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Optimal Design of FoPID Controller for DFIG Based Wind Energy Conversion System Using Grey-Wolf Optimization Algorithm

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Abstract- Because of substantial economic and environmental benefits, the wind turbine has solidified itself as an acceptable replacement for the generation of electricity by fossil fuel or nuclear power plants. Research continues to focus on enhancing the performance and adaptability of Wind Energy Conversion System (WECS). This study proposes a fresh contribution to the field, based on Fractional order PID (FoPID) controller to enhance the performance of DFIG WECS by controlling the converters, as well as optimizing the gains of a FoPID controller based on the Grey wolf optimization (GWO) algorithm. The proposed algorithm brought important features in terms of minimizing the harmonics in rotor current and persistence against system disturbances and parameter variations. The control approach is simulated using a MATLAB/Simulink and has 2.55% THD in rotor current whereas existing methods FPID optimization tool & standard PI regulator has 6.21% and 8.67% respectively. The results achieved using the novel GWO-FoPID controller outperform the FoPID controller tuned using FPID optimization tool & standard PI regulator.

Keywords DFIG, FoPID controller, GWO, Renewable energy, WECS.

NOMENCLATURE

AI	Artificial Intelligence
DFIG	Doubly Fed Induction Generator
FoPID	Fractional Order Proportional Integral Derivative
GWO	Grey Wolf Optimizer
PID	Proportional–Integral–Derivative
PSO	Particle Swarm Optimization
RL	Riemann-Liouville
RSC	Rotor Side Converter
WT	Wind Turbine
V_{sd}	d- axis Stator voltage
V_{sq}	q- axis Stator voltage
I_{rd}	d- axis Rotor current
I_{rq}	q- axis Rotor current
I_{sd}	d- axis Stator current
I_{sq}	q- axis Stator current
V_{rd}	d- axis Rotor voltage
V_{rq}	q- axis Rotor voltage
R_r	Rotor resistance
L_r	Rotor inductance
R_s	Stator resistance
L_s	Stator inductance
M	Mutual inductance
ω_s	Stator pulsation
φ_{sq}	q- axis Stator flux
φ_{sd}	d- axis Stator flux
φ_{rd}	d- axis Rotor flux

φ_{rq}	q- axis Rotor flux
T_e	EM torque
$\Gamma(.)$	Gamma function
t	Upper limit
a	Lower limit

1. Introduction

Renewable Energy (RE) sources, such as wind, solar, geothermal are the alternative energy sources that can provide the Earth with energy without altering the climate. The utilisation of renewable energy sources has become increasingly common as the need for energy has increased. Although these sources are more costly and risky, they can still meet the Earth's energy needs [1]. Wind energy is a clean and safe power source that has become an integral part of the energy mix and is best promising and essential forms of RE in the world [2, 3]. Alternators and squirrel cage induction generators (SCIG) are the most popular generator types utilised in small wind turbine (WT) residential applications, and DFIGs are often used in megawatt-scale turbines [4]. A variable wind generating system with a DFIG outperforms a fixed speed wind system in terms of efficiency. The regulation of variable speed wind turbines has been the subject of much and ongoing research [5]. In DFIG, the rotor must be linked with the network through bidirectional AC/DC & DC/AC converters whereas stator must be linked directly to the network [6]. Furthermore, induction generators may be controlled using various techniques such as field-oriented control, indirect torque control, and so on, with operations aimed at controlling the DFIG's active and reactive power [7, 8]. However, because of its simple design, ease of implementation, and well-decoupled active and reactive powers, the traditional controller based on vector control scheme is utilised to operate the induction machine in many real-life applications [9, 10]. It does, however, have significant drawbacks. One of the key disadvantages of this control technique is that the vector control process performance is largely dependent on the settings of traditional PI/PID controllers [11, 12]. The traditional DFIG control schemes comprise decoupled proportional-integral (PI) rotor current controllers with stator flux orientation and parameter-dependent compensatory terms. The typical PI controllers are the most popular controllers utilised for producing appropriate dynamic performance decoupled control solution of the active and reactive powers for the DFIG due to their simple construction. However, the effectiveness of the PI controller and, subsequently, the performance of the DFIG depends on the selection of the PI gains. Particularly for non-linear systems, tuning the PI parameters using the conventional trial and error approach to optimise the performance takes time and is very laborious [13]. To address this issue, the standard PI controller is replaced by a FOPID controller. It is possible to get better resilient stability and acceptable closed loop performances by using the extra parameters λ and μ in the FOPID controller. In a dynamic system with parametric uncertainties, the gains of the FoPID controller were normally adjusted arbitrarily and manually using approaches that are exceedingly sophisticated, laborious, and time-consuming [14].

To counter these limitations, several research investigations have used unique methodologies such as artificial intelligence (AI) techniques in recent years [15–18]. To improve the rotor current and minimize chattering issues in the active and reactive power fed to the DFIG, several studies and investigations have also been accomplished. Sliding mode regulators were used in a variety of control strategies to regulate the converter [19, 20]. Other researchers have used a variety of AI approaches and random search methods to increase controller performance. Fuzzy systems, PSO, and NNs have all been employed to effectively optimize PID controllers [21, 22]. The use of nature-inspired and bio-inspired optimization methodologies to enhance power system control behaviour has recently been explored in several studies [23, 24]. In this sense, meta-heuristic approaches are inspired by social nature such as biological and physical phenomena, as well as animal behaviour. Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) [25] are few well-known approaches in this field. The Firefly Algorithm (FA) [26], Grey Wolf Optimizer (GWO) [27], and Colliding Bodies Optimization (CBO) [28] are three recently suggested and mentioned algorithms. In addition modified elephant herding random forest algorithm (MEHRFA) [29], particle swarm optimization (PSO), bacterial foraging optimization (BFO), and gravitational search algorithm (GSA) [30] are broadly used to appropriate tuning of diverse controller gains. Only a few researchers have looked at the best control method for the standalone DFIG system. The technical research gap was applied to the new Meta-heuristic optimization Techniques to enhance the RSC & GSC control strategy by designing the optimum control gains.

This paper primary contributions are as follows: i) optimal design of novel FoPID controller for DFIG-based WECS for the analysis of rotor current, output reactive power, stator voltage, stator current, and step response of the DFIG 6th order model; (ii) application of GWO algorithm to obtain optimised controller parameters (proportional, derivative, integral, fractional differentiator & integrator) and (iii) THD of rotor current, output response comparison to determine the best scheme.

The paper is organized as follows: DFIG modelling is described in Section II, Section III portrays optimized FoPID controller using GWO algorithm. Section IV discusses the findings, and Section V presents the conclusion.

2. DFIG Based WECS

Figure 1 shows DFIG based wind turbine. It is modelled in various reference frames stator, rotor & synchronously rotating reference frames [31]. In this paper synchronously rotating reference frame is considered for modelling of DFIG using Eq. (1) to (13), because the signals appear in the form of DC nature [32].

Voltage Equations:

$$V_{ds} = R_s I_{ds} + \omega_s \psi_{qs} \tag{1}$$

$$V_{qs} = R_s I_{qs} - \omega_s \psi_{ds} \tag{2}$$

$$V_{dr} = R_r I_{dr} + \frac{d\psi_{dr}}{dt} - s\omega_s \psi_{qr} \tag{3}$$

$$V_{qr} = R_r I_{qr} + \frac{d\psi_{qr}}{dt} + s\omega_s \psi_{dr} \tag{4}$$

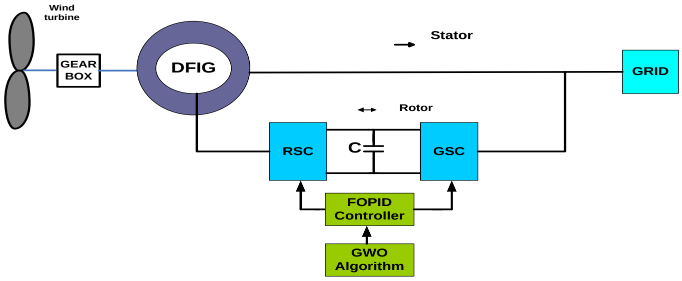

Fig.1. Grid connected DFIG based WT

Flux Equations:

$$\psi_{ds} = L_s I_{ds} + M I_{dr} \tag{5}$$

$$\psi_{qs} = L_s I_{qs} + M I_{qr} \tag{6}$$

$$\psi_{dr} = L_r I_{dr} + M_d \tag{7}$$

$$\psi_{qr} = L_r I_{qr} + M I_{qs} \tag{8}$$

Power Equations:

$$P_s = V_{ds} I_{ds} + V_{qs} I_{qs} \tag{9}$$

$$Q_s = V_{qs} I_{ds} - V_{ds} I_{qs} \tag{10}$$

$$P_r = V_{dr} I_{dr} + V_{qr} I_{qr} \tag{11}$$

$$Q_r = V_{qr} I_{dr} - V_{dr} I_{qr} \tag{12}$$

Torque Equations:

$$T_e = -\frac{3}{2}\frac{P}{2}(\psi_{ds} I_{qs} - \psi_{qs} I_{ds}) \tag{13}$$

Where R_s, R_r, R_r, L_s and L_r represents resistances, inductances of stator and rotor windings respectively. Direct and quadrature components of stator voltage are indicated with V_{ds},V_{qs}. V_{dr},V_{qr} are rotor voltage direct and quadrature components and I_{ds}, I_{qs} denotes direct and quadrature components of stator current. I_{dr}, I_{qr} are direct and quadrature components of rotor current. Ψ_{ds},Ψ_{qs} represents direct and quadrature components of stator flux. Direct and quadrature components of rotor flux are represented with Ψ_{dr},Ψ_{qr}. P is the number of poles.

3. Optimized FoPID Controller via Grey Wolf Algorithm

3.1. Optimized FoPID Control

The proposed FoPID controller for DFIG is shown in Fig.2. Several methods for changing the gain parameters of the FoPID controller were introduced to overcome the system's difficulties. Fractional-order calculus is an overview of differentiation and integration and Eq. (14) demonstrates the formulation of the basic operator ${}_aW_t^{\alpha}$, here $\alpha \epsilon \Re$ point outs the order of operation while t and a point out upper and lower limits [33].

$${}_aW_t^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}}, & \alpha > 0 \\ 1, & \alpha = 0 \\ \displaystyle\int_a^t (d\tau)^{-\alpha} & \alpha < 0 \end{cases} \tag{14}$$

$${}_aW_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}}\, d\tau \tag{15}$$

$${}_aW_t^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau)\, d\tau \tag{16}$$

Equation (15) deploys the Gamma function $\Gamma(.)$, n refers to 1st integer that was larger than operation order α. Furthermore, the RL description for FoPID is specified in Eq. (16). The Laplace transformation of Eq. (15) is derived in Eq. (17).

$$\int_0^{\infty} {}_0W_t^{\alpha} f(t) e^{-st} dt = s^{\alpha} \ell\{f(t)\} - \sum_{K=0}^{n-1} s^K {}_0W_t^{\alpha-K-1} f(t)\Big|_{t=0} \tag{17}$$

Here $\ell\{.\}$ stand for the Laplace operator.

The transfer function of FoPID $Y(s)$ is indicated in Eq. (18), here K_p, K_i, & K_d denotes proportional, integral and derivative gains respectively. In addition, λ and μ point out the fractional integrator and differentiator orders.

$$Y(s) = k_d + \frac{k_i}{s^{\lambda}} + k_p s^{\mu} \tag{18}$$

The proposed method specifications are represented in Table 1.

Table 1. DFIG based WT parameters

Symbol	Parameter	Value
P_r	Rated Power	9 MW
V_r	Rated Voltage	575 V
f	Grid frequency	60 Hz
R_s	Stator Resistance	0.023 p.u.
R_r	Rotor resistance	0.016 p.u.
L_s	Stator inductance	0.18 p.u.
L_r	Rotor inductance	0.16 p.u.
N	Mutual inductance	2.9 p.u.
I	Inertia	0.685 p.u.
V_{dc}	Nominal DC voltage	1150 V

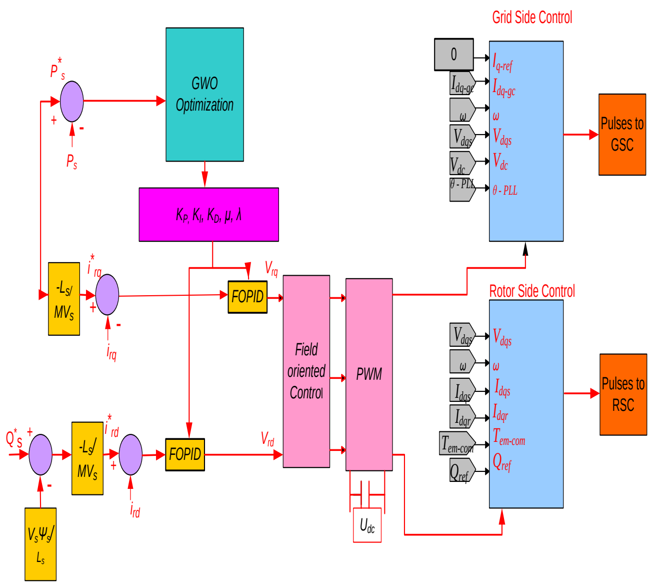

Fig.2. FoPID controller for DFIG based WT

3.2. Grey Wolf Optimization (GWO) Algorithm

It is a type of meta-heuristic approach which is proposed by Mirzalili et.al, by taking inspiration from hunting nature of grey wolves is shown in Fig.3. Grey wolves belongs to Canidae family and are top predators. The average group is 5–12 and have social dominating nature, which is very interesting. In general there are four types of wolves α, β, δ and ω in which the first three are the most significant wolves in terms of the hunting process is shown in Fig.4 [34].

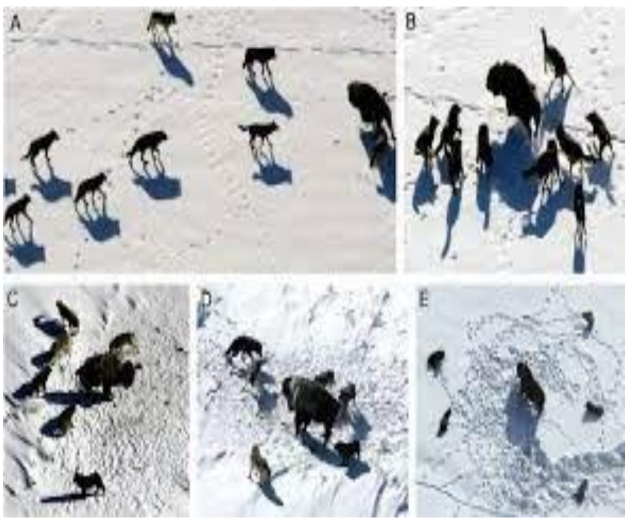

Fig.3. Hierarchy of proposed technique

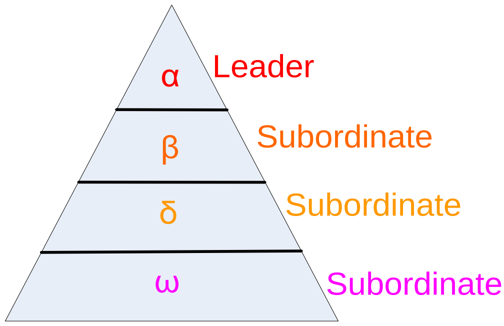

Fig.4. Grey wolves hunting behavior

where α is the leader and in-charge of making judgments on hunting procedures, sleeping locations, and waking times, among other things, while the 2nd and 3rd levels assist in making decisions. As a result, the wolf's last level ω is focused on feeding [35].

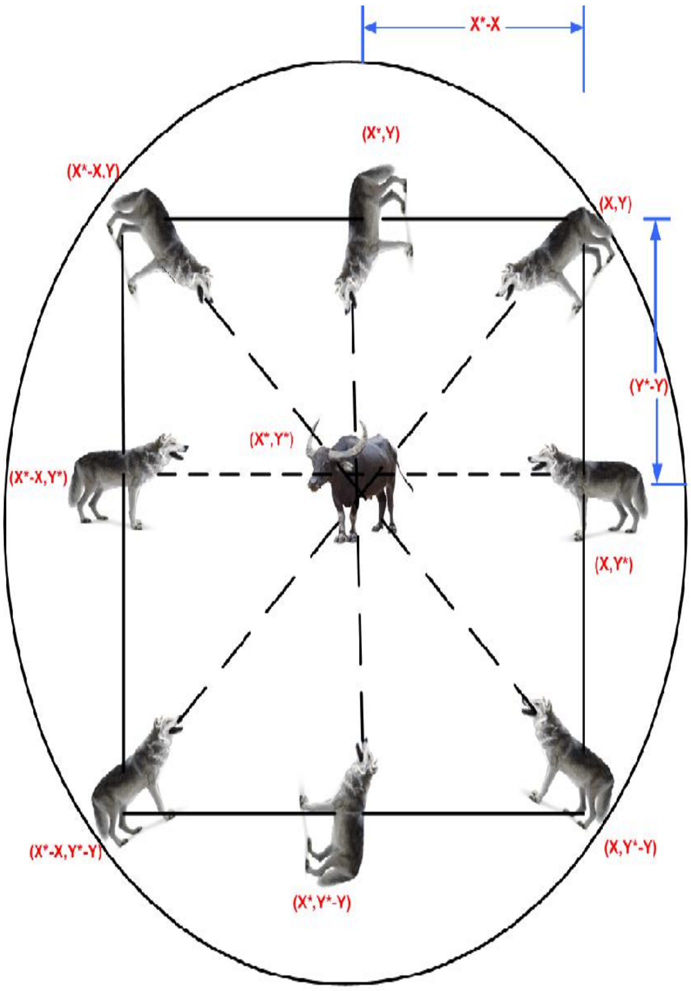

Fig.5. Position vectors of grey wolves

Encircling behaviour is modelled in Eq. (19) and Eq. (20).

$$Z = \left|F.D_p(ip) - D(ip)\right| \tag{19}$$

$$D(ip+1) = D_p(ip) - G.Z \tag{20}$$

Position vectors of grey wolves is shown in Fig.5.

Where D_p is the prey distance vector, D is the wolves distance vector, and ip is the current iteration.

Algorithm for Proposed GWO

Initialization
Calculate the search agents fitness.
Assign D_α as best search agents
Assign D_β as 2nd best search agents
Assign D_δ as 3rd best search agents
While $(ip < ip_{max})$
    For all wolves
        Determine D_3 using Eq. (28)
        Update position using Eq. (29)
    End
    Update $\hat{b}$, G and U
    Compute all search agents fitness
    Update D_α, D_β, and D_δ
    $ip = ip + 1$

End while
Return D_α

Modelling for G and U shown in Eq. (21), Eq. (22). Here b is constant decreased from 2 to 0 for next iterations. Sa_1 and Sa_2 are random vectors and ip_{max} is maximum iteration.

$$G = 2\hat{b}.sa_1 - \hat{b} \tag{21}$$

$$U = 2sa_2 \tag{22}$$

where G and U symbolizes coefficient vectors.

The mathematical modelling for depicting wolves' hunting behaviour is provided in Eqs. (23) to (29).

$$Z_\alpha = |U_1 D_\alpha - D| \tag{23}$$

$$Z_\beta = |U_2 D_\beta - D| \tag{24}$$

$$Z_\gamma = |U_3 D_\gamma - D| \tag{25}$$

$$D_1 = D_\alpha - G_1.(Z_\alpha) \tag{26}$$

$$D_2 = D_\beta - G_2.(Z_\beta) \tag{27}$$

$$D_3 = D_\delta - G_3.(Z_\delta) \tag{28}$$

$$D(ip+1) = \frac{D_1 + D_2 + D_3}{3} \tag{29}$$

Modelling of Proposed algorithm in the form of flowchart is shown in Fig.6.

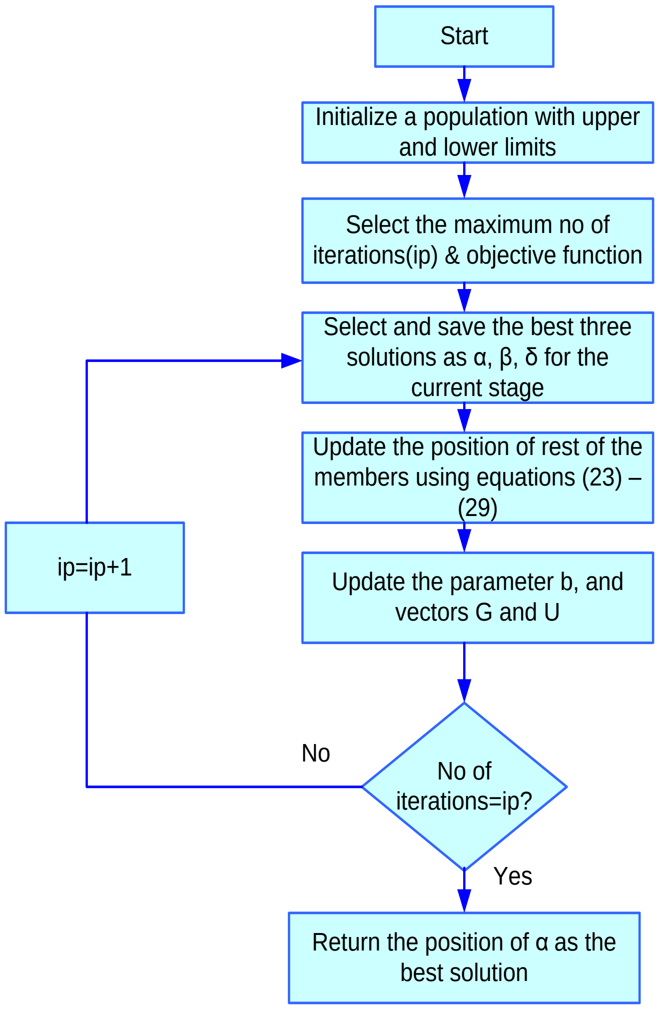

Fig. 6. Flowchart for Proposed algorithm

3.3. *Objective Function and Solution Encoding*

This work intends to make specific enhancements in FoPID controller design for enhancing performance of DFIG. Accordingly, the adopted scheme is modelled for restricting the harmonics in rotor over current and to optimize the FoPID parameters using a novel GWO Algorithm. Fig. 7 shows FoPID controller structure, in which R(s) is the reference input, E(s) is the error between reference input and actual output which is given as input for controller and U(s) is the output of optimal FoPID controller. So as to attain an optimal control, the FoPID parameters are tuned in an optimal manner by means of a GWO model.

The fitness function taken into consideration is Integral time absolute error [14] as in Eq. (30).

$$ITAE = \int_0^t t(|\Delta P| + |\Delta Q| + |\Delta I|) \tag{30}$$

where $\Delta P = P_{ref} - P_{actual}$, $\Delta Q = Q_{ref} - Q_{actual}$, $\Delta I = I_{ref} - I_{actual}$ are the error values between actual & reference values of stator Active power, reactive power and rotor current, respectively.

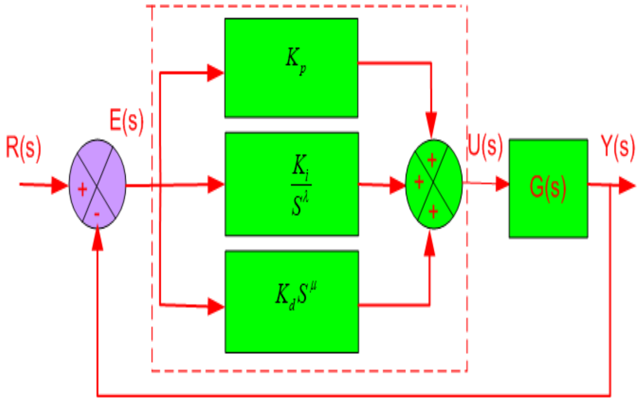

Fig.7. FoPID controller structure

The DFIG plant's 6th order transfer function is shown below [29].

$$G(s)=\frac{0.000324\,s^6-1.75s^5-2366\,s^4+7.9e^6s^3+7.5e^9s^2+5e^{12}s+2.18e^{14}}{s^6+2340\,s^5+8.67e^6s^4+4.79e^9s^3+2.7e^{12}s^2+1.27e^{14}s+9.6e^{14}} \tag{31}$$

4. Simulation Results & Discussion

To examine the effectiveness of the proposed strategy a 9 MW wind farm with a variable speed WT driving the DFIG is considered. It is made up of six 1.5 MW WTs that are coupled to a grid through a feeder. The results of the adopted optimal controller performance utilizing GWA + FoPID were achieved using MATLAB/SIIMULINK environment. This section gives the analysis of results obtained from simulation for proposed model. The implemented technique was examined, and its superiority to the conventional system was demonstrated.

The analysis on rotor current for adopted GWA + FoPID model over conventional approach is revealed in Fig. 8. Here, the analysis is carried out for 0.2 seconds. On examining the graph, the rotor current attained using the adopted model shows minimal oscillations when compared over conventional model. Moreover, the maximal acceptable rotor current is effectively regulated within ±1.5 p.u using the implemented GWO model. As a result, there are no possibilities of over currents for the RSC.

Figure 9 presents the THD spectrum for the proposed GWA + FoPID controller, FoPID controller using FPID tool box & PI controller. For improved controller performance, the suggested scheme's THD should be kept to a minimum. Thus, minimal THD refers to minimal oscillation of the signal. While analyzing the outcomes, the proposed scheme has achieved a least THD value of 2.55%, whereas existing methods has more, therefore the superiority of the presented GWA + FoPID scheme has been proved in terms of THD is presented in Table 2.

The analysis on reactive power attained by the adopted GWA + FoPID model over traditional model is revealed in Fig. 10. On observing the waveform the consumption of reactive power is zero. Thus, the performance of DFIG is enhanced using adopted model in terms of reactive power consumption zero.

The step response specifications rise time, settling time, overshoot and steady state error for the 6th order transfer function model of DFIG using proposed method and existing methods are evaluated and presented in Table 3. On noticing the outcomes, the proposed GWA + FoPID model has attained less rise time, settling time 1.129µs and 1.313µs respectively. However overshoot attained by the adopted method and traditional method is same. Thus enhanced steady state response guarantees the improved performance of the presented model.

The analysis on stator voltage and stator current for the proposed scheme (GWA + FoPID) as well as the conventional scheme is revealed in Fig. 11. On observing the outcomes, the voltage of proposed scheme lies within 1p.u and shows minimal oscillations. In addition, the oscillations of stator current attained using presented model are minimal when compared to the PI controller.

Table.2. THD of Rotor current

Method adopted	**% THD**
PI controller	8.67
FPID optimization tool [14]	6.21
MEHRFA [29]	3.36
GSA [30]	3.45
Proposed	2.55

Table. 3. Comparison of steady state response of DFIG

Specifications	Proposed method	PI controller	FPID optimization tool [14]
Rise Time (µs)	1.129	13.13	6.12
Settling time (µs)	9.027	14.023	11.9
Overshoot (%)	0	0	0
Steady state error	0	0.08	0

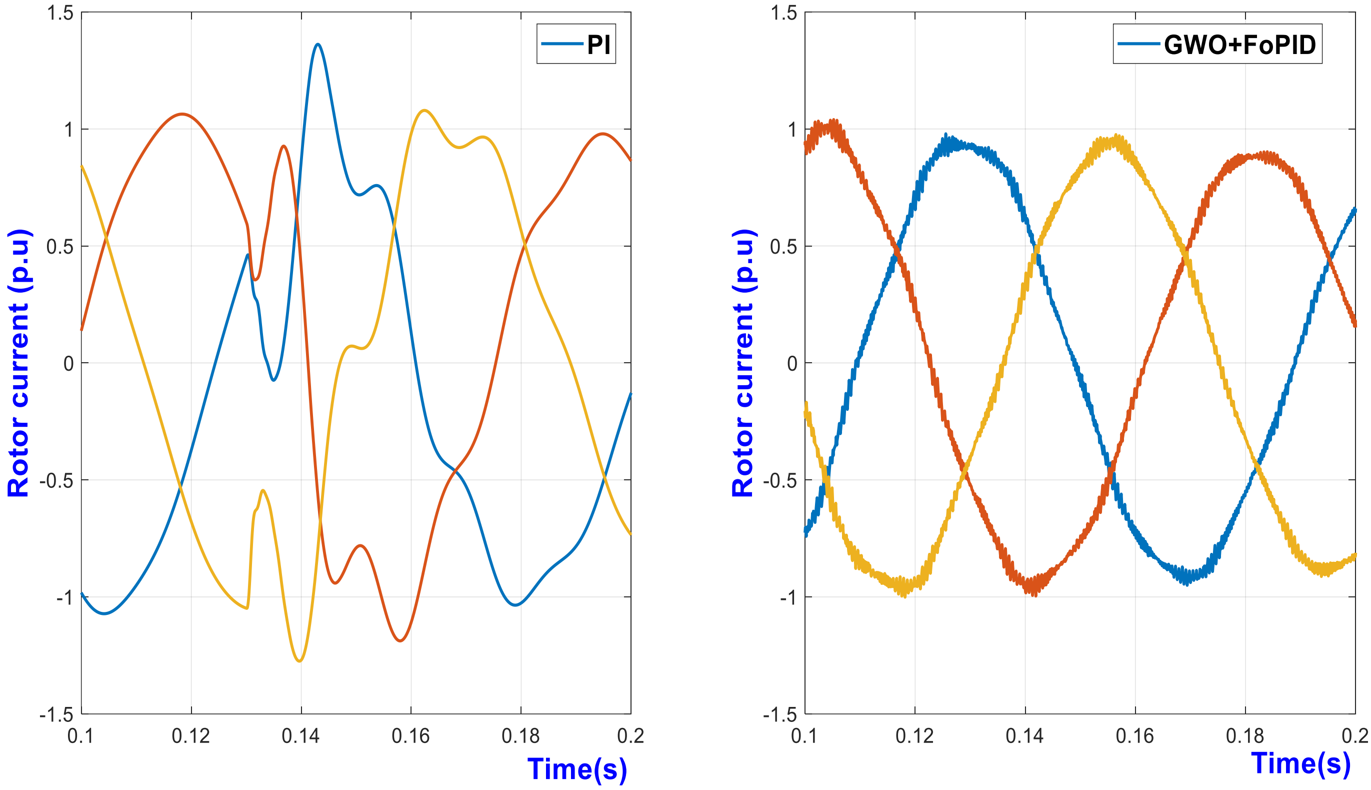

Fig. 8. Rotor current waveform using PI controller and proposed method.

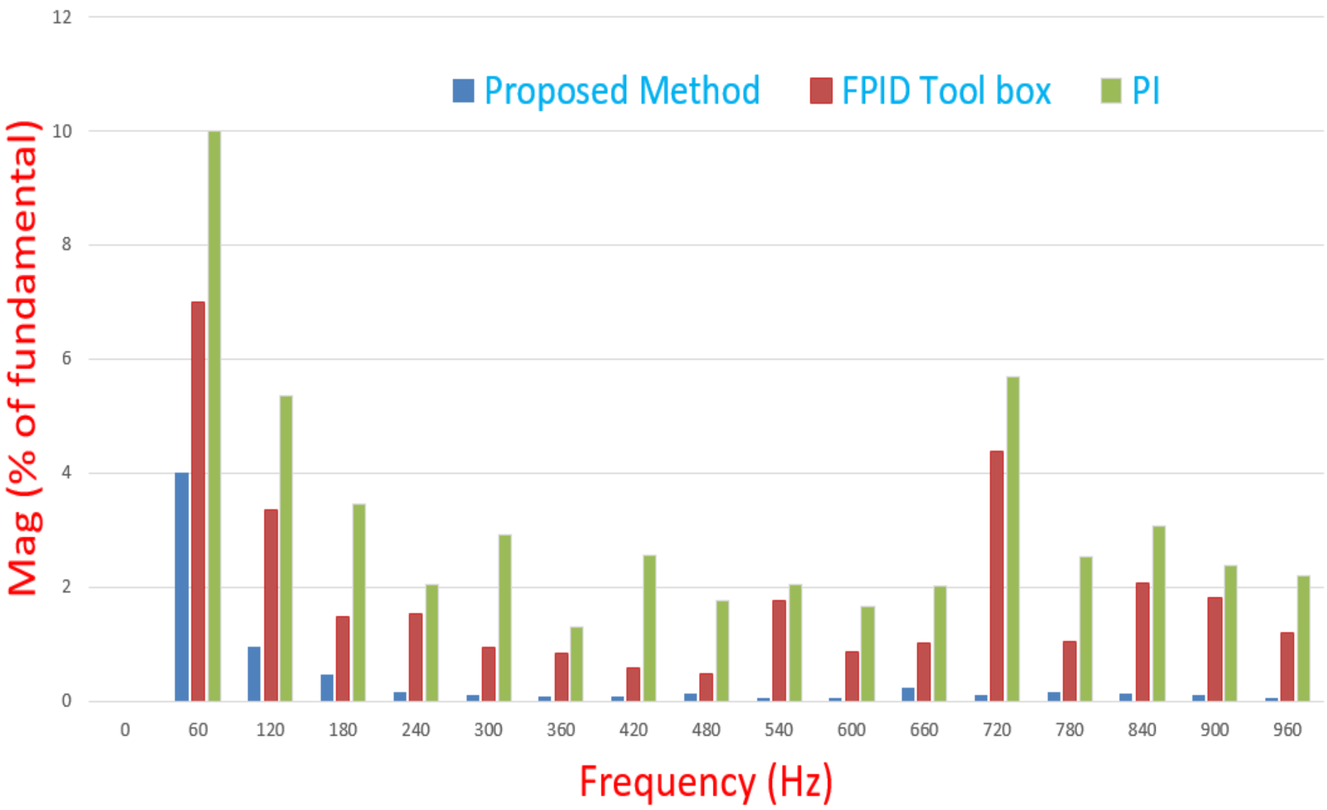

Fig. 9. THD spectrum of the rotor current using proposed method, FPID tool box & PI controller.

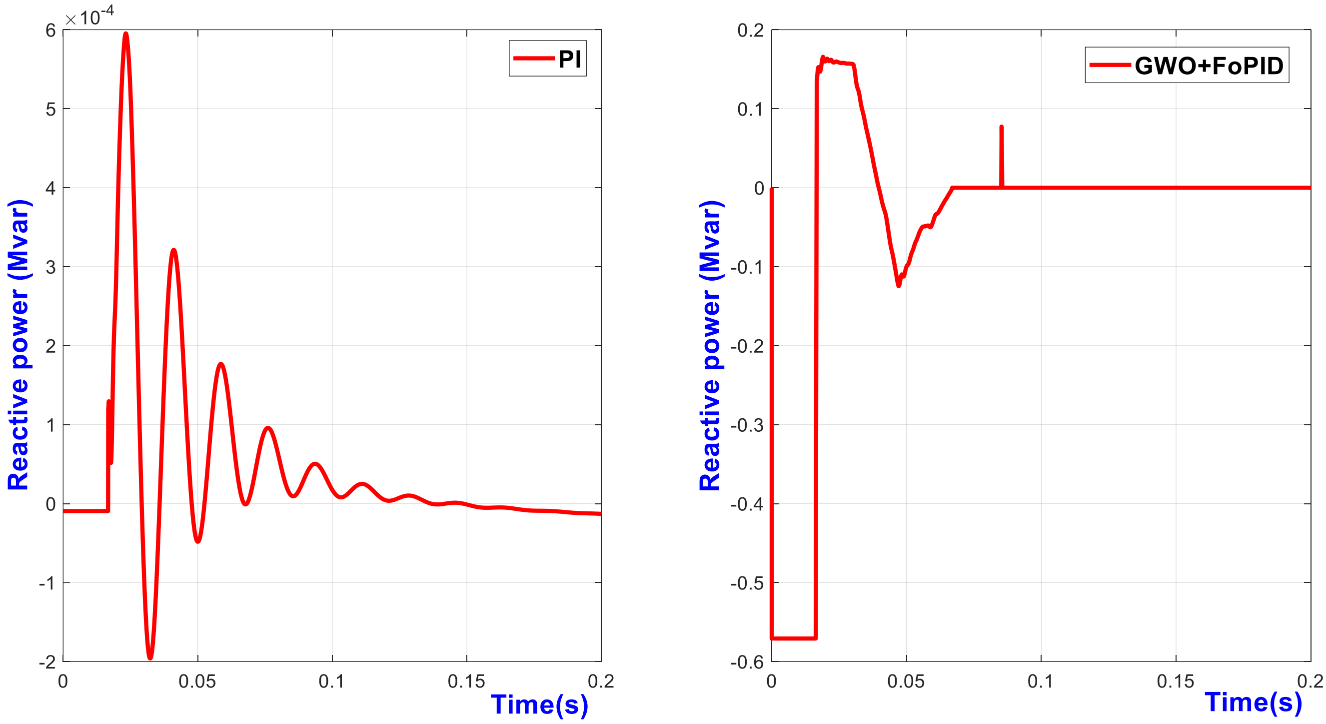

Fig. 10. Reactive power waveform using PI controller and proposed method.

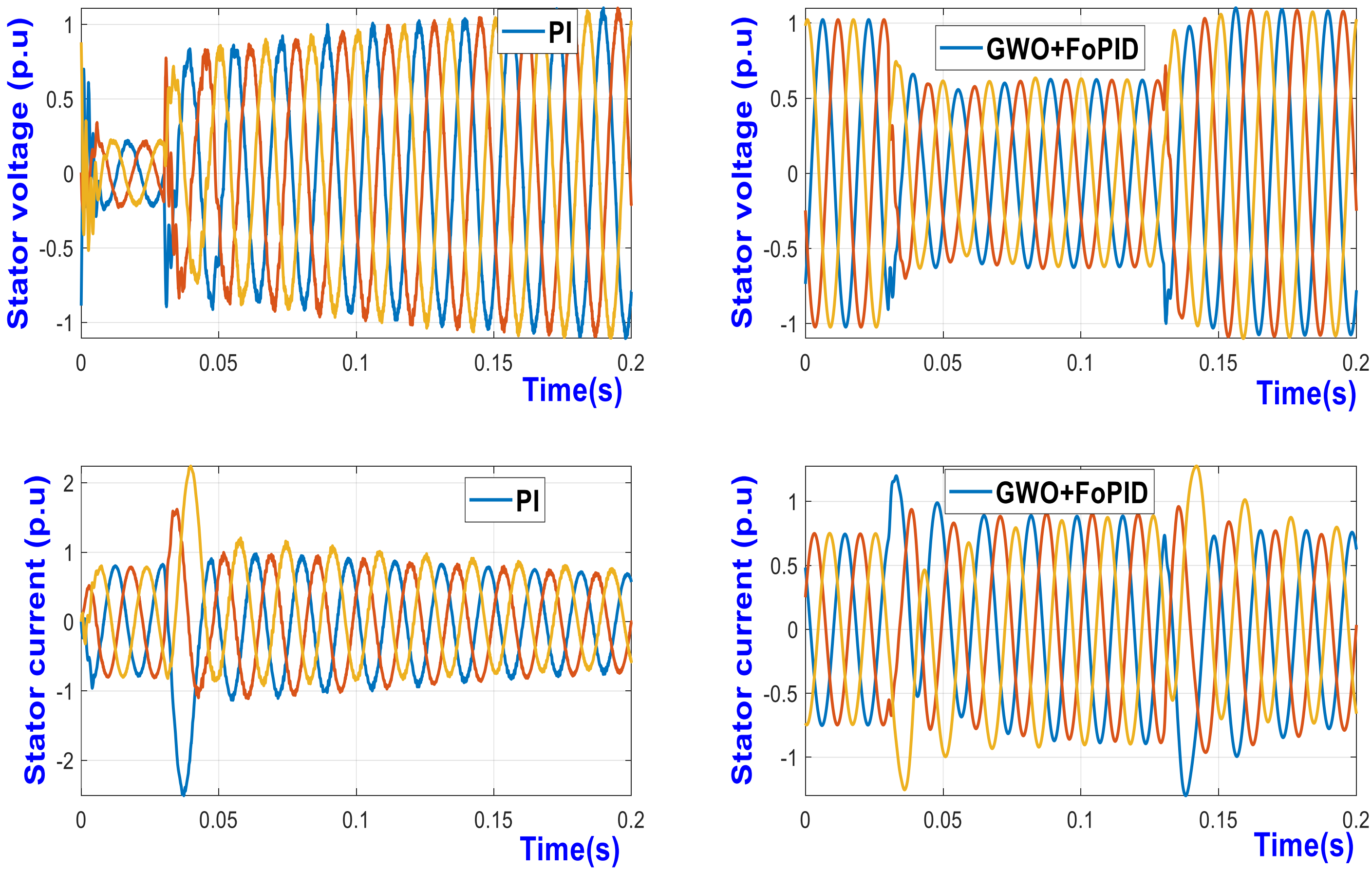

Fig.11. Stator voltage & Stator current waveforms using PI controller and proposed method.

5. Conclusion

This paper examines the effectiveness of novel control method GWO + FoPID controller implemented on DFIG based WECS. Conventional PI, FoPID tuned using FPID optimization tool [14] and GWO + FoPID controller are taken into account. The results shows that the GWO + FoPID controller performs more efficiently than conventional PI controller and [14] by optimizing the controller gain parameters (derivative gain, integral gain, proportional gain, fractional differentiator, and integrator) and decreased the harmonics in rotor current of DFIG to 2.55% whereas existing methods has 6.21% and 8.67% respectively. More particularly, the proposed GWO + FoPID model has attained less rise time 1.129µs, settling time 9.027µs, whereas conventional PI controller and [14] has high specifications. The enhanced steady state response thus guaranteed the improved performance of DFIG based WECS using novel GWO + FoPID controller.

In future part of the work analysis on performance of DFIG based WECS can be done under various unbalanced conditions during LVRT and hardware implementation.

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