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Optimal Energy Harvesting of Large-Scale Wind Farm Using Marine Predators Algorithm

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ABSTRACT A new optimal control strategy for the grid side converter (GSC) and rotor side converter (RSC) of a doubly-fed induction generator (DFIG) is developed in this paper using the Marine Predators algorithm (MPA). To accomplish this study, a comprehensive comparison between the suggested MPA-based control strategy and a well matured Particle Swarm Optimizer (PSO) to enhance transient stability of large-scale wind systems has been presented. MPA is used to determine the optimal gains of proportional-integral (PI) controllers for GSC and RSC to ensure a maximum power point tracking (MPPT) of a large-scale wind farm. The proposed optimal control strategy is analyzed and verified via a benchmark 9-MW DFIG wind farm using MATLAB/SIMULINK simulation. The attained results of the suggested MPA-PI-based controllers are compared to the conventional PI-based MPPT controllers to validate the efficacy of the developed optimal control strategy. The superiority of the proposed MPA-PI and PSO-PI-based optimal controllers over the traditional PI regulators towards enhancing the DFIG system dynamic performance has been proved. The presented MPA-PI-based control scheme has been succeeded in extracting the maximum power of the DFIG wind farm with a reduced settling time of about 1.8% and overshooting range 97% lower than the conventional controller.

INDEX TERMS Doubly fed induction generator, grid side converter, marine predators algorithm, maximum power point tracking, particle swarm optimization, wind plant's performance.

I. INTRODUCTION

The issue of energy resources is no longer a matter of interest only to academics, specialists but also economic and political decision-makers. Nevertheless, these frameworks become the subject of everyone's attention, regardless of their job positions or social lifestyles. All the people over the world, as individuals, become concerned about the future of energy resources in their areas of presence in particular and in the world in general. Energy no longer only affects the level of their daily well-being but also the way they conduct their lives. Still, it also takes on more comprehensive importance related to the crucial issues of different societies [1].

Wind energy is one of the types of renewable energy that had been widely used as an alternative to fossil fuels. It is abundant, renewable and clean that does not produce emissions such as greenhouse gases during its operation [2]–[5]. With the rapid growth of the supplied wind energy at an average rate of 30% in the past few years, providing wind to represent 17% of the world's energy in 2020. Wind energy had created 2 million jobs and saved more than 10,700 million tons of carbon dioxide emissions [6]. Thanks to continuous improvements in the size and capacity of conventional turbines, the cost of wind energy in well-placed locations is expected to decline in 2022, by 45.3-euro cents per kilowatt-hour, 36% less than its cost in 2003, which was 79.3 euro cents / kWh [7]. The wind resources in the world are extensive and well distributed in all regions and countries. With the use of current technology, wind energy can provide about 53,000 TWh per year. It is two times more than the projected world demand for energy in 2022, leaving significant room for growth in maintenance even decades from now [8]. The United States alone has enough wind to cover three times more than its energy needs [9], [10].

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One of the most critical points to consider when designing a wind turbine is to work at its maximum energy conversion output. Therefore, most researchers in wind energy tended to search for improving the efficiency of turbines to work at their maximum energy [11]. The main condition for generating electricity using wind energy is to produce an AC signal with a constant frequency regardless of the wind speed. In other words, the frequency of the alternating current signal generated through the stator must be constant regardless the changes of rotor speed. For this purpose, the frequency of the alternating current signal applied to the rotor coils must be modified. With the increasing spread of wind energy, wind farms have significantly affected the stability of the energy system. There are different types of wind turbines as a result of the development of technology for wind energy. The wind turbines can be either constant or variable speed generators according to their applications [12]. As a result of the features of wind turbines with Doubly-Fed Induction Generators (DFIG) such as flexible control, active and reactive power capabilities, and relatively high Efficiency, most wind farms use a variable speed wind turbine with DFIG [13], [14]. As its name suggests, a DFIG is a three-phase induction generator in which both the rotor and stator windings are fed a three-phase AC signal. It consists of multi-phase coils placed on both the rotor body and the stator. It also consists of a multi-phase slip ring assembly to transmit power to the rotor. It is commonly used to generate electricity in wind turbine generators [15]. For large-scale wind generation systems, the DFIGs have been widely used due to their advantages. In the last few years, the operation and control of DFIG have become one of the most critical research points addressed by researchers worldwide [16].

The control structures of conventional DFIG consist of two Proportional Integral (PI) rotor current controllers with machine parameter-dependent compensating terms and stator flux orientation. Due to the advantages of PI controller such as stability, simple structure, no steady-state error and often robust appearance, it is the most controller used for achieving dynamic performance control solution of the active and reactive power for the DFIG [17], [18].

However, the success of any controller depends on the appropriate choice of the controller parameters. The controller's gains of the conventional PI controller are calculated by the traditional trial and error method. For nonlinear systems, the use of traditional trial and error method to optimize the system's performance is time-consuming and almost cumbersome [19]. In the last few years, researchers had turned to use of the recent intelligent optimization algorithms for tuning of controller gains such as Genetic Algorithms (GAs), Moth-Flame Optimization (MFO), Whale Optimization Algorithm (WOA), Particle Swarm Optimization (PSO) and Grey Wolf Optimizer (GWO) [20]–[28].

To satisfy the required criteria in active and reactive output powers of the DFIG, there are many different performance indices such as Integration of the Time Weighted Square Error (ITWSE), Integration of the Time Weighted Absolute Error (ITWAE), the Integration of the Absolute Error (IAE) and Integration of the Square Error (ISE). The four performance indices had been elaborated in the presented article and the best of the best of them had been selected.

The major contributions of this paper can be summarized as follow:

- Developing a new optimal control strategy for the grid side converter (GSC) and rotor side converter (RSC) of a DFIG using Marine Predators algorithm (MPA) is conducted.
- A comprehensive comparison between the suggested MPA and a well matured Particle Swarm Optimizer (PSO) to enhance transient stability of large-scale wind systems is performed.
- MPA is employed to determine the optimal gains of proportional-integral (PI) controllers for GSC and RSC to ensure a maximum power point tracking (MPPT) of a large-scale wind farm.
- The proposed optimal control strategy is analyzed and verified via a benchmark 9-MW DFIG wind farm using MATLAB^{TM}/SIMULINK simulation.
- The attained results of the suggested MPA-PI-based controllers are compared to the conventional PI-based MPPT controllers to validate the efficacy of the developed optimal control strategy.

The remainder of the paper is organized as follows: Section I offers the introduction and literature survey. Also, Section II describes the plant dynamic model. Section III discusses and analyses doubly-fed induction generator control. Further, Section IV discusses how to achieve optimal gains of PI controller using PSO algorithm. Besides, the Marine Predator Algorithm (MPA) is explained in section V. Moreover, components of the wind farm simulation framework are presented in Section VI. Also, the simulation results and discussion and the comparative statistical analysis are displayed in Section VII. Lastly, the conclusions are established in Section VIII.

II. PLANT DYNAMIC MODEL

In 1919, physicist Albert Betz showed that for a hypothetical ideal wind energy extraction machine, the fundamental laws of conservation of mass and energy allow no more than 16/27 (59.3%) of the kinetic energy of the wind. This Betz's law limit can be approached with modern turbine designs that can be as high as 70-80% of this theoretical limit. In addition to the aerodynamic design of the blades, the design of the complete wind power system should also address the design of the axle, controls, generator, supporting structure and foundation as shown in fig.1 [29].

This study presents a simplified schematic diagram of the wind energy conversion system with a double-fed induction generator as shown in fig.1. As shown in this diagram, the wind turbine produces mechanical energy which is transferred to a double-fed induction generator through a gearbox. The stator winding of the DFIG is directly connected to the grid, whereas the back-to-back Pulse Width Modulation (PWM) converter feeds the rotor winding. The

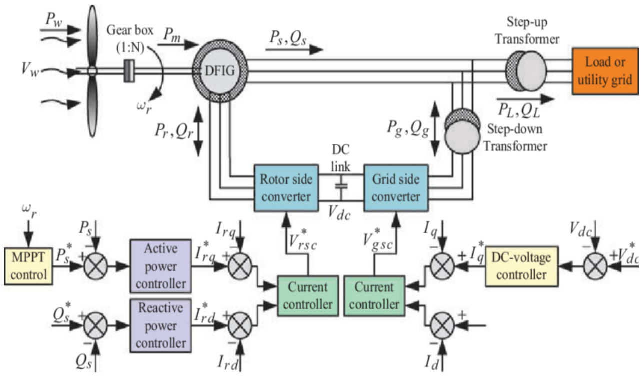


FIGURE 1. Block diagram of the test system.

grid side converter is connected to the grid via three chokes to improve the current harmonic distortion. The power flow from the DFIG to the grid is controlled by a rotor side converter. More design questions arise when wind turbines are integrated into electric power grids. The turbine output power is given by the following Equation [30], [31].

$$P_v = \frac{1}{2}\rho S_w v^3 \tag{1}$$

where ρ is air density (kg/m^3); S_w is wind turbine blades swept the area in the wind (m^2); v is wind speed (m/s).

The output mechanical power of a wind turbine is:

$$P_m = C_p P_v = \frac{1}{2}\rho S_w v^3 \times C_p(\lambda, \beta) \tag{2}$$

where C_p represents the power coefficient. It is a function of the Tip Speed Ratio (TSR) "(λ)" and the blade pitch angle (β) in a pitch-controlled wind turbine. λ is defined as the ratio of the tip speed of the turbine blades to wind speed:

$$\lambda = \frac{\omega_t.R}{v}(3) \tag{3}$$

where R is blade radius (m), ω_t is the angular speed of the turbine (rad/s).

A generic Equation is used to model C_p (λ, β) as follow:

$$C_p(\lambda, \beta) = C_1 (C_2/\lambda_i - C_3 \times \beta - C_4)\, e^{-C_5/\lambda_i} + C_6\lambda \tag{4}$$

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

The induction generator stator and rotor differential equations can be expressed as follow [32]:

$$v_{sabc} = R_s i_{sabc} + \frac{d\Psi_{sabc}}{dt} \tag{6}$$

$$v_{rabc} = R_r i_{rabc} + \frac{d\Psi_{rabc}}{dt} \tag{7}$$

Applying synchronous reference frame transformation rotating by angular speed to the above equations, the differential equations of DFIG in dq-axis are:

$$v_{ds} = -\omega_s \Psi_{qs} + \frac{d\Psi_{ds}}{dt} \tag{8}$$

$$v_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\Psi_{qr} + \frac{d\Psi_{dr}}{dt} \tag{9}$$

$$v_{qr} = R_r i_{qr} - (\omega_s - \omega_r)\Psi_{dr} + \frac{d\Psi_{qr}}{dt} \tag{10}$$

$$v_{qs} = R_s i_{qs} + \omega_s \Psi_{ds} + \frac{d\Psi_{qs}}{dt} \tag{11}$$

$$\Psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \tag{12}$$

$$\Psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \tag{13}$$

$$\Psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds} \tag{14}$$

$$\Psi_{qr} = L_{lr} i_{dr} + L_m (i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs} \tag{15}$$

where the stator L_s and the rotor L_r inductances are defined as:

$$\begin{cases} L_s = L_{ls} + L_m \\ L_r = L_{lr} + L_m \end{cases} \tag{16}$$

In which L_m is the mutual inductance and L_{ls} and L_{lr} are the stator and rotor leakage inductance.

Neglecting the stator and rotor power losses, the active and reactive power are:

$$\begin{cases} P_s = \frac{3}{2}\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right) \\ Q_s = \frac{3}{2}\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right) \end{cases} \tag{17}$$

$$\begin{cases} P_r = \frac{3}{2}\left(v_{dr} i_{dr} + v_{qr} i_{qr}\right) \\ Q_r = \frac{3}{2}\left(v_{qr} i_{dr} - v_{dr} i_{qr}\right) \end{cases} \tag{18}$$

The torque in d-q axis is given by:

$$T_e = \Psi_{ds} i_{qs} - \Psi_{qs} i_{ds} = \Psi_{qr} i_{dr} - \Psi_{dr} i_{qr} = L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \tag{19}$$

where T_e is the electromagnetic torque developed by the induction generator.

III. DOUBLY FED INDUCTION GENERATOR

To achieve maximum wind output power, the control system of a wind turbine with a doubly fed induction generator must be designed to regulate the rotor speed. Various studies had been conducted to separate the control of active and reactive powers. The vector control is the most efficient technique for decoupled control of active and reactive powers. There are different types of controllers used for the vector control scheme for the control of active and reactive powers like fuzzy logic controller and the conventional PI controller [33]–[35]. In industrial applications and electrical power, the conventional PI controller is the most controllers used due to its simplicity. This study presents a modified PI controller to ensure a maximum power point tracking (MPPT) of wind energy for large scale wind farms.

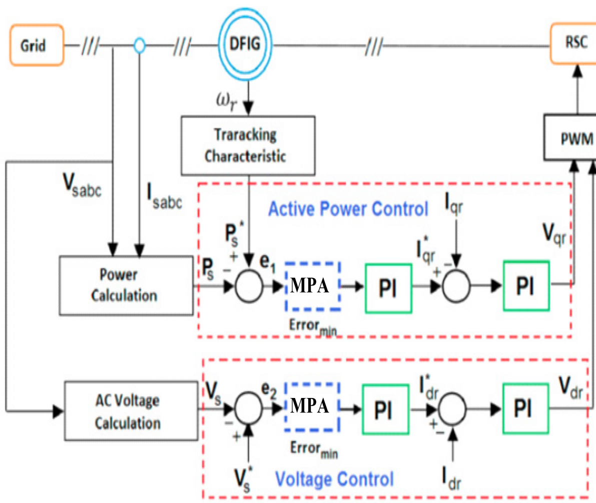


FIGURE 2. Rotor side control of DFIG.

A. ROTOR SIDE CONVERTER CONTROL

The control method for the rotor side converter of the doubly fed induction generator (RSC-DFIG) plays a very important role in the maximum power point tracking (MPPT) operating mode. The most common control strategies on rotor side converter are voltage-oriented control (VOC), flux-oriented control (FOC), direct power control (DPC) and direct torque control (DTC). In this study to control the stator terminal voltage and active power, the vector control is applied to the rotor side converter. The q-axis loop is used for controlling the active power and the d-axis loop for the stator terminal voltage control. Fig. 2 shows the overall vector control scheme of the rotor side converter for a DFIG. By controlling the rotor current I_{rabc}, the stator voltage V_s and active power P_s of DFIG will be controlled, the rotor current I_{rabc} is transferred to I_{dr} and I_{qr} [31].

B. GRID SIDE CONVERTER CONTROL

The main contribution of the grid side converter control is to compensate harmonics and regulate the voltage of DC bus capacitor. At the stator, the grid side converter is directly connected to the grid. The main role of the grid side converter is to maintain the DC-link voltage as a constant value. As shown in figure (3), the voltage signal V_{dc} is compared to its reference signal V_{dc}^* [31]. The proportional-integral (PI) controller uses error signal from inputs to generate the reference current I_{dq}^*. The current regulator controls the magnitude and phase of the voltage generated by GSC (V_g) from the I_{dq}^* reference produced by the DC voltage regulator and specified I_{qg}^* reference.

IV. MODELING OF THE PSO-PI CONTROLLER

Particle swarm optimization (PSO) is a different type of optimization algorithms that depends on the population in which individuals called particles to change their location (state) over time. Particles in PSO system fly in multidimensional

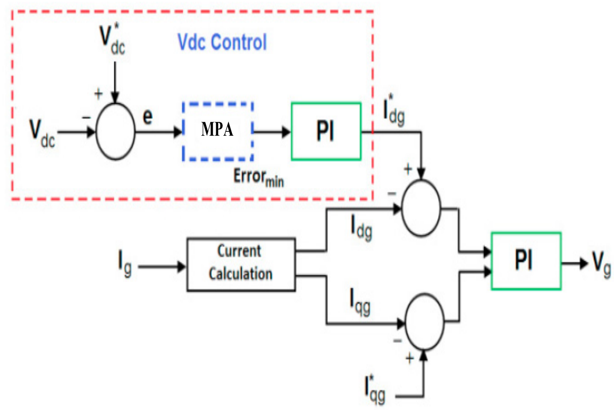


FIGURE 3. Grid r side control of DFIG.

search space. In a PSO system, each particle during a flight changes its location according to its previous experience (This value is called P_{best}), and also change its location according to the experience of a neighboring particle (This value is called G_{best}). This modification made by the particles can be represented by the concept of velocity so that the speed of each particle can be modified by the following equation [36]:

$$V^{k+1} = w.V^k + C_1.rand.\left(P_{best} - X^k\right) + C_2.rand.\left(G_{best} - X^k\right) \quad (20)$$

Depending on the previous equation, the velocity of particles can be calculated from P_{best} and G_{best}. The following equation describes how the current location (searching point in the solution space) is modified.

$$X^{k+1} = X^k + V^{k+1}k = 1, 2, \ldots.., n \quad (21)$$

where X^k is the current searching point, X^{k+1} is the modified searching point, V^k is the current velocity, V^{k+1} is the modified velocity. P_{best} is the best solution observed by current particle and G_{best} is the best solution of all particles, w is an inertia weight, C_1 and C_2 are two positive constants, rand is a random generated number with a range of [0-2].

As shown in Fig. 4, PSO is a technique used to find the global maximum value of the objective function. There are many types of controllers used in the control of the electrical machines, but the PI controller is the most controller used in this field due to its advantages. The main problem in any plant can be summarized in that the mathematical model must be known. So, to solve this problem, many optimization algorithms are introduced to get optimum parameters of PI controller.

In this study, a new technique based on PSO is designed to optimize the parameters of PI controller. Based on quadrature rotor current error I_{rq} linked to active power P_s and direct rotor current I_{rd} linked to reactive power Q_s of the DFIG, PSO is used to optimize the parameters of the active and reactive powers PI controllers.

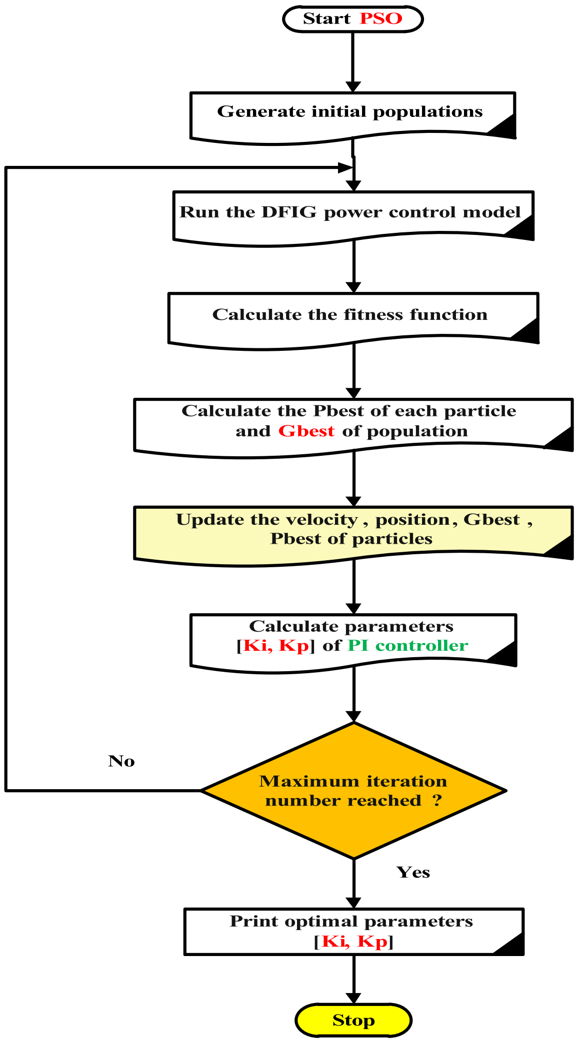


FIGURE 4. The flowchart of the PSO–PI control system.

V. MARINE PREDATORS ALGORITHM

The Marine Predator Algorithm (MPA) is one of the most important optimization methods that depend mainly on the surrounding environment. It is mainly based on the rules used in the optimal search to achieve foraging justice between prey and predators in marine systems. The basic strategy of the idea of marine reserves is to work with the principle of widespread research, which represents the movements of Levy and Brownian in the marine oceans that take place among predators. It also depends on the optimal confrontation policy between prey and predator. Like most optimization techniques, the MPA method depends mainly on the population in the marine oceans, where the first solution is chosen and distributed fairly over the research area as the first experiment [37].

$$X_0 = X_{min} + \text{rand}\,(X_{max} - X_{min}) \tag{22}$$

where X_{min} and X_{max} are the lower and upper bound for variables and rand is a uniform random vector in the range of 0 to 1.

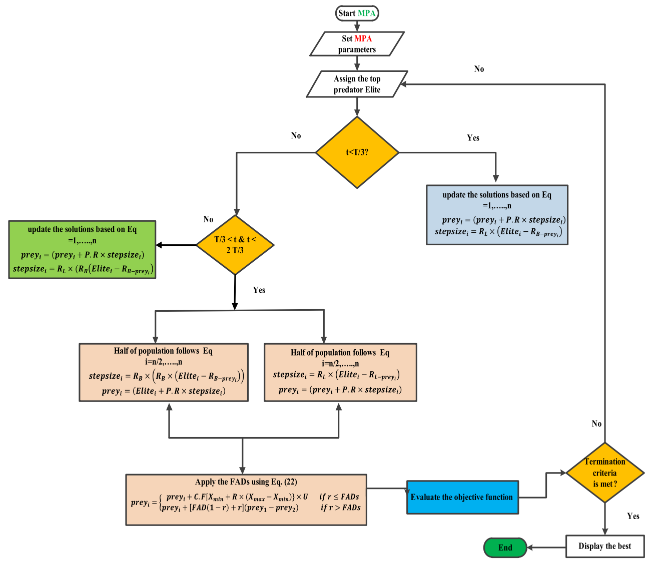


FIGURE 5. The flowchart of the MPA algorithm.

Based on the theory inspired by nature, the oldest predators in nature are more talented and intelligent in the search for prey. Therefore, the optimal solution is nominated as the best predator to build a system called the elite. The flowchart of MPA algorithm is shown in fig.5.

The performance of the DFIG varies according to PI controller gains and is judged by the value of integral time absolute error (ITAE). The performance index (ITAE) is chosen as an objective function. The purpose of stochastic algorithms is to minimize the objective function. All particles of the population are decoded for k_p and k_i. ITAE criterion is widely adopted to evaluate the dynamic performance of the control system. The index ITAE is expressed in Eq. (23), as follows:

$$\text{ITAE} = \int_0^\infty t.\, \|e\,(t)\| \tag{23}$$

In this paper, a time-domain criterion is used for evaluating the PI controller. The performance criteria is used for comparison between using a PI controller which is tuned by MPA and PSO techniques and trial and error approach. PI controller includes integration absolute error (IAE) and integrated of squared error (ISE).

$$\text{ITAE} = \int_0^\infty \|e\,(t)\|\,. \tag{24}$$

$$\text{ISE} = \int_0^\infty e^2. \tag{25}$$

VI. OPTIMIZATION FRAMEWORK OF THE CASE UNDERSTUDY

This section describes the components of the wind farm simulation framework. The simulation framework integrates simulation tools from different vendors. Moreover, the developed simulation framework provides a complete test bench for wind farm design and system parameters optimization.

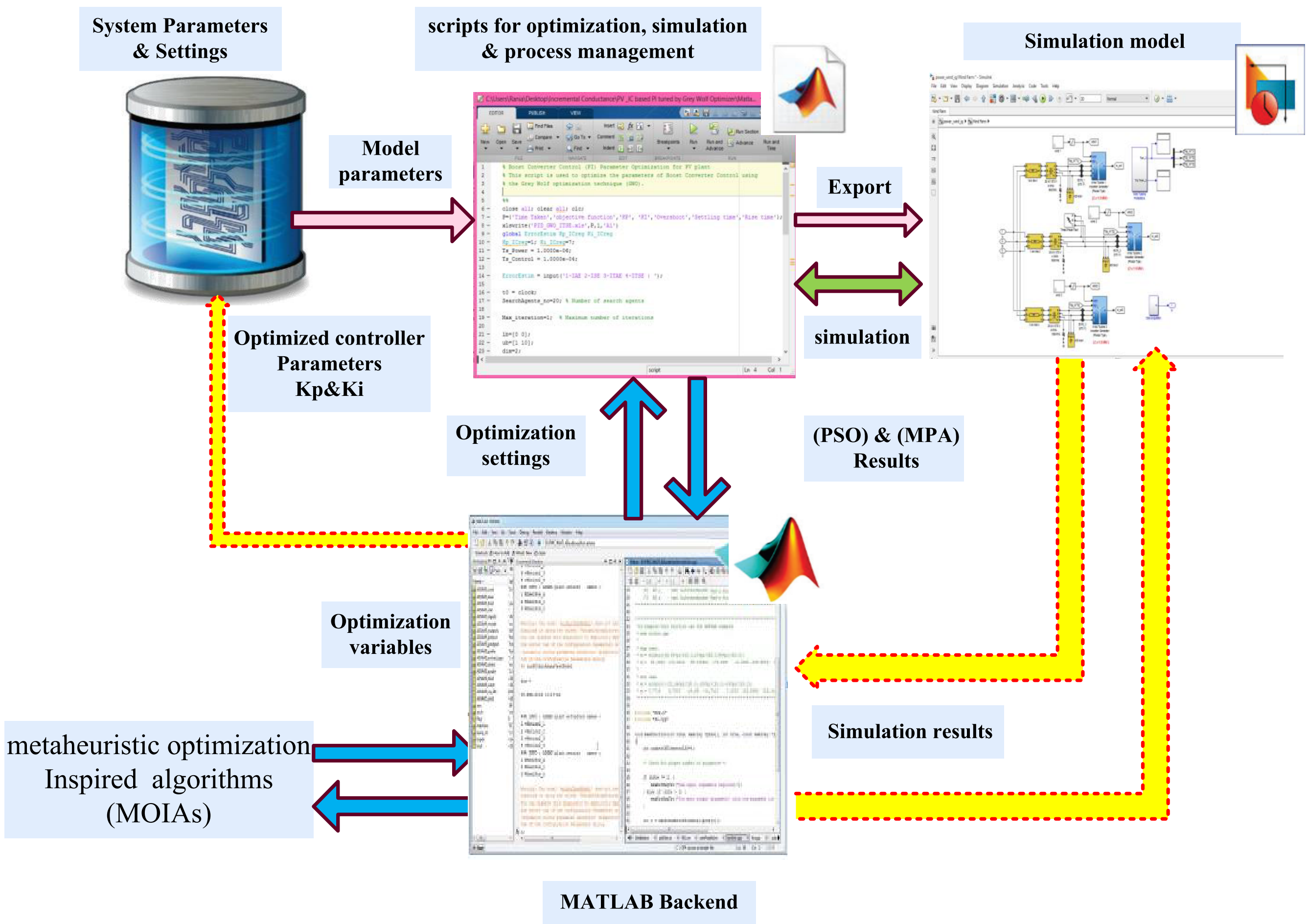


FIGURE 6. A simulation framework for wind farms using MPA and PSO.

Also, in this simulation package, the parameters of different components of a wind farm can be optimally attained. Shortly and after the real operation of the wind farm, the experimental results from the actual site can be compared with the simulation model to verify the advantages of this optimization framework. The optimization operation and construction of the wind farm simulation model are shown in Fig. 6. MPA and PSO techniques are running with 50 search agents and 100 maximum numbers of iterations which is sufficient for this problem with a large number of variables to prevent failures. To speed up the optimization process of the wind farm simulation model, upper and lower limits should be set according to controller type which is two gains k_p and k_i for PI controller. MPA and PSO are run on our wind farm simulation model according to the options above. Then, the best error type among IAE, ISE, ITAE and ITSE is selected to achieve the best results.

VII. SIMULATION RESULTS OF OUR SYSTEM

The main contribution of this study is enhancing the dynamic behavior of DFIG-based wind turbines. The control strategies based on MPA and PSO have been applied on 9-MW DFIG wind turbines. Both MPA-PI and PSO-PI controllers' simulation analyses are compared to the conventional PI controller. For the same operation condition, MPA and PSO algorithms are used for attaining the optimal controller gains for the grid side converter and rotor side converter.

To compare the rotor speed and power responses of the MPA and PSO-based MPPT method and the conventional MPPT method for variable wind speed conditions, a ramp change is applied to the wind speed during the simulation according to Fig. 7. Except for different MPPT methods, all of the other parameters of the DFIG control system are identical for the same control mode.

The simulation is carried out using the MATLAB /Simulink software. The controller parameters of the system can be divided in this test into, six proportional-integral gains for RSC controller namely, ($K_p\_V_{reg}$, $K_i\_V_{reg}$) that express the controller gains of the voltage regulator and ($K_p\_P_{reg}$, $K_i\_P_{reg}$) that express the controller gains of power regulator and ($K_p\_I_{reg}$, $K_i\_I_{reg}$) that express the controller gains of rotor currents as shown in table 1.

TABLE 1. Proposed controllers gains (MPA&PSO).

Controller	Voltage Regulator $K_p\_V_{reg}$ $K_i\_V_{reg}$	Current Regulator $K_p\_I_{reg}$ $K_i\_I_{reg}$	Power Regulator $K_p\_P_{reg}$ $K_i\_P_{reg}$	Overshoot (%)	Settling time (s)	Rise time (s)
PI				7.04	19.45	19.33
K_p	1.25	0.3	1			
K_i	300	8	100			
PSO_PI				6.03	19.36	19.21
K_p	0.57	0.61	1.58			
K_i	146.5	6.80	132.1			
MPA_PI				0.19	19.10	9.12
K_p	1.41	0.76	9.42			
K_i	275.8	12.28	166.2			

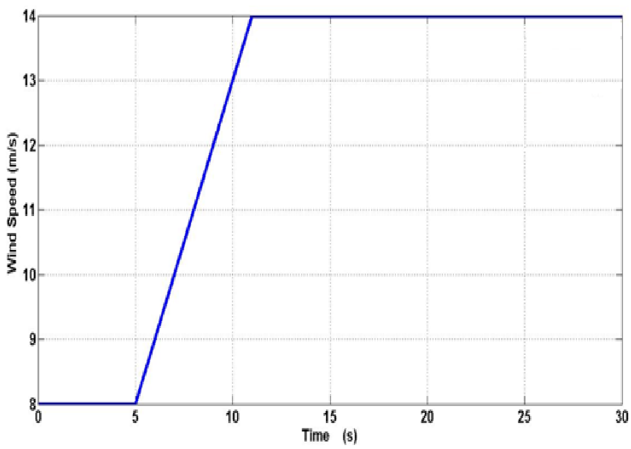


FIGURE 7. Wind speed.

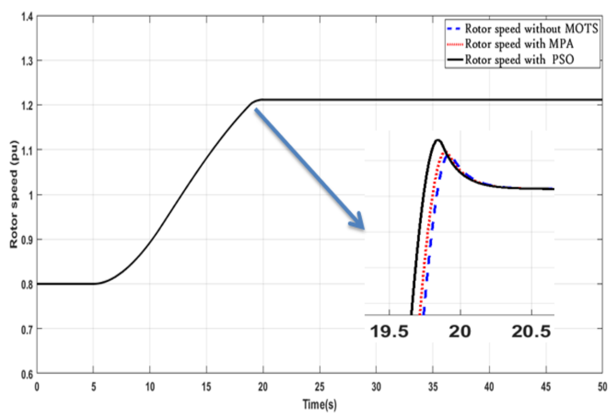


FIGURE 8. Dynamic performance of the rotor speed.

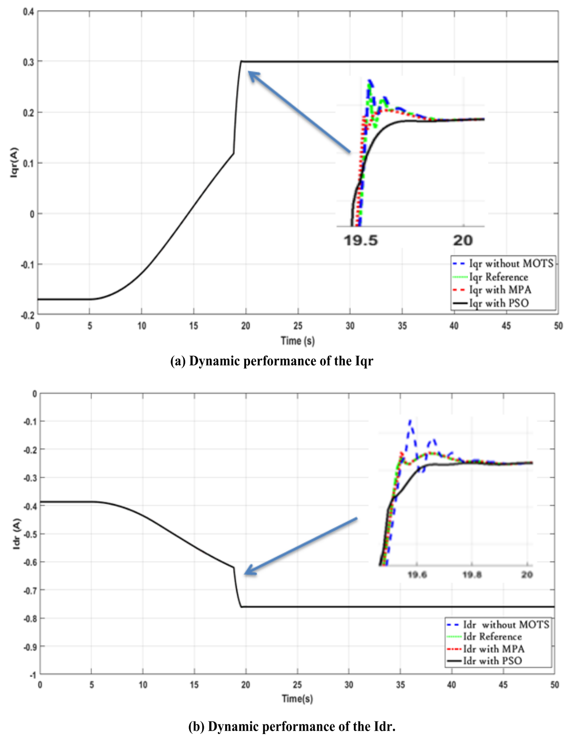
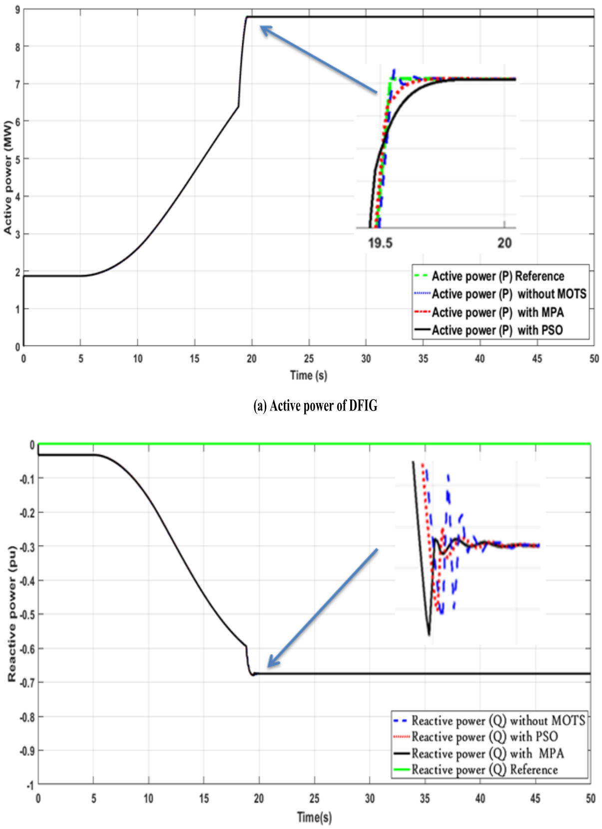


FIGURE 9. Dynamic performance of the Iqr and Idr.

The rotor speed responds much faster when using the MPA-based MPPT control. As shown in Fig. 8, the rotor speed of the DFIG using the MPA-based MPPT settles down to the steady-state with settling time of (19,0002 s) within about 20s during wind speed variations, which is much shorter than that of the turbine power profile-based MPPT.

Fig.9 shows the DFIG rotor current time responses for MPA-PI and PSO-PI, respectively. The rotor current with MPA-PI controller is smooth compared to that of PSO-PI and conventional PI controller. Moreover, the over-current in the rotor circuit is reduced when using MPA-PI as shown in Fig. 8. In this study, a comparison is done with the results obtained from the conventional PI controller, which also aims at active and reactive power ripple minimization. The results of the comparison are that the active and reactive powers' ripples are reduced considerably with the MPA-PI compared to that of PSO-PI and conventional PI controller



(a) Active power of DFIG

(b) Reactive power of DFIG

FIGURE 10. Active power (P) and reactive power generation (Q).

as shown in Fig. 10 (a, b). The dynamic performance of the reactive power of DFIG is shown in the Fig.10 (b). At t = 5 second, It can be noted that the reactive power is absorbed by the rotor circuit. In the normal case the reactive power is adjusted to zero, which means that the grid-side converter operates at unity power factor. Rise time, settling time and maximum overshoot are basic tools used in this comparative analysis. The MPA-PI has better dynamic performance than PSO-PI and conventional PI controllers as shown from the results presented in Table 1. The MPA-PI has better dynamic performance in terms of time domain specifications as follow: MPA-PI ranks the first shorter rise time (19.12 s), lower percentage overshoot with (0.19%) and shorter settling time with (19.10 s) whereas PSO-PI ranks the second shorter rise time (19.21 s) and conventional PI comes in the third rank with rise time of (19.33 s).

VIII. CONCLUSION

The suggested optimal control scheme for DFIG-based wind farms had been developed using Marine Predators Algorithm (MPA). Moreover, the proposed MPA-based control scheme was equipped to a benchmark 9-MW doubly fed induction generator wind farm to validate its efficacy. The attained results proved the superiority of MPA in seeking the global optimum PI parameters concerning the desired performance indices while respecting the subjected constraints compared to the conventional control strategies. The MPA-PI-based controllers' results had been compared to those obtained by the PSO algorithm to differentiate the merits of each one. Both MPA and PSO were successfully used for optimizing the control parameters of the rotor side as well as grid side converters to ensure maximum energy harvesting with the enhanced dynamic performance of the DFIG wind farm under variable speed conditions. The simulation results showed that the MPA-PI-based controllers were more efficient than the PSO in extracting maximum energy from wind in addition to enhancing the dynamic response of the overall system in terms of reduced settling time as well as overshoot about 97% and 1.8%, respectively.

TABLE 2. Supplementary data for the applicable turbine.

Turbine data for one turbine	
Nominal mechanical output power (MW)	*1.5*
Wind speed at nominal speed (m/sec)	*11*
Initial wind speed (m/sec)	*11*
Drive Train data for one turbine	
Wind turbine inertia constant H (s)	*4.32*
Shaft spring constant refers to high-speed shaft (pu of nominal mechanical torque/rad)	*1.11*
Shaft mutual damping (pu of nominal mechanical torque/pu dw)	*1.5*
Turbine initial speed (pu of nominal speed)	*1.2*
Initial output torque (pu of nominal mechanical torque)	*0.83*
Generator data for one turbine	
Nominal power (MVA)	*1.5/0.9575*
Line-Line Voltage (R.M.S)	*1975*
Frequency (Hz)	*50*
Stator resistance (pu)	*0.023*
Stator inductance (pu)	*0.18*
Rotor resistance (pu)	*0.016*
Rotor inductance (pu)	*0.16*
Mutual inductance (pu)	*2.9*
Inertia constant -H(S)	*0.685*
friction factor (pu)	*0.01*
pairs of poles (pole)	*3*

APPENDIX AND SUPPLEMENTARY DATA

See Table 2.

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