Optimization of doubly-fed induction generator (DFIG) based wind turbine to achieve maximum power generation with imperialist competitive algorithm (ICA)

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Abstract
Today, due to the end of fossil fuels and efforts to reduce the use of renewable resources, wind energy is a suitable option for the production of electrical energy due to its high-power generation. To increase the output efficiency of wind turbines, maximum power point tracking techniques are required for wind turbine energy conversion systems. In this research, the maximum...
A power point (MPPT) method for two-way fed wind turbine systems (DFIG) is presented. The performance of the induction generator is presented on both sides of the power and the values of this generator such as speed, torque, voltage, current, and maximum power at the time of wind speed changes. The presented work is presented in two scenarios and the model is performed without the algorithm then, a maximum power point tracking method based on the Colonial Competition Algorithm (ICA) has been applied to estimate the power of the two power induction generators. According to the results, it can be said that in the scenario with the algorithm of generating electric power by the turbine, several times in the production state is 9 MW, which is the rate of the turbine’s nominal power, while in another scenario, the power generated by the turbine is 85% of the power in the state with the algorithm.

**Keywords**
DFIG, maximum power point, imperialist competitive algorithm, optimization

**Introduction**
Sustainable energy supply is one of the most basic prerequisites for a country’s development, and the electricity consumption of any country is one of the most important indicators of development. The lack of electricity networks in remote areas and the high cost of connecting these areas to the national grid due to unfavorable geographical conditions doubles the need to use other energy sources such as off-grid renewable energy systems. The advancement of renewable energy technology over the past few years has led to a reduction in the cost of electricity generated in the world, and with the increase in profit margins, the growth of this industry has accelerated. Wind farms are one of the most important sources of electricity from renewable energy sources. The development of renewable energy in the world shows that these resources have gone beyond the laboratory scale and have expanded on an industrial scale, so wind farms must be a priority for the development of renewable energy in the country.

Control methods for optimizing energy absorption and reducing loads in components under turbulent wind conditions have been extensively studied in recent years. Related research activities were divided into three groups: modeling and dynamics of wind turbines, active control of wind turbines, and passive control of wind turbines. Given the dynamics of the turbine, they discussed physical principles. Advanced control of FACTS devices to improve power quality concerning wind farms is discussed. Olamaei et al. provide a method for errors and failure detection based on fuzzy clustering and distance. Both methods are created in a real wind farm for critical equipment commonly found in wind turbines. A power curve is modeled using fuzzy clustering and parametric fitting methods. Rashad et al., in this research, the performance of squirrel-cage induction generator (SCIG) wind farm, DFIG wind farm, and a combined wind farm during a three-phase network fault is investigated. SCIG and DFIG wind farms are equipped with series controllers. The main advantage of both types of generators, in particular, SCIG is less costly, but its disadvantage is its negative impact on system stability. In other research on the importance of using STATCOM and capacitive banks in the wind farm at constant speeds to improve the quality of network power, they suggested. Since the voltage drop across the bus depends on the share of the reactive power network, they tested the effect of injecting or absorbing reactive power into the network using...
STATCOM and a capacitive bank. Mali et al., studied the network voltage drop in wind turbines with power devices. In the presence of mains voltage drop, there was a mismatch between the power generated and the power delivered to the network in the research, reliability models for DFIGs have been performed by considering topology change under different control strategies and changing data components under adverse operating environments. Bin et al., a new damping control strategy offer to reduce sub-synchronous resonance (SSR) fluctuations in adjacent turbine generators. In the proposed control strategy, SSR attenuation is achieved by increasing the turbine generator speed as a complementary signal in the active power loop of the rotor side converter (RSC) from wind farms based on a dual feed induction generator (DFIG). Verdejo et al., and Afzalan et al., the simultaneous design analysis of STATCOM and power system stabilizer (PSS)-based damping stabilizers in a multi-machine power system using the Search Engine Optimization Algorithm (SOA) is proposed. SOA is used to achieve the best optimal results to minimize the objective function of the optimization problem. Tayal et al., to reduce small signal fluctuations, uses a wide range of fuzzy power system controller (PSC) thyristor-controlled series capacitor (TCSC) controllers to reduce small signal fluctuations.

In this research, a DFIG wind turbine will be used. The grid side converter is used to keep the DC link voltage constant and to obtain the unity power factor on the grid side and the generator side converter is used to transfer the power obtained from the turbine to the grid. The way this converter is connected to the network is different in each generator, In the DFIG, the stator is directly connected to the network, and the rotor is connected to the network through a converter. The DC / DC converter is used to compensate for the output voltage of the wind turbine to keep the voltage constant at the maximum output power. The proposed algorithm measures the maximum power point, voltage, and current at the turbine output and delivers it to the converter. The output voltage characteristics of the wind turbine generator and its output current are determined based on the amount of wind speed, optimal air density, and electrical characteristics of the load.

As a result, maximum power point tracking technologies must be provided in maximum power point control applications to force wind turbine generators to have optimal efficiency of wind energy in different operating conditions. In this research, modeling has been designed and implemented to get the maximum power point in the MATLAB software environment. Most of the recent work in this field has been done with common methods such as controllers, in this work the ICA has been used to improve the maximum power of the system.

**Materials and methods**

**Studied system information**

The single line diagram of the system under study is shown in Figure 1. Information on the various equipment used in the MATLAB / SIMULINK model is presented in Table 1. As can be seen, the wind turbine is connected to the 25 kV distribution network. Some of the power generated by the turbine is consumed by the load in the network, ie 500 kW at 575 V bus, and the rest of the output power is transferred to the network. In Table 2 can be seen Network and load specification.
Simulation of the studied system

In this section, for the correct operation of the system with the proposed algorithm, simulation in two different modes under standard conditions and also under variable wind speed conditions is investigated. The wind turbine system simulation model is shown in Figure 2. To show the performance of the proposed model in the software environment, we first run the proposed model structure and then evaluate the proposed model by applying inputs. The results confirm the accuracy of the proposed modeling. Figure 3 shows the wind turbine system.

**Table 1.** Functional specifications of the studied wind turbine.

| Parameter | \( P_{\text{rate}} \) | \( V_{\text{rate}} \) | \( \text{Wind}_{r} \) | \( \text{Wind}_{\text{rate}} \) | \( f \) | \( R_{\text{stator}} \) | \( R_{\text{rotor}} \) | \( L_{\text{stator}} \) | \( L_{\text{rotor}} \) | \( L_{m} \) | \( \text{Pitch angle} \) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| value     | 9 MW            | 575 v           | 1.2 pu          | 12 m/s          | 60 Hz| 0.00706 pu      | 0.005 pu        | 0.171 pu        | 0.156 pu        | 2.9 pu          | 45              |

**Table 2.** Network and load specification.

| DCbus     | 1200 v          |
|-----------|-----------------|
| Network   | 120 kV          |
| Load      | 500 kW          |

**Simulation of the studied system**

In this section, for the correct operation of the system with the proposed algorithm, simulation in two different modes under standard conditions and also under variable wind speed conditions is investigated. The wind turbine system simulation model is shown in Figure 2. To show the performance of the proposed model in the software environment, we first run the proposed model structure and then evaluate the proposed model by applying inputs. The results confirm the accuracy of the proposed modeling. Figure 3 shows the wind turbine system.
Modeling of doubly-fed induction generator based wind turbine (DFIG)

To better understand and design operation control for a wind turbine system with a generator, it is necessary to have information about the dynamic model of the machine to be able to control it. An electric machine model suitable for control system design should preferably be capable of dynamic operation in transient and permanent states. It must also perform well against momentary changes in voltage and current generated by the converter and sent to the machine. One model that has a good performance against
momentary changes in voltage and current and can adequately describe the performance of the machine in transient and permanent states is the use of the synchronous reference frame model.\textsuperscript{26}

Direct-Quadrature-Zero (dq0) transformation for DFIG

Since the rotor and stator windings are symmetrical to each other, the Zero (0) axis of this model can be omitted. Therefore, the expression of rotor and stator voltages in of Direct-Quadrature (dq) axes can be considered according to relations 1, 2, 3, and 4\textsuperscript{27,28}:

\begin{align*}
V_{ds} &= r_s i_{ds} + L_s \frac{di_{ds}}{dt} + L_m \frac{di_{dr}}{dt} - \omega_s L_s i_{qs} - \omega_s L_m i_{qr} \\
V_{qs} &= r_s i_{qs} + L_s \frac{di_{qs}}{dt} + L_m \frac{di_{qr}}{dt} + \omega_s L_s i_{ds} + \omega_s L_m i_{dr} \\
V_{dr} &= r_r i_{dr} + L_m \frac{di_{ds}}{dt} + L_r \frac{di_{dr}}{dt} - (\omega_s - \omega_r) L_m i_{qs} - (\omega_s - \omega_r) L_r i_{qr} \\
V_{qr} &= r_r i_{qr} + L_m \frac{di_{qs}}{dt} + L_r \frac{di_{qr}}{dt} + (\omega_s - \omega_r) L_m i_{ds} + (\omega_s - \omega_r) L_r i_{dr}
\end{align*}

In the above relations, $L_s$, $L_r$, $L_m$ are the leakage inductance of stator, rotor, and magnetic inductance, respectively. $r_r$, $r_s$ are the Rotor and stator resistance, respectively.
\(i_{ds}, i_{dr}, i_{qs}, i_{qr}\), are the Stator and rotor currents of dq axes, respectively. \(\omega_s, \omega_r\), are synchronous speed and rotor speed, respectively. \(V_{ds}, V_{dr}, V_{qs}, V_{qr}\), are the Stator and rotor currents of dq axes, respectively. If we consider the expression to the right of Equation 5 to 8 as the flux and derivative of the stator and rotor fluxes and omit the resistance voltage, the stator and rotor \(d\) axes fluxes can be considered according to Equations 5, 6, 7 and 8, respectively:\(^{29,30}\):

\[
\begin{align*}
\lambda_{ds} &= L_s i_{ds} + L_m i_{dr} \\
\lambda_{qs} &= L_s i_{qs} + L_m i_{qr} \\
\lambda_{dr} &= L_r i_{dr} + L_m i_{ds} \\
\lambda_{qr} &= L_r i_{qr} + L_m i_{qs}
\end{align*}
\]

In the above relations, \(\lambda_{ds}, \lambda_{qs}, \lambda_{dr}, \lambda_{qr}\) are the stator and rotor flux of dq axes, respectively. By ignoring the 0 axis of this model and placing the relation 5 to 8 in relation 1 to 4, the relations 9, 10, 11 and 12 can be obtained\(^{13,14,28,31}\):

\[
\begin{align*}
V_{ds} &= r_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \\
V_{qs} &= r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \\
V_{dr} &= r_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_s - \omega_r) \lambda_{qr} \\
V_{qr} &= r_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_s - \omega_r) \lambda_{dr}
\end{align*}
\]

Relationships 5 to 12 of the fourth-order model of DFIG, which is generally used in wind turbine systems with an induction generator. Equations related to torque, active and reactive stator powers using the above equations can be considered according to Equations 13.14 and 15.\(^{13,30}\)

\[
\begin{align*}
T_e &= \frac{3}{2} \left(\frac{p}{2}\right) [\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}] \\
P_s &= \frac{3}{2} (V_{ds} i_{ds} + V_{qs} i_{qs}) \\
Q_s &= \frac{3}{2} (V_{qs} i_{ds} - V_{ds} i_{qs})
\end{align*}
\]

Concerning 13 to 15, \(p\) is equal to the number of poles of the machine, \(T_e\) is electromagnetic torque and active, \(P_s\) and \(Q_s\) are the stator active and reactive powers, respectively. Relationships 13 to 15 relate to the DFIG and express the torque and active and reactive power relations that will be used to design the controller in the next section. If the
derivative of the stator flux is set to zero, the relations 16 and 17 are obtained:\(^{30,32}\):

\[
\frac{d\lambda_{ds}}{dt} = 0 = L_s \frac{di_{ds}}{dt} + L_m \frac{di_{dr}}{dt} \Rightarrow \frac{di_{ds}}{dt} = -\frac{L_m}{L_s} \frac{di_{dr}}{dt} \tag{16}
\]

\[
\frac{d\lambda_{qs}}{dt} = 0 = L_s \frac{di_{qs}}{dt} + L_m \frac{di_{qr}}{dt} \Rightarrow \frac{di_{qs}}{dt} = -\frac{L_m}{L_s} \frac{di_{qr}}{dt} \tag{17}
\]

\[
V_{ds} = r_s i_{ds} - \omega_s L_s i_{qs} - \omega_s L_m i_{qr}
\]

\[
V_{qs} = r_s i_{qs} + \omega_s L_s i_{ds} + \omega_s L_m i_{dr}
\]

From Equations (18) and (19), \(i_{ds}\) and \(i_{qs}\) of stator currents can be obtained as a function of rotor currents. relation 20 can be obtained\(^{13,14,28}\):

\[
i_{qs} = (V_{qs} - \omega_s L_s i_{ds} - \omega_s L_m i_{dr}) / r_s \tag{20}
\]

By substituting Equation (20) for Equation (18), the d axis stator current can be obtained from Equation 21:

\[
V_{ds} = r_s i_{ds} - \omega_s L_s \left(\frac{(V_{qs} - \omega_s L_s i_{ds} - \omega_s L_m i_{dr})}{r_s}\right) - \omega_s L_m i_{qr}
\]

The q axis stator current can be obtained by substituting the d axis stator current in Equation 18, so the stator component current can be obtained by equations 22 and 23\(^{14,33}\):

\[
i_{ds} = \frac{r_s V_{ds} + \omega_s L_s V_{qs} - \omega_s^2 L_s L_m i_{dr} + \omega_s r_s L_m i_{qr}}{\omega_s^2 L_s^2 + r_s^2}
\]

\[
i_{qs} = \frac{r_s V_{qs} - \omega_s L_s V_{ds} - \omega_s^2 L_s L_m i_{qr} - \omega_s r_s L_m i_{dr}}{\omega_s^2 L_s^2 + r_s^2}
\]

the rotor voltage relation of (22) and (23) can be considered as relation 24 and 25\(^{13,14,28,34}\):

\[
V_{dr} = r_r i_{dr} + \left(L_r - \frac{L_m^2}{L_s}\right) \frac{di_{dr}}{dt} - (\omega_r - \omega_s)(L_r i_{qr} + L_m i_{qs})
\]

\[
V_{qr} = r_r i_{qr} + \left(L_r - \frac{L_m^2}{L_s}\right) \frac{di_{qr}}{dt} + (\omega_r - \omega_s)(L_r i_{dr} + L_m i_{ds})
\]

**The objective function**

The purpose of the proposed algorithm is to provide a maximum power point tracking controller for DFIG wind turbines. Equation 26 is used to get the maximum output power point. However, we can present an adaptive and new algorithm based on the equation that uses an algorithm with wind turbine torque information based on the generating flow and rotational speed as the input variables of the algorithm.
Wind turbine torque and rotational speed are related to the output power as shown in Equation:

\[ T = \frac{P_m}{w} \]  \hspace{1cm} (28)

The output power of the DFIG cannot reach its nominal value until the wind speed reaches its nominal value, so this control method is used to obtain the maximum wind power at speeds below the nominal wind speed. To obtain maximum power by controlling the wind turbine torque, which changes the speed of the wind turbine rotor with wind speed, and is achieved at the optimal tip speed \((\lambda_{opt})\).

**Convergence of ICA algorithm**

The ICA algorithm is used in the studied system to obtain the maximum power optimization. In this research, for the optimal alternative as proposed in the objective function in the figure, it is suggested that according to the problem formulation, the proposed algorithm determines the maximum possible value for the maximum power of the wind system. In this section, the study of the studied system is performed with the ICA.
algorithm for convergence of the objective function. In Figure 4 can be seen configuration of the algorithm in the wind turbine model.

Results

Scenario 1: results from the simulation without algorithm

To obtain the maximum power, which changes the speed of the wind turbine rotor with the wind speed, and is obtained at the optimum tip speed ($\lambda$), in simulating a wind turbine, the torque produced at different speeds by the turbine is required to be applied to the machine. Here, the torque is in the turbine shaft and is always determined by the shape block diagram and applied to the machine. Figure 5 shows the proposed wind speed. The base speed for a wind turbine is 12 m/s, and as the wind speed increases, the power drawn from the turbine will exceed the nominal value, which will damage the mechanical parts. For this purpose, to control the power and speed of the wind turbine rotor at high speeds, the pitch angle controller will be implemented. In the work presented, the analysis of the pitch angle controller is omitted. Power changes and speed changes are usually considered as control inputs for the algorithm. These days, power changes or work cycle changes, all of which are part of the electrical system, are used as input.

One of the methods to control the power of the wind turbine is to change the angle of the wind turbine blade in proportion to the changes in wind speed, which is done with the control of the rotor speed. The blade angle is only activated at high wind speeds. In such a situation, the rotor speed cannot be controlled by increasing the electromechanical torque because this will cause the generator and converters on the rotor side to overload. So, the goal is the rotor speed control in the nominal speed range and the power is kept constant at the nominal value.

Figure 5. The proposed wind model of the wind turbine.
Figure 3 shows a block diagram of an adjustable wind turbine model without an algorithm. The control problem is that the power factor ($C_p(\lambda, B)$), which is a function of the blade tip speed $\lambda$ and the blade angle, calculates the wind turbine $\lambda$ from the input values, and the power control angle of the blades until the power the wind turbine rotor speed keeps the optimum power and speed of the reference rotor in the optimal

![Figure 6. Mechanical torque.](image)

![Figure 7. Rotor speed.](image)
value. As a result of applying this wind speed to the wind turbine, it produces the mechanical torque shown in Figure 6. The optimal torque control method in this method, when the wind speed changes, the generator torque is continuously controlled at its optimum value.

Figure 7 shows the rotor speed due to mechanical torque. The rotor of the generator is one of the effective factors in the output power of the wind turbine which directly affects it. The optimum rotor speed varies at different wind speeds, and since there is only one optimum rotor speed for each given wind speed, which results in maximum turbine power, so by

![Figure 8](image1.png)

**Figure 8.** Dc link voltage of wind turbine.

![Figure 9](image2.png)

**Figure 9.** Wind turbine power production.
changing the wind speed, the rotor speed must also be changed to its new optimal state. Also, the DC voltage of the wind turbine link, which is 1200 volts, is shown in Figure 8.

The active power of the wind turbine shown in Figure 9 may be the most important factor. Because this power is the power of the converters between the rotor and the network. The nominal power of the wind turbine is 9 MW. Based on the proposed wind speed and without the maximum power controller (algorithm), the turbine power is extracted in a smaller amount. As shown in Figure 9, the system without the algorithm has very low output power, this is because the power factor is so low that it is not optimized. It can be seen in the figure that the turbine in nominal wind conditions can only produce less than its maximum power in steady-state, which causes a very low efficiency of this system. However, using the maximum power point tracking control algorithm, the turbine power factor curve will increase, which will greatly increase the output power of the system.

**Scenario 2: results with the addition of the algorithm and achieving the maximum wind turbine power**

Figure 10 shows the Wind turbine model using ICA.

In designing the estimation for the turbine system, it is very important to consider the changes in the reference angular velocity followed by the output velocity error. So that in rapid changes of the angle estimation variable in the system dynamics, it is

![Wind turbine model using ICA](Figure 10. Wind turbine model using ICA.)
necessary to determine the controller parameter using an algorithm, which was previously considered constant.

The optimal rotor speed varies at different wind speeds, and since there is only one optimal rotor speed for each given wind speed, which results in a maximum turbine power, as the wind speed changes, the rotor speed must also change and be in its new

**Figure 11.** Rotor speed with ICA algorithm.

**Figure 12.** Mechanical torque with ICA algorithm.
optimal state and show a value close to the base value. The base speed is 1.2 per unit, which is improved by the algorithm compared to the first scenario. In the comparison section, the results will be visible that the optimal value of the rotor speed has been optimized. In Figure 11 can be seen rotor speed with ICA algorithm.

The mechanical torque is also improved in some parts and has a maximum value, which can be seen in Figure 12. The active power is interesting and in Figure 13 it can be seen that the turbine produces its steady-state maximum power in nominal

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**Figure 13.** Wind turbine power with ICA algorithm.

**Figure 14.** Rotor speed.
wind conditions with ICA algorithm. It also has very little fluctuation compared to the first scenario. In this figure, it can be seen that the proposed wind energy conversion system can produce its maximum power in any wind speed range with minimum oscillation.

**Figure 15.** Mechanical torque.

**Figure 16.** Wind turbine power.
Comparison of the results

In this section, the results presented in the first scenario and the second scenario are presented in the form of a graph. To emphasize the accuracy of the method proposed in this research and to confirm the simulation results, this method has been compared with the presented results. Figure 14 shows a comparison of rotor results, Figure 15 shows a comparison of torque results, and Figure 16 compares wind turbine power results.

According to Figure 14, it can be seen that the maximum rotor speed in the system mode with the algorithm is 1.66 pu, which is normally 1.7 and the minimum value for both modes is 0.7 pu.

According to Figure 15, it can be seen that the maximum mechanical torque in the system mode with the algorithm is 0.2 pu, which is normally 0.05 and the minimum value for the mode with the algorithm and normal mode is −1.6 and −0.85 pu, respectively.

According to Figure 16, it can be seen that the maximum output power in system mode with the algorithm is 8.89 MW/s, which is 7.9 in normal mode and the minimum value for mode with algorithm and normal mode is 0.4 and 0.45 MW/s, respectively.

Conclusion

Generation of electric power with the aim of receiving maximum for wind turbine units in the power grid is one of the most important issues for modern systems. In this research, the wind turbine is a dual-feed induction generator that the stator is directly connected to the network and the rotor is connected to the network through two back-to-back transducers. To extract the maximum energy in the wind, the generator must be controlled so that the generator works at its optimal point.

The proposed algorithm in this study, initially, according to the power and speed of the generator, is generalized by the colonial competition algorithm, and by comparing the wind speed, the maximum power is estimated. The proposed power fluctuations in the second scenario presented by the algorithm have been significantly reduced compared to the first state and the maximum power is obtained. And it also has very little oscillation compared to the first scenario.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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