# Adaptive Reactive Power Control of Doubly Fed Induction Generator By using GWO Algorithm

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**ABSTRACT:**
The most commonly used variable speed wind turbine is based on Doubly Fed Induction Generator (DFIG). To control the reactive power of DFIG-based wind turbines, several methods are suggested that controls the reactive power of the DFIG with slow dynamics and considerable ripples. This paper proposes a new control method based on the adaptive reference model which controls the active and reactive powers of DFIG with high dynamics and low ripples. Given that, the proposed technique has proportional-integral (PI), selecting the proper coefficient for PI controller is significant. To overcome this problem, the grey-wolf algorithm is used to optimize the PI coefficients. The results show that the proposed method gives satisfactory performance with lower overshoots and faster dynamic response.

**KEYWORDS:** Doubly Fed Induction Generator, Grey Wolf Optimization Algorithm, Variable Wind Turbine, Adaptive Control, Reactive Power Control.

## 1. INTRODUCTION

The whole capacity of global wind turbine generators at the end of 2016 was 486.6 GW. The statistics show their importance in the power systems. Wind energy conversion systems (WECS) are classified into fixed-speed and variable-speed wind turbines. In the DFIG, a fractionally rated back to back power electronic converter is used and stator is connected to the grid directly without any converter. While for the Permanent Magnet Synchronous Generator (PMSG), the full rated power electronic converter is needed in power transferring to the network [1].

Recently, the DFIG-based wind turbines have been more used in wind energy conversion systems. Thus, they can operate with variable speed and also better efficiency in the power system stability during large disturbances. The main benefits of variable speed wind turbines are as follow:

- Mechanical stress reduction



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- Fundamental noise reduction
- Ability of active and reactive power control

To reach the above mentioned, a power converter is used in its structure. It should be noted that the reactive power control is needed and is necessary to maintain voltage stability [2].

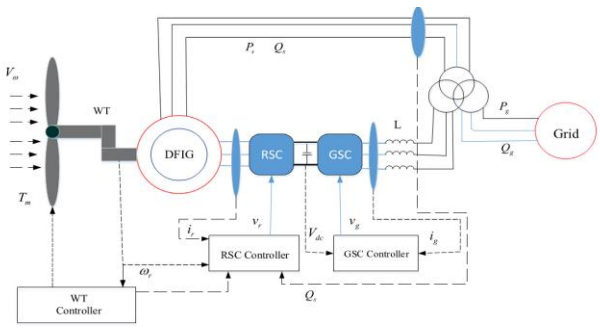



**Fig. 1.** Control block diagram of grid connected DFIG based wind turbine [3].

With the increase of wind power penetration into the power system, different control modes such as voltage control mode and reactive power control mode are considered. Being and performance in unity power factor would be preferred by many operators. In [3], a non-linear adaptive power control was presented to control the active power of the DFIG. Also, a sensor-less rotor position based on back stepping strategy is used in [4]. As a result, reactive power could be generated if there is adequate financial support [5]. Voltage control for DFIG-based wind turbines has been discussed in [6]. Dynamic simulation results indicate that the voltage control operation is better for variable wind speed. This work compares the rotor side converter steady-state currentrating for different reactive power generation modes. The grid-side converter is not considered and there are no consequences for large disturbances in which electronic power converters operate within their range.

The steady-state performance ofDFIG is evaluated by considering the RSC flow and thermal constraints in [7]. Dynamic and static powerfactor control of DFIG is expressed in this reference. However, reactive power of the rotor and stator was also considered, in which the reactive power of the rotor is independent of the network, and only the DFIG reactive power control connected to the infinite bus was investigated. Therefore, the paper does not evaluate the contribution of DFIG in the control of dynamic reactive power in steady state and transient conditions. Various reactive power control algorithms are presented in [8]. These algorithms are only proposed for controlling rotor-side and network-side converters without considering the share of reactive power of the DFIG stator, which can be an important solution.

In [9], a dynamic control architecture for reactive power control of DFIG has been proposed. Also, an adaptive sliding mode control method for controlling the reactive power is proposed in [10]. In [11], a synchronized reactive power control model using RSC in conjunction with a pulse changer at load is proposed. However, the limit for the reactor current of the rotor is set to a small value (ie 0.2 p.u.) and Q changes and the transient conditions are not evaluated. Another synchronized voltage control scheme is proposed in [12] and [13], in which the GSC, together with the RSC, assists the control of Q in the event of major disturbances. Stator flux based, an adaptive observer to sensor-less control of DFIG is proposed in [14]. Robust identification-based sensor-less control method for power control of the DFIG has been presented in [15]. Improved model reference adaptive sensor-less rotor observer is used for a brush-less DFIG based on control winding power factor [16]. However, in these references and other studies that have been done so far, two important issues have not been considered and evaluated:

1. Ability to control DFIG reactive power with lower GSC and RSC ratings and the effect of active or reactive power prioritization and the effect of R / X ratio.
2. Proposing a method with high dynamics and low ripples for reactive power control of stator of DFIG.

The paper proposes a new control method to control the active and reactive power of the DFIG. The proposed strategy is based on an adaptive reference model. Since the proposed controller has PI controllers, choosing the proper coefficient for them is very important. To optimize the PI controllers, the gray wolf optimization algorithm is utilized.

## 2. ANALYSIS

### 2.1. Conventional control Model of DFIG-based WT

In the variable speed DFIG-based wind turbines, there are several advantages such as: variable speed drive, power control capabilities (active and reactive). This system also results in lower power electronic converter costs and lower power losses compared to a system based on a fully fed synchronous generator [1]. Diagram of a DFIG-based wind turbine is shown in Fig. 1.

In DFIG, the rotor current is controlled for controlling the power [11]. In other word, by using the rotor current the speed and the reactive power of the DFIG can be controlled. A DFIG can change its speed by ± 30% around the synchronous speed. This feature makes the DFIG good choice to use as a wind generator. Also, the capability of reactive power control in the

DFIG results in supporting for the grid voltage drop and the controllable speed allows the DFIG to operate at a higher efficiency over a wide range of wind speeds [12]. In [1-3], field-oriented control-based methods have been proposed for the DFIG. The rotor current with stator-flux orientation has been used to power control of the DFIG. The control system is usually defined in the synchronous d–q reference frame fixed to either the stator voltage [1], [2] or the stator flux [5] and it involves relatively complex equations of voltages, currents among the stationary, the rotor and the synchronous reference frames.

As shown in Fig.1, the power electronic converter includes two parts RSC and GSC. The GSC is used to control the power factor and dc-link voltage. In most studies, the grid side reference reactive power is assumed 0 pu. On the other hand, the RSC is used to control generator speed for maximum power point tracking. Also, it is used to control stator active and reactive power. In this paper, a new control algorithm is proposed to control the reactive power of the stator.

According to previous sections and [1-12], in this paper stator flux-oriented control is implemented in RSC control to vector control. In other words, the reference frame is aligned with the stator flux. It means that:

$$\lambda_{ds} = \lambda_s \quad , \quad \lambda_{qs} = 0 \tag{1}$$

Where $\lambda_{ds}$ and $\lambda_{qs}$ are stator flux in the d-q reference frame. So, for stator voltage $V_s$ in this reference frame, the following equation can be obtained:

$$V_{ds} = 0 \quad , \quad V_{qs} = V_s \tag{2}$$

So, the relationship between the stator current and the fluxes can be written as:

$$\begin{aligned} i_{ds}L_s + i_{dr}L_m &= \lambda_s \\ i_{qs}L_s + i_{qr}L_m &= 0 \end{aligned} \tag{3}$$

Where $L_m$ and $L_s$ are the magnetizing and stator inductance, respectively. According to the above equations, the stator active and reactive powers are equal to:

$$P_s = \frac{3}{2}V_{qs}i_{qs} = -\frac{3}{2}V_s \frac{L_m}{L_s} i_{qr} \tag{4}$$

$$Q_s = \frac{3}{2}V_{qs}i_{ds} = \frac{3}{2}\left(\frac{V_s^2}{\omega_s L_s} - V_s \frac{L_m}{L_s} i_{dr}\right) \tag{5}$$

Therefore, it is possible to control active and reactive power of the generator with q and d components of rotor current, respectively and as a result through rotor voltage that is controlled with a fractionally power electronic converter. As explained in section I, this method has a low dynamic and considerable ripple. In the next section, the proposed adaptive reference model is evaluated and added to the conventional control system.

### 2.2. Adaptive Reference Model

In the adaptive control method, it is necessary to select appropriate inputs for power control. In the previous section, the components of rotor reference current were calculated by PI controllers. Here, the previous method is adapted for obtaining rotor reference voltage components. Then these signals are sent to the converter for output reactive power control of DFIG.

From [14], for modeling, the first order linearization method is used where *X(t)* is the state of the variable and *u(t)* is input as the control signal:

$$\dot{X}(t) = -a.X(t) + b.u(t) \tag{6}$$

Where, *a*, and *b* are system parameters that may vary in different conditions. With an adaption of *u(t)* with the system, this signal may differ from the reference value. So, *u(t)* can be written as:

$$u(t) = K(t).X(t) + K_r(t).r(t) \tag{7}$$

*K(t)* and $K_r(t)$ are adaptive backward and forward gains. For obtaining them, it is needed to compare the reference of state model $X_m(t)$ and estimated variable *X(t)* and calculate their difference. The objective is to minimize this difference. It is assumed that:

$$\dot{X}_m(t) = -a_m.X_m(t) + b_m.r(t) \tag{8}$$

Where, $a_m$, $b_m$ are system reference parameters. From (6), (7), (8), the error signal is expressed as:

$$X_e(t) = X_m(t) - X(t) \tag{9}$$

Therefore, according to (8) and (6):

$$\begin{aligned} \dot{X} &= a_m.X_e(t) + (a - a_m - b.K(t)).X(t) + \\ &(b_m - b.K_r(t)).r(t) \end{aligned} \tag{10}$$

According to [16], $K_e$ *and* $K_r$ operate such as PI controllers and are equal to:

$$K_e(e,t) = \int_0^t I_1.y_e.i_{rdq}^T.dt + P_1.y_e.i_{rdq}^T \tag{11}$$

$$K_r(e,t) = \int_0^t I_2.y_e.i_{rdqref}^T.dt + P_2.y_e.i_{rdqref}^T \tag{12}$$

Where, $P_1, I_1, P2, I_2$ are weighting factors of adaptive control. Also, $y_e$ is the weighting function for $X_e(t)$ equal to [17]:

$$y_e = C_e . X_e \tag{13}$$

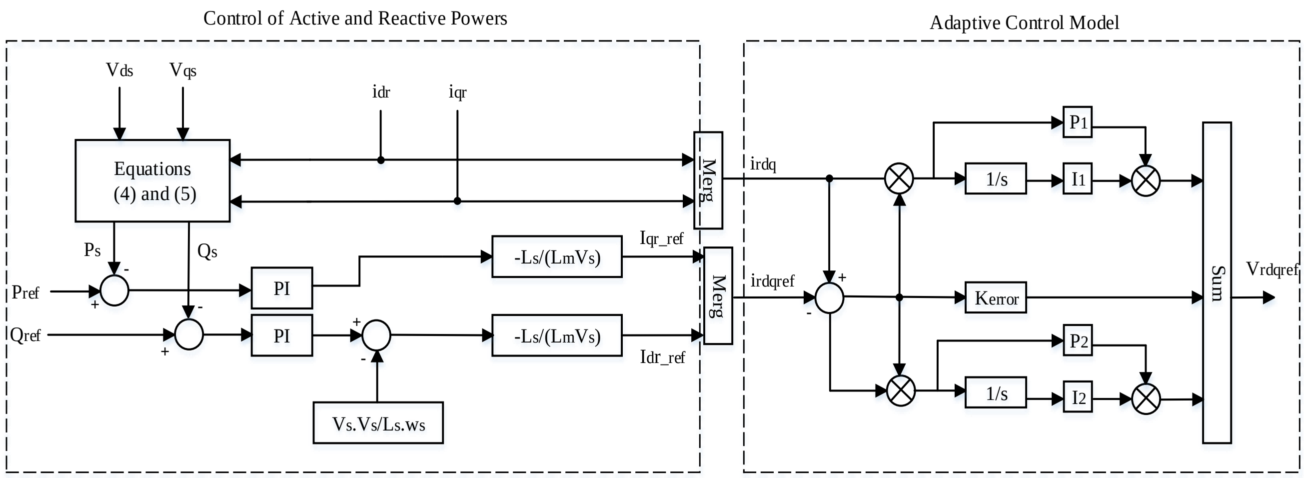



**Fig. 2.** Proposed control method based on adaptive reference model.

In (13), $C_e$ is constant value that is set for assurance of stability maintaining in forward part. Fig. 2 shows proposed control method based on the adaptive reference model. According to this figure, the reference value of active and reactive powers is compared with their actual values that are computed through equations (4) and (5). Then, an adaptive reference model block diagram is added to the conventional control method.

## 3. GREY WOLF OPTIMIZATION ALGORITHM

The Gray Wolf Optimization (GWO) algorithm was proposed in [20] firstly. It is a novel meta-heuristic algorithm motivated by the social behavior and the hunting mechanism of gray wolves in nature. Wolves in the package have a very severe social commanding hierarchy. The alpha wolf is in the first stage in the hierarchy, where his orders must be followed by all of the pack. The beta wolves are at the second stage of the hierarchy and they are subordinate to alphas and help them to make decisions. The third stage is implemented by delta wolves, which have to yield to alphas and betas but prevailing the omega. Finally, the lowest rank of the package is the omega, which has to yield to all the other dominant wolves. The order of steerage hierarchy stage of the wolf package is shown in Fig. 3.

In addition to the social hierarchy, social hunting is a very significant behavior in this pack. The main steps of grey wolves for hunting are as follows [20]:

1) Tracking, following, and drawing nearer the prey.
2) Adopting, surrounding, and bothering the prey until it stops moving.
3) Attacking the prey.

The mathematical model of the GWO algorithm based on the social hierarchy and hunting stages is introduced as follows:

***1) Social hierarchy:*** To mathematically model the social behavior of the gray wolves, the proper solution is considered alpha. Consequently, beta and delta are the second and third nominees for the fittest explanation, respectively. The remaining solutions are supposed as omega, which is helped by the other wolves. The searching (optimization) process in the GWO algorithm is guided by alpha, beta, and delta, where omega usually follows these three wolves.

***2) Enclosing:*** The gray wolves encircle around the prey during hunting. To model the encircling behavior, the following equations are expressed [21]:

$$\vec{D} = \left| \vec{C}.\vec{x}_p(t) - \vec{x}(t) \right| \quad , \quad \vec{x}(t+1) = \vec{x}_p(t) - \vec{A}\vec{D} \tag{14}$$

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \quad , \quad \vec{C} = 2.\vec{r}_2$$
(15)

Where, $t$ is the current repetition, $x_p(t)$ presents the current position of the sacrifice, and $A$ and $C$ are the coefficient vectors, and $r_1$, $r_2$ are random vectors between [0,1] and the component of $a$ is linearly reduced from 2 to 0 over each course of the repetition.

*3) Hunting:* Hunting is guided by alphas. During the hunting phase, the positions of the gray wolves are updated. The alphas are the main elements in the hunting phase. However, betas and deltas also are involved in the hunting process, every so often. To update the wolf positions around the prey, the following formulas are implemented:

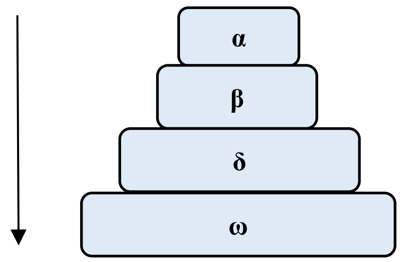



**Fig. 3.** Hierarchy of grey wolf [13].

$$\vec{D}_\alpha = |\vec{C}_1.\vec{X}_\alpha - \vec{X}|, \quad \vec{D}_\beta = |\vec{C}_2.\vec{X}_\beta - \vec{X}|$$
$$\vec{D}_\delta = |\vec{C}_3.\vec{X}_\delta - \vec{X}|$$
(16)

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha), \quad \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.(\vec{D}_\beta)$$
$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3.(\vec{D}_\delta)$$
(17)

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (18)$$

***4) Attacking prey (utilization):*** The gray wolves end the hunt by attacking prey when it stops moving.

***5) Search for prey:*** The optimum search of the grey wolf algorithm is usually based on the positions of alpha, beta, and delta. When they explore for prey, they separate from each other and assemble to attack, when they find the prey. The steps of GWO algorithms can be summarized as:

*a)* The nominee solutions are initialized accidentally to start the search process in the search space.

*b)* Based on the position of prey, the alpha, beta, and delta wolves are appraised.

*c)* Position of each wolf is updated to find the optimum placement of the prey.

*d)* For better searching, *a* linear decreases from 2 to 0.

*e)* When $A>1$ nominee solutions are separate and they assemble when $A<1$.

*f)* In the end, the optimum solution is obtained from the GWO algorithm.

Fig. 4 illustrates the usual flowchart of the GWO algorithm.

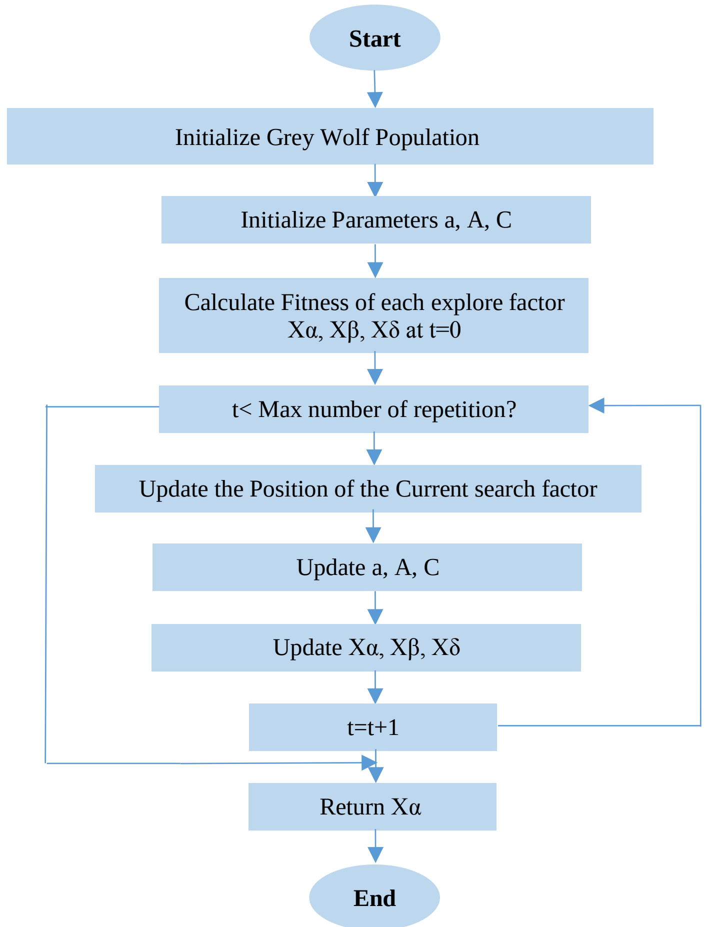



**Fig. 4.** Flow chart of the GWO algorithm [14].

## 4. IMPLEMENTATION OF THE ALGORITHM

In the optimization process under the principles of GWO the algorithm, an objective function is defined to achieve minimum reactive power tracking error. Thus, according to the proposed control method, the proportional coefficients ($K_{p1}$, $K_{p2}$) and integral coefficients ($K_{i1}$, $K_{i2}$) are designed to minimize the objective function. To improve dynamic response, the objective function includes reactive power tracking error during transients. Therefore, the mathematical expression of objective function based on a trapezoidal integral equation can be expressed as follows:

$$J = \frac{h}{2}\sum_{k=1}^{N}\left(\left|Q^*(k) - Q(k)\right| + \left|Q^*(k-1) - Q(k-1)\right|\right) \quad (19)$$

Where, $Q^*$ is the reference reactive power of DFIG and $Q$ is the actual value of reactive power. Also, N is the number of samples and h is the distance between samples. The system is modeled in discrete mode. The defined objective function can improve system responses such as settling time, overshoots and undershoots, and transient reactive power tracking error.

It should be noted that PI-controller parameter bounds are considered constraints of the optimization problem. In this case, the considered bound for optimization coefficients is [0 1000]. Optimization results for determining these parameters are in Table. 1.

**Table 1.** Optimal PI-controllers coefficients.

| Algorithm | $K_{p1}$ | $K_{i1}$ | $K_{p2}$ | $K_{i2}$ |
|---|---|---|---|---|
| Grey Wolf | 52.5847 | 351.0490 | 60.7380 | 323.1213 |

## 5. SIMULATION AND RESULTS

In this section, the proposed control algorithm is simulated in MATLAB/Simulink software and the results are shown and discussed to examine the effectiveness and performance of the optimized adaptive reference control model.

The nominal parameters of DFIG based wind turbine that is used in this paper are presented in Table.2.

**Table. 2.** DFIG-based wind turbine parameters for simulation.

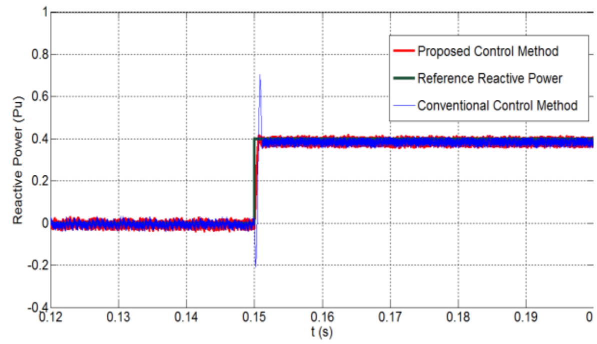
| Rated power of wind turbine | 10 KW |
|---|---|
| Wind turbine type | HAWT |
| Inertia moment | 0.00065 $kg.m^2$ |
| Friction Coefficient | 0.017 N.m/sec |
| Air density | 1.22 $kg/m^3$ |
| Rated power of DFIG | 4 KW |
| Rated mechanical power | $9*10^6$ watt |
| Rated 3phase voltage | 600 v |
| Rated speed | 1440 rpm |
| Pole pairs | 2 |
| Nominal frequency | 50 Hz |
| Stator resistance | $2.33*10^{-4}$ ohm |
| Rotor resistance | $1.65*10^{-4}$ ohm |
| Stator inductance | $9.4*10^{-5}$ H |
| Rotor inductance | $8.58*10^{-5}$ H |
| Magnetic inductance | $1.59*10^{-5}$ H |
| DC link Voltage | 300 v |

In this paper, the simulations are carried out in two sections. The total time of simulation is 0.2 seconds in both sections.

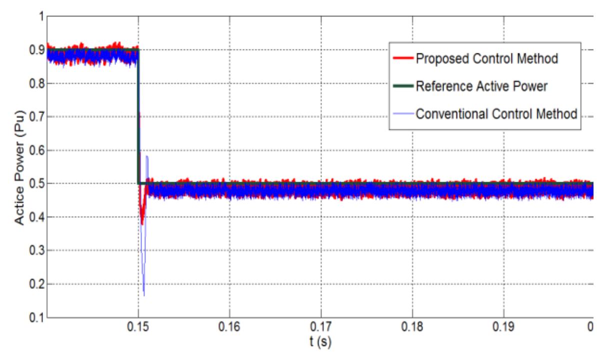
### *A. Active and Reactive Power Changes:*

In this section, the reference value of reactive power changes from 0 to 0.4 per unit (pu). There are two goals: observation of the proposed control algorithm performance in reactive and active power control and comparison of it with conventional control. Also, in the next step, the reference value of active power changes from 0.9 pu to 0.5 pu. Fig. 5 shows the results of this section of simulation.

According to this figure, a variable speed DFIG-based wind turbine can control its reactive and active power in sudden changes employing the proposed method. In addition. the proposed control method that uses an adaptive active and reactive power algorithm and optimized with GWO, has a better dynamic response in comparison with conventional reactive power control methods of DFIGs in [1]-[14]. As shown in Fig. 5(a) and Fig.5 (b), overshoot and undershoot in the proposed control method are less and the studied variables (*Ps*, *Qs*) reach their reference value in the least possible time.




(a)

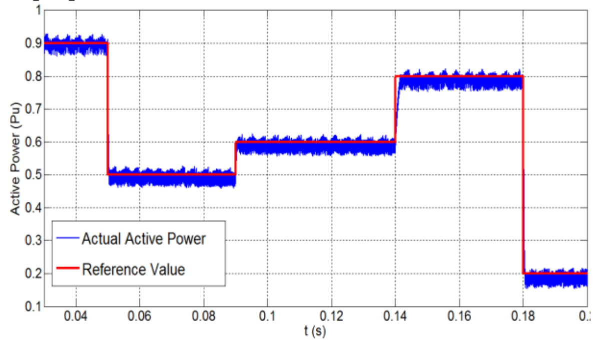



(b)

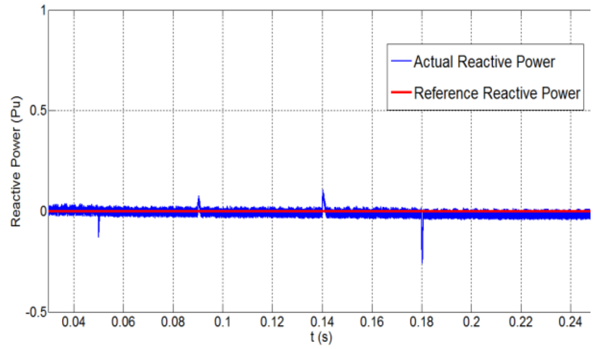
**Fig. 5.** Comparison of the proposed control algorithm with the conventional method in the sudden variation of reference value: (a) Reactive Power of DFIG, (b) Active Power of DFIG.

### *B. Wind Speed Variations:*

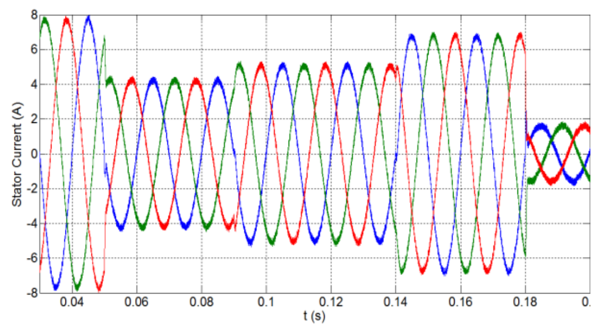
In this section, it is assumed that a DFIG-based wind turbine operates at a unity power factor (PF=1). In addition, it is supposed that in the simulation duration (0.2 s), wind speed changes in four steps, and as a result, the reference value of active power varies in four steps as shown in Fig. 6(a). The aim is to evaluate the proposed control method in the variable conditions that are near to real status. Fig. 6 shows the performance of the proposed model.




(a)




(b)




(c)

**Fig. 6.** Evaluation of proposed control method in the wind speed variations (PF=1): (a) Active Power of DFIG, (b) Reactive Power of DFIG and (c) Stator Current of DFIG

## 6. CONCLUSION

This paper proposes a new control scheme that uses an adaptive reference model to control the active and reactive powers of variable speed DFIG-based wind turbine. Since the suggested controller has proportional-integral controllers, selecting the proper coefficient for them has high importance. Hence, the grey-wolf optimization algorithm is used to optimize the controller coefficients. Simulations are carried out and the results show the effectiveness and performance of the proposed control algorithm with high dynamics and low ripples.

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