MODIFIED HYBRID OPTIMISATION TECHNIQUE USED FOR CONTROLLING THE TRANSIENTS OF THE DOUBLY-FED INDUCTION GENERATOR IN A WIND POWER PLANT

R. Madavan[1], Dhrubajyoti Banerjee[2], B. Karthikeyan[3], Subhashree Choudhury*[4], R. Palanisamy[5], Bidrohi Bhattacharjee[6], Arabinda Das[7]

[1]Department of Electrical and Electronics Engineering, K.Ramakrishnan College of Technology, Trichy, madavanr.eee@krct.ac.in
[2]Department of Electrical Engineering, Budge Budge Institute of Technology, Nischintapur, Budge Budge, Kolkata - 700138, West Bengal, India, banerjeedhrubo@gmail.com
[3]Department of Mechatronics Engineering, KPR Institute of Engineering and Technology, karthikeyankrct@gmail.com
[4*]Department of Electrical and Electronics Engineering, Siksha O Anusandhan (Deemed to be University), Bhubaneswar, Odisha 751030, India, subhashreechoudhury@soa.ac.in
[5]Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Kattankulathur, Chengalapttu, India, palanisr@srmist.edu.in
[6]Department of Electrical Engineering, Budge Budge Institute of Technology, Nischintapur, Budge Budge, Kolkata - 700138, West Bengal, India, onlybidrohi@gmail.com
[7]Electrical Engineering Department, Jadavpur University, 188, Raja S. C. Mullick Road, Kolkata -70003, West Bengal, India, arabinda.das@jadavpuruniversity.in

ABSTRACT
RiDouble-fed induction generators play an important role in the wind energy sector due to their ability to operate at variable speeds, superior efficiency, and compatibility with the grid. The optimal controller design for a doubly-fed induction generator ensures efficient power conversion, stable operation, and fault tolerance in wind turbines. To maintain stability and control active and reactive power, this article suggests the design of a PI controller. This article proposes a new PI controller to maintain stability and regulate active and reactive power in a doubly-fed induction generator. A novel modified hybrid grey wolf cuckoo search algorithm tunes PI controller parameters. Furthermore, this work applied a modified Grey Wolf Cuckoo search algorithm to tune PI controller parameters. In this work, the proposed controller has been tested for a 2 MW DFIG wind power system. The results obtained with the proposed controller are compared with those of the Jaya and Whale optimisation algorithms. The results show that the proposed method reported only 4.1% total harmonic distortion and took only 10-12 iterations. In contrast, other methods exhibit higher total harmonic distortion and require more iterations. Other control parameters, such as rise time, peak time, and maximum overshoot, are minimised for the proposed methods shown in the results section.

KEYWORDS: Doubly Fed Induction Generator (DFIG); Modified Hybrid Grey Wolf Cuckoo Search Algorithm (MGWOCS); Wind Energy Conversion System (WECS); Proportional Integral controller (PI), Total Harmonic distortion.

1. INTRODUCTION
Electricity is important to improve people's living standards. It plays an important role in boosting a country's economy [1]. Fossil fuels are available all the time; that's why most power plants use them to generate electrical power. Since fossil fuels are limited and emit toxic gases into the environment, it is necessary to use alternative sources [2]. Now we can focus on renewable energy sources that are environmentally friendly and meet people's needs. A wind energy conversion system is the best substitute for conventional fossil-fuel power plants [3].
Wind power plants have one major problem: the airflow is not constant. Due to such changes in airflow, transients arise in wind generators. These transients caused numerous power-quality issues in the generated power [4]. Transients can affect the reactive power, frequency, and voltage profiles. This work implements a PI controller for the transient operation of a wind power plant with a doubly-fed induction generator. To achieve accurate control of the DFIG generator gain, the PI controller is tuned using a hybrid optimisation technique. The DFIG is a type of electrical generator used in wind turbines to generate renewable electrical energy [5]. The DFIG wind energy conversion system is shown in Figure 1. For stable operation and control of active and reactive power, the stator and rotor currents of a DFIG must be controlled.
The main objective of the proposed article is to improve the transient response of the DFIG-WECS. For this purpose, a PI controller is mathematically modelled. After that, they find the optimised PI controller parameters to control the operation of the DFIG-WECS. A novel hybrid algorithm (Grey Wolf and Cuckoo Search) is used to determine the optimal values of the PI controller gain parameters (Kp and Ki). The DFIG output results are verified by comparing THD values. The unique approach of the proposed work is the use of a modified hybrid algorithm, which no other researcher has proposed for DFIG operation and control.
In the first section of the paper, an introduction to the current scenario of renewable and wind power generation is given, and it is explained that DFIG-WECS are an essential part of the wind power system. Section 2 presents the literature

review and existing research in this field and discusses the research gap. The mathematical modelling of DFIG and its controller design are explained in Section 3 of the paper. In this subsection, a vector-oriented control strategy is applied to the design of a rotor-side controller. The MGWOCS optimisation method was developed by proposing small modifications to the hybrid Cuckoo Search and Grey Wolf algorithms described in section 4. Section 5 explains the implementation of MGWOCS in an experimental model. In the same section, we implemented simulations of Jaya optimisation, the MGWOCS method, and the whale optimisation method for tuning of PI controller parameters. The results of the proposed experimental model are presented in graphs and numerical values, and the comparative results are listed alongside those of the Jaya and Whale optimisation algorithms. The final section of the paper concludes the research work.

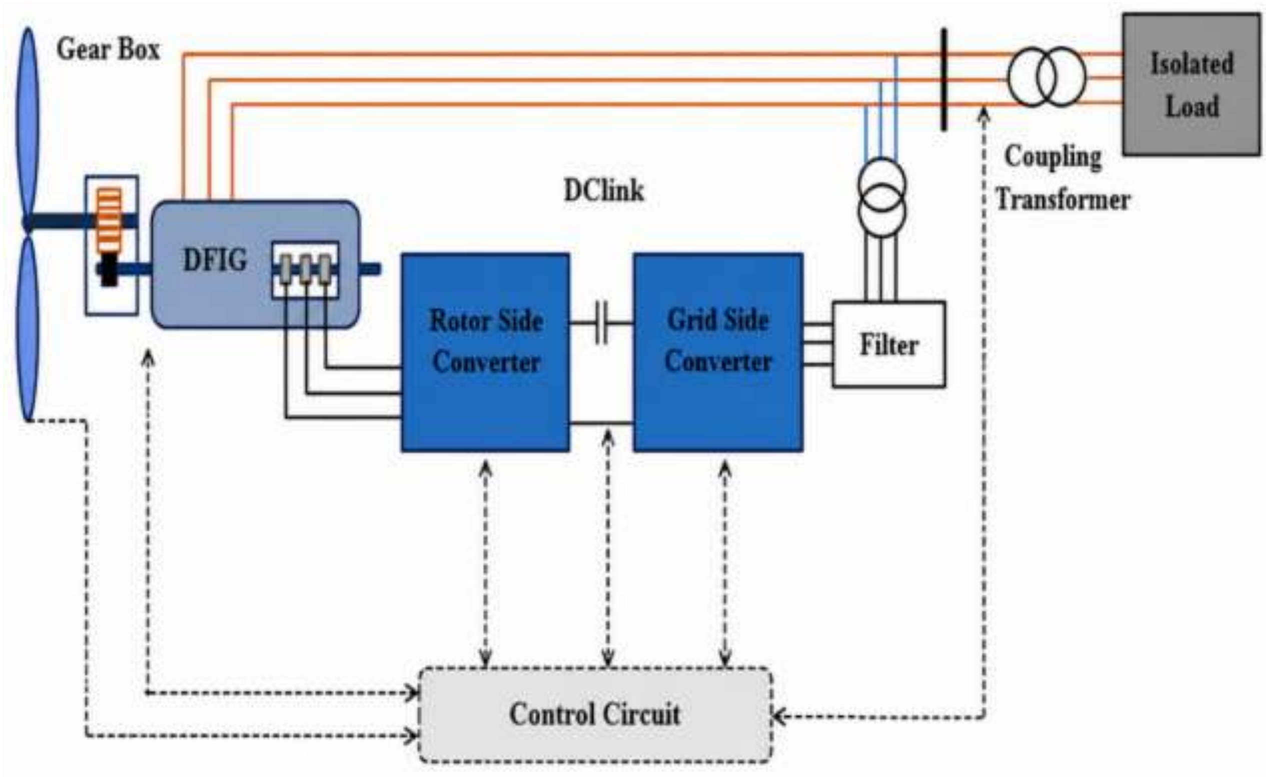

Figure 1. Schematic diagram of the DFIG-WECS

2. RELATED WORK

Vector and direct control methods are suggested for the stable operation of the DFIG system. Such control schemes are effective but fail when loads increase [1]. Wind conversion system with maximum power point tracking to enhance wind generation harvest, as suggested in article [2]. MPPT moves the position of the head of the generator in the direction of the flow of air, and hence the rotor of the wind generator maintains a good speed and generates high power [2]. The slip power recovery control technique used in article [3]. They used a power converter attached to the rotor windings to recover part of the slip power. The entire system's productivity can be improved by feeding this recovered energy back into the grid.

Pitch control in turbines involves adjusting the angle of the turbine blades to regulate the aerodynamic load on the rotor. This helps prevent overspeeding and overloading of the generator in high-wind conditions [4]. The DFIG's power converter enables precise control of active and reactive power. This is crucial for grid integration and stability, as the generator can respond to grid demands and support voltage regulation [5].

The DFIG power converter regulates the generator terminal voltage, ensuring it remains within permissible limits even under changing operating conditions. In the event of short-term faults, DFIG systems must maintain the grid connection and continue operation [6]. In many cases, DFIG systems must remain connected to the grid to operate during short-term grid faults [7]. Modern control techniques allow the generator to withstand these faults without shutting down. By limiting the maximum permissible rotor current [8], the control system can prevent rotor overload and overheating of the associated power electronics. These techniques are often implemented with advanced control algorithms and real-time monitoring systems to ensure optimal performance, grid stability, and efficient energy conversion in DFIG-WECS [9].

The optimal design of proportional-integral-derivative (PID) controllers for DFIG wind generators is proposed in [10]. They control the DFIG-based wind generators via a grid-interconnection system. The fundamental principles of PID control, including proportional, integral, and derivative components, form the basis for developing effective controllers for DFIG wind generators [11]. Researchers have explored various tuning methods to optimise the PID parameters. Classical approaches such as Ziegler-Nichols [12] and Internal Model Control (IMC) [13] have been adapted and extended for DFIG applications.

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More recent studies have explored advanced optimisation techniques and adaptive strategies to tune the PI controller in DFIG wind generators. Metaheuristic algorithms, such as particle swarm optimisation [14], genetic algorithms [15], and artificial bee colony [16], have been employed to search for optimal PI parameter sets that balance stability, performance, and energy capture.
In addition, adaptive PI control strategies that adjust controller gains in real time based on system dynamics have shown better transient response and higher robustness. The integration of advanced control methods with PI controllers has shown promise in improving the overall performance of DFIG wind generators [17]. Fuzzy logic, artificial neural networks, and model predictive controllers (MPC) have been combined with PI strategies to improve fault tolerance, power tracking, and grid synchronisation [18]. These hybrid approaches leverage the strengths of multiple techniques to overcome complex challenges.
The study of the transient behaviour of DFIGs, including faults in DC links, converters, rotor terminals, and other stator-terminal faults, such as phase-to-phase and phase-to-ground, remains lacking in the literature. However, these studies can only investigate and analyse the DFIG's response to three-phase short circuits. There is still a lack of research on the optimal design of regulators. To address this gap, the proposed study employs swarm intelligence, specifically the modified Grey Wolf Optimisation method. This work aims to design an optimal controller for DFIG-WECS. A novel modified hybrid grey wolf-cuckoo search algorithm is proposed and applied to obtain the optimal parameters of the PI controller. To the best of the author's knowledge, this optimisation method has never been applied to DFIG-WECS in the past.

3. Mathematical Modelling

Mathematical modelling of the DFIG system using the direct-quadrature (d-q) transform is a fundamental step in developing a controller that regulates the DFIG's transient behaviour [19]. The d-q transform is a powerful mathematical tool for simplifying the analysis of three-phase systems. The d-q transformation comprises two orthogonal components: the direct (d-axis), which is connected to the rotor flow, and the quadrature (q-axis), which is orthogonal to the d-axis [20]. The three-dimensional distribution of the dq-transformation is explained in mathematical equations as follows:

$$V_{qs} = r_s i_{qs} + \omega_s \lambda_{ds} + \lambda'_{qs} \quad (1)$$

$$V_{ds} = r_s i_{ds} - \omega_s \lambda_{qs} + \lambda'_{ds} \quad (2)$$

$$V_{qr} = r_r i_{qr} + \sigma L_r i'_{qr} + (\omega_s - \omega_r)\lambda_{dr} + \lambda'_{qr} \quad (3)$$

$$V_{dr} = r_r i_{dr} - (\omega_s - \omega_r)\lambda_{qr} + \lambda'_{dr} \quad (4)$$

Flux linkages for stator and rotor in d-q frame are given as:

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (5)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (6)$$

$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} \quad (7)$$

$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} \quad (8)$$

In the above equations, V_{qs}, V_{ds}, V_{qr}, V_{dr}, i_{qs}, i_{ds}, i_{qr}, i_{dr}, λqs , λ_{qr}, λ_{dr}, λ_{ds} are the stator and rotor emf, currents, and the flux-linkages respectively; rs and rr denote resistance, Ls, Lr self-inductance of stator and rotor windings, Lm is the mutual-inductance and ωs, ωr are the synchronous and rotor angular speed.
The active, reactive power, and torque in the d-q frame in mathematical form can be written as:

$$Ps = \frac{3}{2}\ Re\{V_s\ .\ i_s{}^*\} = \frac{3}{2}\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right) \quad (9)$$

$$Pr = \frac{3}{2}\ Re\{V_r\ .\ i_r{}^*\} = \frac{3}{2}\left(v_{dr} i_{dr} + v_{qr} i_{qr}\right) \quad (10)$$

$$Qs = \frac{3}{2}\ Im\{V_s\ .\ i_s{}^*\} = \frac{3}{2}\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right) \quad (11)$$

$$Qr = \frac{3}{2}\ Re\{V_r\ .\ i_r{}^*\} = \frac{3}{2}\left(v_{qr} i_{dr} - v_{dr} i_{qr}\right) \quad (12)$$

$$Te = \frac{3}{2}\{\lambda_s \cdot I_r^*\} = \frac{3}{2}\frac{d}{dt}\left(\frac{L_m}{L_s}\left(\lambda_{qs} i_{dr} - \lambda_{ds} i_{qr}\right)\right) \quad (13)$$

In above equations "*" denotes the complex conjugate of quantity.

3.1 Controller Designing Using Vector Control Strategy

A vector-oriented control strategy was used to design a rotor-side controller [21]. The basic equations of current, flux and Emf of DFIG are given by assuming a reference frame connected to the stator flux (i.e. $\lambda ds = \lambda s$, $\lambda qs = 0$).

$$i_{ds} = \frac{1}{L_s}\left(\lambda_{ds} - L_m i_{dr}\right) \quad (14)$$

$$i_{qs} = \frac{-L_m}{L_s}\left(i_{qr}\right) \quad (15)$$

$$\lambda_{dr} = \frac{L_m}{L_s}\lambda_{ds} + \sigma L_r i_{dr} \quad (16)$$

$$\lambda_{qr} = \sigma L_r i_{qr} \quad (17)$$

Real and reactive powers and electromagnetic torque are given as:

$$Ps = \frac{-3L_m}{2L_s}\left(v_{qs} i_{qr}\right) \quad (18)$$
$$Qs = \frac{3v_{qs}}{2L_s}\left(\lambda_{ds} - L_m i_{dr}\right) \quad (19)$$
$$Te = \frac{-3}{2}\frac{d}{dt}\left(\frac{L_m}{L_s}\left(\lambda_{ds} i_{qr}\right)\right) \quad (20)$$
Where, $\sigma = 1 - \frac{{L_m}^2}{L_s L_r}$

Then we get,
$$V_{dr} = r_r i_{dr} + \sigma L_r i'_{dr} + error_1 \quad (21)$$
$$V_{qr} = r_r i_{qr} + \sigma L_r i'_{qr} + error_2 \quad (22)$$
Similarly, we get:
$$i_{dr} = \frac{(v_{dr} - error_1)}{r_r + s.\sigma L_r} \quad (23)$$
$$i_{qr} = \frac{(v_{qr} - error_2)}{r_r + s.\sigma L_r} \quad (24)$$
Gain for the current control is given by
$$G(s) = \frac{i_{dr}}{v_{dr}} = \frac{i_{qr}}{v_{qr}} = \frac{1}{r_r + s.\sigma L_r} \quad (25)$$

After adding the PI controller, the governing equations are as follows.
$$v_{qr} = (r_r + L_r \sigma s) i_{qr} = \left(k_p + \frac{k_i}{s}\right)\left(i_{qrref} - i_{qr}\right) \quad (26)$$
$$v_{dr} = (r_r + L_r \sigma s) i_{dr} = \left(k_p + \frac{k_i}{s}\right)\left(i_{drref} - i_{dr}\right) \quad (27)$$
So, The Transfer function of the current controller is,
$$\frac{i_r}{i_{rref}} = \frac{\frac{1}{\sigma L_r}(sk_p + k_i)}{s^2 + \frac{s(r_r + k_p)}{\sigma L_r} + \frac{k_i}{\sigma L_r}} \quad (28)$$

4. Optimisation techniques

This article implemented a new technique, a modification of the hybrid Grey-Wolf and Cuckoo Search algorithm (MGWOCS). The MGWOCS method was developed by modifying the hybrid methods of Cuckoo Search and the Grey Wolf algorithm (GWOCS).

- Advantages of using MGWOCS and GWOCS over other methods are as follows:
- These techniques have a better balance between exploration and exploitation.
- The convergence rate of these techniques is very fast, yielding the global best solution.
- These techniques handle complex and multimodal problems easily.

4.1 Cuckoo Search Algorithm (CSA)

The CSA method is based on the behaviour of young cuckoos, which efficiently search for new nests in the surrounding area. The random walk model known as Lévy's flight, named after the mathematician Paul Lévy, is characterised by a power-law distribution of step lengths [19].
$$N(s) = s^{-1} \quad (29)$$
.

The probability distribution of the length of run or jump steps is given by
$$P(i) = i^{-x} at 1 < x \leq 3 \quad (30)$$
Via Lévy's flight Cuckoo search a new position as given by equation (37):
$$s_i^{(t+1)} = s_i^{(t)} + \alpha \oplus \text{Lévy}(s, y) \quad (31)$$
where, α is the length of the step taken after the Lévy flight distribution, which has a variance and infinite mean value [20] and, s is the step range is given as;
$$\text{Lévy}(s, y) \sim s^{-y}, \quad (1 < y \leq 3) \quad (32)$$

4.2 Grey Wolf Optimisation (GWO) Method

The social structure and hunting strategy of grey wolves serve as inspiration for the GWO metaheuristic [21]. This algorithm mimics the hierarchy and hunting patterns found in wolf packs. In GWO, a population of predicted solutions (wolves) is developed and iteratively updated to search for optimal solutions to complex optimisation problems. Alpha is the first optimal solution of the GFO's algorithm; similarly, beta, gamma, and omega are the second, third, and fourth optimal solutions, respectively. It is assumed that the remaining possible solutions are omega [21].

The hunt in the GWO method is led by these three wolves (α, β, and δ) and followed by the ω-wolves. The alpha wolf, representing the best candidate solution, surrounds the prey (the optimal solution) to reduce the search space. The wolves coordinate their hunting efforts to approach and catch the prey together. This hunting behaviour is carried over into the optimisation process, where candidate solutions collaborate to refine the search space. This hunting process involves (i) chasing, running, and moving towards the prey; (ii) following and circling until the prey keeps moving; and (iii) capturing the prey [21, 22]. The mathematical equations to represent the encircling behaviour are given below [22].
$$G = |CK_P - AK(t)| \quad (33)$$
$$K(t+1) = K_p(t) - A * D \quad (34)$$
Where t is the initial iteration, A, C and D are constants, Kp(t) is the grey wolf position vector, and K(t) is the grey wolf position vector at the initial iteration. Constant A and C are given as:

$$\vec{A}=2\vec{q}\,\overrightarrow{n_1}-q \quad (35)$$

$$\vec{C}=2\,\overrightarrow{n_2} \quad (36)$$

Where n1 and n2 are random vectors between [0, 1] and q decreases from 2 to 0 as the iteration increases.

The best three solutions for grey wolf hunting are saved. The remaining other agents update their potions. It is mathematically expressed by the following equations [23, 24].

$$G_\alpha = |C_1K_\alpha - AK(t)| \quad (37)$$

$$G_\beta = |C_2K_\beta - AK(t)| \quad (38)$$

$$G_\delta = |C_3K_\delta - AK(t)| \quad (39)$$

$$X_{g1} = X_\alpha - A_1 * (G_\alpha) \quad (40)$$

$$X_{g2} = X_\beta - A_2 * (G_\beta) \quad (41)$$

$$X_{g3} = X_\delta - A_2 * (G_\delta) \quad (42)$$

$$X'(t+1) = \frac{X_{g1}+X_{g2}+X_{g3}}{3} \quad (43)$$

Grey wolves attack when prey pauses. The value of A lies randomly between -2n and 2n, and a declines from 2 to 0 with the iterations. Wolves attack the prey if |A| is less than one, which is called exploitation activity. If |A| is greater than one, it indicates the wolves are searching for others, so they diverge from the present prey [25]. This process aims to balance exploration and exploitation, helping the algorithm efficiently navigate the search space and converge to optimal solutions.

4.3 Modified Hybrid Grey Wolf Optimisation and Cuckoo-Search Method (MGWOCS)

To improve exploration in the GWO method, this work employs a modified GWOCS technique. A new factor γ is introduced to amend the encircling and position-update calculations [22]. The next phase of the MGWOCS is encircling, which follows population initialisation and involves grey wolves working together to encircle the prey before attacking. A vector-sum approach is used to write the equation for encircling. Factor γ is applied to measure the distance appropriately and to have the wolves in an improved loop. The improved encircling process of GWO is shown by the following equations [22],

$$\vec{D}=1/\gamma\ |\vec{G}p\ (i)+\vec{G}(i)| \quad (44)$$

$$\vec{G}(i+1)=1/\gamma\ \{\vec{G}p\ (i)+\vec{A}\vec{D}\ \} \quad (45)$$

where D is the position from the prey, $\overrightarrow{G_p}$ and $\overrightarrow{G(i)}$ are the positions of the prey and the current wolf; γ is the scaling factor (γ=1.4 is the optimal value for effective results) [22].

The MGWO-CS hybrid method is developed by proposing small modifications to the GWO and CSA algorithms. GWO is a metaheuristic inspired by the hunting behaviour of grey wolves. In the hybrid MGWO-CS algorithm, GWO location updates are incorporated into the CSA position update equation to achieve faster convergence.

The equation is modified to include a fourth term in the numerator to compute the position update in the MGWO-CS algorithm, as shown in the following equation [23].

$$\vec{G}(t+1) = \frac{\vec{G}_1+\vec{G}_2+\vec{G}_3+\vec{G}_4}{4} \quad (46)$$

Above, $\vec{G}_1, \vec{G}_2$, and $\vec{G}_3$ are the positions of hunting agents. After the best hunting agent's position G_αThe following are the best hunting positions. G_β and G_δ [23]. $\vec{G}_4$ Position vector is estimated using the CS update rule [19].

Every egg in the nest is a solution, and it is replaced by a more effective one. Such a process is used to update the locations of $\vec{G}_4$ terms in the hybrid MGWO-CS algorithm. The equations below [24] give it.

$$\vec{G'}_4 = \vec{G}_t + \alpha \oplus \text{Lévy}\ (\lambda') \quad (47)$$

Here, $\vec{G}_t$ is the candidate's position in the current iteration is, the step dimension α, is multiplied by the input and has a range of 0 to 1. The proposed algorithm gets more effective as $\vec{G}_4$ It is introduced because it uses Lévy flights to explore the search space.

Figure 2 shows the flowchart for implementing the MGWOCS algorithm. The following steps are adopted for the implementation of the MGWOCS algorithm:

Generate the initial population of grey wolf X (Let population = n).

Set vector A, C and a.

Compute the fitness of every grey wolf (search agent) and find the three best grey wolves and assign them the names α,β, and δ. After that, find the magnitude of $X_\alpha, X_\beta, X_\delta$ 4. While t<iteration_{max} (

For each grey wolf

Initialise a random value of r_1, r_2 .

Find the value of the distance.G_α,G_β, G_δ using equation (45)

$$\vec{D}=1/\gamma\ |\vec{G}p\ (i) + \vec{G}(i)| \quad (48)$$

Find the positionG_1,G_2, G_3 using equation (46)

$$\vec{G}(i+1)=1/\gamma\ \{\vec{G}p\ (i) +\vec{A}\vec{D}\ \} \quad (49)$$

One more term G_4 is found using equation (47)

$$\vec{G}_4 = \vec{G}_t + \alpha \oplus \text{Lévy}\ (\lambda) \quad (50)$$

Update the position of prey using equation (48)

$$\vec{G}(t+1) = \frac{\vec{G}_1+\vec{G}_2+\vec{G}_3+\vec{G}_4}{4} \quad (51)$$

Update vector A, C and a, then determine the fitness of all grey wolves (search agents) and discover the three best grey wolves and assign them names α, β, and δ. After that, update the magnitude of $X_\alpha, X_\beta, X_\delta$.
Increase iteration number t=t+1.
Repeat the steps until the criteria are met or the maximum number of iterations is reached.

5. Implementation of the proposed techniques
An experimental model of a 2 MW DFIG-operated wind generation system is used in this work. A Simulink model of the DFIG-based wind generation system is developed in MATLAB to test and validate the proposed controller optimisation by the MGWOCS method. A simulation model of DFIG [25, 26, 30] is given in Fig.3. The data for the test DFIG system are given in Table 1.

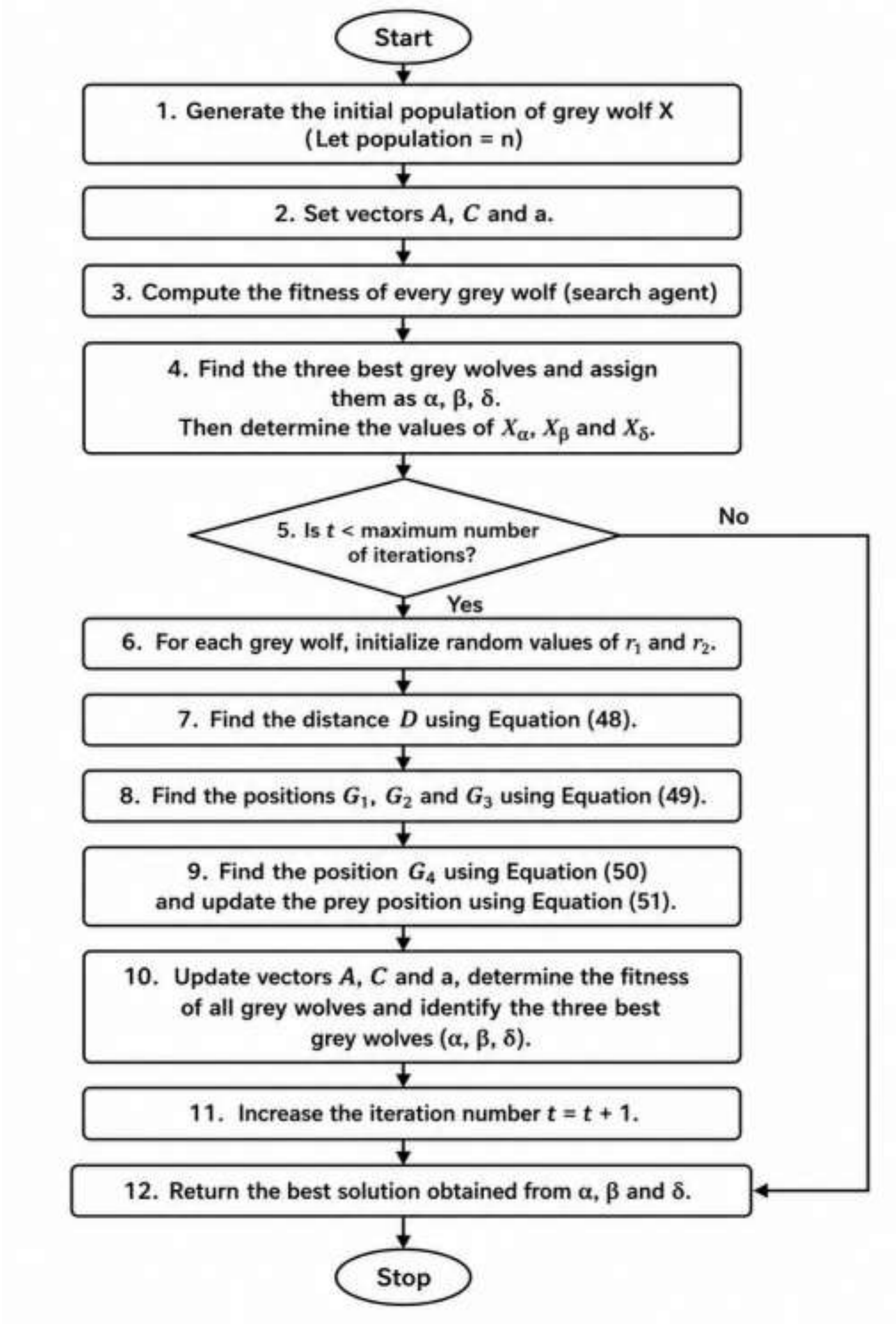

Figure 2. Flow chart of the MGWOCS method

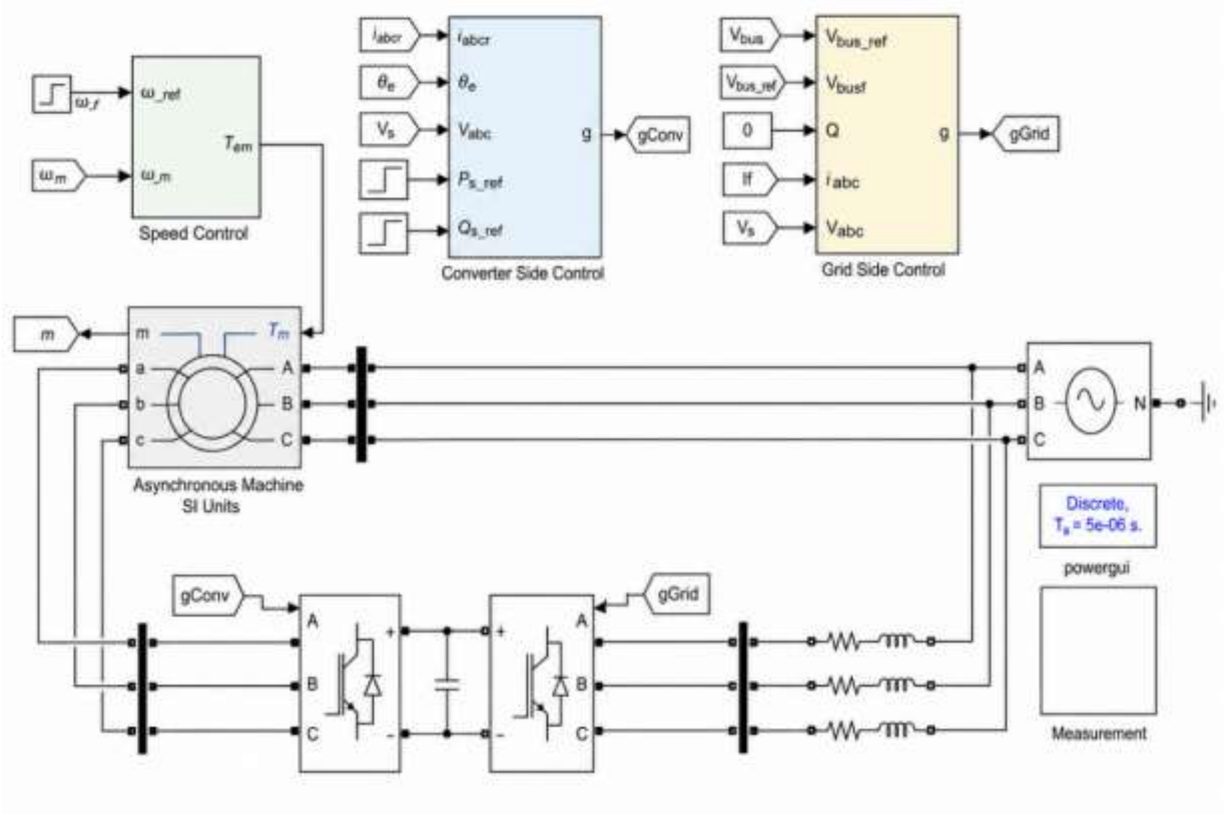

Figure 3. Simulink model of DFIG

The optimum tuning of the PI controller parameter is obtained by running the MGWOCS algorithm in MATLAB. These tuned PI controller parameters are fed into the Simulink model of the DFIG. In this model, a sudden load change at t = 4 seconds is introduced to simulate fault conditions. The output waveforms for true power, reactive power, emf, and current are plotted in the results section. The Jaya and Whale optimisation algorithms are also implemented on the same experimental Simulink model. Results obtained by MGWOCS are compared with those of the Jaya and whale optimisation algorithms.

Table 1. Datasheet of the 2 MW DFIG systems

Specifications	Values
Rotor Equivalent Resistance R_r	0.00289Ω
Stator Equivalent resistance R_s	0.00259Ω
Inductance of Rotor L_r	0.002586 H
Stator load L_s	0.002587 H
Mutual-Inductance M	0.0025 H
Real power proportional gain K_P	2.42
Reactive power proportional gain K_Q	2.34
Rated power P	2MW
Frequency f	50 Hz.
Generator (EM) Torque T_{em}	13000 N-M

6. RESULTS AND ANALYSIS

In this section, the result waveforms acquired from the experimental model are plotted and compared for different methods. Values obtained using the Jaya optimisation method [27, 28], the MGWOCS method, and the whale optimisation method [29] are fed into the DFIG model, and the results are mapped.

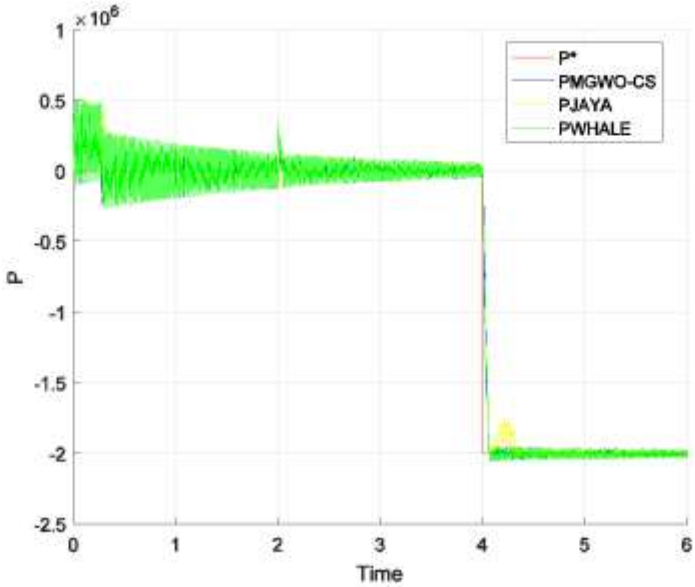

Figure 4 Variation of the active power

Figure 4 shows the active power variation when the PI controller is tuned by the MGWO-CS method (blue colour), the Jaya optimisation method (yellow colour), and the Whale optimisation method (green colour), respectively. Figure 9 shows that the output power of the DFIG optimised by MGWO-CS and Jaya is much better than that of the DFIG optimised by the Whale optimisation controller.

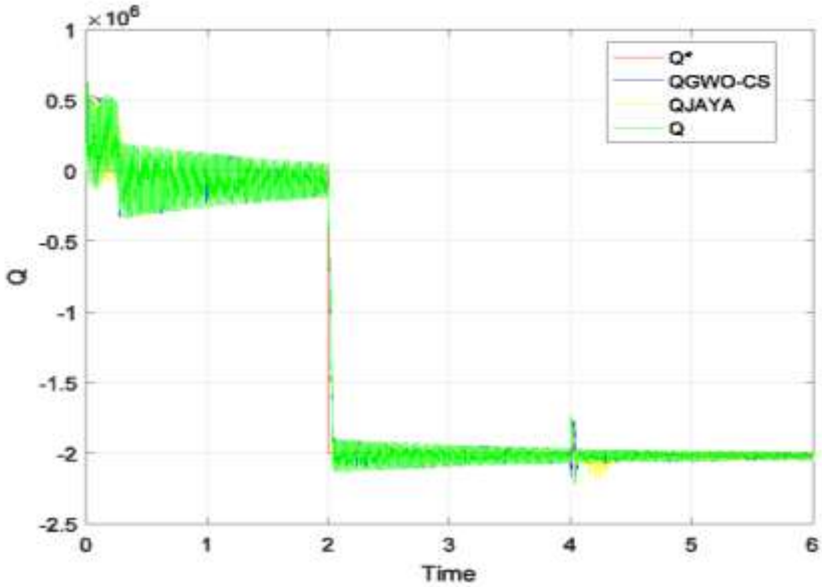

Figure 5 Reactive power variation with respect to time for DFIG with different optimisation methods

Figure 5 shows the change in reactive power over time when the controller is implemented. The diagram in Figure 6 shows that the output power of the DFIG optimised by MGWO-CS and Jaya optimisation is much better than that with the Whale optimisation controller. When the machine is loaded, the load torque increases, raising reactive power demand and disrupting the DC link voltage profile. Fig. 6 shows that MGWO-CS [30] gives better results and contains fewer transients than whale optimisation and the Jaya algorithm.

It is observed here that there is a large overshoot in the bus voltage. This large overshoot is due to an increase in the system's sensitivity. It is well known that feedback control systems increase system sensitivity, thereby increasing overshoot [30, 31, 32]. This may be considered a drawback of using a feedback control system with a PI controller; however, in the DFIG system, the stator winding is directly connected to the grid; hence, our main objective is to control the stator output, which is achieved in this work. The DC link is not directly connected to the load or the grid, so it does not directly affect the output power quality.

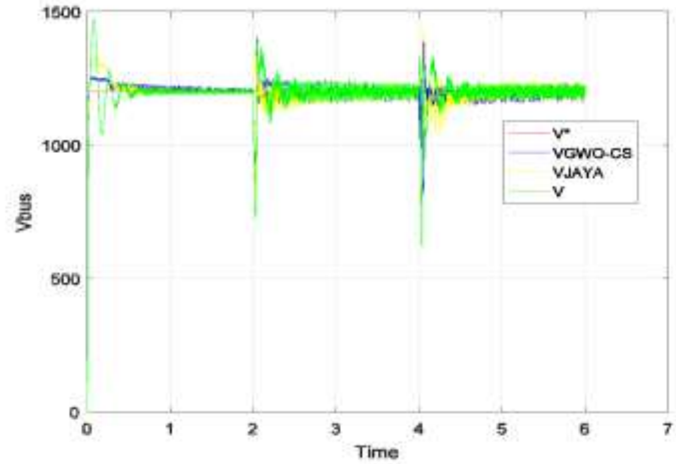

Figure 6. DC link voltage variation with different optimisation methods

This transient is also harmless to the grid or load because the DC link is not directly connected to either. To control this voltage, a capacitor or battery is placed between the two converters to eliminate these spikes, and this transient voltage can also be controlled through a grid-side converter. The comparative results for the proposed methods and other techniques are presented in Table 2.

Responses obtained using different optimisation techniques for the proposed practical wind generation model with a DFIG system are shown in Table 2.

Table 2 shows that WOA, MGWO-CS, and JOA all improve the response, and that the three best responses are obtained from the PI optimised by the MGWO-CS method. The optimal value of a new factor γ, used in the suggested MGWOCS to modify the encircling and position-update calculations, is also evaluated by comparing convergence rates. It is observed that convergence speed varies with γ.

Table 2. Comparative results of different methods

Parameters	Normal PI	PI optimised by WOA [28]	PI optimised by MGWO-CS	PI optimised by Jaya Optimisation
Rise Time	0.0885	0.0314	0.0263	0.0287
Settling Time	0.1363	0.0535	0.0386	0.0412
Overshoot	1.9099	1.12	1.08	1.10
Undershoot	0.85	0.809	0.913	0.956
Peak	1.6171	1.415	1.378	1.504

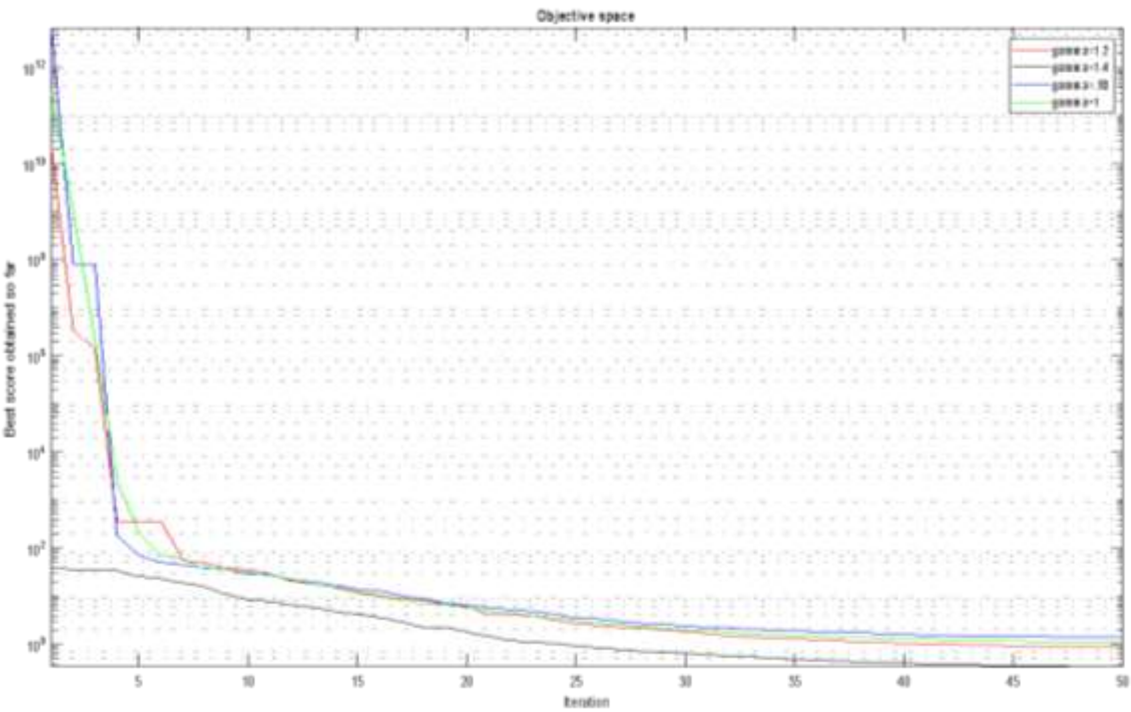

Figure 7. Effect of γ on the convergence plot

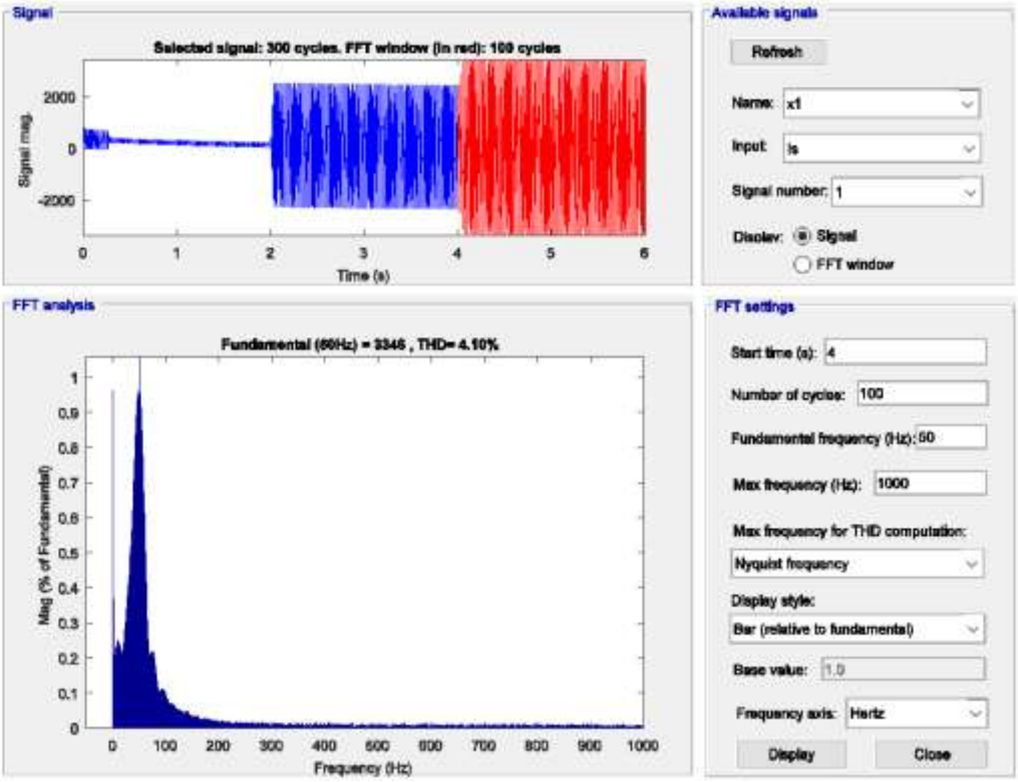

Figure 8. THD measurement in DFIG optimised by MGWO-CS Optimisation

Convergence is compared for different values of γ. The values of γ are taken as 0.93, 1, 1.2, and 1.4. From Figure 7, it can be concluded that the function converges quickly when $\gamma = 1.4$. Figure 8 shows the FFT analysis of the input load at 5 seconds, with a fundamental frequency of 50 Hz. The achieved THD (total harmonic distortion) is 4.10%, which is below the acceptable limit of 5% [32, 33].

6.1 Comparative Analysis in terms of Convergence and THD Values

The convergence characteristics of the Grey Wolf optimisation, MGWO-CS, and Jaya optimisation methods [34] are shown in Figures 9, 10, and 11, respectively.

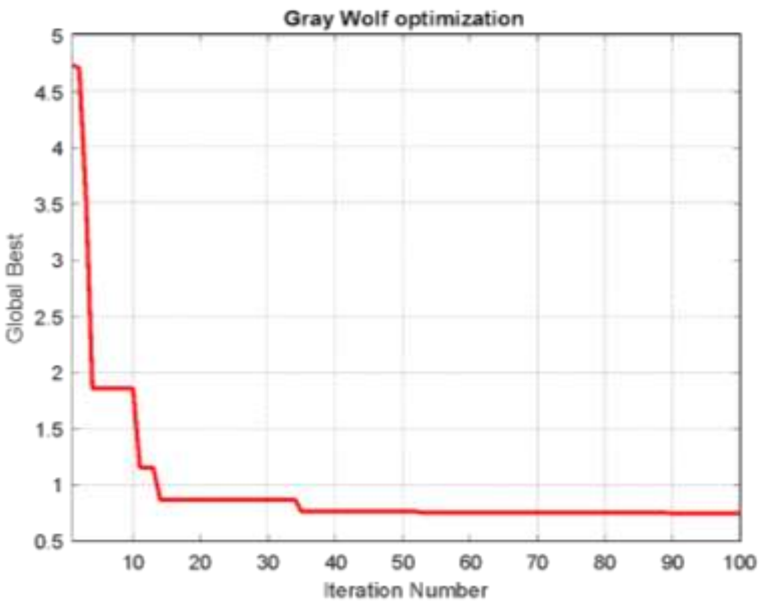

Figure 9. Graph of Convergence for the GWO method

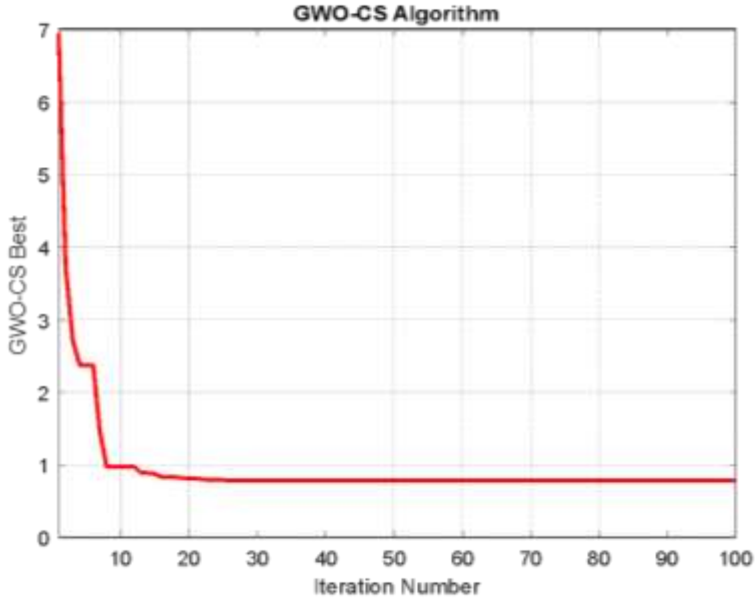

Figure 10. Graph of Convergence for the MGWO-CS method

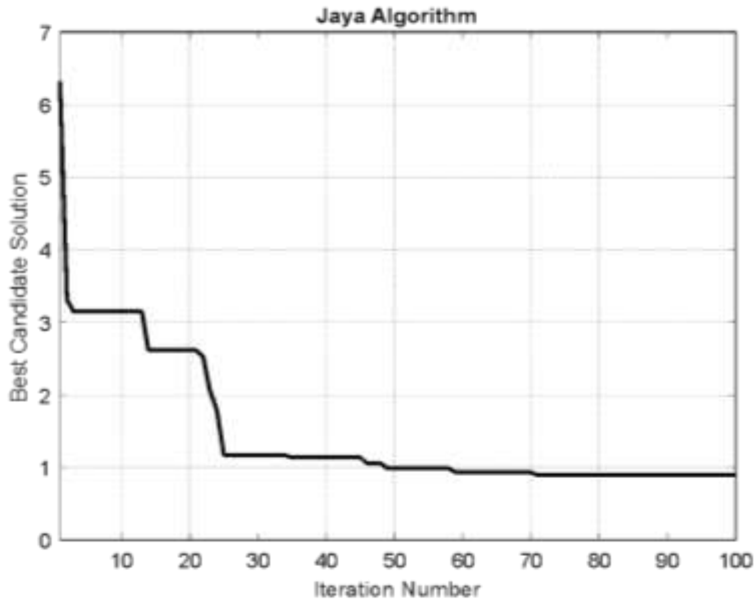

Figure11.Graph of Convergence for Jaya Optimisation Method

THD values of stator current obtained through different controllers are also compared. Table 3 shows that THD values and convergence rates are better with the MGWOCS method than with the GWO and Jaya optimisation methods.

Table 3. Comparison of the obtained THD values and the convergence speed of different techniques

S. No.	Technique used for optimisation	THD Values	Number of iterations required to converge
1	Jaya Optimisation Method	4.49	71
2	GWO Method	5.52	52
3	MGWO-CS Method	4.1	12

CONCLUSION

DFIG-WECS is mathematically modelled, and its rotor-side PI controller has been successfully designed. The Novel Modified Hybrid Grey Wolf Cuckoo Search Algorithm is applied in this work to obtain the optimal parameter values of the controller. The gains obtained from the optimisation method are fed to the 2 MWDFIG Simulink model. Simulation results are compared with those obtained using the Jaya and Whale Optimisation algorithms. A sudden transient is created at t = 4 seconds, and the waveform of voltage, current, and power is analysed. Analysis of the waveforms indicates that MGWOCS provides satisfactory results. Performance is also evaluated in terms of rise time, settling time, overshoot time, and undershoot time, and it was found that MGWOCS gives much better results than other methods. The convergence rate is also compared for different values of γ. It is found that the convergence rate depends on γ, with the highest rate at $\gamma = 1.4$. The results of MGWOCS and Grey Wolf Optimisation are illustrated. THD and convergence speed are compared, and it is concluded that convergence speed is increased. Also, THD values are lowest when using a controller optimised with MGWOCS. The work's future objective is to analyse the efficacy of the MGWOCS method on other DFIG test systems. Also, this method can be compared with newer metaheuristic optimisation methods.

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