Optimal Power Control Based-Metaheuristic Algorithm Based Variable Speed Wind Energy System of DFIG

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***Abstract*— This article presents a novel method for controlling a doubly fed induction generator (DFIG) wind energy system in the presence of variable wind speeds. In order to achieve decoupling control of the active and reactive power, the rotor-side converter (RSC) of the DFIG is controlled using field-oriented control (FOC). The system is very complicated and nonlinear, making it challenging to adjust the PI gains appropriately. The present research proposes the utilization of the Grey Wolf Optimization (GWO) algorithm as an approach to optimize the gains of a Proportional-Integral (PI) regulator. The simulation results demonstrate that the GWO-PI provides a lower criterion value and an improved response than the conventional PI.**

Keywords*— *Doubly fed induction generator, DFIG, Wind turbine, PI controller, FOC, GWO.

Introduction

Renewable energy plays an important role in sustainable development. The most competitive forms of renewable energy are wind energy and solar energy [1].

Wind energy is one of the most important and promising sources of renewable energy in the world. The doubly fed induction generator (DFIG) has many advantages over other generator technologies, such as a lower converter cost, less power loss, and the ability to work at different speeds [2].

Most wind turbines with variable speeds have a double-fed induction generator (DFIG). In fact, DFIGs are wound-rotor induction generators [3]. The stator is directly connected to the grid, and the rotor is connected to the grid through back-to-back electronic power converters. The rotor-side-converter (RSC) is the part of the (DFIG) based wind turbine system that changes the amount of active and reactive power needed [4].

Field-oriented control (FOC) is a control technique used in electrical engineering, especially in controlling electric motors. It is based on a vector control method that controls the magnitude and phase of the stator currents in an AC motor. This method is also known as flux vector control. (FOC) is used to accurately and efficiently control the speed, torque, and position of an AC motor. The technique uses a mathematical model of the motor to calculate the required current for each phase of the motor in order to achieve the desired output. The current is applied to each phase of the motor using power electronics such as inverters or amplifiers. FOC provides precise control over AC motors, allowing them to be used in many applications such as robotics, machine tools, and automated manufacturing systems [5],[8].

Many works of literature have been written about how to control the power of an induction machine. Field control (FOC) was the first control strategy studied [5],[6],[7]. This type of regulator remains the most commonly used for DFIG control as well as in many industrial control systems.

In recent years, various modern control techniques, such as intelligent control, have been intensively studied for controlling the nonlinear components in power systems [8],[9],[10]. In [11], authors applied the (PSO) algorithm for tuning PI regulator of (DFIG). Therefore, the conventional PI controllers, because of their simple structures, are still the most commonly used control techniques in power systems, as can be seen in the control of the wind turbines equipped with DFIGs [12]. Unfortunately, adjusting the PI controllers is laborious, and it may be complicated to effectively tune the PI gains owing to the system's nonlinearity and complexity [13],[19]. A grey wolf optimization is one of the modern meta-heuristic algorithms that can be applied to nonlinear systems [14],[15].

In this paper, we use PI controllers tuned by GWO in comparison to PI tuned manually to implement the vector transformation control method of FOC to control the decoupling of the active and reactive power.

I. SYSTEM MODELLING

A. *Wind turbine model*

Wind energy is kinetic energy. A wind turbine system uses the energy of the wind to create mechanical torque on the rotating shaft of the turbine, while an electrical generator on the same shaft is controlled to produce an opposing electromagnetic torque [16].

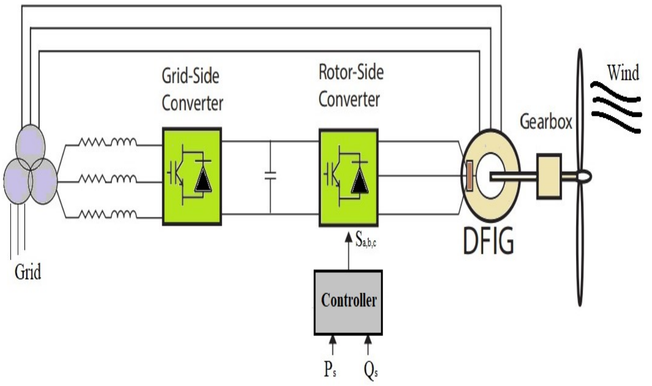


Fig. 1. The structure of the considered DFIG system.

The aerodynamic power captured by the rotor is given by the following nonlinear expression:

$$P_v = \frac{1}{2}\rho\pi R^2 V^3 \qquad (1)$$

Where V is the wind speed (m/s), ρ is the density of the air, and R is the radius of the wind turbine (m). The wind turbine can recover only a fraction of the available power that appears to the rotor; thus, the mechanical power of the turbine (P_t) can be represented by [20]:

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

Where:

$$C_p(\lambda,\beta) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \qquad (3)$$

C_p: the power factor that characterizes the aerodynamic efficiency of the turbine. It is a function of the tip speed ratio and the blade pitch angle β in a pitch-controlled wind turbine. is defined as the ratio of the tip speed of the turbine blades to wind speed:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (4)$$

Where:

$$\lambda = \frac{\Omega_t R}{V} \qquad (5)$$

Where: Ω_t is the angular speed of the turbine.

In Fig.2. For each pitch angle of the rotor blades, there are an optimum tip-speed ratio λ_{opt} for which $C_p(\lambda_{opt},\beta)$ takes a maximum value.

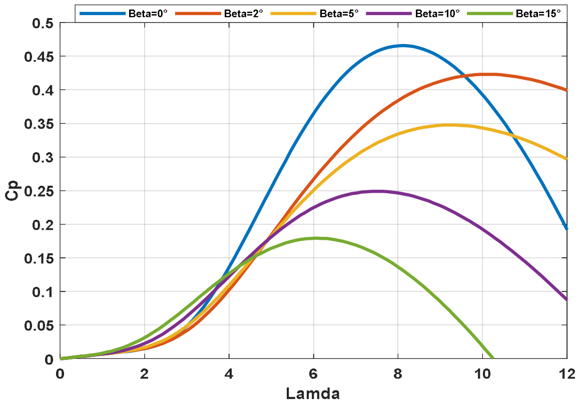


Fig. 2. The characteristics of the power coefficient Cp (λ, β).

The following relationship describes the aerodynamic torque:

$$J\frac{d\Omega_{mec}}{dt} = C_{mec} = C_g - C_{em} - C_f\Omega_{mecc} \qquad (6)$$

C_{em}: The electromagnetic torque.

C_{mec}: The mechanical torque.

C_f: The viscous friction torque.

J: Total inertia.

B. *DFIG model*

The modelling of the DFIG in (d-q) synchronous reference frame given by [17]:

The stator voltage:

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d\varphi_{ds}}{dt} - \varphi_{qs}\omega_s \\ V_{qs} = R_s I_{qs} + \dfrac{d\varphi_{qs}}{dt} + \varphi_{ds}\omega_s \end{cases} \qquad (7)$$

The rotor voltage

$$\begin{cases} V_{dr} = R_r I_{dr} + \dfrac{d\varphi_{dr}}{dt} - \varphi_{qr}(\omega_s + \omega_r) \\ V_{qr} = R_r I_{qr} + \dfrac{d\varphi_{qr}}{dt} + \varphi_{dr}(\omega_s - \omega_r) \end{cases} \qquad (8)$$

The stator fluxes

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + L_m I_{dr} \\ \varphi_{qs} = L_s I_{qs} + L_m I_{qr} \end{cases} \qquad (9)$$

The rotor fluxes

$$\begin{cases} \varphi_{dr} = L_r I_{dr} + L_m I_{ds} \\ \varphi_{qs} = L_r I_{qr} + L_m I_{qs} \end{cases} \qquad (10)$$

The stator active and reactive power

$$\begin{cases} P_s = \frac{3}{2}\left(V_{ds}I_{ds} + V_{qs}I_{qs}\right) \\ Q_s = \frac{3}{2}\left(V_{qs}I_{ds} - V_{ds}I_{qs}\right) \end{cases} \tag{11}$$

The electromagnetic torque

$$T_{em} = \frac{3}{2}p\frac{L_m}{L_s}\left(\varphi_{qs}I_{dr} - \varphi_{ds}I_{qr}\right) \tag{12}$$

II. FIELD ORIENTED CONTROL OF DFIG

The (RSC) is controlled in a synchronously rotating (d-q) axis frame.

With:

$$\begin{cases} \varphi_{sd} = \varphi_s \\ \varphi_{sq} = 0 \end{cases} \tag{13}$$

For high power machines, the stator resistance is neglected and it is also assumed that the flux is constant so we can write:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \omega_s\varphi_s \end{cases} \tag{14}$$

Reference frames for the DFIG in the field orientation with angle and angular speed definitions arc displayed in Fig.3.

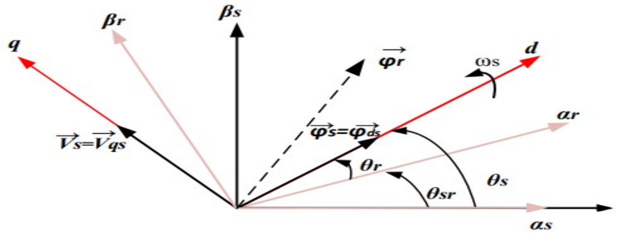


Fig.3. Orientation of the stator flux.

$$\begin{cases} P_s = -\frac{3}{2}\frac{L_m}{L_s}V_sI_{qr} \\ Q_s = \frac{3}{2}V_s\left(\frac{V_s}{L_s\omega_s} - \frac{L_m}{L_s}I_{dr}\right) \end{cases} \tag{15}$$

III. THE GREY WOLF OPTIMIZATION (GWO)

The Grey Wolf Optimizer (GWO) is an optimization algorithm inspired by the leadership hierarchy and hunting mechanism of grey wolves. It is a meta-heuristic algorithm that can be used to solve optimization problems in engineering, machine learning, and data science. It uses three main operators: alpha (α), beta (β), and delta (δ) wolves. The alpha wolf leads the pack and determines the direction of search while the beta and delta wolves follow the alpha wolf's lead to explore the search space. The GWO algorithm works by generating a set of random solutions (wolves) in the search space and then iteratively improving them using a combination of exploration (beta and delta wolves) and exploitation (alpha wolf). The best solution found so far is called the global best solution or leader. The GWO algorithm has been successfully applied to various optimization problems such as function optimization, feature selection, clustering, image processing, etc [14],[15],[18].

During hunting, the grey wolves encircle prey. The mathematical model is presented in the following equations:

$$\begin{cases} \vec{D} = \left|\vec{C}\,\vec{X}^i_p - \vec{X}^i\right| \\ \vec{X}^{i+1} = \vec{X}^i_p - \vec{A}\vec{D} \end{cases} \tag{16}$$

Where:

D: is the distance.

$\vec{X}^i_p$: is the position vector of the prey.

$\vec{X}^i$: indicates the position of the grey wolf.

i : indicates the current iteration.

$\vec{A}, \vec{C}$: coefficient vectors.

$$\begin{cases} \vec{A} = 2\vec{a}\cdot\vec{r}_1 - \vec{a} \\ \vec{C} = 2\cdot\vec{r}_2 \end{cases} \tag{17}$$

The other search agents (wolves) follow them and update their positions according to the best search agent by the following expression:

$$\begin{cases} \vec{D}_\alpha = \left|\vec{C}_1\vec{X}_{\alpha i} - \vec{X}_i\right| \\ \vec{D}_\beta = \left|\vec{C}_2\vec{X}_{\beta i} - \vec{X}_i\right| \\ \vec{D}_\delta = \left|\vec{C}_3\vec{X}_{\delta i} - \vec{X}_i\right| \end{cases} \tag{18}$$

$$\begin{cases} \vec{X}_1 = \vec{X}_{\alpha i} - \vec{A}_1\vec{D}_\alpha \\ \vec{X}_2 = \vec{X}_{\beta i} - \vec{A}_2\vec{D}_\beta \\ \vec{X}_3 = \vec{X}_{\delta i} - \vec{A}_3\vec{D}_\delta \end{cases} \tag{19}$$

$$\vec{X}_{i+1} = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{20}$$

IV. THE OPTIMIZATION METHOD

The PI controller is a good controller in the field of machine control, but the problem is the mathematical model of the plant must be known (nonlinear-system) [13]. In order to solve the problems in the overall system, several methods have been introduced to tuning PI controller.

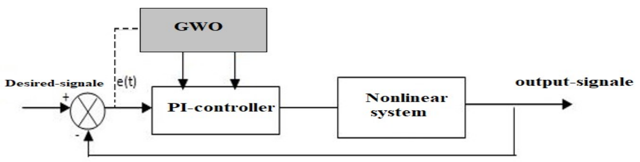


Fig.4. PI controller optimized by the GWO.

Our proposed method use the GWO to optimize the active and reactive power PI controller parameters, the GWO is utilized off line to determine the controller parameters (Kp and Ki) (based on quadrature rotor current error i_{rq} linked to active power Ps and direct rotor current i_{rd} linked to reactive power Qs) of the DFIG.

The equations below of Integral Square Error (ISE) and Integral Time Square Error (ITSE) performance indices are used as fitness by the GWO.

$$ISE = \int_0^{\infty} e(t)^2 \, dt \qquad (21)$$

To see how GWO is theoretically able to solve optimization problems, the flowchart is presented as follow:

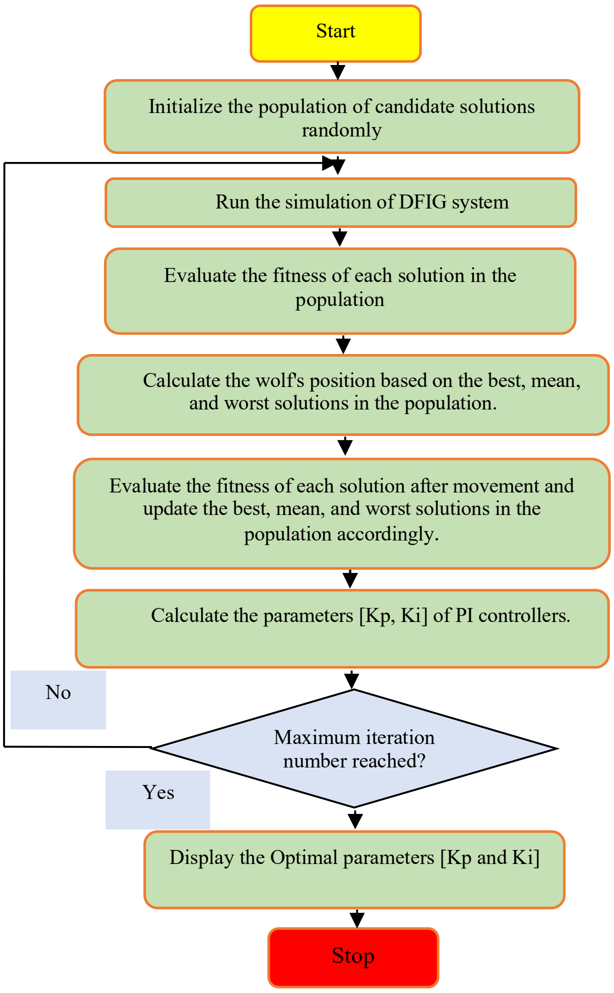


Fig.5. Flowchart of GWO for tuning PI controller gains

V. SIMULATION RESULTS

The (DFIG) used in this paper is (P_n=1.5MW) and its parameters are presented in Table.1.

Table.1. The parameters of system.

Parameters	values
Stator rated voltage (Vs)	398/690 V
Rated DC-Link voltage (Vdc)	1200 V
Rated current (In)	1900 A
Rotor inductance (Lr)	0.0136 H
Stator inductance (Ls)	0.0137 H
Mutual inductance (M)	0.0135 H
Stator rated frequency (*f*)	50 Hz
Rotor resistance (Rr)	0.021 Ω
Stator resistance (Rs)	0.012 Ω
Number of pair of poles (p)	2
Number of blades	3
Rotor radius (R)	35 m
The density of the air (ρ)	1.225 kg/m3
Moment of total inertia (J)	1000 Kg.m2

The simulation results using Matlab/Simulink under variable speed conditions is presented.

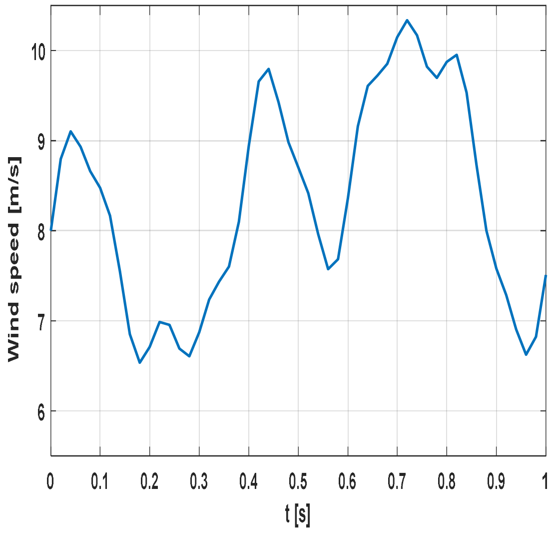


Fig.6. Wind speed.

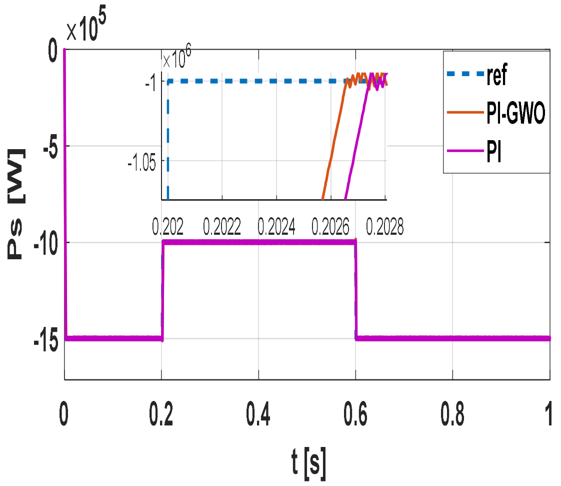


Fig.7. The stator active power response.

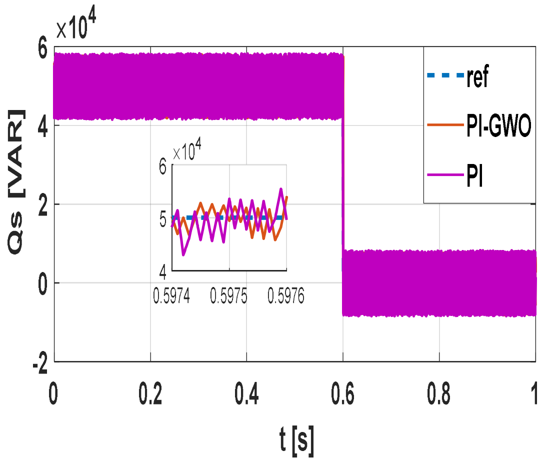


Fig.8. The stator reactive power response.

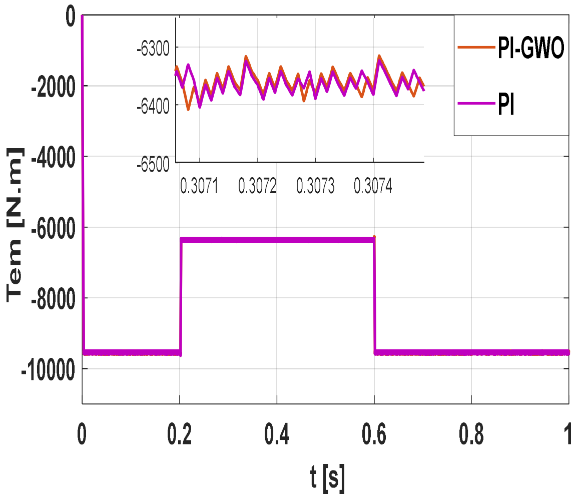
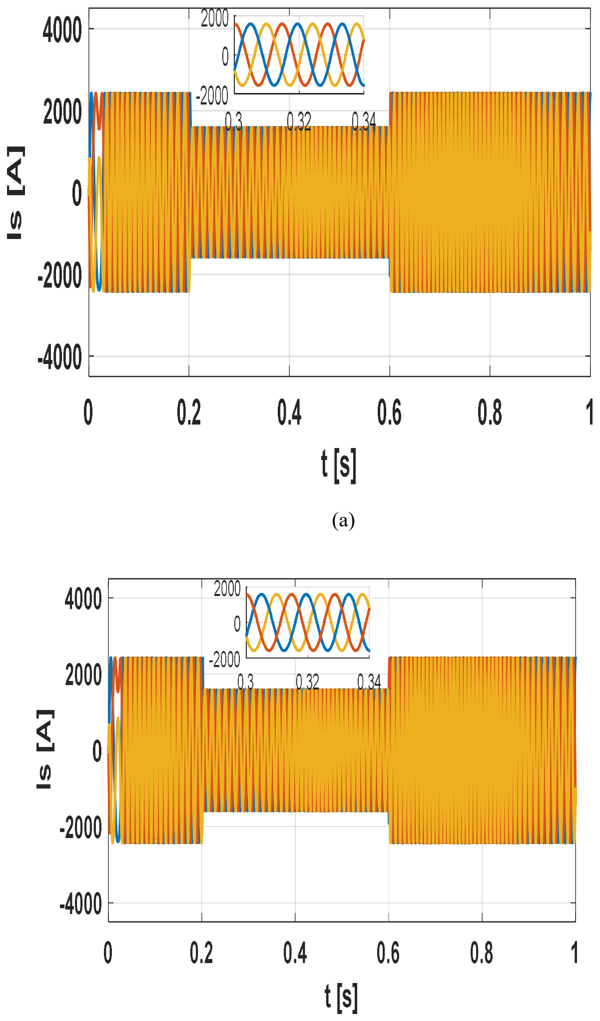


Fig.9. Electromagnetic torque of DFIG.



(a)

(b)

Fig.10. The stator current of DFIG: (a) PI-GWO, (b) PI.

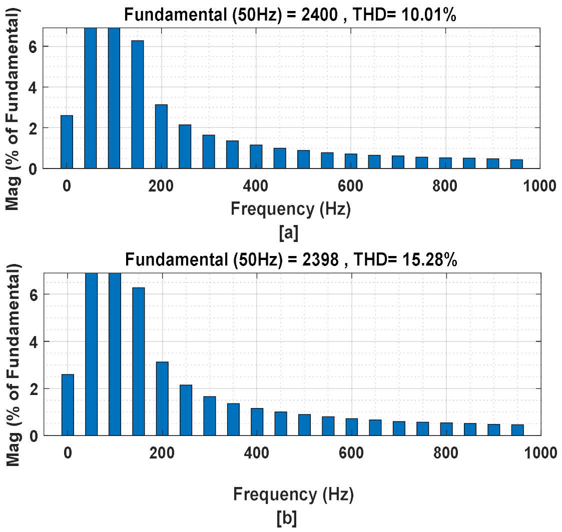


Fig.11. Spectrum harmonic of stator current: (a) PI-GWO, (b) PI.

A random wind speed is illustrated in Fig. 6. Successively, Fig.7, Fig.8, and Fig.9 present the stator active power, the stator reactive power, and the electromagnetic torque controlled by PI tuning manually and using GWO.

As we can see, in Fig.7 at 0.202s the zoom clearly shows the difference overshoot and rising time between manually tuning the PI controller and using GWO.

Besides, the zoom in Fig.8 and Fig.9 the comparison shows that using GWO greatly reduced the ripple of both the reactive powers as well as the electromagnetic torque.

Fig.10 illustrated the three phases of the stator currents without and with GWO respectively.

In Fig.11 the spectrum harmonic of stator current for two control is presented. In PI tuning manually has a high (THD =15.28%) as compared to the PI tuning by GWO with (THD=10.01%).

The ISE criteria have been shown in Table 2. It can be seen the PI tuning by GWO show better cost function, which means that the GWO algorithm gives the best optimum parameters (Kp = 1200 and Ki=1.052e+03) compared to the conventional PI.

From the results obtained the control system that we proposed presents a good response and better reference tracking.

Table.2. Comparison between PI and PI-GWO.

Parameters	PI	PI-GWO
ISE	1.737e+10	1.543e+09
Kp	0.5	1200
Ki	75	1.052e+03

VI. CONCLUSION

The field-oriented control (FOC) method is a solution for the doubly fed induction generator (DFIG) in order to provide good control.

To ensure the best quality of energy supplied to the grid an optimal PI controllers design of a DFIG using the Grey Wolf Optimization is presented. The conventional PI controller results are compared to that obtained by (GWO) using ISE as fitness to explain the qualities of each one.

The results show that the proposed design method works well to find the best optimal parameters for the PI controllers and improves the wind turbine generator system's performance in a wide range of operating conditions.

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