explored the use of power electronic converters, such as VSCs and STATCOMs, to regulate voltage levels and mitigate voltage fluctuations. Harmonic mitigation is another important aspect of power quality enhancement in off-grid wind power systems. Harmonic distortions can arise from the nonlinear characteristics of power electronic converters and can degrade the performance of connected loads. To address this issue, researchers have proposed various filtering techniques, such as active filters and passive filters, to suppress harmonics and improve system reliability. In addition to predictive control, voltage regulation, and harmonic mitigation, researchers have also explored the integration of ESSs to enhance power quality in off-grid wind power systems. ESS can store surplus energy during periods of high wind availability and release it during periods of low wind, thereby smoothing out power fluctuations and improving system stability [8–15].

Off-grid wind power systems often incorporate multiple renewable energy sources, energy storage devices, and power electronics components, making system integration and coordination a complex task. Advanced control techniques have to be employed to effectively manage the interactions between different system components and optimize overall system performance while ensuring power quality and reliability [16–18].

The goal of the paper is to enhance the power quality of grid-integrated wind energy conversion systems:

- Investigate the efficacy of advanced control techniques, such as predictive control and adaptive algorithms, in enhancing power quality in off-grid wind energy systems.
- Evaluate methods to enhance power generation efficiency by analyzing rotor current, stator current, and voltage gain in the boost converter.
- Investigate the impact of grid phase voltage variations on stable power generation and assess techniques such as filter integration to reduce THD in the inverter output.
- Explore ways to maximize the utilization of wind resources by analyzing parameters such as rated power, wind speed, power coefficient, and technical specifications like the number of blades and tip speed ratio.
- Identify opportunities for further improvement and refinement of control strategies to optimize power quality enhancement in off-grid wind energy systems and promote their widespread adoption in diverse applications.

2. Off grid isolated wind turbine conversion system.

Operation of isolated WECS. The off-grid wind turbine conversion system comprises several interconnected components working synergistically to convert wind energy into usable electrical power. At its core lies a DFIG directly coupled to the wind turbine, harnessing wind energy to generate AC electricity. This AC output is then rectified by a diode rectifier to convert it into DC, suitable for further processing. The DC power undergoes voltage regulation and conditioning through a DC/DC converter. This converter ensures a stable and controlled DC output, crucial for maintaining the integrity of downstream components. Control of the DC power is facilitated through PWM techniques, adjusting the duty cycle of the converter to optimize power flow and efficiency. The conditioned DC power is then fed into a three-phase inverter, where it undergoes conversion back into AC electricity. The inverter, controlled by PWM signals, ensures the quality and stability of the AC output, synchronizing it with the grid or local loads' requirements. Before the electricity is distributed, it passes through a transformer for voltage stepping to match the grid or load voltage levels. This transformer also provides isolation and impedance matching to improve system performance and reliability. Throughout the operation, various control systems play crucial roles. The wind turbine control system monitors and optimizes turbine performance, adjusting blade pitch and yaw angles to maximize energy capture efficiency. The grid operator control system oversees the integration of the wind power into the grid, managing power flow, frequency, and voltage to ensure stability and reliability. Overall, the operation of the off-grid wind turbine conversion system involves seamless coordination and control of multiple components, from the wind turbine itself to the grid connection point. Through advanced control strategies and efficient power conversion techniques, this system enables the reliable and sustainable harnessing of wind energy in remote or off-grid locations, contributing to the transition towards clean and renewable energy sources. Figure 1 illustrates the off-grid WECS.

The kinetic energy of a WECS is:

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

where m is the mass; v is the velocity.

The power available in wind can be defined as:

$$P = \frac{1}{2} \rho A v^3 , \tag{2}$$

where A is the cross-sectional area of the wind turbine; ρ is the air density.

The coefficient factor C_p for the wind turbine can be expressed as:

$$C_p = P_0 / P . \tag{3}$$

The power converted from the wind speed is expressed as:

$$P_0 = \frac{1}{2} C_p \rho A v^3 . \tag{4}$$

Tip-speed ratio of wind turbine can be expressed as:

$$\lambda = R\omega / v , \tag{5}$$

where R is the radius of the wind turbine; ω is the angular speed of wind turbine.

DFIG d and q axis change in current, it can be expresses as:

$$\frac{\mathrm{d}I_d}{\mathrm{d}t} = -\left(\frac{R_a}{L_d}\right) I_d + \omega_s \frac{L_q}{L_d} I_q + \frac{1}{L_d} U_d ; \tag{6}$$

$$\frac{\mathrm{d}I_q}{\mathrm{d}t} = -\frac{R_a}{L_q} I_d - \omega_s \left(\frac{L_d}{L_q} I_d + \frac{1}{L_q} \psi_p\right) + \frac{1}{L_q} U_q , \tag{7}$$

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 rotor; ψ_p is the excitation flux; U_d is the d-axis voltage; U_q is the q-axis voltage.

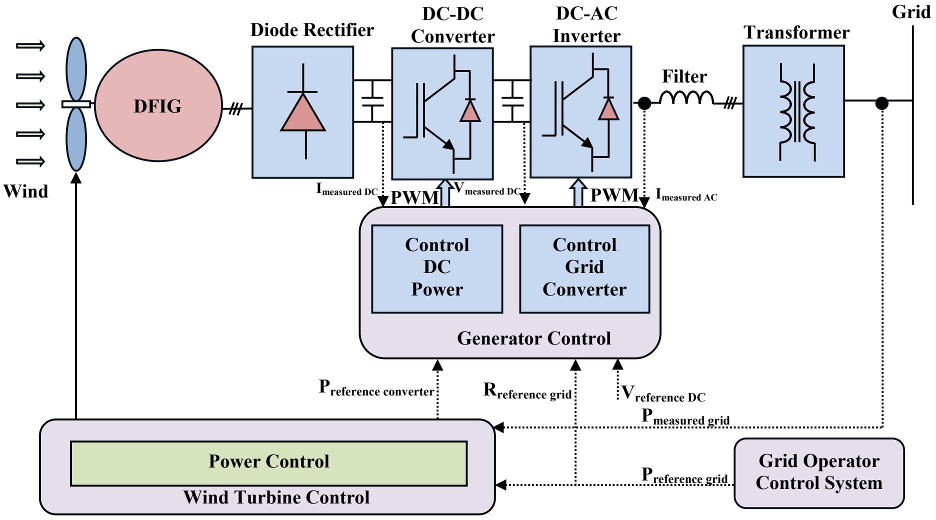

Fig. 1. Off grid WECS

The electromechanical torque produced by the wind turbine can be expressed as:

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

Three phase voltage transformation of three axis system can be expressed as:

$$U_{ga} = U_{Ia} - L\frac{\mathrm{d}I_a}{\mathrm{d}t} - IR_a\,; \quad (9)$$

$$U_{gb} = U_{Ib} - L\frac{\mathrm{d}I_b}{\mathrm{d}t} - IR_b\,; \quad (10)$$

$$U_{gc} = U_{Ic} - L\frac{\mathrm{d}I_c}{\mathrm{d}t} - IR_c\,. \quad (11)$$

Two axis voltage transformation system can be expressed as:

$$U_d = R_a I_d - \omega_s L_q I_q + \frac{\mathrm{d}I_d}{\mathrm{d}t}L_d\,; \quad (12)$$

$$U_q = R_a I_q + \omega_s L_d I_d + \frac{\mathrm{d}I_q}{\mathrm{d}t}L_q + E_s\,. \quad (13)$$

Transformed *d* and *q* axis controller can be expressed as:

$$U_d = e_d - RI_d + \omega L I_q - L\frac{\mathrm{d}I_d}{\mathrm{d}t}\,; \quad (14)$$

$$U_q = -R_a I_q - \omega L I_d - L\frac{\mathrm{d}I_q}{\mathrm{d}t}\,. \quad (15)$$

Simplifying the above two equations final simplified expression can be illustrated as:

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

where θ is the estimated angle in *a-b-c* to *d-q* transformation.

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 it 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.

Boost converter-fed diode rectifier and inverter system is a complex arrangement designed to efficiently manage power flow in renewable energy applications, particularly in off-grid or hybrid systems. At its core, the boost converter serves to regulate the voltage level of the DC link, ensuring that the system operates within specified voltage limits. The diode rectifier, connected to the DC link, converts AC power from the three-phase source into DC, which is then smoothed and regulated by the boost converter. The three-phase inverter, controlled by PWM techniques, converts the regulated DC power back into AC, suitable for grid or load connection. The PWM control adjusts the switching of the inverter devices to regulate output voltage and frequency, ensuring compatibility with the grid or load requirements. PI controller is typically employed to regulate the DC link voltage. It compares the actual DC voltage (actual V_{dc}) with a reference voltage (reference V_{dc}), adjusting the duty cycle of the boost converter to maintain the desired voltage level. In hybrid systems, a battery has been included in the DC link to store excess energy or provide backup power during periods of low renewable energy generation. The integration of the battery adds flexibility to the system, allowing for improved energy management and enhanced reliability.

Figure 2 illustrates the boost converter with diode and inverter connected system and Fig. 3 shows WECS to load system through diode rectifier and three phase inverter system. In a grid operator control system, power control and wind turbine control are crucial components. Power control involves regulating the output of wind turbines to match grid demand, ensuring grid stability and reliability. This requires real-time monitoring and adjustment of power generation levels to maintain grid frequency and voltage within acceptable limits. Wind turbine control encompasses pitch control, yaw control, and rotor speed regulation to maximize energy capture and minimize mechanical stress. Integrating advanced control algorithms enables efficient coordination between power control and wind turbine control, optimizing energy production while ensuring grid compatibility and reliability.

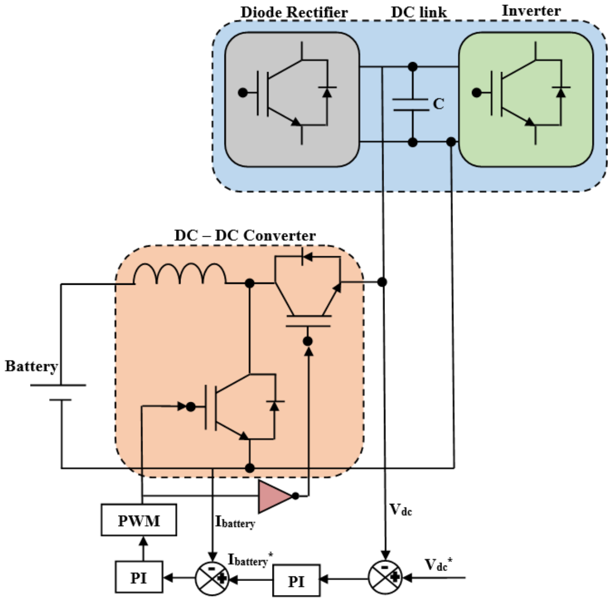

Fig. 2. Boost converter with diode and inverter connected system

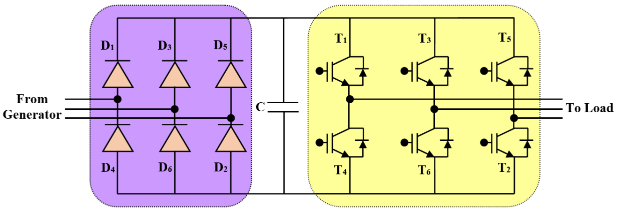

Fig. 3. WECS to load system

The performance of a wind turbine is essential for producing energy efficiently, and the incorporation of a PI controller within its DC-DC converter is a key 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. In order to ensure that the wind turbine runs at its peak power for optimum energy extraction, it strikes a balance between the trade-off between transient reaction and steady-state precision. 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 last component, an inverter system, making it eligible for grid connection. A seamless integration with the electrical grid is made possible by the PI controller in the inverter system, which makes sure 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 the use of renewable energy sources and sustainable power generation.

Figure 4 illustrates the interconnection of three phase diode rectifier, boost converter, three phase inverter to load and generator.

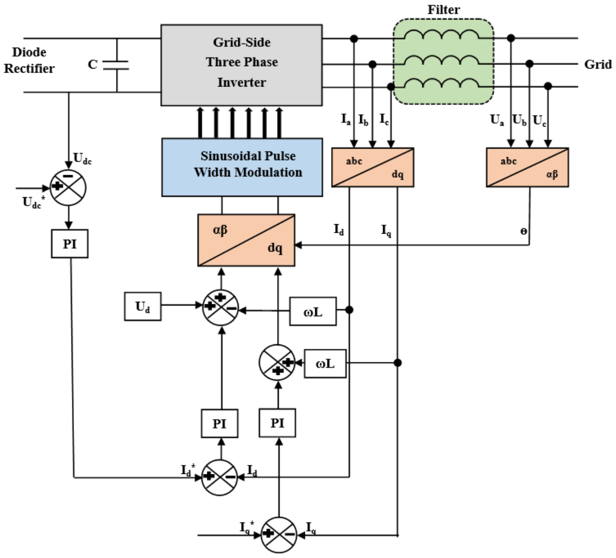

Fig. 4. Three to two axis transformation diode bridge rectifiers to grid integration

3. Results and discussion. WECS is a vital component in harnessing renewable energy from wind sources. Figure 5 displays the relationship between turbine mechanical power and rotor speed across various velocities ranging from 3 m/s to 13 m/s. The rotor current in a DFIG comes from the excitation of the coil, inducing a magnetic field that generates the current.

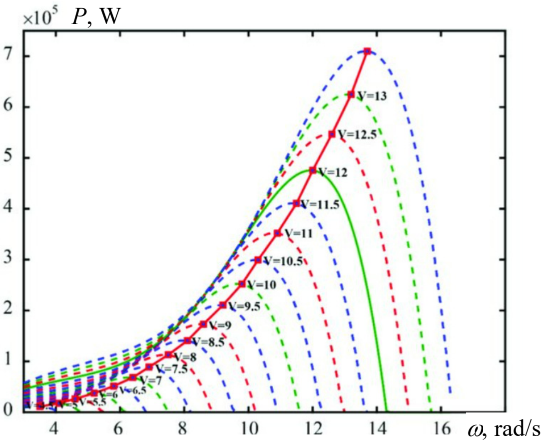

Fig. 5. Turbine mechanical power vs rotor speed at different velocities

Figure 6 provides key operational parameters at a cut-in speed of 1200 rpm, with rotor current at 1.7 A and stator current at 1.3 A.

Figures 7, 8 detail the output voltages of the diode bridge rectifier and DC link boost converter, respectively, crucial for maintaining stable power generation.

Figure 9 illustrates grid phase voltage variations during inductive filter and non-filter conditions, essential for grid integration.

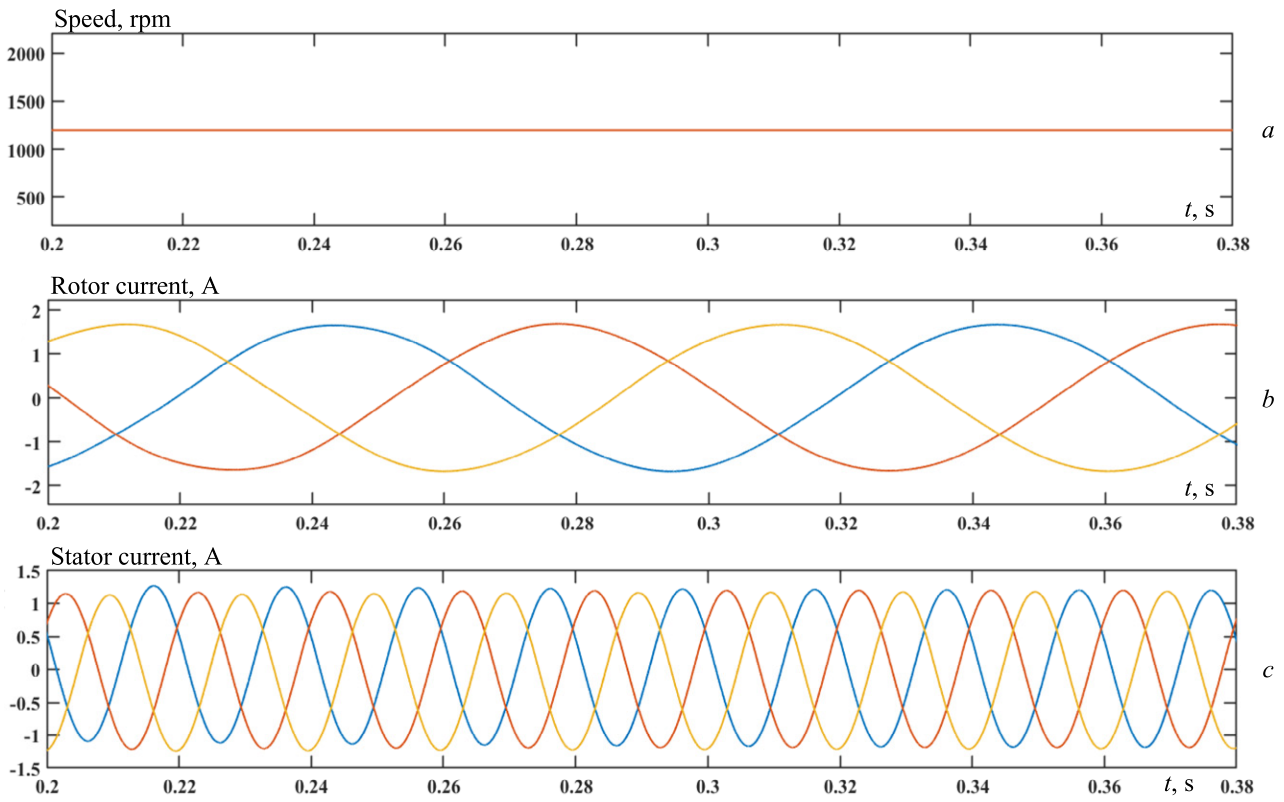

Fig. 6. WECS rotor speed (*a*), rotor current (*b*) and stator current (*c*)

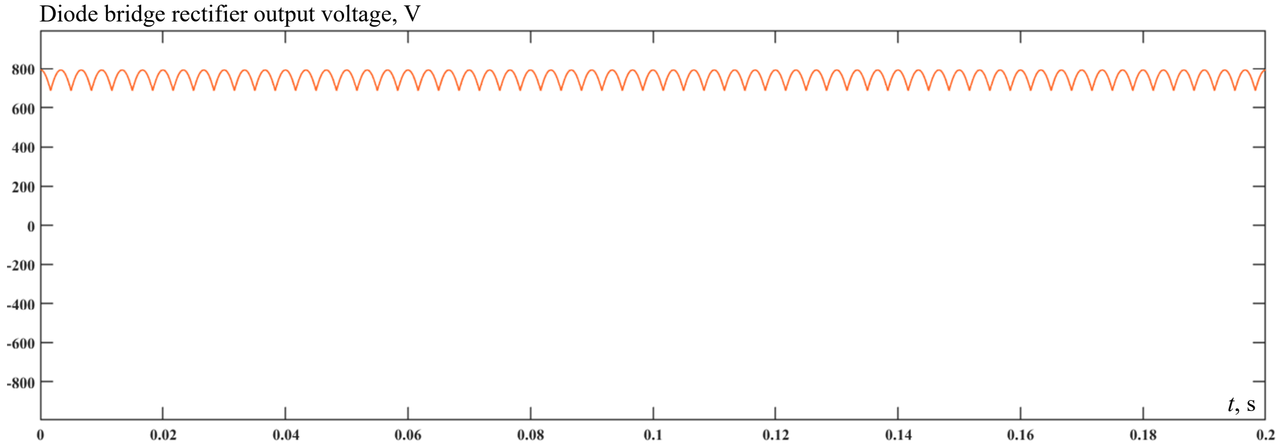

Fig. 7. Diode bridge rectifier output voltage

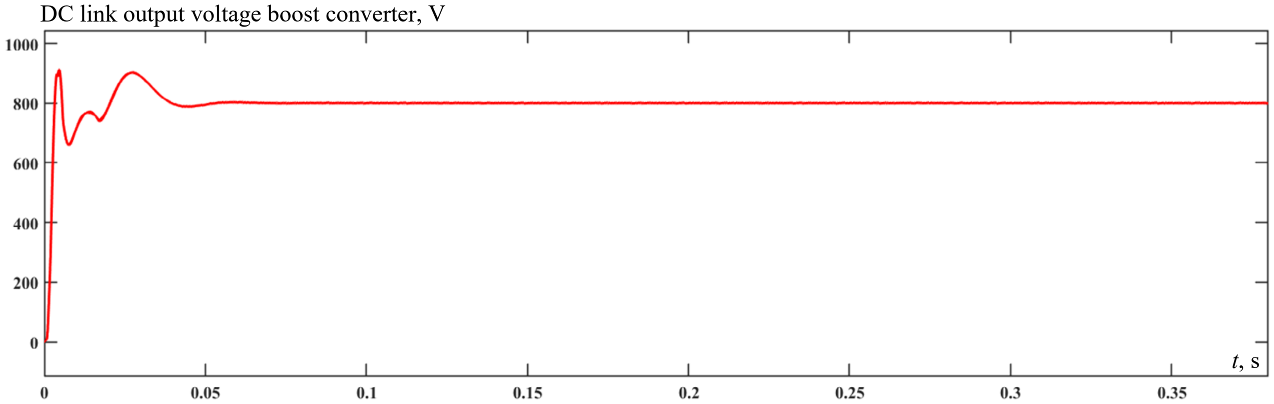

Fig. 8. DC link output voltage boost converter

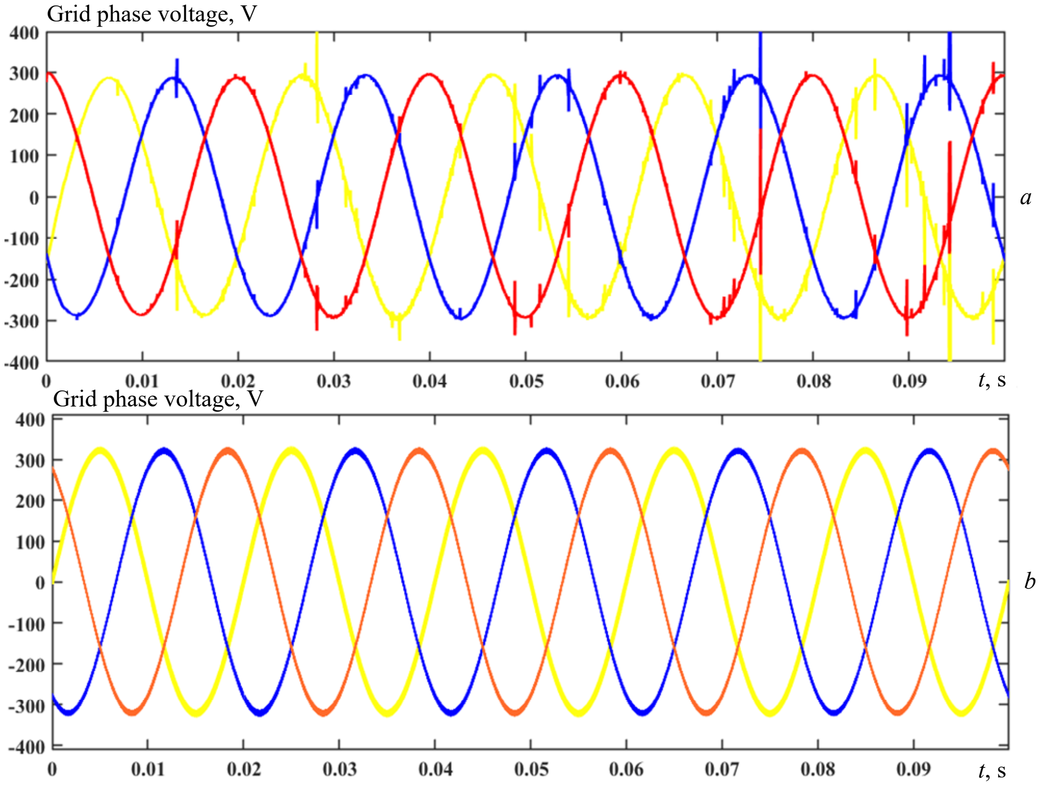

Fig. 9. Grid phase voltage during filter (*a*) and non-filter (*b*)

Figure 10 presents a comparative analysis of voltage gain in the boost converter, ranging from 0.1 to 0.8, crucial for optimizing power conversion efficiency. Meanwhile, while investigating electricity quality solely with a filter isn't groundbreaking, Fig. 11's depiction of THD in the inverter is noteworthy. It illustrates a substantial decrease from 18 % without a filter to 2.3 % with a filter, crucial for ensuring grid compatibility, validating the filter's effectiveness

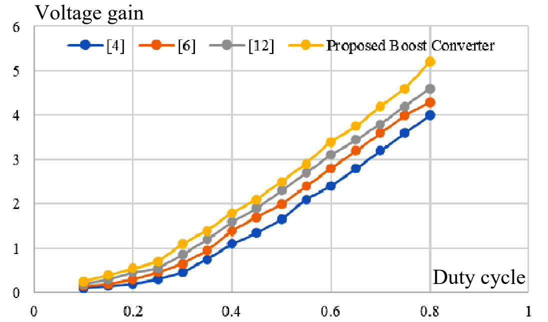

Fig. 10. Comparative analysis of voltage gain of boost converter

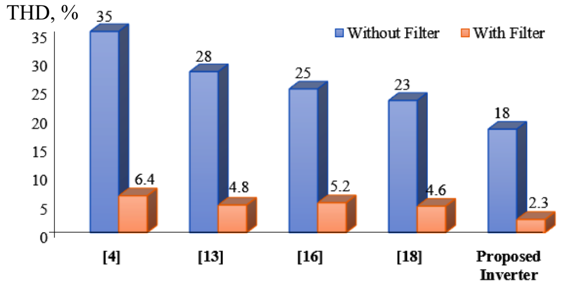

Fig. 11. Comparative analysis of THD in inverter

Table 1 encapsulates essential WECS parameters, including rated power, wind speed, power coefficient and technical specifications like the number of blades, tip speed ratio and gear ratio. Notably, the listed parameters provide a comprehensive overview of the system's capabilities and operational characteristics.

Table 1

WECS parameters

Name	Parameters	Value
DFIG	Rated power, kW	2
	Rated wind speed, m/s	8
	Power co-efficient	0.3
	Number of blades	2
	Tip speed ratio	6
	Cut-in speed, m/s	3
	Cut-in turbine speed, rpm	45
	Cut-in generator speed, rpm	1200
	Rotor winding resistance, mΩ	2.63
	Stator winding inductance, mH	5.6438
	Rotor winding inductance, mH	5.6068
	Magnetizing inductance, mH	5.4749
DC regulated converter	Output voltage, V	400
	Power device	MOSFET
	Switching frequency, kHz	50
	RMS inductor current, A	10.2
	Conduction loss	523.4
Three phase VSI	Power device	IGBT
	Number of devices	6
	On-off frequency, kHz	2.2

4. Conclusions

4. Conclusions. The integration of optimized control strategies in off-grid wind energy systems represents a significant advancement in addressing the challenges associated with intermittent wind resources and lack of grid connectivity. Through the implementation of advanced control techniques such as predictive control and adaptive algorithms, these systems can effectively enhance power quality by regulating voltage, frequency, and mitigating harmonics. The results obtained from the proposed topology, implemented in MATLAB/Simulink, demonstrate substantial improvements in power quality metrics, including reduced voltage fluctuations and harmonics. This not only ensures smoother operation of off-grid wind energy systems but also minimizes disturbances on the grid, thereby enhancing overall system reliability and performance.

Conflict of interest. The authors declare that they have no conflicts of interest.

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