Grid-Integrated Dual Wind Turbine System Using SEPIC Converter with Whale Optimized PI Controller

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Abstract. Main objectives of the study are to progress a dual independent doubly fed induction generator (DFIG)-based wind energy conversion system (WECS) for stable and efficient power delivery to an AC microgrid while ensuring grid stability and compliance with power quality standards. In order to achieve the set goals, the following tasks were accomplished: integration of a Pulse Width Modulation (PWM) rectifier for AC to DC conversion, implementation of a SEPIC converter for voltage boosting, tuning of proportional integral (PI) controller parameters using whale optimization algorithm (WOA) for dynamic DC voltage regulation, and design of a 3Φ Voltage Source Inverter (VSI) for efficient management of active and reactive power to the grid. The scientific novelty of the proposed work is the inclusion of dual independent DFIG system with SEPIC converters and optimized PI controllers. The most important results are the demonstration of consistent DC voltage stabilization, improved power quality under varying wind conditions, and an overall system efficiency of 97%, verified through MATLAB simulations. These attained outcomes are found to be more efficient when compared to other existing converters and optimized controllers thereby satisfying the objectives of meeting desired voltage demands of grid and achieving highly stabilized output power. The significance of obtained results is the establishment of an advanced DFIG-WECS-based wind energy system capable of enhancing grid performance, ensuring reliable integration of renewable energy, and maintaining power quality and stability in compliance with modern grid standards.
Keywords: renewable energy source(RES), DFIG-WECS, SEPIC Converter, WOA-PI Controller, Grid system.

UDC: 69.004
DOI: https://doi.org/10.52254/1857-0070.2025.1-65.13

Sistem de turbină eoliană duală integrată în rețea care utilizează controler PI optimizat Whale cu convertor SEPIC

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Rezumat. Obiectivele principale ale studiului sunt de a promova un sistem de conversie a energiei eoliene (WECS) bazat pe un generator cu inducție dublu alimentat independent (DFIG) pentru livrarea de energie stabilă și eficientă către o microrețea de curent alternativ, asigurând în același timp stabilitatea rețelei și conformitatea cu standardele de calitate a energiei electrice. Pentru a atinge obiectivele stabilite, au fost îndeplinite următoarele sarcini: integrarea unui redresor cu modulație în lățime a impulsurilor (PWM) pentru conversia AC la DC, implementarea unui convertor SEPIC pentru creșterea tensiunii, reglarea parametrilor controlerului integral proporțional (PI) folosind whale algoritm de optimizare (WOA) pentru reglarea dinamică a tensiunii continue și proiectarea unui invertor de sursă de tensiune de 3Φ (VSI) pentru gestionarea eficientă a puterii active și reactive la rețea. Noutatea științifică a lucrării propuse este includerea unui sistem DFIG dual independent cu convertoare SEPIC și controlere PI optimizate. Cele mai importante rezultate sunt demonstrarea stabilizării consecvente a tensiunii continue, a calității îmbunătățite a energiei în condiții variate de vânt și a unei eficiențe generale a sistemului de 97%, verificată prin simulări MATLAB. Aceste rezultate obținute se dovedesc a fi mai eficiente în comparație cu alte convertoare existente și controlere optimizate, satisfăcând astfel obiectivele de a îndeplini cerințele de tensiune dorite ale rețelei și de a obține o putere de ieșire foarte stabilizată. Semnificația rezultatelor obținute este stabilirea unui sistem avansat de energie eoliană bazat pe DFIG-WECS, capabil să sporească performanța rețelei, să asigure integrarea fiabilă a energiei regenerabile și să mențină calitatea și stabilitatea energiei în conformitate cu standardele moderne de rețea.

Cuvinte-cheie: sursă de energie regenerabilă (RES), DFIG-WECS, Convertor SEPIC, Controler WOA-PI, Sistem de rețea.

Интегрированная в сеть двойная ветряная турбина с использованием преобразователя с несимметрично нагруженной первичной индуктивностью (SEPIC) с оптимизированным по алгоритму оптимизации китов (Whale Optimization Algorithm) ПИ-контроллером

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Аннотация. Основными целями исследования являются разработка системы преобразования энергии ветра (WECS) на основе двух независимых индукционных генераторов с двойным питанием (DFIG) для стабильной и эффективной подачи электроэнергии в микросеть переменного тока, обеспечивая при этом стабильность сети и соответствие стандартам качества электроэнергии. Для достижения поставленных целей были выполнены следующие задачи: внедрение выпрямителя с широтно-импульсной модуляцией (ШИМ) для преобразования переменного тока в постоянный, реализация преобразователя SEPIC для повышения напряжения, настройка параметров пропорционально-интегрального (ПИ) регулятора с помощью кита алгоритм оптимизации (WOA) для динамического регулирования напряжения постоянного тока и проектирование трехфазного инвертора напряжения (VSI) для эффективного управления активной и реактивной мощностью в сети. Научная новизна предлагаемой работы заключается во включении в нее двойной независимой системы DFIG с преобразователями SEPIC и оптимизированными ПИ-регуляторами. Наиболее важными результатами являются демонстрация последовательной стабилизации напряжения постоянного тока, улучшение качества электроэнергии при изменении ветровых условий и общая эффективность системы 97%, подтвержденная с помощью моделирования MATLAB. Достигнутые результаты оказались более эффективными по сравнению с другими существующими преобразователями и оптимизированными контроллерами, что позволяет достичь целей удовлетворения требуемых требований к напряжению сети и достижения высокостабилизированной выходной мощности. Значимость полученных результатов заключается в создании передовой ветроэнергетической системы на базе DFIG-WECS, способной повысить производительность сети, обеспечить надежную интеграцию возобновляемых источников энергии, а также поддерживать качество и стабильность электроэнергии в соответствии с современными сетевыми стандартами.

Ключевые слова: возобновляемые источники энергии (ВИЭ), DFIG-WECS, преобразователь SEPIC, контроллер WOA-PI, сетевая система.

I. INTRODUCTION

Electricity turned into one of the prominent and essential needs along with the technological development of humankind [1-2]. Depletion and environmental impacts due to the excess usage of fossil fuel evolved people's concern towards RES [3-4]. Amongst, various RES, wind power generation offered significant improvement in terms of clean, sustainable energy with reduced carbon emission[5]. Thus, the instant development of wind energy assisted to DFIG added up to the leading power generation wind forms [6-7]. Moreover, due to the dependence on the environmental aspects, power converters are required for the WECS [8]. Various converters such as Boost converter [9] and Cuk [10-11] are considered for enhancing the output voltage. Boost converter produce high-level output voltages but still cannot reach the desired performance. Thus, to further raise the output voltage, a Cuk converter is introduced. Though the Cuk converter provides consistent input and output current with reduced ripples, it is not completely reliable as it produces high current stress and requires higher number of reactive components [12-13]. Therefore, a DC-DC SEPIC converter is deployed in this study to overcome the above-stated drawbacks. The introduction of SEPIC converter raises the output voltage obtained from DFIG-based WECS and provides consistent output voltage with reduced current ripples.

Additionally, to regulate and stabilize output voltage, PI controller is most widely utilized [14]. However, to attain augmented controller performance, parameter tuning plays a crucial part. Thus, several conventional parameter tuning algorithms along with their demerits are listed in Table 1 below, Henceforth, this research proposes a WOA-based optimization algorithm that outdraws the above-listed uncertainties. WOA achieves higher convergence rate with better problem-solving ability, thereby providing enhanced voltage with better output quality.

Thus, the incorporation of both DC-DC converter with WOA optimized PI controller ensures to provide high regulated and stabilized output voltage to attain desired output level for the grid applications.

Table 1

Demerits of Parameter Tuning Algorithms

Reference	**Conventional optimization algorithms**	**Demerits**
[15]	Particle Swarm Optimization (PSO)	PSO struggles with slow convergence rate during high diemensional spaces which makes it hard for them to find the global optimum.
[16]	Ant Colony Optimization (ACO)	ACO suffers from high complexity issues and acquires high space complexity along with time.
[17]	Grey Wolf Optimization (GWO)	GWO is not applicable due to its minimized solving accuracy with slow convergence rate.
[18]	Gravitational Search Algorithm (GSA)	GSA struggles with slow processing time with high computational difficulty
[19]	Antlion Optimization Algorithm (ALO)	ALO requires longer processing time with slow convergence rate

The overall outline and contributions of the proposed work is enlisted as follows,

- Dual DFIG-based WECS is implemented to meet the desired voltage demands of the grid which produces clean and sustainable energy generation.
- The deployment of DC-DC SEPIC converter boosts the output voltage
- obtained from the DFIG-WECS and provides higher output voltage levels with reduced losses.
- Integrating WAO-optimized PI controller to attain enhanced parameter tuning to provide highly stabilized output power quality.

II. PROPOSED SYSTEM DESCRIPTION

A parallel wind power system illustrated in Fig. 1, is developed to address the challenges in traditional WECS.

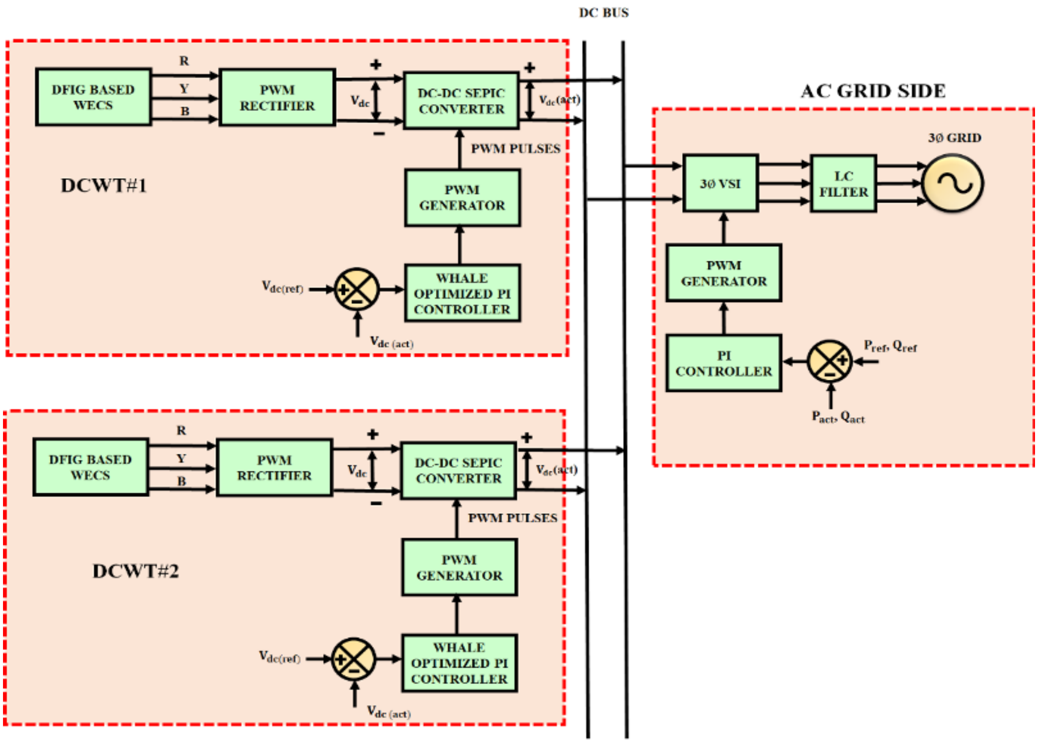

Fig. 1. Block diagram of the developed work.

The system comprises two independent DFIG-based wind turbine systems, labeled as WT#1 and WT#2, which perform the parallel operations. The turbines capture the wind energy and then converts it to electricity via DFIG system. This AC voltage is rectified into DC by a PWM rectifier, and fed to SEPIC converter for boosting of DC voltage suitable for transmission.

The SEPIC converter is regulated using WOA-PI controller, ensuring stabilized DC link voltage by dynamic adjustment of controller parameter. Both WT#1 and WT#2 feed a common DC bus, which collects power from both wind turbines. The voltage from DC bus is supplied to grid via a $3\Phi VSI$. The inverter converts the DC voltage back into AC, making it well-matched with the requirements of grid. On the grid side PI controller is incorporated to control the power flow by adjusting active and reactive power outputs based on reference for optimal grid integration. The control strategy ensures that the power from the wind turbines is dynamically adjusted to meet grid demands while maintaining system stability and power quality.

III. MODELLING OF SYSTEM COMPONENTS

A. Modelling of DFIG-WECS

(a) Modelling of WECS

The main function of WECS is to convert kinetic energy obtained from the rotational torque of wind turbine to electricity. Power contained in wind is given by the equation,

$$P_v = \frac{1}{2} \rho A V_v^3 \tag{1}$$

Where, A denotes Area covered by turbine blades, ρ indicates the air density and V_v represents the wind speed. The power obtained from the wind by the turbine is given as,

$$P_t = \frac{1}{2} \rho \pi R^2 V_v^3 C_p(\lambda, \beta) \tag{2}$$

Where, R indicates radius of turbine rotor, $C_p(\lambda, \beta)$ implies the power coefficient respectively. The acquired mechanical energy from the WECS is converted into electricity by the use of DFIG.

(b) Modelling of DFIG based WECS

WECS utilizes DFIG to convert wind energy to electrical energy, the DFIG stator is directly attached to isolated load and rotor is attached to the battery with the help of the Rotor Side Converter (RSC). The structure of the DFIG based WECS is shown in Fig. 2.

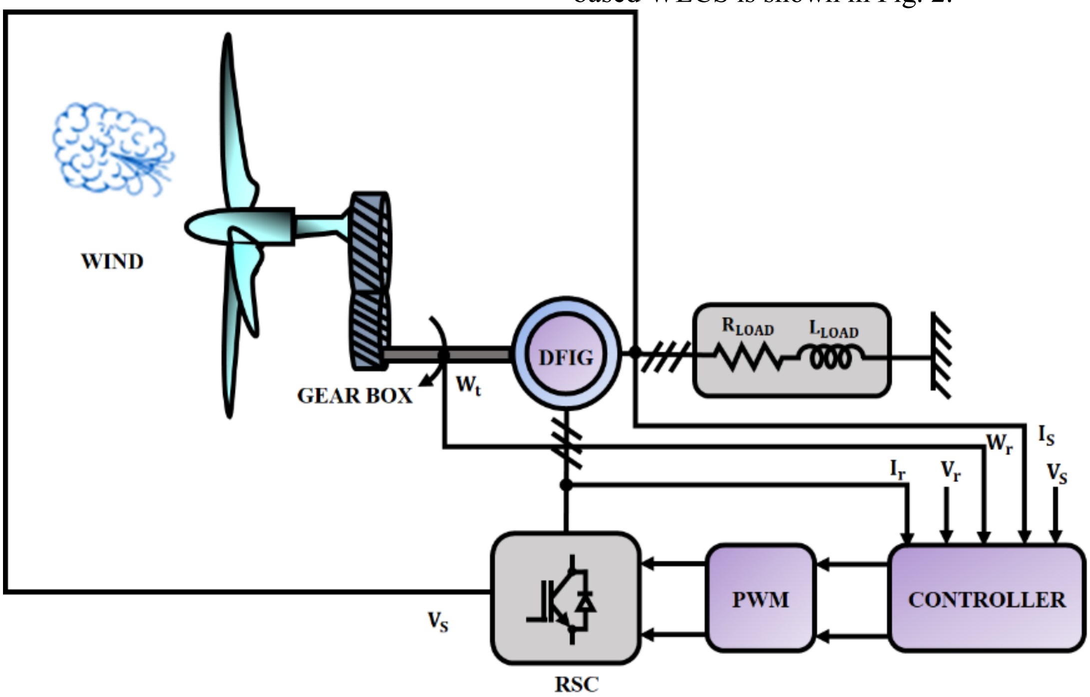

Fig. 2. Structure of DFIG based WECS.

The DFIG stator and rotor flux are given as follows,

$$\begin{cases} \psi_{sd} = L_s I_{sd} + M I_{rd} \\ \psi_{sd} = L_s I_{sd} + M I_{rd} \end{cases} \quad (3)$$

$$\begin{cases} \psi_{rd} = L_r I_{rd} + M I_{sd} \\ \psi_{rq} = L_r I_{rq} + M I_{sq} \end{cases} \quad (4)$$

The electromagnetic torque is given by,

$$C_{em} = \frac{3}{2} p \frac{M}{L_s} \left(I_{rd} \ \psi_{sq} - I_{rq} \ \psi_{sd} \right) \quad (5)$$

The DFIG electromechanical equation is given as,

$$\frac{d\omega_r}{dt} = \frac{p}{j} \left(C_m - C_{em} \right) \quad (6)$$

The stator voltage of DFIG based WECS is evaluated as follows,

$$\begin{cases} V_{sd} = R_{LP} i_{sd} + L_{LP} \dfrac{d}{dt} i_{sd} - \omega_1 L_{LP} i_{sq} \\ V_{sq} = R_{LP} i_{sq} + L_{LP} \dfrac{d}{dt} i_{sq} - \omega_1 L_{LP} i_{sd} \end{cases} \quad (7)$$

However, WECS power production is dependent on the wind pattern and environmental impacts such as sudden wind changes affect the efficacy of the system performance along with reduced voltage generation. Thus, DC-DC converters are implemented, SEPIC converter is utilized to achieve enhanced voltage gain.

B. Design of SEPIC Converter

SEPIC converter structure shown in Fig. 3, comprises two inductors L_1 and L_2 which are wound to the same core as they are powered using the same voltage throughout the switching cycle, two capacitors C_s and C_{out} and a single diode D_1. The capacitor C_s separates the input from output, thereby, preventing shorted load circumstances. SEPIC converter works based on two operating modes (a) Mode 1 and (b) Mode 2.

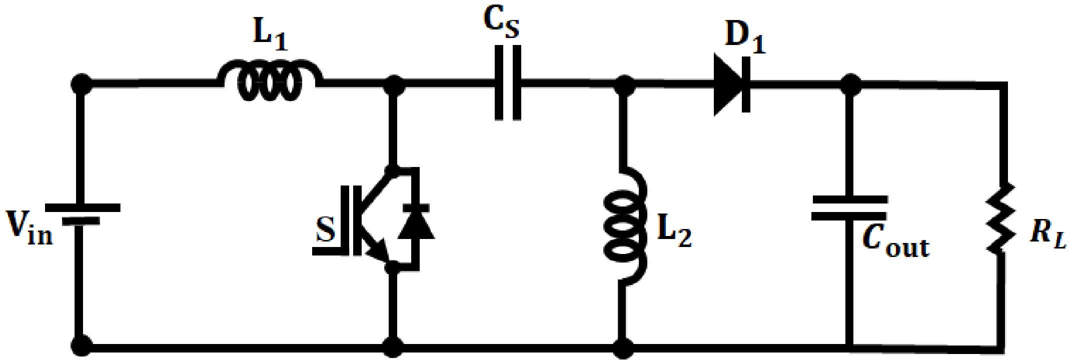

Fig. 3. Structure of SEPIC converter.

(a) Mode 1 : The circuit diagram displaying the operation of mode 1 is depicted in Fig. 4. In this mode, Switch S is turned ON while diode D_1 is turned OFF, thus, the inductor L_1 gets charged from the source and L_2 gets charged from capacitor.

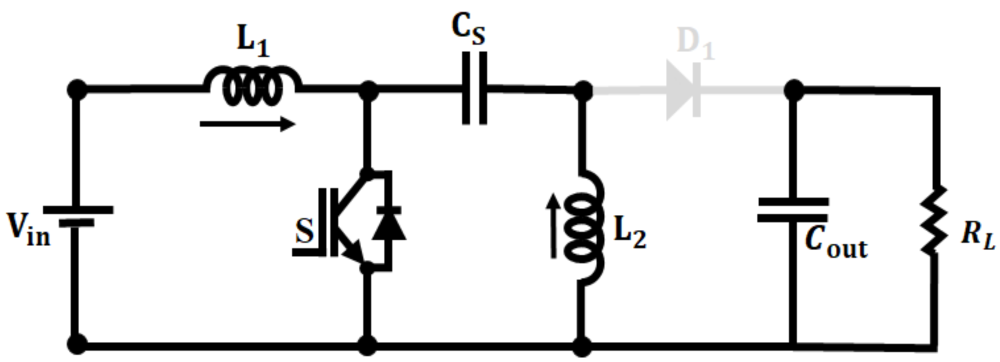

Fig. 4. SEPIC converter-Mode 1 Operation.

(b) Mode 2: The operational flow of mode 2 is shown in Fig. 5, In which switch S is turned OFF whereas, diode D_1 is turned ON, thus, output capacitor gets charged using both the inductors L_1 and L_2.

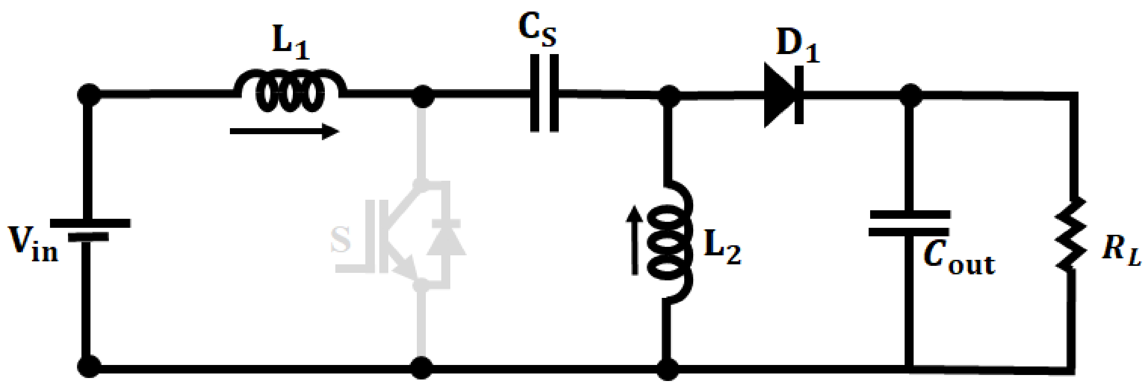

Fig. 5. SEPIC converter- Mode 2 operation

The waveform of the SEPIC converter is shown in Fig. 6. The duty cycle of the SEPIC converter operating in continuous conduction mode is given by,

$$D = \frac{V_{out} + V_D}{V_{in} + V_{out} + V_D} \quad (8)$$

Where, V_D denotes the forward voltage drop of the diode and the maximum duty cycle attained is calculated using,

$$D_{max} = \frac{V_{out} + V_D}{V_{in(min)} + V_{out} + V_D} \quad (9)$$

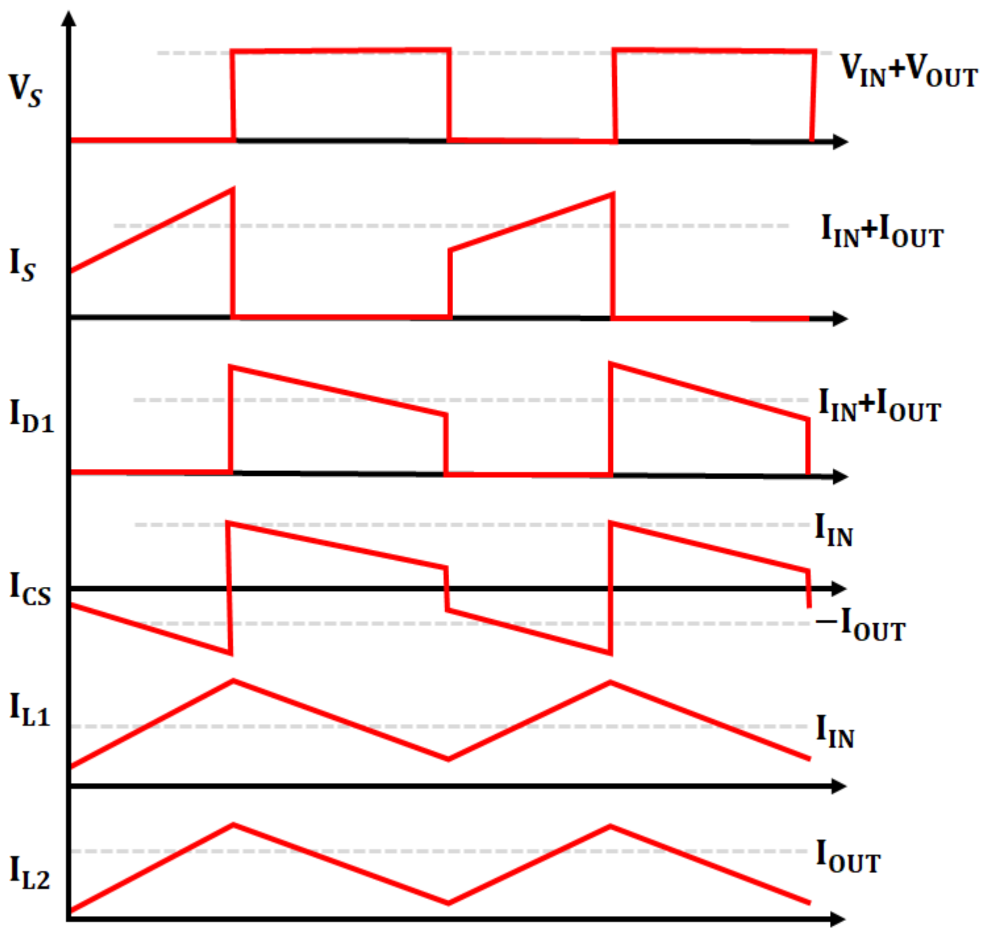

Fig. 6. SEPIC converter waveform.

The inductor value is evaluated using,

$$L_1 = L_2 = L\frac{V_{in(min)}}{I_L \times F_{sw}} \times D_{max} \quad (10)$$

The voltage gain obtained is given by,

$$V_0 = \frac{D}{D'} V_g \quad (11)$$

The output produced by the converter contains certain instability and deviations, thus, to remove these fluctuations and to regulate the converter performance controller plays a crucial part. Hence, this paper utilizes WAO optimized PI controller which is described in the below section.

C. Whale Optimized PI Controller

WOA is a meta-heuristic optimization algorithm that is developed from the inspiration of hunting pattern of humpback whales. The hunting behavior of humpback whales is considered the most interesting strategy, as they prefer to prey on swarms or large group of small fish and this behavior is termed as Bubble-Net Feeding method, which is detailed in Fig. 7. This method is exhibited by whales in circular motions or "9" shaped patterns in which they release specific bubbles that help them to establish the hunting process.

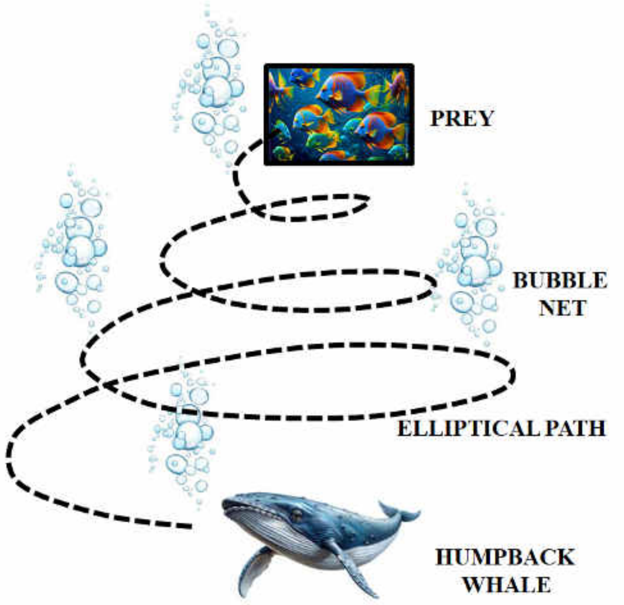

Fig. 7. Bubble-Net Feeding method of humpback whales.

The hunting pattern of humpback whales comprises three main strategies which are

- Encircling Prey
- Bubble-Net Attack
- Searching for prey.

(i) Encircling Prey

During this phase, whales locate the position of their prey to encircle them, similarly, in search phase the selected position is encircled as the finest position. The mathematical representation of this phase is given as,

$$\vec{H} = \left| \vec{E}.\overrightarrow{Y^p}\ (i) - \vec{Y}(i) \right| \tag{12}$$

$$\vec{Y}(i+1) = \overrightarrow{Y^p}\ (i) - \vec{D}.\vec{H} \tag{13}$$

Where, i denotes the present iteration, $\dot{Y}$ indicates the present best position vector and $\overrightarrow{Y^p}$ represents the finest position vector respectively. The vector coefficients $\dot{D}$ and $E^{'}$ are evaluated using,

$$\dot{E} = 2r_2 \tag{14}$$

$$\dot{D} = 2\dot{d}.\,r1 - \dot{d} \tag{15}$$

(ii) Bubble-Net Feeding Method

In this phase, two feeding strategies are exhibited by the humpback whales, which are the shrinking encircling method and spiral position updation method. The shrinking method is executed by minimizing the value of $\dot{d}$ whereas, the spiral method is achieved by upgrading the position, that is expressed as,

$$\vec{Y}(i+1) = \vec{F}.\,b_{el}(2\pi r) + \overrightarrow{Y^p}\ (i) \tag{16}$$

Furthermore, to upgrade the whale position, 50% probability is considered for the above mentioned two methods which are given as,

$$\vec{Y}(it+1) = \begin{Bmatrix} \overrightarrow{Y^p}\ (i) - \vec{D}.\vec{H} & p < 0.5 \\ \vec{F}.b_{el}(2\pi r) + \overrightarrow{Y^p}\ (i) & p \geq 0.5 \end{Bmatrix} \tag{17}$$

Where, $\dot{F}$ denotes the finest position between the whale and the prey.

(iii) Searching for prey

The search for prey is performed based on the vector deviations and the best position is selected on a random basis. The optimal global position is determined as,

$$\dot{F} = \left|\vec{D}.\overline{Y^{rand}} - \vec{Y}(i)\right| \qquad (18)$$

$$\vec{Y}(i+1) = \overline{Y^{rand}} - \vec{D}.\vec{H} \qquad (19)$$

Where, Y^{rand} represents the vector position randomly selected by the whales. However, optimization techniques require random solutions for optimized parameter hence, PI controller is utilized for attaining parameters tuning for WOA and to obtain the equivalent objective function .

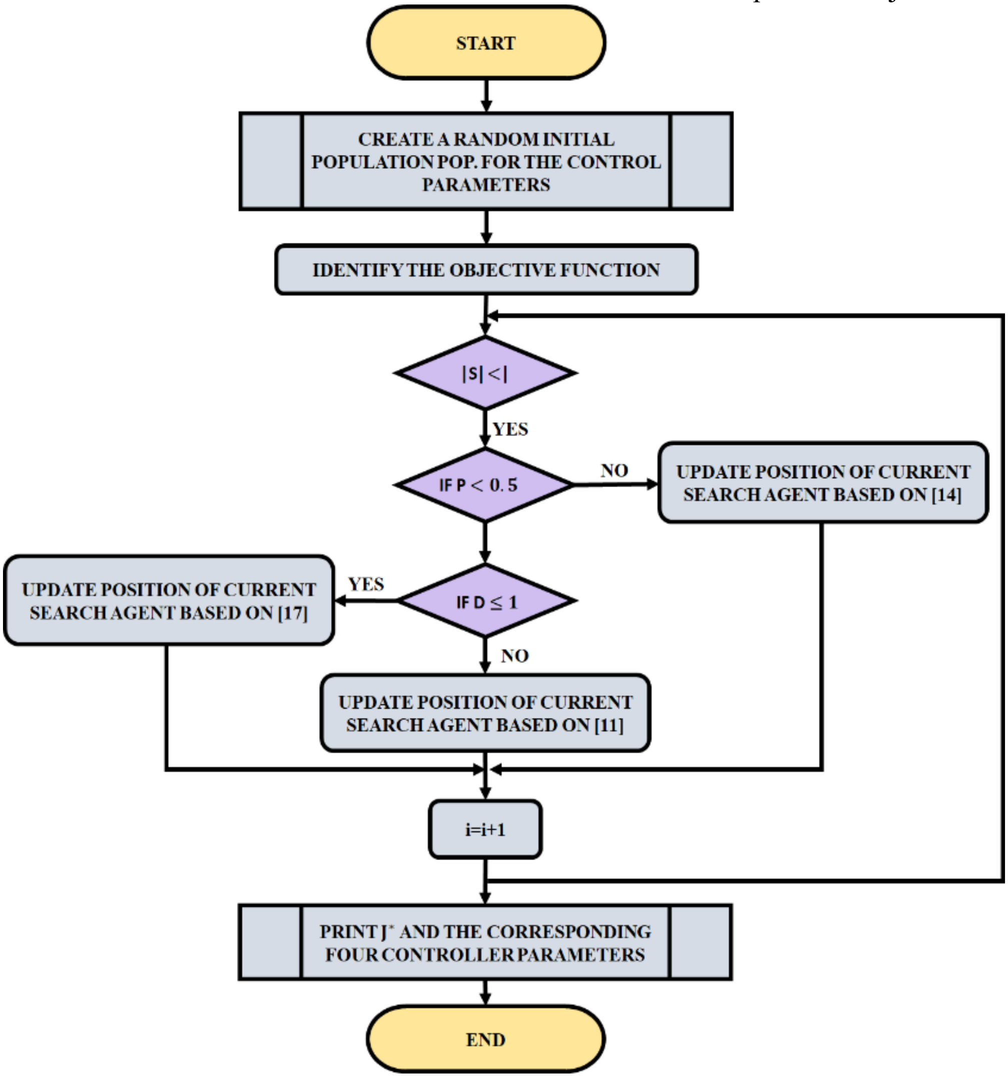

Fig. 8. Flowchart of WOA Optimized PI controller.

The search agent is used in WOA for determining the updated position and these updated positions are utilized for determining the objective functions. These steps are looped until they find the best suitable position and the flowchart of WOA optimized PI controller is depicted in Fig. 8. Furthermore, the perfect grid synchronization is achieved by using a PI controller, which is detailed below.

D. Grid Synchronization

The voltage and frequency points are fed as the input to the VSI control structure, Nevertheless, during standalone operating mode, the grid works using its voltage and frequency, which are later fed to VSI and this concept is utilized for grid synchronization where voltage point is interchanged with utility. The control structure of VSI with voltage points from the grid is shown in Fig. 9.

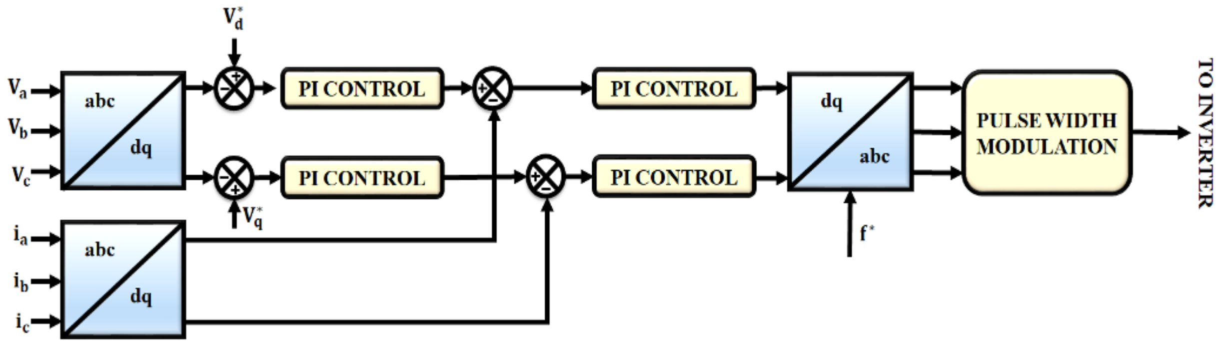

Fig. 9.Grid Synchronization.

The phase-locked loop is utilized for controlling both the phase angle and frequency through grid integration. To implement grid synchronization, SRF-PLL is deployed for which the reference frequency is fed as the input. In addition to this, $q-$axis voltage to zero secures the phase angle to the reference for attaining the desired frequency. Significantly, during this process, DG aims to attain similar phase angle and frequency level of the grid, thus, acquiring new frequency and phase points respectively and here, rather than attaining $-$axis voltage to zero, V_q point is obtained by driving the phase angle difference to the PI controller. The overall system ensures effective functioning by providing clean and consistent supply to meet the grid power requirements.

IV. RESULTS AND DISCUSSION

The proposed system is validated using the MATLAB/Simulink implemented and their obtained results are discussed in this section along with their comparative analysis, to determine the performance efficacy of the proposed system.

Table 2

Parameter Specifications

Parameter	Specifications
SEPIC Converter	
L_1, L_2	4.7 mH
C_s	22 µF
C_{out}	2200 µF
DFIG	
No. of Turbines	4
Inertia Constant	0.685Hs
Pairs of Poles	3
Friction Factor	0.01F(pu)
Magnetizing Inductance	2.9mH
Rotor Inductance	0.16mH(pu)
Rotor Resistance	0.016 Ω (pu)
Stator Resistance	0.023 Ω (pu)
Stator Inductance	0.18mH (pu)
Frequency	50Hz
Line-Line Voltage	415V
Nominal Power	10kW

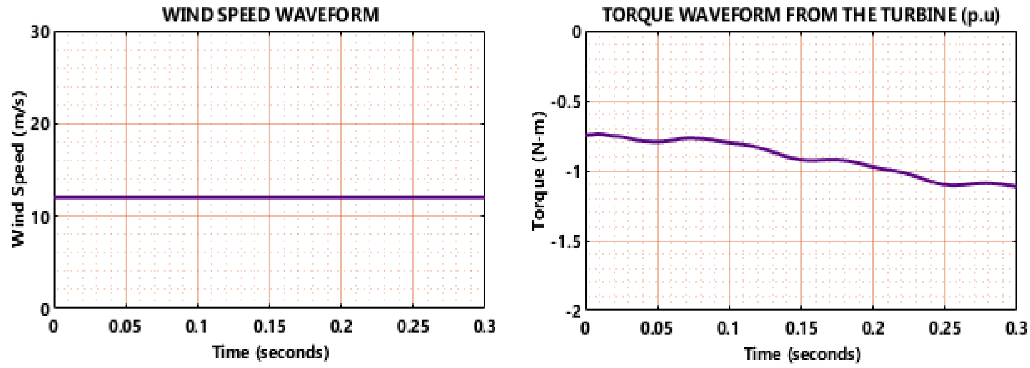

Fig. 10. Wind speed and Torque Waveform.

Fig. 10 represents the wind speed and torque waveform, where wind speed is constantly maintained at 12 m/s , ensuring consistent and stable power to DFIG for producing stable electrical output. While, torque from the turbine reduces gradually below -1 N-m , indicating enhanced conversion of mechanical power into electrical power.

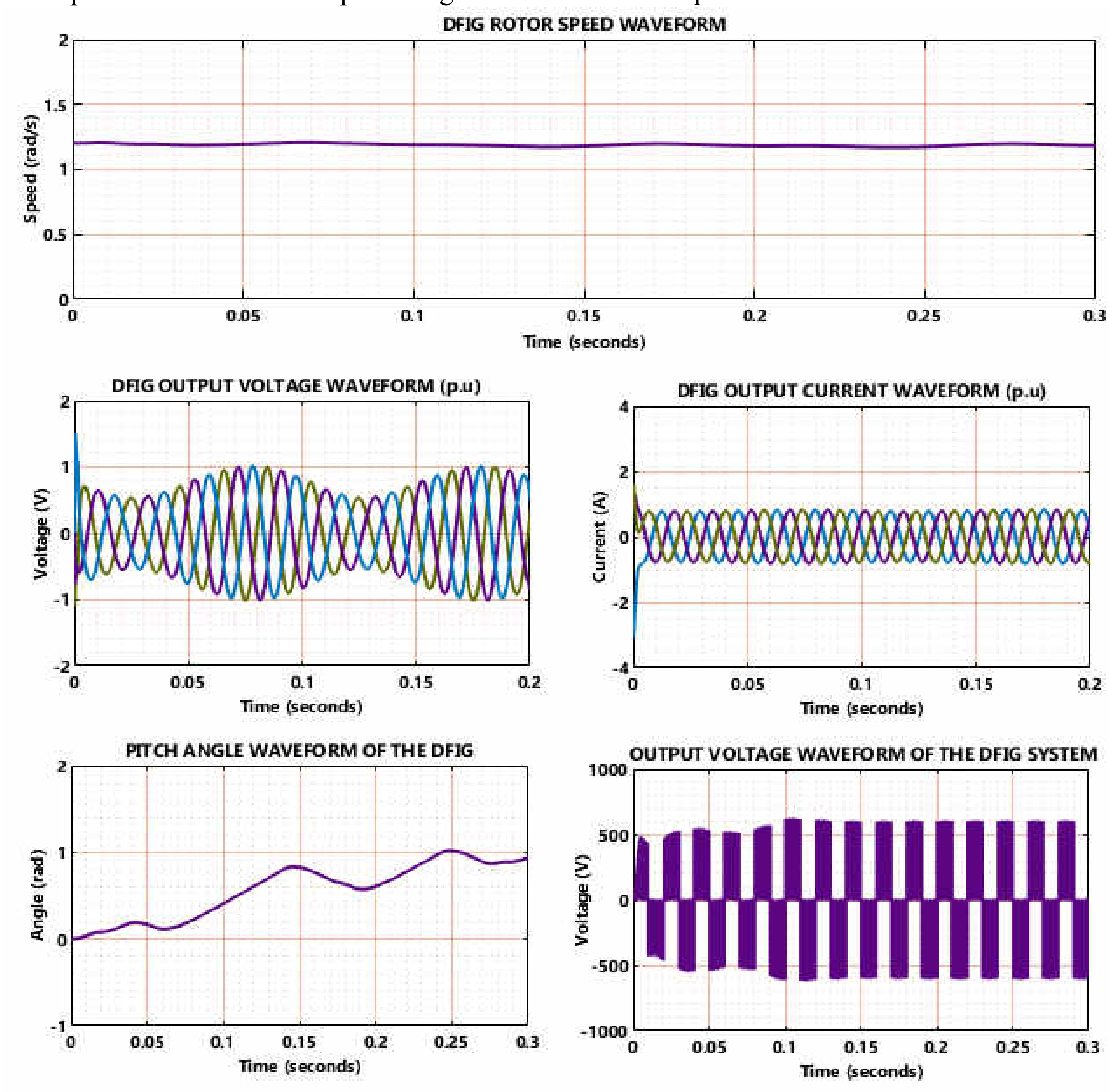

Fig. 11. DFIG 1 Performance Waveforms.

Fig. 11 represents the waveform of DFIG 1, where the first graph shows the rotor speed which is fixed at certain speed with limited deviations. The second and third graph comprises the output voltage and current waveform, where both voltage and current display sinusoidal oscillation. The third graph depicts the pitch angle that progressively increases and then stabilizes. Finally, the last graph shows the output voltage of the DFIG system, which initially fluctuates and then stabilizes at 600V without any further variations indicating improved DC supply form the rectifier.

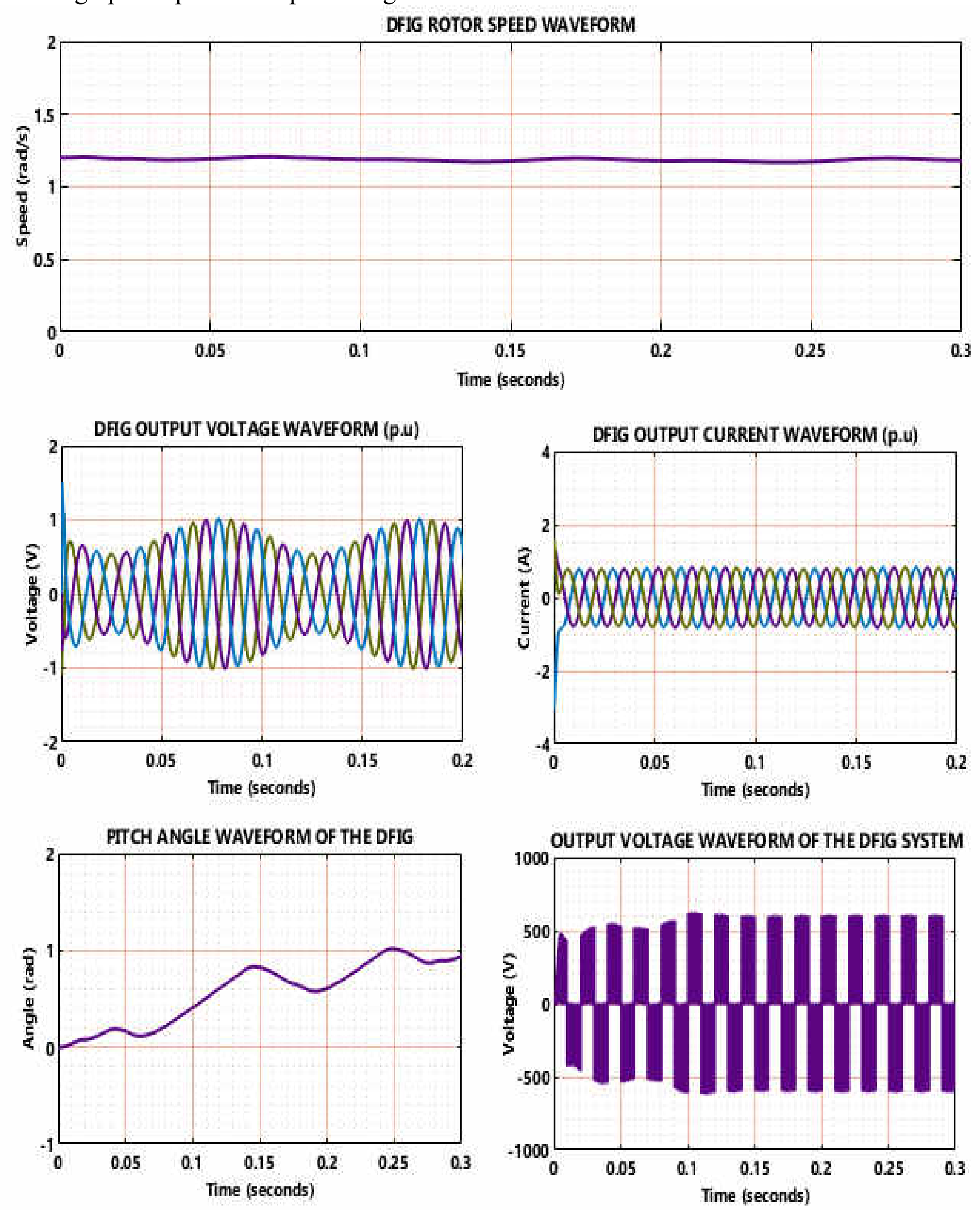

Fig. 12. DFIG 2 Performance waveforms.

Fig. 12 comprises of five waveforms showcasing the functional characteristics of DFIG 2 system. The steady rotor speed waveform depicts consistent performance with reduced fluctuations. The output voltage and current waveform show sinusoidal oscillations with voltage displaying certain temporary decay. The pitch angle waveform depicts gradual increase and later stabilizes. Lastly, the DFIG system output voltage displays initial deviations with stable high voltage of 600V, indicating overall performance efficiency of DFIG system even under varying circumstances.

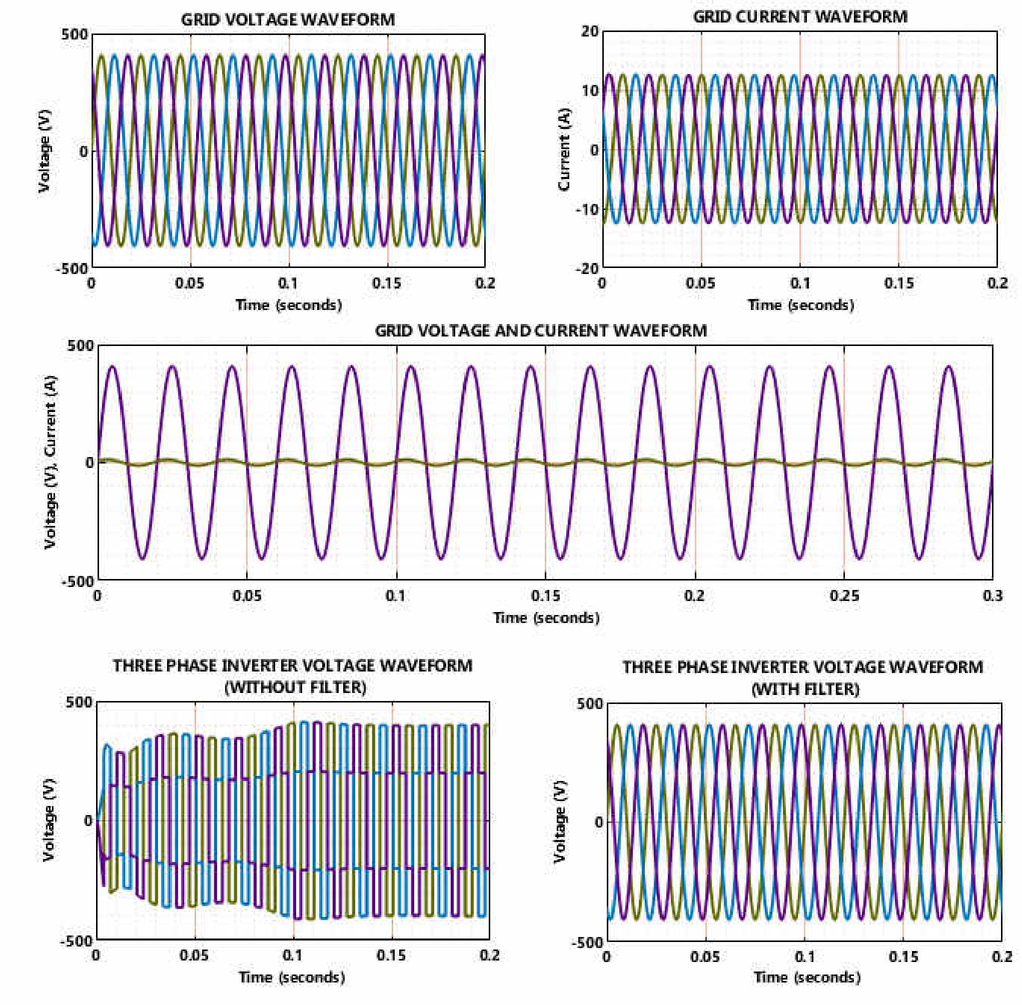

Fig. 13. Grid and Three-phase inverter waveform.

Fig. 13 represents the grid and inverter waveform, where the first and second graph shows the gird voltage and current which are maintained at fixed voltage ranging below ±500 V and current ranging between ±12A respectively. The third graph showcases the perfect synchronization of voltage and current. And the fourth and fifth graph comprises of three phase inverter voltage waveform with and without filter, where the inverter waveform with filter shows consistent and smooth waves. Ensuring minimized interferences, thus, enhancing the overall grid performance.

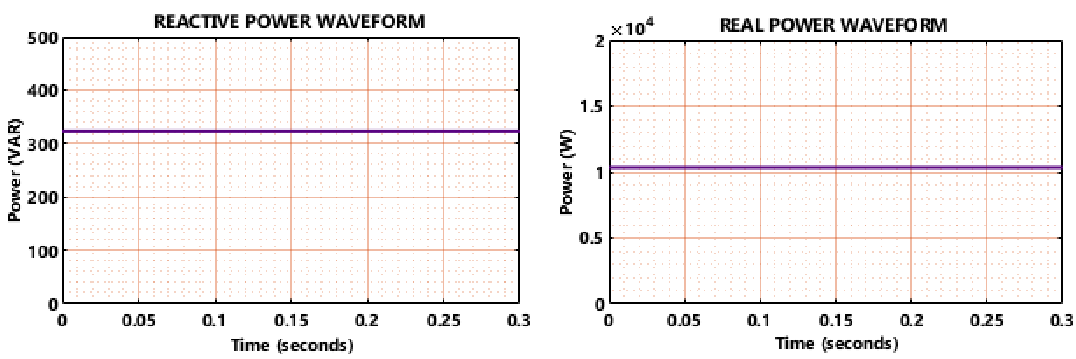

Fig. 14. Reactive and Real Power Waveform.

Fig. 14 showcases the reactive and real power, where both reactive and real power remain fixed 320 VAR and 1.1×10^4 W. Reactive power being lesser than real power signifies reduced power losses with effective system functioning.

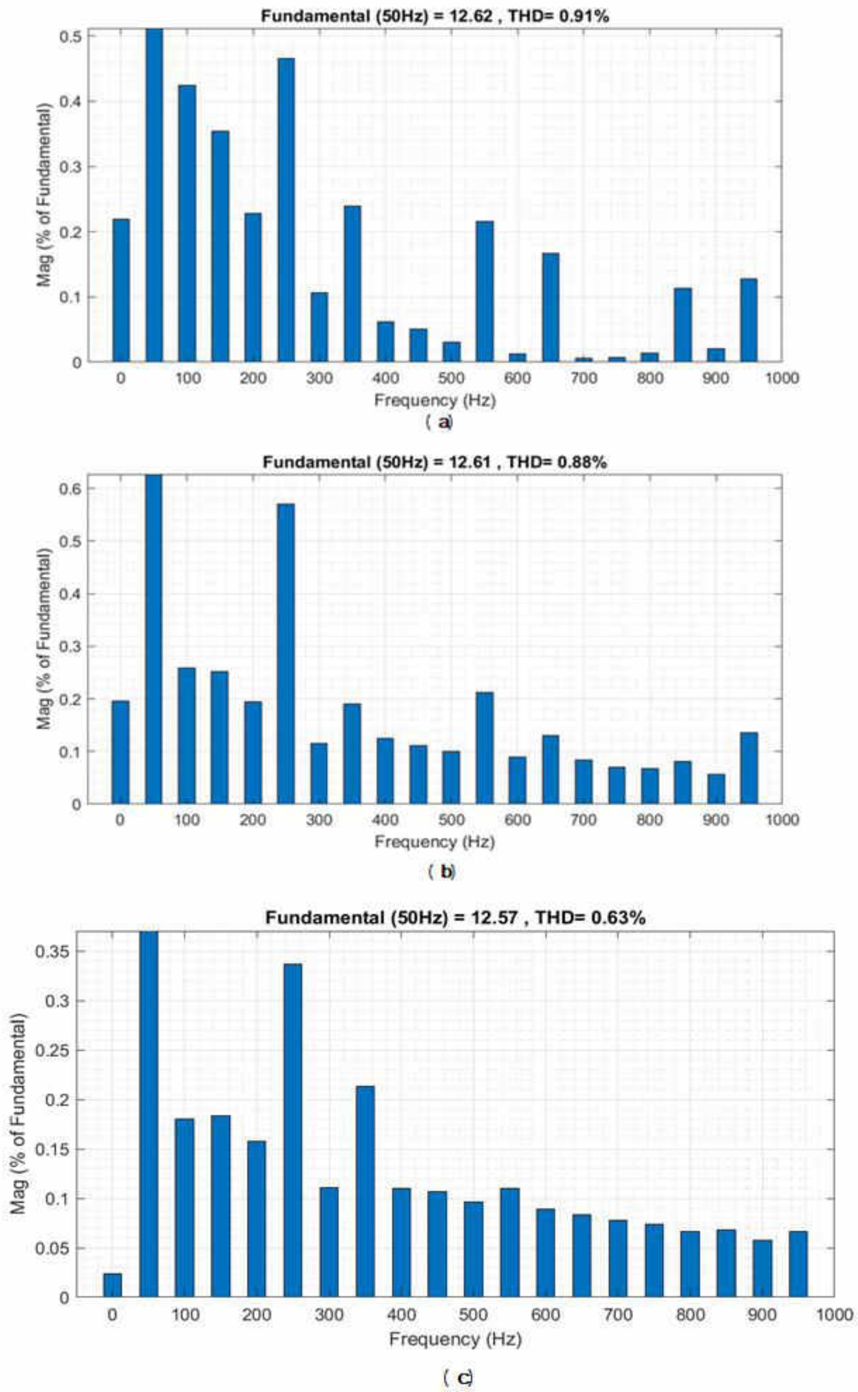

Fig. 15. THD waveform.

Fig. 15 implies the THD waveforms of R,Y and B phases. In Fig. 15 (a) THD value of 1% is attained by the R-Phase, indicating the presence of harmonic distortion, While in Y-Phase as shown in Fig. 15 (b) THD drops down to 0.88%, referring to the slight decrease in harmonic distortion and finally in Figure 15 (c) In B-Phase a THD attains a lowest value of 0.68%, ensuring highly reduced harmonic distortion respectively.

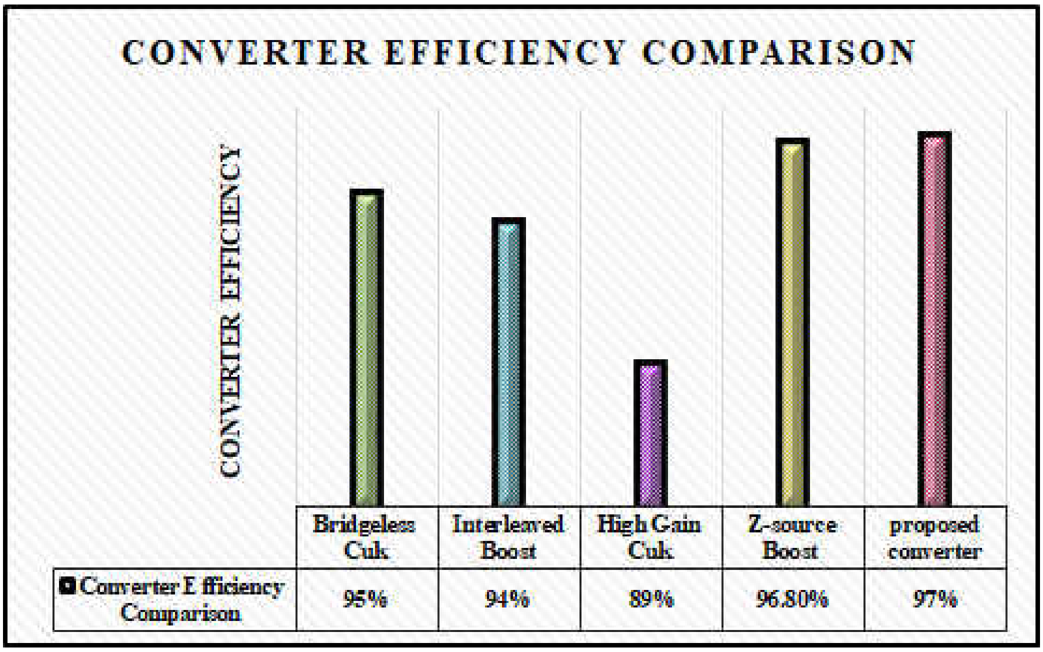

Fig. 16. Efficiency Comparison.

Fig. 16 denotes the efficiency comparison of various conventional converters with proposed converters. The Bridgeless Cuk converter [20] depicts an efficiency of (95%) , Interleaved Boost Converter (IBC) [21] attained slightly reduced efficiency of (94%), Whereas, the High gain Cuk converter [22] displays the lowest efficiency of (89%) . Meanwhile, Z-source Boost converter [23] attained 96.8% , Despite of the fact that, the proposed converter attained higher efficiency out of all the conventional converters, indicating the effectiveness of the proposed system with reduced losses.

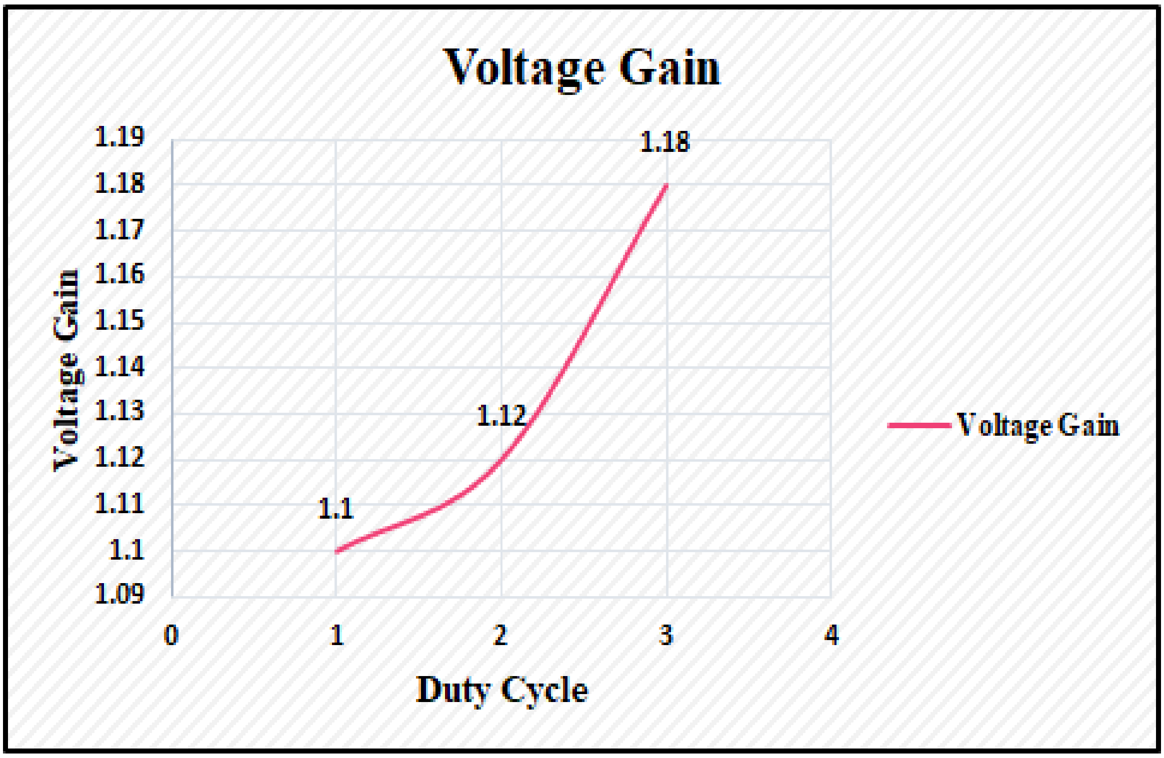

Fig. 17. Voltage Gain comparison.

Fig. 17 represents the voltage gain comparison, to determine the performance efficacy of the proposed converter. The above chart showcases the comparison of two different converter voltage gain with proposed converter voltage gains, from which it is depictable that, IBC [21] attained a voltage gain of (1.10) , while Z-source boost converter [23] acquired a voltage gain of (1.12). When compared to these converters, proposed converter attained higher voltage gain of (1.18) respectively, assuring enhanced system performance. Table 3 demonstrates the comparison of settling time for various optimized control approaches.

Table 3.Comparison of settling time

Optimization Algorithm	Settling Time
MGO-PI [24]	0.18
TLBO-PI [25]	2.4
proposed controller	0.15

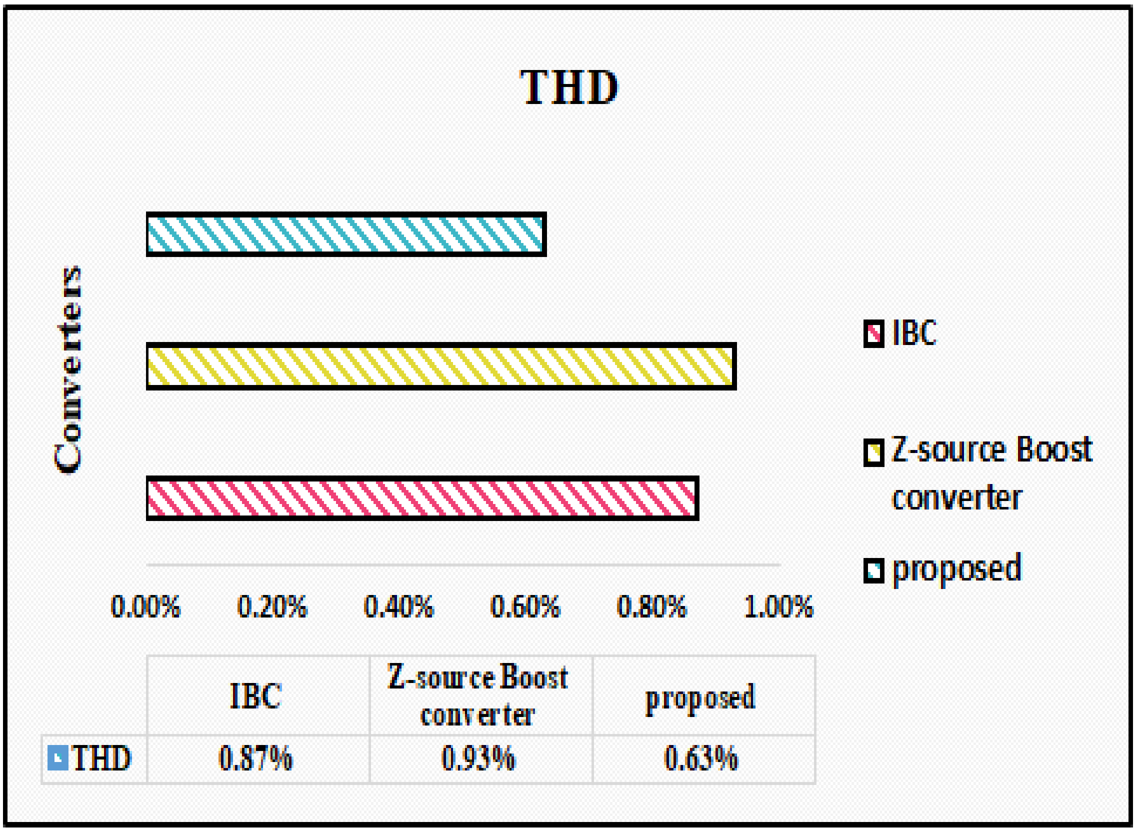

Fig. 18. THD comparison.

Fig. 18 indicates the comparison of THD, where IBC and Z-source Boost converter attained slightly higher THD of 0.87% and 0.93% when compared to the proposed DC-DC SEPIC converter which attained highly reduced THD of 0.68% respectively, indicating improved power quality with reduced distortions.

V. CONCLUSION

This paper presents a Dual DFIG based WECS for achieving sustainable energy to meet the power demand of the grid. The implementation of SEPIC converter with WAO optimized PI controller attained enhanced system performance in terms of higher efficiency and voltage gain. SEPIC converter effectively raised the voltage level obtained from the DFIG-WECS, thereby, producing enough voltage output to satisfy the grid demand. Additionally, WAO optimized PI controller produced regulated and stabilized output, thus, improving the the output power quality. The outcomes obtained from MATLAB validate that, this system acquired enhanced energy conversion with higher efficiency (97%), voltage gain (1.18) and reduced settling time (0.15) respectively. Henceforth, the introduced SEPIC converter with WAO optimized PI controller shows improved performance leading to enhanced powerS quality even under varying wind circumstances.

REFERENCES

[1] Velpula S., Thirumalaivasan R., Janaki M. Stability analysis on torsional interactions of turbine-generator connected with DFIG-WECS using admittance model. *IEEE Transactions on*

Power Systems, 2020, vol. 35, no. 6, pp. 4745-4755.

[2] Hussain H. A., Loncarski J., Ristic L. B., Bellini A. DFIG-based WECS with Partial-Scale Converter: Efficiency, Cost and Volume Comparison of SiC-based and IGBT-based Converter Solution. *IEEE Access*, 2024.

[3] Chojaa H., Derouich A., Zamzoum O., Watil A., Taoussi M., Abdelaziz A. Y., Elbarbary Z. M., Mossa M. A. Robust control of DFIG-based WECS integrating an energy storage system with intelligent MPPT under a real wind profile. *IEEE Access*, 2023.

[4] Leon A. E., Amodeo S. J., Mauricio J. M. Enhanced compensation filter to mitigate subsynchronous oscillations in series-compensated DFIG-based wind farms. *IEEE Transactions on Power Delivery*, 2021, vol. 36, no. 6, pp. 3805-3814.

[5] Musarrat M. N., Fekih A. A Fault-Tolerant Control Framework for DFIG-Based Wind Energy Conversion Systems in a Hybrid Wind/PV Microgrid. *In IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2021, vol. 9, no. 6, pp. 7237-7252.

[6] Dhineshkumar K., Subramani C, Prakash G., Vimala C. A modified static gain SEPIC converter renewable applications. *In AIP Conference Proceedings*, 2019, vol. 2112, no. 1. AIP Publishing.

[7] Sai B. S. V., Chatterjee D., Mekhilef S., Wahyudie A. An SSM-PSO Based MPPT Scheme for Wind Driven DFIG System. *In IEEE Access*, 2022, vol. 10, pp. 78306-78319.

[8] Yunus A. S., Abu-Siada A., Mosaad M. I., Albalawi H., Aljohani M., Jin J. X. Application of SMES Technology in Improving the Performance of a DFIG-WECS Connected to a Weak Grid. *In IEEE Access*, 2021, vol. 9, pp. 124541-124548.

[9] Puchalapalli S., Singh B., Tiwari S. K., Goel P. K. Design and analysis of grid-interactive DFIG based WECS for regulated power flow. *IEEE Transactions on Industry Applications*, 2020, vol. 56, no. 5, pp. 5396-5407.

[10] Prasad R. M., Mulla M. A. Rotor position-sensorless algorithms for direct power control of rotor-tied DFIG." *IEEE Transactions on Power Electronics*, 2020, vol. 36, no. 6, pp. 6213-6217.

[11] Han H., Li Z., Wang H., Feng Q., Guo R., Yang Z., Liu X. Design of a Parallel All-DC Wind Power System With Turbine-Side Boost Based on a New DC Conversion. *IEEE Access*, 2024.

[12] Meena V. P., Gupta A., Singh V. P. Improved control strategy for cuk converter assisted wind-driven seig for dc nanogrid. *IET Electric Power Applications*, 2020, vol. 14, no. 10, pp. 1906-1917.

[13] Bharti O. P., Sarita K., Vardhan A. S., Vardhan A. S., Saket R. K. Controller design for DFIG- based WT using gravitational search algorithm for wind power generation. *IET Renewable Power Generation*, 2021, vol. 15, no. 9, pp. 1956-1967.

[14] Abdelsalam I., Alajmi B. N., Marei M. I., Alhajri M. F. Wind energy conversion system based on open- end winding three- phase PMSG coupled with ac− dc buck- boost converter. *The Journal of Engineering*, 2019, no. 17, pp. 4336-4340.

[15] Bharti O. P., Sarita K., Vardhan A. S., Vardhan A. S ., Saket R. K. Controller design for DFIG- based WT using gravitational search algorithm for wind power generation. *IET Renewable Power Generation*, 2021, vol. 15, no. 9, pp. 1956-1967.

[16] Mahfoud S., Derouich A., El Ouanjli N., Quynh N. V., Mossa M. A. A new hybrid ant colony optimization based PID of the direct torque control for a doubly fed induction motor. *World Electric Vehicle Journal*, 2022, vol. 13, no. 5, pp. 78.

[17] Abbaszadeh M., Abbasi R. Optimization of the DFIG Wind Turbine Controller Parameters by the Gray Wolf Algorithm. *Journal of Computer & Robotics*, 2021, vol. 4, no. 2, pp. 53-66.

[18] Mohamed N. A., Hasanien H. M., Alkuhayli A., Akmaral T., Jurado F., Badr A. O. Hybrid Particle Swarm and Gravitational Search Algorithm-Based Optimal Fractional Order PID Control Scheme for Performance Enhancement of Offshore Wind Farms. *Sustainability*, 2023, vol. 15, no. 15, pp. 11912.

[19] Zeghdi Z., Barazane L., Bekakra Y., Larabi A. Improved backstepping control of a DFIG based wind energy conversion system using ant lion optimizer algorithm. *Periodica Polytechnica Electrical Engineering and Computer Science*, 2022, vol. 66, no. 1, pp. 43-59.

[20] Singh, Kumar Abhishek, Ayushi Chaudhary, and Kalpana Chaudhary. "Three-phase AC-DC converter for direct-drive PMSG-based wind energy conversion system." *Journal of Modern Power Systems and Clean Energy* 11, no. 2 (2022): 589-598.

[21] Balakishan P., Chidambaram I. A., Manikandan M. An ANN Based MPPT for Power Monitoring in Smart Grid using Interleaved Boost Converter. *Tehnički vjesnik*, 2023, vol. 30, no. 2, pp. 381-389.

[22] Haider Z., Ulasyar A., Khattak A., Zad H. S., Mohammad A., Alahmadi A. A., Ullah N. Development and analysis of a novel high-gain CUK converter using voltage-multiplier units. *Electronics*, 2022, vol. 11, no. 17, pp. 2766.

[23] Sathish C., Chidambaram I. A., Manikandan M. Switched Z-Source Boost Converter in Hybrid Renewable Energy System for Grid-Tied Applications. *Journal of Electrical Systems*, 2023, vol. 19, no. 1, pp. 64-81.

[24] Magdy F. E., Hasanien H. M., Sabry W., Ullah Z., Alkuhayli A., Yakout A. H. Mountain gazelle algorithm-based optimal control strategy for improving LVRT capability of grid-tied wind

power stations. *IEEE Access*, 2023, vol. 11 pp. 129479-129492.
[25] Ramalingegowda C. H., Rudramoorthy M. Transient stability enhancement using optimized PI tuning of static synchronous series compensator in wind power conversion system. *Frontiers in Energy Research*, 2023, vol. 11, pp. 112540.

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