Maximum power optimization of a direct-drive wind turbine connected to PMSG using multi-objective genetic algorithm

Najoua Mrabet[1], Chirine Benzazah[1,2], Ahmed El Akkary[1], Yassine Ennaciri[1], Ilyas Lahlouh[1]
[1]LASTIMI Laboratory Systems Analysis Information Processing and Industrial Management Higher School of Technology, Mohammed V University Rabat, Rabat, Morocco
[2]LPFAS Laboratory of Fundamental and Applied Physics, Polydisciplinary Faculty of Safi, Cadi Ayyad University, Marrakech, Morocco

Article Info

Article history:

Received May 5, 2023
Revised Nov 5, 2023
Accepted Dec 7, 2023

Keywords:

GA optimization
MPPT
PI controller
PMSG
Wind turbine

ABSTRACT

This work aimed to develop and evaluate a maximum power point tracking (MPPT) control system for a wind energy conversion system (WECS) based on a permanent magnet synchronous generator (PMSG). PMSG is commonly used to generate direct-drive and variable-speed wind energy. Initially, the generator and converter on the DC load side are controlled to follow the wind speed reference set by the MPPT algorithm. The paper presents the optimization problem formulation, including the optimization space, constraints, and objectives. The genetic algorithm (GA) is used to extract the maximum power from the WECS in this design improvement. In this study, to control and stabilize the maximum power point (MPP) of the wind turbine, a proportional integral (PI) controller and a GA heuristic approach were utilized. The GA approach was employed to determine the best settings (Kp, Ki) using MATLAB/Simulink with a 12.3 kW PMSG to model and simulate the proposed system. Based on four performance indicators-integrated squared error (ISE), integrated absolute error (IAE), integrated time absolute error (ITAE), and integrated time squared error (ITSE), the GA approach was used to optimize the controller settings. The results of the simulation show that the wind turbine (WT) can effectively track the necessary MPP. The simulation's output also includes generated power, DC bus voltage, electromagnetic torque, and currents.

Corresponding Author:

Najoua Mrabet
LASTIMI Laboratory Systems Analysis Information Processing and Industrial Management Higher School of Technology, Higher School of Technology, Mohammed V University Rabat
Avenue des Nations Unies, Agdal Rabat, Maroc B.P, 8007 N.U., Morocco
Email: najouamrabet2@gmail.com

1. INTRODUCTION

With the rising price of nuclear and fossil fuels, there has been a growing emphasis on harnessing sustainable energy sources. Renewable energy options, like that wind energy, have gained significant attention due to their dependability, accessibility, and environmentally friendly nature [1], [2]. Wind turbines have a crucial part in converting wind energy into electrical power efficiently by adjusting their shaft acceleration to operate optimally across various wind speeds [3], [4]. Among the wind energy conversion systems, turbines equipped with permanent magnet synchronous generators (PMSGs) have garnered significant interest.

PMSGs offer advantages such as a simple structure, low-speed operation, ease of maintenance, and high reliability. These generators utilize power converters to control the maximum power point tracking

(MPPT) for different wind speeds, thus ensuring maximum power extraction [5], [6]. However, variations in wind speed can cause fluctuations in turbine rotor speed, necessitating effective MPPT algorithms to find the optimal power point and enhance overall system performance [7]. This research proposes using the incremental conductance method (INC) for MPPT in wind energy conversion systems (WECS).

Existing MPPT methods, including the INC approach, can be affected by the nonlinear interaction between environmental variables and the maximum power point. To address these issues, several MPPT techniques have been developed [8]. The INC strategy, although straightforward, relies on adjusting the duty cycle using the proportional-integral (PI) controller to achieve the maximum power point. However, accurately identifying stable regulator characteristics with various parameters proves to be a challenge [9].

To overcome these challenges, our research proposes a novel technique to predict the area of stability based on the PI controller's parameters. We aim to employ genetic algorithm (GA) optimization to fine-tune the PI controller's parameters, achieving positive outcomes, such as reduced setup time and improved voltage, current, torque, and power responses [10]. By utilizing the GA heuristic strategy, we can determine the optimal settings for the PI controller, and we have implemented and tested this approach using the MATLAB/Simulink system. The primary objective is to regulate the DC-DC boost converter effectively, generating that ideal voltage for achieving the maximum power point in wind energy conversion systems (WECS). This study makes a significant contribution by incorporating the GA-based soft technology to modify the specifications of the proportional-integral (PI) controller. Within the subsequent sections of this paper, we will delve deeper into the details of the proposed GA-based optimization approach for the PI controller and discuss the simulation setup and results. We will also compare our findings with existing classical technique, displaying the advancements and benefits offered by our novel approach.

2. THE PROPOSED SYSTEM

The wind turbine (WT) uses wind speed as an input to produce mechanical power. By maintaining the optimum stable voltage throughout that load, MPPT control algorithms will accustomed to acquire maximum power output among the wind that is available. Numerous MPPT approaches have been used to (WECS) in earlier literature. DC/DC converters function as MPP monitor and link wind energy conversion systems [11] to diverse load needs. Buck-boost and buck-boost converters most used. The efficiency of WECS tracking devices has already been significantly improved by a significant amount of study. Due to a multitude of variables, including accuracy while determining the genuine MPP, cost, convergence speed, and sensitivity, it is essential to choose that optimal MPPT Regarding the work. No matter how much the load or input voltage fluctuates, the controller must always keep the voltage regulated [12].

The suggested energy conversion system is founded on a permanent magnet synchronous generator (PMSG). This device offers crucial characteristics for wind energy applications, including minimal rotor losses, a soft start, and permanent magnet magnetization. The proposed architecture of the wind energy conversion system is demonstrated in Figure 1. The system includes a diode bridge rectifier, a boost converter, a permanent magnet synchronous generator, and a wind turbine. The output of the rectifier is connected to a DC-DC boost converter. The boost converter receives that maximum power point tracking (MPPT) control signal, which increases that voltage across that load.

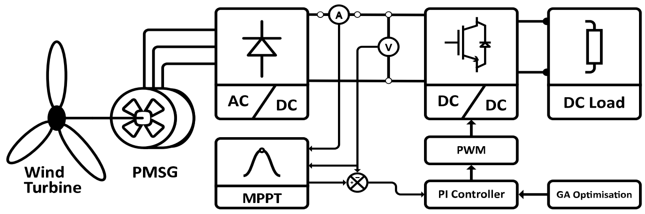

Figure 1. Schematic of maximum power optimization of WECS

2.1. Modeling of wind turbine

That wind turbine's (WT) mechanical power generated is determined by:

$$P_m = \frac{1}{2}\rho A c_p(\lambda, \theta) v^3 \quad (1)$$

where, ρ is the air density (kg/m^3), A is the swept area (m^2), cp is the performance coefficient of the turbine which is a function of the pitch angle of rotor blades β (in degrees), and v is the wind speed (in m/s). λ: The tip-speed ratio. The (2) represents the ideal rotor speed at which the turbine works at maximum power [13].

$$\lambda = \omega_m R/v \tag{2}$$

Where R and ω_m are the blade length (in m) and the wind turbine rotor speed (in rad/sec), respectively. The wind turbine mechanical torque output Tm offered as [14].

$$T_m = \frac{1}{2}(\rho A C_P(\lambda,\beta)v^3)/\omega_m \tag{3}$$

Due to the modeling turbine features mentioned in [15], that coefficient of power conversion cp = (λ, β) is modelled using that following general equation: a mechanical output power turbine is depicted in Figure 2 as a result of turbine speed in several wind speeds [16].

$$c_p = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3} \tag{5}$$

Also, Figure 2 characteristics show that there is a certain turbine speed at so it the most power may be generated since each wind speed. For instance, only when a turbine speed is kept at 1.2 pu can the maximum power be collected derived from a wind speed of 12 m/s. Consequently, the aforementioned circumstance suggests that Cp can only be kept at a tall value if the rotor speed is changed to the best working point for various wind velocities. A hypothetical wind turbine's highest efficiency is 16/27, or 59.25%. For all practical purposes, the efficacy varies between 25% and 45%. The Table 1 contains the dimensions of wind turbine.

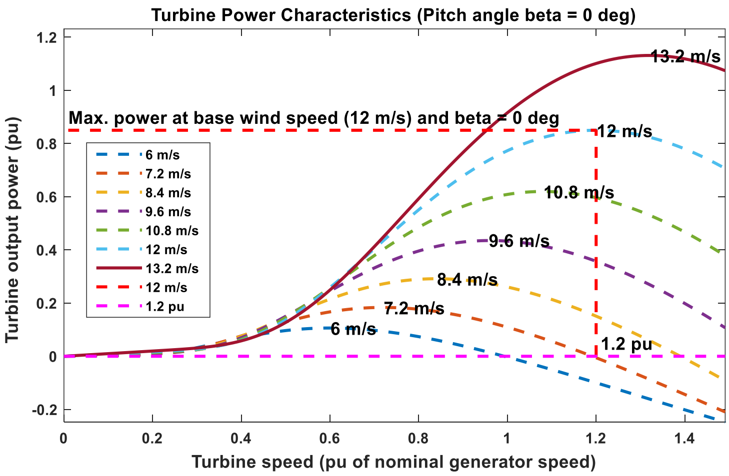

Figure 2. Turbine power characteristics

Table 1. Wind turbine parameters

S.L.	Dimensions	Value
1	Minimum mechanical output power	12.3 kw
2	Initial wind speed	12 m/s
3	maximum mechanical power (of nominal wind speed pu)	0.85 pu
4	Base rotor speed	1.2
5	Beta frequency angle	0°

2.2. PMSG modeling

Its d-q equivalent circuits serve as a paradigm for PMSG. In synchronous d-q coordinates, a surface mounted PMSG's equations are written as:

$$V_{ds} = R_s + L_s \frac{di_{ds}}{dt} - \omega_e L_s i_{qs} \quad (6)$$

$$V_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} + \omega_e L_s i_{qs} + \omega_e \psi \quad (7)$$

where L_s is the inductance of the stator winding, R_s is the resistance of the stator winding, V_{ds}, V_{qs}, i_{qs}, and i_{qs} are the d-q components of the stator voltage and current, respectively, ψ is the magnetic flux, and ω is electrical angular speed of the generator. The generator's output power and electromagnetic torque are provided as [17], P is the generator's pole number. That Table 2 contains the dimensions of the PMSG

$$T_e = \frac{3}{2}\frac{P}{2}\psi i_{qs} \quad (8)$$

$$P_{gen} = \frac{3}{2}\frac{P}{2}\psi i_{qs}\omega_m - \frac{3}{2}R_s i_{qs}^2 - \frac{3}{2}R_s i_{ds}^2 \quad (9)$$

Table 2. PMSG modeling dimensions

S.L.	Dimensions	Value
1	Resistance stator Rs	0.45573 (Ω)
2	Inductances [Ld, Lq]	[0.395 mH,0.395 mH]
3	Nombre of Poles	3
4	Rotor Inertie	0.0026 J
5	Fluid damping F	0.004925 $N.m.s^{-1}$
6	Flux Linkage ψ	0.1194 wb

2.3. DC-DC converter of boost

An IGBT anti-parallel diode transistor, an ultrafast diode, a capacitor, and an inductor make up the converter under investigation. According to Figure 1, the MPPT-based controller provides a pulse width modulation (PWM) signal the controls the switching IGBT converter's boost. The computation the appropriate duty cycle is important in order to regulate this DC-DC converter of boost circuit. To be able to compute PWM, an incremental inductance (INC) approach is used. Table 3 shows component values of the DC-DC boost converter.

Table 3. Measurements of the DC-DC boost converters elements

S.L.	Dimensions	Value
1	Inductor	0.45573 uH
2	Source Capacitor	0.066094 uF
3	Load resistor	500 Ω
4	Switching frequency	50 kHz

2.4. Three phase AC-DC converter

The most straightforward, affordable, and durable architecture utilized in power electronic applications is the unregulated rectifier. Although it is not necessary in our situation, this diode rectifier's inability to operate in a bi-directional power flow is a drawback. The boost converter and rectifier circuits are linked to the generator. It is expected that diode bridge rectifier circuits are utilised convert an AC energy from the generator to DC power. A three phase diode rectifier's average DC voltage and current values [18], [19].

2.5. Incremental conductance method (INC)

The Incremental technique is required to maximize one's power energy feasible at all times. For wind turbines with variable and constant speeds, the method demonstrates that we are circling the desired operational point. The immediate conductance I/V and incremental conductance dI/dV are especially in comparison in the INC technique to ascertain the MPP. The maximum power point is identified using the INC approach, which is founded on observation this peak of the PV curve is zero at MPP. When the point of operation is distant by that MPP, that move size is big for quick tracking whereas it is less when the turning point is near to the MPP to decrease steady state oscillation. The authors present a novel way for applying the incremental conductance method (INC) utilizing a PMSG generator. This INC approach needs a DC/DC conversion stage to be put into practice. As the PMSG's output power is AC, multiple topologies are used in the literature study to convert AC to DC. The three phase AC-DC rectifier plus DC-DC boost converter are used in WECS, the previous studies claims that this topology has an extra benefit due to the intermediate boost-improved converter's dependability, making it the best back-to-back converter alternative. The authors examined a wide range of MPPT techniques, compared them, and denounced the release of MPPT techniques. They came to the conclusion that, based on the effectiveness It is recommended to employ one of each approach the incremental conductance method with direct control because optimum power occurs at the location where the different versions of dP/dV = 0 [20].

$$\frac{dI}{dV} = -\frac{I}{V} \tag{10}$$

$$\frac{dI}{dV} > -\frac{I}{V} \tag{11}$$

$$\frac{dI}{dV} < -\frac{I}{V} \tag{12}$$

$$\frac{dP}{dV} = 0 \tag{13}$$

The MPPT controller measures the voltage and current of the PV module whereas the incremental conductance approach utilizes (13) to detect the MPP. (11) is satisfied, the reduce the duty cycle of the converter. The duty cycle ought to be raised if condition (12) is satisfied. The duty cycle shouldn't be altered if (13) is reached.

2.6. Proportional integral controller design

Proportional integral, or PI for short, it a type in device employed in industrial settings to control numerous process factors. All the every process parameters in this controller are governed by a control loop feedback device to direct a structure toward an otherwise level of goal [21] location, use this type of command. In order to keep a technique's true output as near to the objective as is practical, this controller uses closed-loop feedback; if this is not possible, fixed-point output is employed; the transfer function c(s) provided by [22] (14); without a doubt, [23], [24] the process control industry's most widely utilized control algorithm is the PI controller. The primary reason is it many advanced control systems, the foundation for such predictive modeling is its relatively basic structure, which is straightforward to comprehend and put into practice. There is no widely acknowledged design technique for the controller despite its widespread use. traditionally, PI controllers have been adjusted experimentally, for example, using the Ziegler and Nichols approach (1942). This approach has the huge advantage of needing minimal effort knowledge however, there is, a considerable drawback due to the technology naturally offers extremely poor damping.

$$c(s) = K_p + \frac{K_i}{s} \tag{14}$$

In this paper, the PI parameters will be changed using the tuning technique, multi-objectives genetic algorithm (MOGA), which have been found to achieve beneficial PI gains and enhance controller efficiency, have lately gained popularity as a means of optimizing the value of Kp and Ki. The block graph of MOGA with a PI controller in Figure 3. That illustrates how MOGA will adjust the gain worth to reduce the difference tween the reference values and feedback [25].

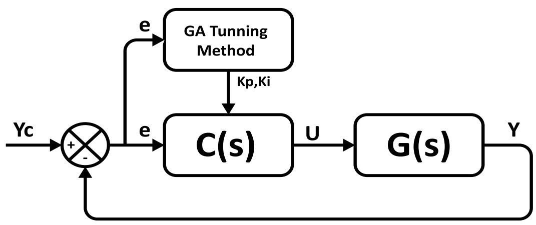

Figure 3. Turbine power MOGA desing method of the PI controller

3. METHOD

The genetic algorithm is one of the most advanced evolutionary algorithms that employs approaches drawn from natural processes like reproduction, mutation, selection, and crossover to produce answers to optimization issues. The fundamental goal of this method is to identify a size of population. Every member among this group represents a set of dimensions. The following phase entails choosing the people who minimize the fitness function. The procedure is repeated premised on the new population until the error reaches a specified threshold. Genetic algorithms (GA) techniques distinct from other traditional optimization methods in that instead than focusing on a single spot, they work with a population of individuals and may after the identification of control or decision-making factors, that are chromosomal rather than directly controlling functions or variables [25]. In contrast to other approaches that rely on auxiliary data, such as the derivative, this optimization strategy optimizes due to the dimensions of the functions. Genetic algorithm transitional principles are stochastic, in contrast to many other approaches' deterministic transitional principles. The diagram in Figure 4 displays a fundamental genetic algorithm. GA's evolutionist look is only due to a fitness function, and it employs each individual's fitness value as the search input. As a result, selecting the appropriate fitness function is essential since it directly affects the GA's ability to converge fast and find the optimum solution. Determine the fitness function and the goal function of the specific issues in compliance as for the requirements of being single, continuous, nonnegative, and maximizing. In order to optimize the value of (kp, ki) gains of the PI controller made via GA, it is vital to pick a suitable fitness function. Numerous publications use the integral of absolute magnitude of error (IAE), integral time multiplied by absolute error (ITAE), integral of the squared error (ISE), and Integral time multiplied by squared error (ITSE) in this paper we will compared the four already cited objective function of error. These goal functions are theoretically expressed as follows to be able to calibrate the (kp, ki) of the PI controller [26]:

– Integral of time multiplied by absolute error (ITAE) is the erroneous signal's average duration.

$$\mathrm{ITAE} = \sum_{0}^{t_{max}} t|e(t)| \tag{15}$$

– The integral of the square of the error (ISE), known as the energy of the erroneous signal.

$$\mathrm{ISE} = \sum_{0}^{t_{max}} e(t)^2 \tag{16}$$

– Integral of the absolute magnitude of the error (IAE), often known as the error signal's absolute value integral.

$$\mathrm{IAE} = \sum_{0}^{t_{max}} |e(t)| \tag{17}$$

– Integral of time multiplied by square error (ITSE) is the error signal's quadratic mean time.

$$\mathrm{ITSE} = \sum_{0}^{t_{max}} te(t)^2 \tag{18}$$

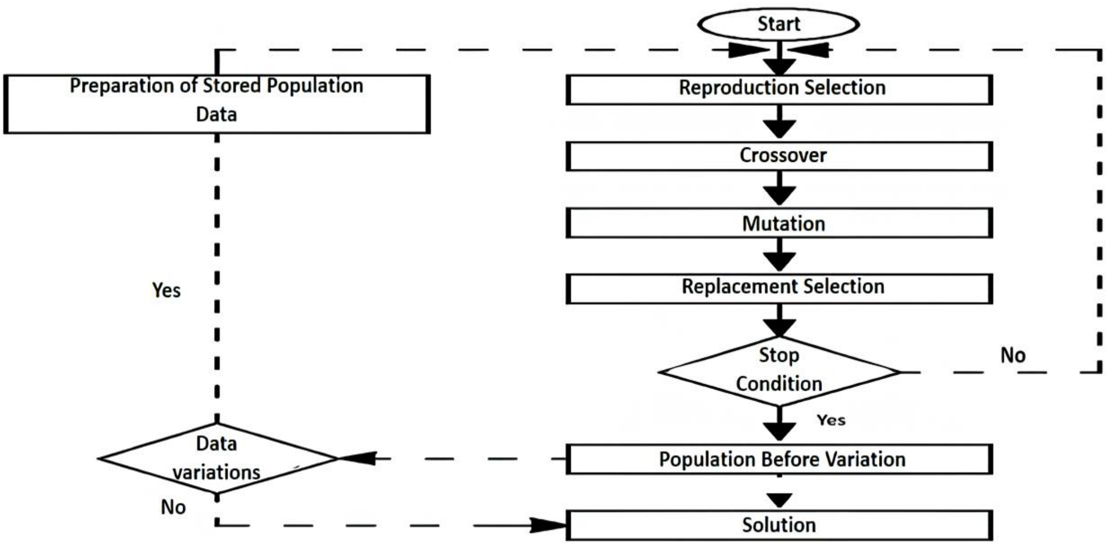

Figure 4. Diagram of genetic algorithm method

4. RESULTS AND DISCUSSION

MATLAB/Simulink software is when simulating the specified mechanism so that they may be examined functioning among the suggested WECS with MOGA. The four fitness function specification code is created before it is included in the optimization tool. Table 4 presents the standard initial settings used in simulations of GA algorithms. Figure 5 demonstrates the MATLAB/Simulink programming design for the GA to PI controller this project proposes a 12.3 kW as generated WECS based power, DC-DC bus converter voltage, load current, output power, and torque electromagnetic of the system were obtained. To build a PMSG under a set of requirements and restrictions: time parameters and power optimization is presented in this section. A toolkit for genetic algorithms built on MATLAB was used to complete. The majority of design optimization techniques involve using an algorithm that evaluates dependent variables in a machine model with independent variables as inputs. These inputs are then varied to maximize an objective function. The subsections below present the optimization variables The MOGA technique, founded on ITAE, IAE, ISE, and ITSE criteria provided to the MATLAB workspace, is utilized to determine the ideal PI values. To assess the system's dynamic behavior under a unit step response, several standard performance metrics that have been chosen, considering their relevance to the wind turbine (WT) system. The following criteria have been chosen to categorize and rate the system's performance i) Stability: this criterion evaluates the major points of the essay using settling time and overshoot as references. ii) Speed: the objective is to reduce dead time, which is equally important as the first criterion. The criteria for rising time and settling time are examined to quantify the value of this criterion. iii) Accuracy: the steady-state error parameter measures the accuracy of a control system. These selected standards play a crucial role in evaluating and enhancing that performance of that WT system's control strategy, particularly when subjected to a unit step reaction. By considering these indicators, the design optimization process aims to achieve an efficient and reliable wind power generation system.

Table 4. GA parameters

S.L.	Dimensions	Value
1	Generation	100
2	Population size N	40
3	Reduced bound	[-20 200]
4	Upper limit	[20 200]
5	Selection process	Stochastic uniform
6	Elite count	0.04

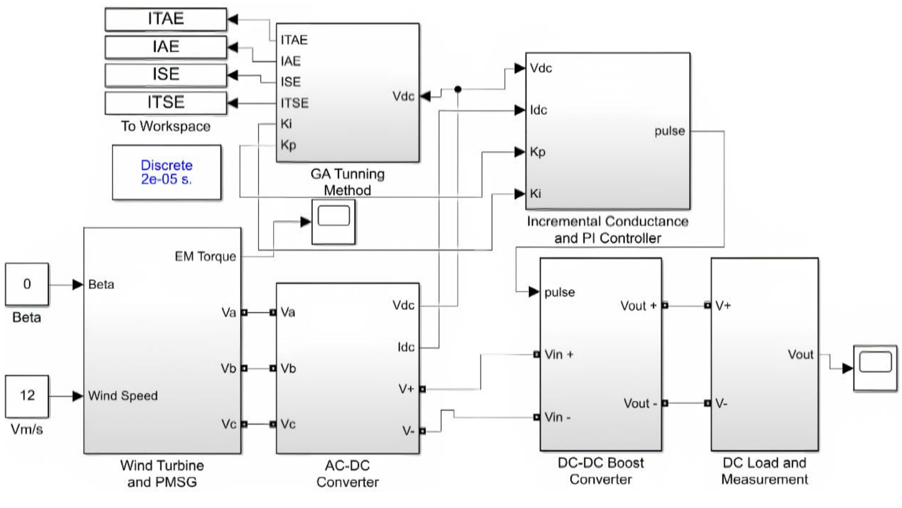

Figure 5. Simulink presentation of WECS chain with MOGA

The results obtained from the proposed PI controller with MPPT without MOGA and the proposed PI controller with MPPT optimized with MOGA are compared in this section. A detailed analysis and comparison of the test findings are presented to highlight the differences between the two approaches. Figure 6 presents the DC bus voltage profile of the system with and without MOGA optimizing the PI controller at a wind speed of 12 m/s. The intended reference DC bus voltage for the system is 177.19 V. With the PI controller without MPPT, it took 0.035 s to reach the reference DC bus voltage and 0.05 s to stabilize.

In contrast, the improved system reached the reference DC bus voltage in 0.015 s and stabilized in 0.02 s, demonstrating a faster response.

However, it is important to note that the optimized controller with MOGA shows a significant voltage overshoot compared to the system without MOGA. Despite the overshoot, the system utilizing GA optimization control achieves the reference 177.19 V DC bus voltage more quickly and stabilizes without further oscillation. The suggested improved system offers more suitable and appropriate outcomes in terms of WECS security. The main parameters studied in this research were produced power, response time, electromagnetic torque, and currents. That comparison and analysis of these parameters highlight the advantages of the proposed MOGA approach for optimizing the PI controller in the wind energy conversion system. As shown in Figure 7, that PMSG machine initially operates in motor mode. In this figure, it can be observed that the proposed MOGA for optimizing the PI controller consumes only 10.20 kW of power at its maximum, whereas the PI controller system without MOGA consumes 20 kW. Afterward, both systems start producing power. The system is expected to generate 10.20 kW of power at a nominal wind speed of 12 m/s. The DC bus voltages of that designed system were also examined.

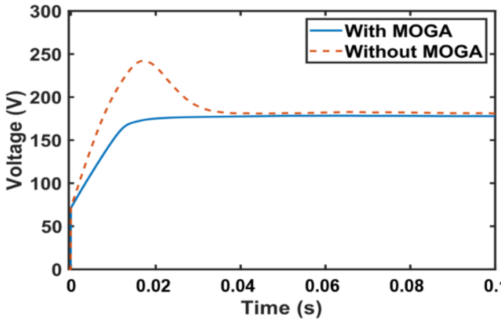

Figure 6. Simulation result of voltage response with and without MOGA after DC-DC boost converter

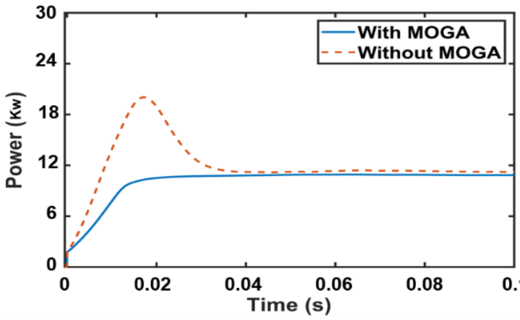

Figure 7. Simulation result of power response with and without MOGA after DC-DC boost converter

As shown in the current figures (Figure 8), the phase currents of the PI-controlled structure with MPPT are greater than those of the PI-controlled structure with GA-optimized MPPT. However, from the final results, it is evident that the response time of the GA-optimized PI-controlled WECS is superior to the response time of that non-optimized PI-controlled WECS. An analysis of the torque response (Tem) in the proposed system was also performed from an electromagnetic torque perspective, as shown in Figure 9. Compared to the typical non-optimized controller, the PMSG with the aid of the upgraded controller achieved the reference torque more quickly. The optimized controller successfully tracked the reference torque value, resulting in a smoother Tem curve using the suggested approach. Upon examining the results, it is clear that the response time of the non-optimized structure is greater than that of the optimized structure. The GA-optimized PI controller demonstrates better performance in terms of torque response and faster tracking of the reference values, contributing to the improved overall system performance in the wind energy conversion system.

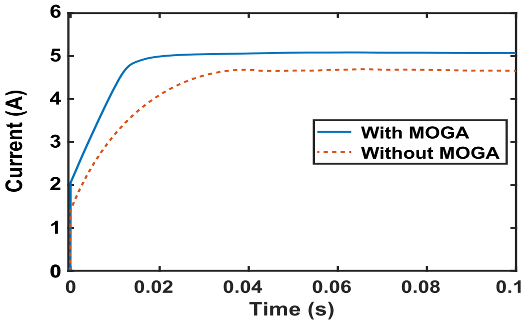

Figure 8. Simulation result of current response with and without MOGA after DC-DC boost converter

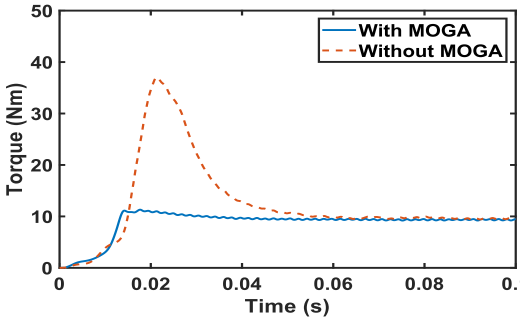

Figure 9. Simulation result of current response with and without MOGA after DC-DC boost converter

Figures 10 to 13 depict the closed-loop step response of the specified voltage, power, and set current, and electromagnetic torque using the MOGA algorithm. These figures provide information on the rising time, settling time, overshoot, and steady-state error values, which have been summarized in Table 5. The MOGA algorithm's performance is evident from the step responses, indicating improved control and system behavior in the wind energy conversion system.

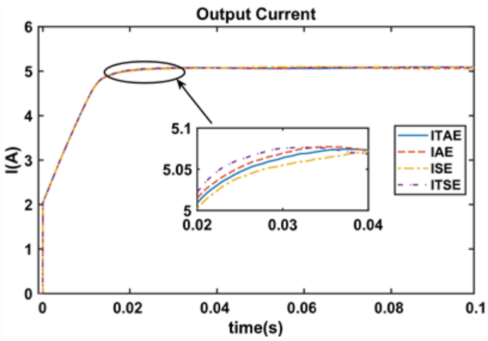

Figure 10. Power output with the four fitness factors After DC-DC boost converter

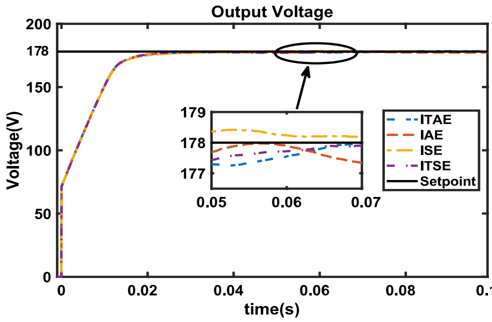

Figure 11. Voltage output with the four fitness factors After DC-DC boost converter

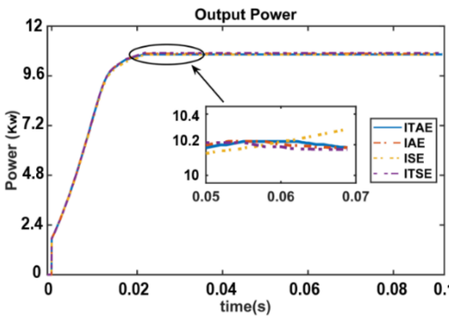

Figure 12. Current output with the four fitness factors After DC-DC boost converter

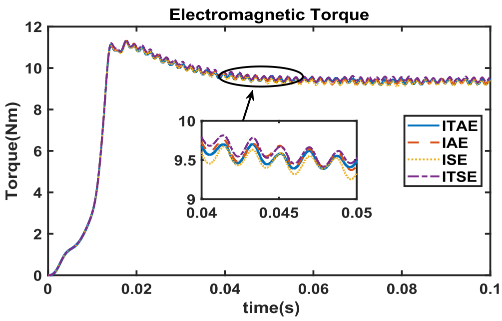

Figure 13. Torque output with the four fitness factors After DC-DC boost converter

Table 5. Numerical performance measured of the closed loop response with four objective functions

	S.L.	Criterion	ISE	ITAE	IAE	ITSE
Voltage	1	Kp	7.0656	0.0122	0.7550	23.0189
	2	Ki	7.0656	0.0122	0.7750	23.0189
	3	Settling time (ms)	18.3515	0.5024	2.2466	23.1999
	4	Rise time (ms)	0.0370	0.0369	0.0380	0.0373
	5	Overshoot (%)	0.0115	0.0113	0.0114	0.0116
	6	The steady state error	0.0755	0.0354	0.0972	0.0822
Power	1	Settling time (ms)	0.0398	0.0397	0.0423	0.0403
	2	Rise time (ms)	0.0133	0.0132	0.0135	0.0134
	3	Overshoot (%)	1.7966	1.3251	1.4686	1.6042
	4	The steady state error	0.7852	0.0347	0.0658	0.0857

It is observable from Table 5 that the rising time and settling time obtained using the ITAE objective function are preferably less compared to those obtained using the (IAE, ISE, and ITSE) criteria. However, the overshoot rate is somewhat higher when employing the ITAE criterion, while the ITSE function yields a noticeably better result. In general, the rising time and settling time values obtained using the various GA optimization objective functions are closer. This indicates that the ITAE objective function provides improved performance in terms of system response time and stability. The various PWM signals controlled by the MOGA are depicted in Figure 14. By adjusting the Kp and Ki parameter values, it can be observed that, as expected when using an optimization strategy, a distinct PWM signal is generated to drive that transistors for each of that four computed values obtained through the proposed method.

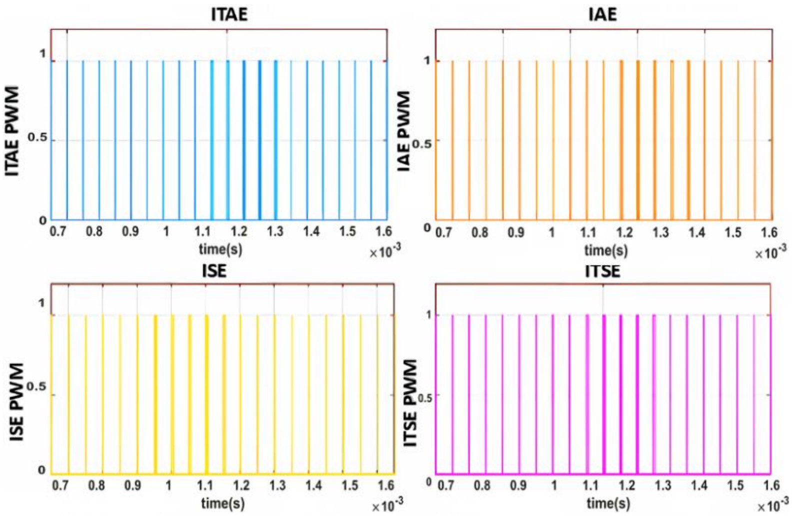

Figure 14. PWM output using the four fitness functions

5. CONCLUSION

Demand for extremely dependable wind power, despite lower output. For both constant and changing wind speeds, the dynamic modeling of wind turbines, equation-based modeling of PMSG, and implementation of MPPT controllers using MATLAB/Simulink have all been researched and analyzed. Utility activities, power markets, and electricity dispersion are all negatively impacted by variable penetration rates brought on by variations in wind intensity. The results of this research on voltage, current, torque electromagnetic and power legislation.

Suggest that the best tuning parameters for the PI controller may be found using a genetic algorithm (GA) technique. Under typical test conditions, the multi-loop control approach has been employed to simulate the synthesis of the wind MPPT system application. The settling time and the least overshoot have been calculated with the integrated time absolute error (ITAE) criterion. It is significant to highlight that the ITAE criterion may be used to change the wind MPPT system's strategy control in a technically sound and extremely helpful way. Even in the presence of a severe disruption, the simulation results on the WECS show how well and how long-lastingly the GA approach can be used to quickly follow the intended internal parameters. Analysis of the moving display of the MPPT structure has taken into account rising time, settling time, and overshoot rate. The stability, speed, and damping quality of the system are all described by these three parameters. The results obtained WECS demonstrate good system performance overall, demonstrating the wisdom of the MOGA approach for PI dimensions optimization proposed in this brief and the PI controller tuning approach employed.

Looking ahead, the research on wind power generation can be further extended to explore advanced control techniques, incorporating artificial intelligence (AI) algorithms and predictive models. Additionally, investigating the integration of energy storage systems to enhance the stability and reliability of wind power plants during varying wind conditions could be a valuable direction for future research. Furthermore, real-world testing and validation of the proposed control strategies on larger-scale wind farms can provide practical insights for industry adoption and implementation

REFERENCES

[1] T. Y. Heng, T. J. Ding, C. C. W. Chang, T. J. Ping, H. C. Yian, and M. Dahari, "Permanent Magnet Synchronous Generator design optimization for wind energy conversion system: A review," *Energy Reports*, vol. 8, pp. 277–282, Dec. 2022, doi: 10.1016/j.egyr.2022.10.239.

[2] S. Vishnoi, S. Nikolovski, M. Raju, M. K. Kirar, A. S. Rana, and P. Kumar, "Frequency Stabilization in an Interconnected Micro-Grid Using Smell Agent Optimization Algorithm-Tuned Classical Controllers Considering Electric Vehicles and Wind Turbines," *Energies*, vol. 16, no. 6, p. 2913, Mar. 2023, doi: 10.3390/en16062913.

[3] T. Magesh, G. Devi, and T. Lakshmanan, "Improving the performance of grid connected wind generator with a PI control scheme based on the metaheuristic golden eagle optimization algorithm," *Electric Power Systems Research*, vol. 214, p. 108944, Jan. 2023, doi: 10.1016/j.epsr.2022.108944.

[4] X. Hu, W. Tan, and G. Hou, "PIDD2 Control of Large Wind Turbines' Pitch Angle," *Energies*, vol. 16, no. 13, p. 5096, Jul. 2023, doi: 10.3390/en16135096.

[5] E. Chetouani, Y. Errami, A. Obbadi, and S. Sahnoun, "Self-adapting PI controller for grid-connected DFIG wind turbines based on recurrent neural network optimization control under unbalanced grid faults," *Electric Power Systems Research*, vol. 214, p. 108829, Jan. 2023, doi: 10.1016/j.epsr.2022.108829.

[6] C. H. Ramalingegowda and M. Rudramoorthy, "Transient stability enhancement using optimized PI tuning of static synchronous series compensator in wind power conversion system," *Frontiers in Energy Research*, vol. 11, Feb. 2023, doi: 10.3389/fenrg.2023.1125408.

[7] D. Abdeljalil, M. Chaieb, N. Benhadj, M. Krichen, and R. Neji, "Design and optimization of permanent magnet synchronous generator dedicated to direct-drive, high power wind turbine," *Wind Engineering*, vol. 46, no. 3, pp. 737–758, Jun. 2022, doi: 10.1177/0309524X211046379.

[8] F. Rerhrhaye, I. Lahlouh, Y. Ennaciri, C. Benzazah, A. El Akkary, and N. Sefiani, "New Solar MPPT Control Technique Based on Incremental Conductance and Multi-Objective Ant Colony Optimization," *International Review of Automatic Control (IREACO)*, vol. 15, no. 3, p. 113, May 2022, doi: 10.15866/ireaco.v15i3.22076.

[9] N. Mrabet, C. Benzazah, and A. El Akkary, "Technical Analysis and Comparative Study of three Wind Turbines for a 50MW wind farm in Laayoune City Morocco," *ITM Web of Conferences*, vol. 46, p. 01002, Jun. 2022, doi: 10.1051/itmconf/20224601002.

[10] W. Gul, Q. Gao, A. Walker, T. Zou, H. Huang, and C. Gerada, "Mitigation of Cogging Torque in a Double-Stator Single-Rotor PMSG for Direct Drive Offshore Wind Turbines," in *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, IEEE, May 2023, pp. 1–6. doi: 10.1109/IEMDC55163.2023.10238922.

[11] F. Rerhrhaye, I. Lahlouh, Y. Ennaciri, C. Benzazah, A. El Akkary, and N. Sefiani, "New Solar MPPT Control Technique Based on Incremental Conductance and Multi-Objective Genetic Algorithm Optimization," *International Journal on Energy Conversion (IRECON)*, vol. 10, no. 3, p. 70, May 2022, doi: 10.15866/irecon.v10i3.22156.

[12] N. A. Mohamed, H. M. Hasanien, A. Alkuhayli, T. Akmaral, F. Jurado, and A. O. Badr, "Hybrid Particle Swarm and Gravitational Search Algorithm-Based Optimal Fractional Order PID Control Scheme for Performance Enhancement of Offshore Wind Farms," *Sustainability*, vol. 15, no. 15, p. 11912, Aug. 2023, doi: 10.3390/su151511912.

[13] Y. Wang, F. Luo, C. Long, G. Tao, Y. Xu, and R. Yang, "Robust Subsynchronous Damping Control of PMSG-Based Wind Farm," *Energies*, vol. 16, no. 7, p. 3144, Mar. 2023, doi: 10.3390/en16073144.

[14] Y. Chiba and A. Smaili, "Advances in Green Energies and Materials," in *Selected Articles from the Algerian Symposium on Renewable Energy and Materials (ASREM-2020)*, Y. Chiba, A. Tlemçani, and A. Smaili, Eds., in Springer Proceedings in Energy. Singapore: Springer Singapore, 2020. doi: 10.1007/978-981-16-0378-5.

[15] Z. J. Mohammed, M. O. Mustafa, and S. E. Mohammed, "Adaptive Hybrid Pitch Angle Control and MPPT for PMSG-Based Wind Power Generator Systems," *International Journal on Energy Conversion (IRECON)*, vol. 10, no. 5, p. 153, Sep. 2022, doi: 10.15866/irecon.v10i5.22586.

[16] H. Zhang, Y. Zhang, D. Jiang, J. Leng, Z. Zhang, and X. Peng, "Modeling Method for Wind Farm Based on Equivalent Dynamic Response," in *2023 3rd International Conference on Energy Engineering and Power Systems (EEPS)*, IEEE, Jul. 2023, pp. 377–381. doi: 10.1109/EEPS58791.2023.10256763.

[17] K. Palanimuthu, G. Mayilsamy, S. R. Lee, S. Y. Jung, and Y. H. Joo, "Comparative analysis of maximum power extraction and control methods between PMSG and PMVG-based wind turbine systems," *International Journal of Electrical Power & Energy Systems*, vol. 143, p. 108475, Dec. 2022, doi: 10.1016/j.ijepes.2022.108475.

[18] P. Rajesh, S. Muthubalaji, S. Srinivasan, and F. H. Shajin, "Leveraging a Dynamic Differential Annealed Optimization and Recalling Enhanced Recurrent Neural Network for Maximum Power Point Tracking in Wind Energy Conversion System," *Technology and Economics of Smart Grids and Sustainable Energy*, vol. 7, no. 1, p. 19, 2022, doi: 10.1007/s40866-022-00144-z.

[19] S. Motahhir and B. Bossoufi, "Digital Technologies and Applications," in *Lecture Notes in Networks and Systems*, 2021, p. 1,836. doi: 10.1007/978 3-030-738822.

[20] M. M. Mahmoud, B. S. Atia, A. Y. Abdelaziz, and N. A. N. Aldin, "Dynamic Performance Assessment of PMSG and DFIG-Based WECS with the Support of Manta Ray Foraging Optimizer Considering MPPT, Pitch Control, and FRT Capability Issues," *Processes*, vol. 10, no. 12, p. 2723, Dec. 2022, doi: 10.3390/pr10122723.

[21] Q. Zhu, W. Xiong, H. Wang, and X. Jin, "Refined Equivalent Modeling Method for Mixed Wind Farms Based on Small Sample Data," *Energies*, vol. 16, no. 20, p. 7191, Oct. 2023, doi: 10.3390/en16207191.

[22] E. Bekiroglu and M. D. Yazar, "MPPT Control of Grid Connected DFIG at Variable Wind Speed," *Energies*, vol. 15, no. 9, p. 3146, Apr. 2022, doi: 10.3390/en15093146.

[23] S. W. Ali, C.-L. Su, A. K. Verma, C. B. Mellado, and C. Gonzalez-Castano, "Enhancing Single-Phase Grid Integration Capability of PMSG-Based Wind Turbines to Support Grid Operation under Adverse Conditions," *Sustainability*, vol. 15, no. 13, p. 10662, Jul. 2023, doi: 10.3390/su151310662.

[24] Z. Maheshwari, K. Kengne, and O. Bhat, "A comprehensive review on wind turbine emulators," *Renewable and Sustainable Energy Reviews*, vol. 180, p. 113297, Jul. 2023, doi: 10.1016/j.rser.2023.113297.

[25] S. Chauhan, B. Singh, and M. Singh, "Modified ant colony optimization based PID controller design for coupled tank system," *Engineering Research Express*, vol. 3, no. 4, p. 045005, Dec. 2021, doi: 10.1088/2631-8695/ac2bf3.

[26] H. Yang, W. Zhang, L. Dai, W. Feng, and H. Zhang, "Annual Energy Production Design Optimization for PM Generators Considering Maximum Power Point Trajectory of Wind Turbines," *Energies*, vol. 16, no. 10, p. 4120, May 2023, doi: 10.3390/en16104120.

BIOGRAPHIES OF AUTHORS

Najoua Mrabet was born in Oudkha Taounate Morocco, in 1996. She is a Ph.D. Student at Mohammadia Engineers School Rabat/Mohamed V University, in Control Systems Engineering. She obtained the Master's degree in energy mechanics option renewable energy materials from the Sciences Faculty of Rabat December, 2020. Her research synthesis of nonlinear control laws for the control of generator power supply and storage system, dedicated to a wind power production system. She can be contacted at email: najouamrabet2@gmail.com

Chirine Benzazah received her engineering degree in Electric Systems and Telecommunications from the Faculty of Sciences and Technology, Cadi Ayyad University, Morocco, in 2012. She obtained a Ph.D. in Electrotechnics and Power Electronics from the Faculty of Sciences and Technology, Sultan Moulay Slimane University, Beni Mellal, Morocco, in 2018. From 2019 to 2023, she served as a professor of physics at the Higher School of Technology of Salé, Mohammed V University of Rabat, Morocco. Currently, she holds the position of a professor of physics at the Polydisciplinary Faculty of Safi, Cadi Ayyad University, of Marrakech, Morocco. Her research interests span across various fields, including electrical and electronics engineering, electrical power engineering, power converters, renewable energy technologies, harmonics, grid integration, high power electronics, power factor correction, and voltage regulation. She can be contacted at email: ch.benzazah@gmail.com.

Ahmed El Akkary graduated at The Superior Normal School of Technical Education (ENSET) Rabat in 1995, in 2003 he obtained his Advanced Diploma of Higher Education (DESA) specialty automatic and manufacturing, then, in 2009, he obtained his Ph.D. from the Mohammadia School of Engineers of Mohammed V university of Rabat, in Automatic specialty. He obtained the ability degree Professor in July, 2017. His research interest is in control systems. He can be contacted at email: aelakkary@gmail.com

Yassine Ennaciri was born in Tighassaline, Khenifra Morocco, in 1995. He is a Ph.D. Student at Mohammadia Engineers School Rabat/Mohamed V University, in Control Systems Engineering. He obtained the engineer degree in electrical engineering and industrial systems control from the High School of Technical Education Mohammedia in July, 2020. His research interests are in electrical traction drive control, BMS, and 3D printing. He can be contacted at email: yassine.ennaciri.ing@gmail.com.

Ilyas Lahlouh received with honors the Ph.D. degree in Electrical Engineering from the Mohammadia School's of Engineers, Rabat, Morocco in 2020. Since 2021, he has been a Professor at Higher School of Technology, Salé, Morocco. His research interests in regulation and control of systems, optimization methods, robust control, non-linear systems, and renewable energy. He can be contacted at email: ilyaslahlouh@research.emi.ac.ma.