JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 12(4), DECEMBER, 2024
ISSN: 2277-0011; Journal homepage: www.atbuftejoste.net

Optimal Tuning of Proportional Integral Controller using Graylag Goose Optimization Algorithm for Control of Permanent Magnet Synchronous Generator-based Wind Turbine with Tip Speed Ratio for Maximum Power Point Tracking

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ABSTRACT
This research presented the Maximum Power Point Tracking (MPPT) control of Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion (WEC) system using Graylag Goose Optimization (GGO) algorithm for effective Maximum Power Point Tracking (MPPT) under different wind speed profiles. Owing to the dynamic nature of the wind, inconsistent wind speed affects the output power quality of the wind energy conversion system. Therefore, for variable speed wind turbine systems, a generator side converter is usually connected to the generator to help ensure that when there are changes in the wind speed, the converter alters the generator speed to help track the maximum for that wind speed. This research presents the development of a Maximum Power Point Tracking (MPPT) control of Permanent Magnet Synchronous Generator-based Wind Energy Conversion (WEC) system using GGO algorithm to address this issue. To achieve this, a PMSG based WECS equipped with its Proportional Integral (PI) MPPT was developed in Simulink. PI- MPPT based was designed and GGO technique was employed to optimize the gain parameters of PI in order to enhance its performance. Simulation and performance evaluation of the developed maximum power point tracking control of PMSG-based WEC system in MATLAB/Simulink 2023b. The results were compared with existing steering system that utilized the PMSG based WECS equipped with PSO-PI MPPT using electromagnetic torque and deviations of the generator speed performance as metrics. Results obtained in terms of electromagnetic torque showed that the MPPT control of PMSG based WEC system using GGO algorithm outperforms the existing scheme by 15.39% and 29.48% in speed deviation respectively.

ARTICLE INFO
Article History
Received: September, 2024
Received in revised form: October, 2024
Accepted: November, 2024
Published online: December, 2024

KEYWORDS
Maximum Power Point Tracking, Wind Energy Conversion, Proportional Integral, Graylag Optimization Algorithm

INTRODUCTION

Wind is a source of renewable and sustainable power from air current flowing across the earth's surface. The increasing energy demand and the need for clean power generation leads to the fastest growth of wind power generation, and the annual growth rate in excess of 30% and a foreseeable penetration equal to 12% of global electricity demand by 2020 (Ahmad & Zhang, 2020). Wind energy has tripled its worldwide generation capacity in the last five years, being once again the fastest growing energy source in the world (Garcia-Sanz, 2009). Wind turbines harvest wind kinetic energy and

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convert it into usable electrical power. Reliable and effective wind turbines help offer a solution to the steadily growing world energy demand Especially, variable speed wind turbines exhibit the ability to operate near to its optimum tip-speed ratio and thus become dominant in modern wind turbines (Song *et al.*, 2010). Due to the inherent nonlinear nature of components, indispensable disturbances and inaccurate mathematical modeling, modern wind turbine systems exhibit complex dynamics and rapidly changing characters. Therefore, reliable and cost-effective electric energy generation from wind power calls for enabling technologies, especially advanced control schemes to ensure system stability and desirable performance in the presence of system nonlinearities, model uncertainties and unpredictable disturbances. This is particularly true for large scale wind turbines and offshore wind turbines (Johnson *et al.*, 2006).

Wind energy generation is experiencing the most significant growth, this has led to researchers looking for ways of increasing and sustaining the continuous growth of energy from the wind (Pantea *et al.*, 2019). Development of different types of generators and different wind turbine concepts has been done in order to ensure the installation of more reliable and powerful wind turbines in windier zones. This has led to the development of more offshore wind farms which provide greater productivity. However, hostility and remoteness of the environment which increase the maintenance cost are the major drawbacks of offshore generation (Pantea *et al.*, 2018). Thus, there is serious need to ensure the robustness and efficiency of the wind generator in use.

Generators driven by variable speed wind configuration are now preferred over the fixed speed type due to the ability it has in ensuring maximum possible extraction from wind. The wind energy conversion system (WECS) configuration is classified into several categories depending on the type of generators employed with the with the wind turbine. The configurations are: "doubly fed induction generator with partial scale converters, asynchronous generator with full scale power converter and permanent magnet synchronous generator with full scale power converter". The first set of generators used in generating power is the synchronous generators. Doubly fed induction generators are also frequently used. However, due to the higher degree of control that is obtained from full power configurations as compared to partial power topologies using doubly-fed induction generators (DFIGS), generators that are using full power configurations (induction generator) are now currently appreciated in the wind energy conversion system (Chinmaya & Singh, 2018).

Several techniques have been employed in literature to develop a control scheme for generators in wind energy conversion system (Burton *et al.*, 2011). Traditionally, control of wind turbine system was based on stator-oriented vector control, in which the control objectives were achieved with a rotor current controller. One main drawback of this system is that its performance depends heavily on accurate machine parameters such as stator, rotor resistances and inductances. Direct Torque Control (DTC) of induction machines provides an alternative to vector control. This method directly controls machine torque and flux by selecting voltage vectors from a look-up-table using the stator flux and torque information. Modern control strategies aim to overcome the uncertainty and nonlinear factors in order to obtain better performance. (Jelavić & Perić, 2009). Kim *et al.*, (2013), discusses a torque compensation strategy for PMSG WT to ensure system stability. Also, a method of finding PI controller parameters of a PMSG wind turbine to enhance control performance by (Busca *et al.*, 2010). Based on intelligent control techniques such as metaheuristic algorithms, these classic controllers can be optimized for more efficient results. On-Off control is a robust control method to maximize the captured power of WECS. This technique tracks the optimum torque value (Busca *et al.*, 2010). In order to extract the maximum power from wind power, we can formulate the objective of on-off control and an optimization problem whose objective function is maximized or minimized. The Particle Swarm Optimization algorithm (PSO) is a population algorithm, proposed in 1995 by Russel Eberhart and James Kennedy (Eberhart &

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Kennedy, 1995).This algorithm considered as a global and stochastic optimization technique is inspired by the collaborative behavior of biological populations and organisms such as schools of fish and flocks of birds. The approach based on the swarm particle optimization algorithm emits to reduce the number of parameters of an algorithm during the disappointed definition of adaptation rules. The PSO optimization technique is an easy and simple method to implement compared to other metaheuristic algorithms (Bechouat *et al.*, 2015).

Hence, this work aim is to develop a maximum power point tracking control of permanent magnet synchronous generator-based wind energy conversion system using Graylag Goose Optimization (GGO) algorithm.

RELATED WORKS

Over the last decade, several new control techniques such as the variable structure control, adaptive control, and intelligent control have been intensively studied to control non-linear components in electrical machines. Numerous works of literature on wind turbine control performance problems have been discussed such as Jha (2017) has implementing a sliding mode observer to estimate the rotor position of the generator based on the r voltages controlled and the measured stator currents. Rajan (2016) describes two different methods of permanent magnet synchronous generator based wind turbine (PMSG WT) control. The author uses, on the one hand, the field-oriented control (FOC) in which it is necessary to know the position of the rotor and the speed. On the other hand, the non-linear sliding control mode (SCM) is presented in order to improve the efficiency of the control. A genetic algorithm was applied to regulate the controller parameters of a PMSG WT. Kim et al. (2013) used a torque compensation strategy for PMSG WT to improve system stability. Also, a method to search for the proportional–integral (PI) controller parameters of a PMSG wind turbine to develop control performance is studied by Kim et al. (2015). An implementation of the direct torque and field control strategy was developed by Busca et al. (2010). In spite of the good results given by these control techniques, they have few real applications. On the one hand, their stability has a lack of confidence. On the other hand, their structures are complicated. In contrast, conventional PI controllers are still the most commonly used control techniques in power systems because of their simple structures. Unfortunately, setting up traditional PI controllers can be difficult to properly adjust PI gains due to non-linearity. The metaheuristic particle swarm optimization (PSO) is a calculation algorithm based on the intelligence of the swarm originally proposed by J. Kennedy and R. Eberhart (Hajihassani et al., 2018). This stochastic and global optimization technique is stimulated by the collaborative behavior of populations and biological organisms such as schools of birds and schools of fish. The exchange of information among individuals in the population solves various complex optimization problems in various engineering domains (Nath et al., 2018). In this article, types of the PSO algorithm such as the case of the canonical PSO algorithm (Liu et al., 2012), PSO with decreasing linear inertia (Raska and Ulrych, 2015), and the disturbed PSO variants (Jensi and Jiji, 2016) particularly used for the optimization of the PI controller parameters. The speed regulation problem has behaved as a constrained optimization problem that is effectively solved by proposed PSO algorithms whose error performance criteria will be minimized as an objective function.

This article is organized as follows. Section ‘‘Model of wind turbine’’ presents the modeling of the wind turbine. A mathematical model of permanent magnet synchronous generator (PMSG) is then established. In section “PMSG model,” the decoupling problem, specifically the determination and adjustment of parameters of the PI controller, is formulated as an optimization problem. Section ‘‘Field-oriented control of PMSG’’ is devoted to the presentation of the proposed PSO algorithms, namely canonical PSO, PSO with a linear decrease in its inertia factor, and the disturbed PSO, used to solve the PI controller agreement problem formulated. In the section ‘‘Tuning PI using PSO,’’ all the simulation results, obtained with the proposed metaheuristic

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approaches, are shown and compared with each other. The document is finished with a conclusion

Model of Wind Turbine in Wind Energy Conversion System

Wind turbine in electricity generation works under the principle of transforming the air kinetic energy into mechanical power of the turbine rotor blades. Horizontal axis propeller comprising of two or three blades mounted on a tower is commonly used. For a location A, perpendicular to the direction of the wind speed, the power is as shown in equation (1).

$$P = \frac{1}{2}.\rho.A.C_p.v^3 \qquad (1)$$

The aero generator is able to convert the wind energy to mechanical energy. The mechanical torque Cm is defined as follows

$$\mathrm{C_m} = \frac{P_{mec}}{\cup} \qquad (2)$$

Where ∪ is the turbine rotor speed. The mechanical power, $\mathrm{P_{mec}} =$ also called aerodynamic power, depends on the coefficient of power $\mathrm{C_p}$. It is given by

$$\mathrm{P_{mec}} = C_p V_p \qquad (3)$$

Mathematical model of Permanent Magnet Synchronous Generator (PMSG)

The synchronous generator is such a device that transforms mechanical energy into the electrical energy delivered by the prime mover of the generator. It is also known as an alternator. It called a synchronous generator because its rotation speed is equal to the rotating speed of the field at the stator of the generator called synchronous speed. But for the purpose of this research, the mathematical model reported in the work of (Hannach *et al.*, 2021) would be considered. The mathematical model is presented as follows. The equations of the synchronous generator with permanent magnets in the reference d-q are defined by

$$U_d = -R_s\, i_{d-s} L_d \frac{d_{id}}{dt} + wL_q i_q \qquad (4)$$

$$U_q = -R_s\, i_{q-s} L_q \frac{d_{iq}}{dt} - wL_d i_d + w\varphi_f \qquad (5)$$

$$w = p\Omega \qquad (6)$$

Where p is the number of pairs of poles; L_d, L_q are, respectively, the inductances of the direct and quadrature axis; C_f is the inductive flux; and v is the electrical pulsation of the PMSG voltages. The electrical power can be expressed in the DQ-axis reference frame as follows:

$$P_{em} = \frac{3}{2} w\big((L_d - L_q) i_q i_3 - \varphi_f i_q\big) \qquad (7)$$

The expression of the electromagnetic torque is given by

$$C_{em} = \frac{3}{2}\, p\varphi_f i_q \qquad (8)$$

PI for Field Oriented Control of PMSG

To simplify the control, the proposed strategy is applied to the generator by optimizing the speed with tip speed ratio for maximum power point tracking (TSR-MPPT) to maximize the power produced by the wind turbine. The d-axes stator current of PMSG can be set to zero during the operation to achieve a linear relationship between the stator current and the electromagnetic torque. Then again, the generator can be controlled to produce maximum torque with minimum direct current. In this case, the torque will be controlled by the quadrature component. This command consists of controlling the two components of the stator current i_d and i_q by imposing the voltages U_d and U_q. Consequently, in order to require these voltages and to solve the coupling problem between the axes d and q, it suffices to impose the references voltages U_{dref} and U_{qref} at the input of the generator which are written in this form:

$$U_{dref} = K_p e_d + K_i \int e_d\, dt - \Omega L_s i_q \qquad (9)$$

$$U_{qref} = K_p e_q + K_i \int e_q\, dt + \Omega L_s i_d \qquad (10)$$

K_p and K_i are the parameters (proportional and integral) of the current controller PI, e_d and e_q are the errors of the current given by

$$e_d = i_{dref} - i_d \qquad (11)$$

$$e_q = i_{qref} - i_q \qquad (12)$$

Tuning using GGO

Regarding the field of machine control, the PI controller is widely used. It is a good

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controller except that the problem of the mathematical model of the installation must be known thus the presence of the error between the desired value and the mustered one. As a solution to this disadvantage, several methods have been introduced to adjust the PI controller. In this work, the proposed method is to use the GGO algorithm to optimize PI controller parameters based on the error of stator current id and iq also that of speed. The performance of the PMSG varies according to the gains of the PI controller and is judged by the value of the integral time absolute error (ITAE) of which the sum of the performance indices (ITAE) is chosen as the objective function. Stochastic algorithms are to minimize the objective function so that all particles in the population are decoded for K_p and K_i. The ITAE is the one used in this search, which is described by:

$$ITAE = \int_0^\infty t|e(t)|dt \quad (13)$$

MATERIALS AND METHODS

This section present materials and methods used for the development and simulation PMSG The material used includes a desktop computer with its specification stated in Table 1 below, and MATLAB R2023b software, for simulating the developed maximum power point tracking control of permanent magnet synchronous generator-based wind energy conversion system using Graylag Goose Optimization (GGO) algorithm with the wind turbine model.

The Method highlight step-by-step process leading to the implementation of the stated objectives based on the following. The mathematical model of the control action containing the gains parameters was first obtained from the work of (Hannachi *et al.*, 2021). The objective function was formulated in terms of K_p and K_i. Then, the both GGO and PSO algorithms were applied on the formulated objective function

PI Controller Parameter Selection

PI controller was tuned to search for best gains using PSO and GGO, after running 25 iterations, the best parameters were found as shown below.

Table 1: *Optimal Parameters of PI Obtained from both PSO and GGO*

Parameters	PSO	GGO
K_p	99.9706	26.3492
K_i	16.6618	4.3915

Development of the Simulink model of wind turbine system via MPPT Algorithm

The mathematical model of turbine system presented in equations (2.1) to (2.4) in chapter two was modeled in Simulink to obtain the system's output Tm which represent respectively mechanical torque, power coefficient, beta, and omega. The resulting Simulink model of the wind turbine system is presented in Figure 3.1:

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JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 12(4), DECEMBER, 2024
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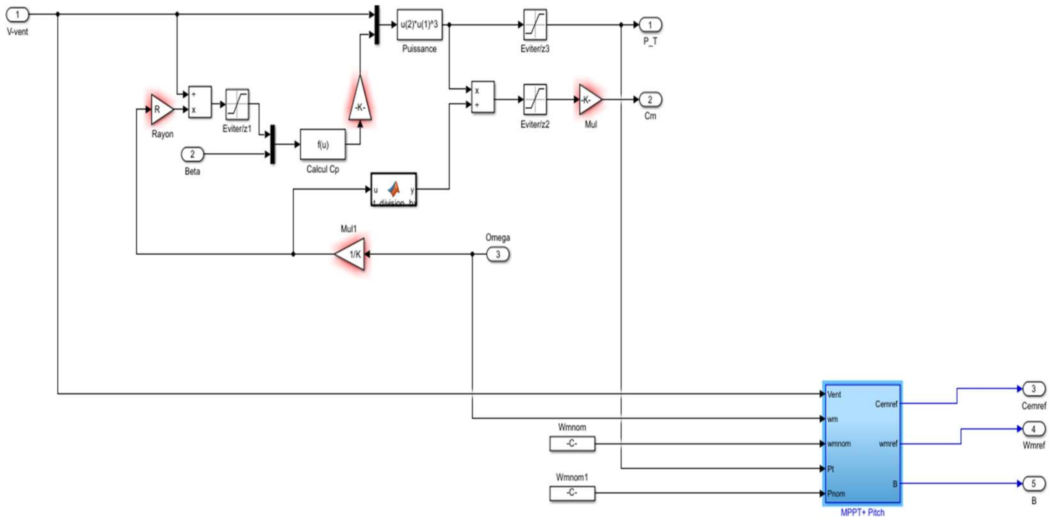

Figure 4: Simulink Model of Wind Turbine System.

Development of Permanent Magnet Synchronous Generator

The permanent magnetic synchronous generator was developed in order to track the maximum power of the wind generator speed. The control law for IBC was designed in Simulink using equation (1) to (5) while the virtual stabilization was designed based on equations (6) and (7). The equations (9) and (13) were used in modeling the PMSG subsystem. The complete model of the PMSG control system is presented in Figure 3.2:

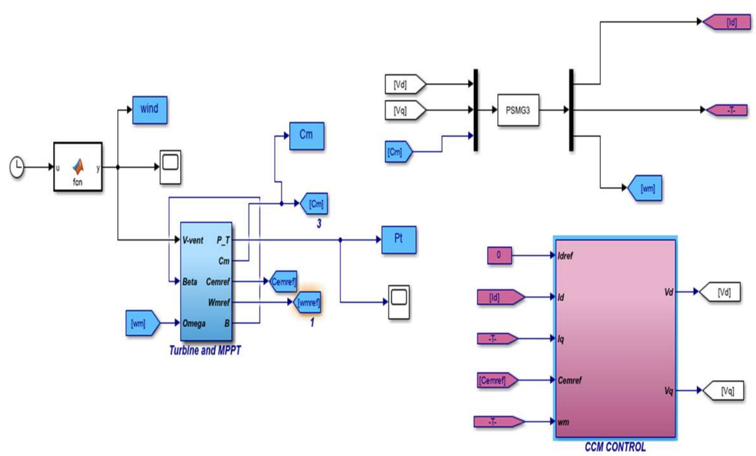

Figure 5: Simulink Model of PMSG Model

Figure 5 showed the developed Simulink model of the PMSG model. The model made up of three subsystem blocks: the wind turbine and MPPT model, ccm control and function block. The response of the states of the system was generated using scope block. The initial conditions reported in the work of (Hannachi *et al*., 2021) were adopted and presented in Table

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2 for the simulation of the system. The initial conditions reported in the work of Hannachi et al., (2021) were adopted and presented in Table 2 for the simulation of the system.

Table 2: Wind Turbine and PMSG Model Parameters (Hannachi *et al*., 2021)

Parameters	Values	Unit
Density of air (ρ)	1.222	KgL^{-3}
Length of the blade (R)	2	M
Optimum tip speed (γ_{opt})	8.1	_
Power Converter $(\mathrm{P_n})$	3.5Kw	Kw
Armature Resistance $(\mathrm{R_a})$	0.82	Ohms
Stator Inductor $(\mathrm{L_s})$	$15.1e^{-3}$	H
Amount of Inertia of the Machine (J)	0.05	min^{-1}
Viscosity coefficient of friction (f)	4.5	mUL^{-1}
Φ	0.09259	Wb
P	4	_

Performance evaluation

To evaluate the performance of the developed PI based MPPT Controller using Graylag Goose Optimization (GGO) with the research of Hannachi *et al*., (2022) that uses the PI based PMSG variable speed wind energy conversion MPPT PI-PSO controller was replicated in Simulink and the resulting model is presented in Figure 6:

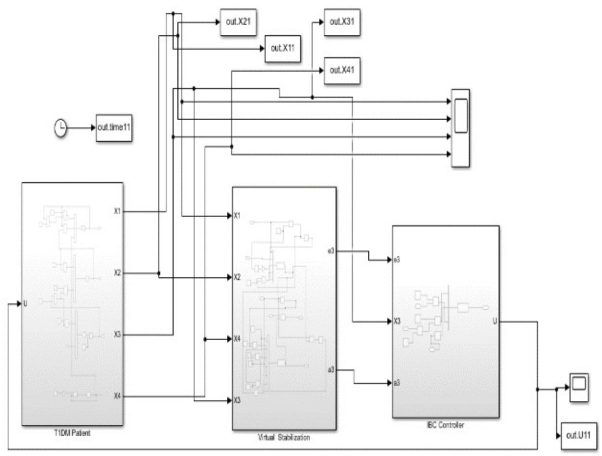

Figure 6: PI-PSO Control System Model

Figure 6 showed the replicated Simulink model of PMSG variable speed wind energy conversion MPPT control. The model is also made up of four subsystem blocks: the wind turbine, PMSG, TSR-MPPT and control block. The response of the states of the system was generated using scope blocks.

The performance of the GGO and PSO controllers were then evaluated using generator speed and electromagnetic torque from their reference as performance metrics. The percentage improvement of the PI-GGO over the PI-PSO based TSR MPPT was evaluated based on the equation:

$$\eta = \frac{K_{PSO} - K_{GGO}}{K_{PSO}} \times 100\% \quad (3.6)$$

Where η represent percentage improvement of the developed GGO over the particle Swarm

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JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 12(4), DECEMBER, 2024
ISSN: 2277-0011; Journal homepage: www.atbuftejoste.net

Optimization (PSO) TSR-MPPT, K_{PSO} is the value obtained on PSO TSR-MPPT and K_{GGO} is the value obtained when GGO was used.

RESULTS AND DISCUSSIONS

The results obtained based on the methodologies and research objectives are discussed and presented in this section.

Simulation Results

The results obtained for the simulation of both GGO and PSO with MPPT wind energy conversion presented in Figure Figures below:

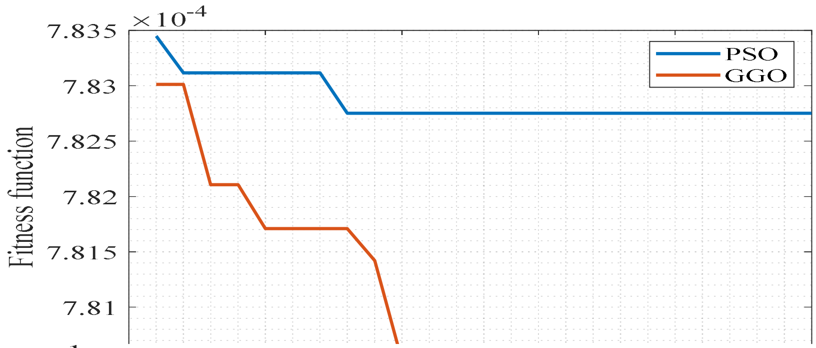
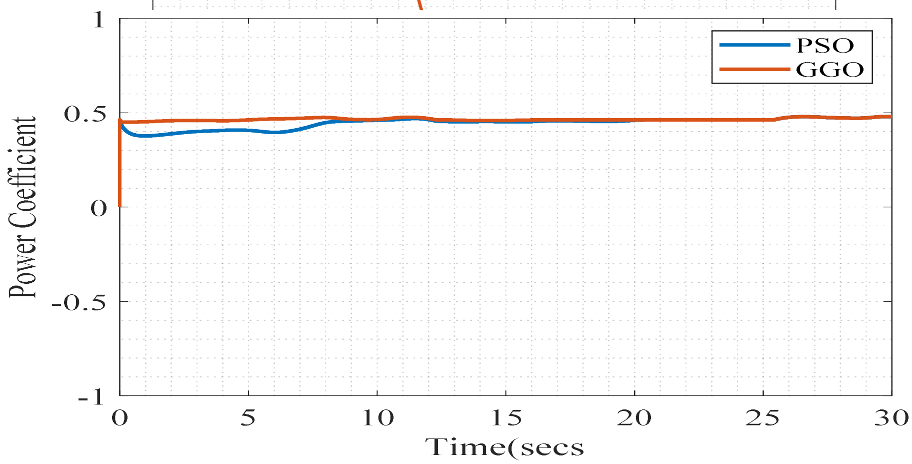


Figure 10: PSO and GGO



Convergence plot

Figure 11: Power Coefficient

Figure 10 shows the PSO and GGO algorithms convergence plots. From the Figure, it was observed that, the PSO converge with at 8th iterations with an optimized cost function of 7.835×10^{-4} the GGO converged at the 10th iteration with an optimized cost of 7.83×10^{-4} thereby demonstrating the superiority of the developed system.

Figure 11: shows the power coefficient when both algorithms were used and the desired trajectory to be tracked by the developed GGO algorithm which is the optimal value of power coefficient whose constant value is 0.48. From the

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Figure 11, it was also observed that, the developed GGO algorithm tracked the optimal value faster without and remains fixed without any delay unlike the Particle Swarm Optimization (PSO) technique, which took longer time to converge to the optimal value of the power coefficient with the presence of variability

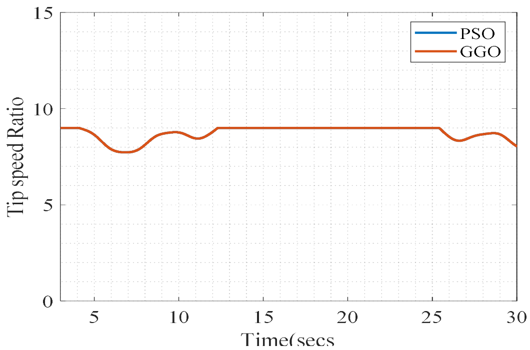


Figure 12: Tip Speed Ratio

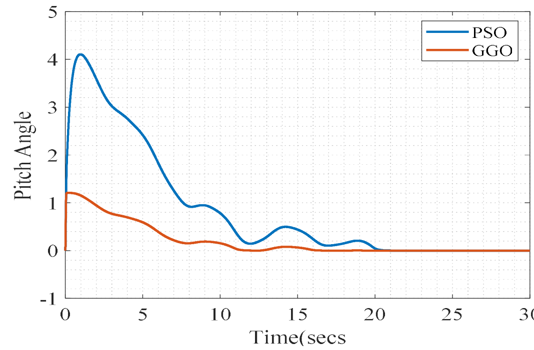


Figure 14: Pitch Angle

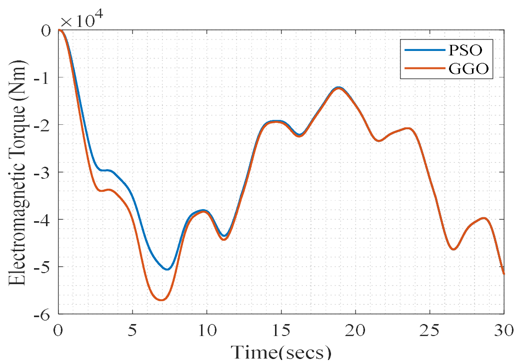


Figure 13: Electromagnetic Torque

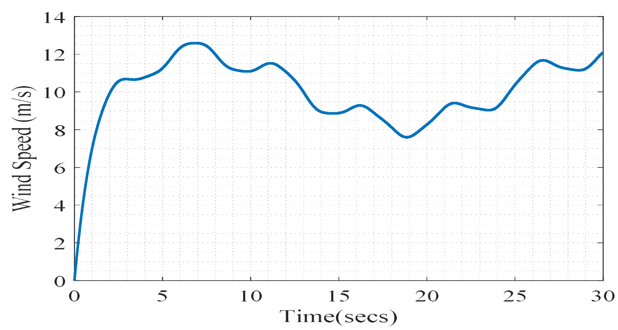
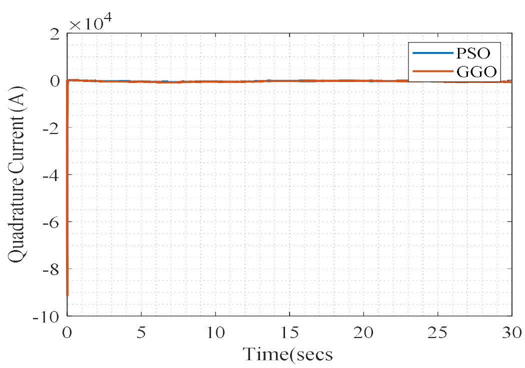


Figure 15: Wind Speed



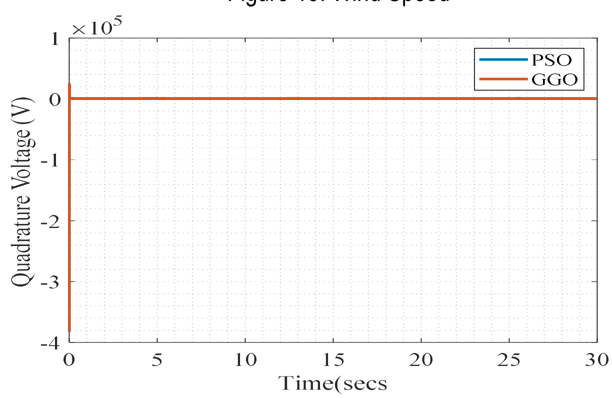


Figure 17: Quadrature Voltage

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ISSN: 2277-0011; Journal homepage: www.atbuftejoste.net

Figure 16: Quadrature Current

Figure 12. Shows the tip speed ratio obtained with used of both GGO and PSO in order to show the efficiency of the speed control strategy. It was observed from the Figure above, that the curve obtained by GGO takes the optimal value of (8.1) while that given by PSO varies around this value.

Figure 13 depicted an electromagnetic torque obtained when both algorithm were applied on the PMSG. It has been drawn for the comparative performance of the GGO and PSO for tracking wind maximum power. It can be observed from the graph that the GGO undergoes a little undershoot and takes more time to tracked the reference trajectory, whereas the PSO gives better tracking response with a negligibly small undershoot.

From figure 14, shows the case of the pitch angle used to extract maximum wind power using FOC and an optimal speed reference that is estimated from the wind speed. It was observed from the Figure 14 that GGO and PSO have nearly similar times of convergence to the equilibrium point, but the PSO experienced larger amplitude than that of the proposed GGO. Both track the reference value quite nicely.

Figure 15 represent the wind speed obtained during the simulation. It is observed that, the curve obtained that the curves obtained with the use of GGO was very remarkable which shows the efficiency of the speed control strategy developed since the measured speed is identical to the reference speed.

Figure 16 shows the response plot of quadrature current during the tracking of wind maximum power. From the Figure, using GGO, it was observed that, the system states exhibit little changes in amplitude. After some time, the system states stabilized to the zero equilibrium point unlike using PSO, as it can be seen in Figure 17 above that there was a noticeable negligence in amplitude.

Figure 17 shows the quadrature voltage when two algorithms were implemented. It was observed that GGO undergoes a larger rise in amplitude until it was later attained equilibrium point while it can be clearly observed that the performance of the PSO was satisfactory when compared with the GGO in terms of attaining the equilibrium due to which the power generated was maximum.

Performance Comparison of the Developed GGO and PSO based MPPT WEC System

The performance of the Proportional Integral controller designed with GGO algorithm was assessed on the basis of deviations of the generator speed and electromagnetic torque from their reference as performance metrics as reported in Hannachi *et al*., (2021). The performance of the developed PI controller with GGO and PI controller augmented PSO with respect to the performance metrics were presented in Table 3.

Table 3: Performance Comparison between the Developed GGO and PSO MPPT WEC System

Performance Specification	**Controller**		**Percentage Improvement (%)**
	Developed GGO	**PSO**	
Electromagnetic Torque (Nm)	9.73	11.5	15.39
Speed Deviation (m/s)	5.5	7.8	29.48

Table 3 summarizes the performance comparison of the developed Graylag Goose Optimization (GGO) algorithm and that of Particle Swarm Optimization (PSO) reported in the work of (Hannachi *et al*., 2021). It can be shown that both the techniques satisfy the design specification of

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JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 12(4), DECEMBER, 2024
ISSN: 2277-0011; Journal homepage: www.atbuftejoste.net

electromagnetic torque and speed deviation. However, the developed GGO implemented on PI controller has the overall improvement of 15.39% in electromagnetic torque and 29.48% when compared to the work reported by (Hannachi *et al*., 2021).

CONCLUSION AND RECOMMENDATION

The research presents the development of a maximum power point tracking control of permanent magnet synchronous generator-based wind energy conversion system using Graylag Goose Optimization (GGO) algorithm in order to address the issues of intermittent nature of varying wind speed affects the output power quality of the wind energy conversion system. To ensure effective tracking of the generator speed and torque which in turn affects the output power quality. The model of the PMSG based WECS equipped with its MPPT controller was developed in MATLAB/Simulink. Subsequently, the gains of PI based MPPT controller was optimized using GGO algorithm. The Simulation of the developed system was carried out in MATLAB/Simulink 2023b. The performance evaluation of the results was carried out and compared to the system reported in the work of Hannachi *et al*., (2021) in terms of electromagnetic torque and deviations of the generator speed. The simulation results reveal that the developed GGO PI based MPPT has the overall improvement of 15.39% electromagnetic torque and 29.54% deviation of generator speed

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ISSN: 2277-0011; Journal homepage: www.atbuftejoste.net

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