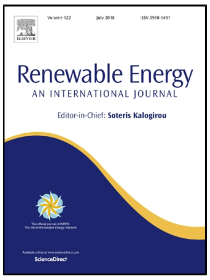

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PII: S0960-1481(18)30360-4

DOI: 10.1016/j.renene.2018.03.049

Reference: RENE 9918

To appear in: *Renewable Energy*

Received Date: 09 May 2017

Revised Date: 04 March 2018

Accepted Date: 20 March 2018

Please cite this article as: Yacine Mokhtari, Djamila Rekioua, High Performance of Maximum Power Point Tracking Using Ant Colony Algorithm in Wind Turbine, *Renewable Energy* (2018), doi: 10.1016/j.renene.2018.03.049

High Performance of Maximum Power Point Tracking Using Ant Colony Algorithm in Wind Turbine

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Abstract: The growing interest in wind power as a source of electric power generation with minimal environmental impact and the advancement of aerodynamic designs, including wind turbines, have been the subject of numerous studies. When wind energy is integrated into the grid, this gives a significant amount of power added to the one produced by other types of plants. Several researchers aim to achieve high efficiency in wind power systems using maximum power point tracking (MPPT) of a variable-speed turbine but this technique is complicated because the different approximations that occur during the online calculations. The main objective of this work is to develop and improve a maximum power tracking control strategy using metaheuristic methods. Ant colony optimization (ACO) algorithm is used to determine the optimal PI controller parameters for speed control. The optimization of the speed gets a better value of power coefficient therefore the extracting power.

Keywords: MPPT, Wind turbine, Ant colony algorithm, Artificial Intelligence, Optimization, Wind Energy

Nomenclature

C_p	Power ratio
f	Viscous friction, N.m.s/rad
G	Gearbox
J	Inertia, Kg.m²
k	Number of ants
L_m	Magnetization inductance, H
L_s	Stator inductance, H
p	Number of pole pairs
P	Pair pole number
P_s, Q_s	Active and reactive stator power, W, VAR
P_N	Nominal power, W
P_t	Turbine power, W
R	Blade length, m
R_s	Stator resistance, Ω
T_{dfig}	Torque of the machine, N.m
T_r	Resistant Torque, N.m
$T_{turbine}$	Turbine torque, N.m

V	Wind speed, m/s
α	Pheromone degree
β	Visibility parameter
□	pitch angle, degree
Γ_{em} ,	Electromagnetic Torque, N.m
η_{ij}	Heuristic factor
λ	Tip-speed ratio
λ_{opt} .	Optimal tip-speed ratio
ρ	Air Density, Kg/m^3
ρ	Evaporation Rate
τ	Response time, s
τ_{ij}	Pheromones amount
Ω	Mechanical speed, rad/s
Ω_{mec}	Shaft speed, rad/s
$\Omega_{turbine}$	Turbine speed, rad/s
ω_{opt}	Optimal Angular Speed, rad/s
ACO	Ant Colony Optimization
DFIG	Doubly Fed Induction Generator
HCS	Hill Climbing Searching
ITAE	Integral Time Absolute Error
MPPT	Maximum Power Point Tracking
P&O	Perturbation and Observation
PI	Proportional Integral
PSF	Power Signal Feedback
WSM	Wind Speed Measurement

1. INTRODUCTION

During the last decade, renewable energies have taken on a great importance in the development of some countries. Developing this energy is increasingly the axis explored by the scientific community. The energy can be extracted from many sources, to cite fossil, solar and wind [1].Wind turbine technology has developed rapidly in recent years and Europe is at the hub of this high-tech industry. Wind turbines are becoming more powerful, with the latest turbine models having larger blade lengths which can utilize more wind and therefore produce more electricity, bringing down the cost of renewable energy generation. Wind turbines produce electricity by using the natural power of the wind to drive a generator. The wind is a clean and sustainable fuel source, it does not create emissions and it will never run out as it is constantly replenished by energy from the sun. In many ways, wind turbines are the natural evolution of traditional windmills, but now typically have three blades, which rotate around a horizontal hub at the top of a steel tower. Most wind turbines start generating electricity at wind speeds of around 3-4 meters per second (m/s), (8 miles per hour); generate maximum 'rated' power at around 15 m/s (30mph); and shut down to prevent storm damage at 25 m/s or above (50mph)[2].The main challenge encountered on wind energy is to be able to extract a maximum of power at each instant of the operating cycle of a turbine.

There are several MPPT methods to extract the maximum of wind power, such as PI control [21], linear quadratic Gaussian (LQG) control [22], optimal control [23], sliding mode control (SMC) [24], predictive control [25], fuzzy control [26], combination of fuzzy ANN and PSO algorithm [27], harmony search algorithm [28], , perturbation and observation (P&O) or hill climbing searching (HCS) [31], wind speed measurement (WSM), tip speed ratio (TSR) control and power signal feedback (PSF) [29], [30]. In the P&O method, the rotor speed is perturbed by a small step, and then the power output is observed to adjust the next perturbation on the rotor speed [3].With power signal feedback (PSF) the reference optimum power curve of the wind turbine should be obtained first from the experimental results [4].The perturbation and observation (P&O), or hill-climb searching (HCS) methods are a mathematical optimization technique used to search for the local optimum point of a given function [4].Although the methods show good performance the research has never ceased to further improve the power rates extracted. In this article we will optimize and maximize the extracted power rate using an Ant colony optimization method. Ant colony optimization is based on cooperative behavior of real ant colonies, which are able to find the shortest path from their nest to a food source[5]**.**This report deals the tuning of the control system for the classical MPPT of variable speed wind turbine. Where: PI-regulators are calculated with classical methods regulating rotor speed with ant colony algorithm PI-ACO. The disadvantage of the classical method is the obligation to calculate the machine parameters before make the control but, in this method we have no need to know the machine parameters, this represent a great advantage of resolution.

In this paper, our focus is on the capture of the maximum wind power. The output power of a WECS is maximized when the rotor is driven at an optimal speed. To achieve the maximum power point tracking (MPPT), PI controllers are usually used. In our contribution an optimal proportional-integral (PI) controller is proposed based on ant colony optimization method.

This proposed method combine ant colony optimization (ACO) algorithm with proportional integral controllers. it allow to tune the parameters of the regulator in each instant of wind speed and maximize the power captured.

The wind turbine is modeled at the first, then, the wind turbine control of speed is given with the classical set of parameters and by using the ant colony algorithm. The steps of the algorithm are given and the results of ACO-PI show that this method presents a great advantage since it allows converging and giving the best parameters. Thereby, show the importance of the use of the met heuristics methods in wind system.

2. Wind Turbine Modeling

The studied system is represented in the following Fig. 1:

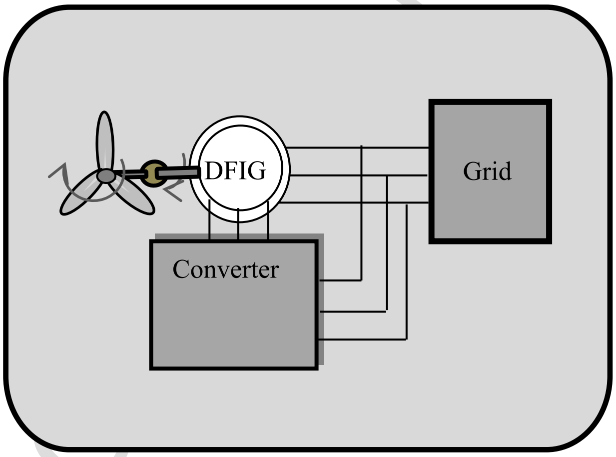

Fig. 1. DFIG configuration in system wind energy

The power capacity produced by a wind turbine is dependent on the power ratio C_p . It is given by:

$$P_t = \frac{1}{2}.C_p.\rho.S.V^3 \tag{1}$$

The turbine torque is the ratio of the output power to the shaft speed $\Omega_{turbine}$, where

$$T_{turbine} = \frac{P_t}{\Omega_{turbine}} \tag{2}$$

The turbine is normally coupled to the generator shaft through a gear box whose gear ratio **G** is chosen so as to maintain the generator shaft speed within a desired speed range. Neglecting the transmission losses, the torque and shaft speed of the wind turbine, referred to the generator side of the gearbox, are given by:

$$T_{dfig} = \frac{T_{turbine}}{G} \tag{3}$$

And

$$\Omega_{mec} = G.\Omega_{turbine} \tag{4}$$

Where

T_{dfig} is the torque of the machine and Ω_{mec} is its shaft speed.

The wind turbine can be characterized by its $C_p(\lambda)$ (curve shown in Fig 2.). Where λ is the ratio between the linear speeds of the tip of the blade with respect to the wind speed. It is shown that the power coefficient C_p varies with the tip-speed ratio. It is assumed that the wind turbine is operated at high C_p values most of the time [6].

$$C_p(\beta,\lambda)=0.5176\left(\frac{116}{\lambda_i}-(0.4\beta-5)^{\frac{-21}{\lambda_i}}+0.0068\lambda\right) \tag{5}$$

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \tag{6}$$

$$\lambda=\frac{\omega R}{V} \tag{7}$$

ω: Angular speed

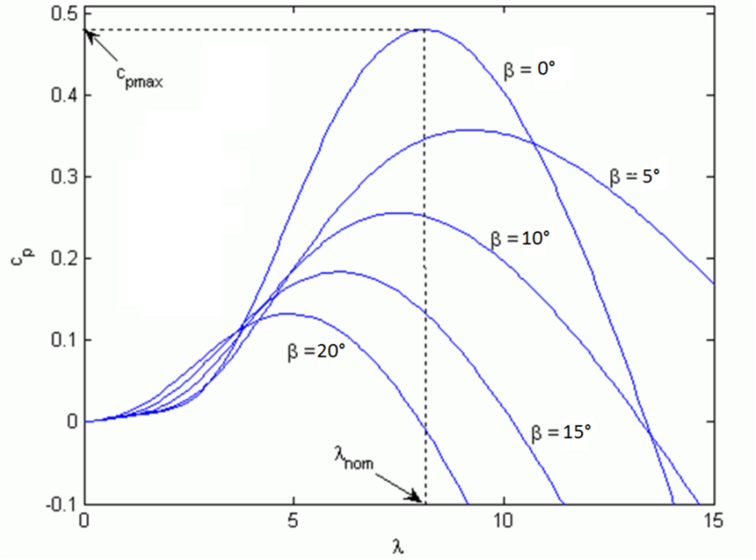

Fig. 2. Relationship between the power coefficient and the tip-speed ratio**[3]**

From Fig.2, we observe that for a fixed pitch angleβ, a maximum *Cp* is achieved when the tip speed ratio is at the optimal value λ_{opt}. Recall Eq.7, for a given wind speed (V), to achieve the maximum *Cp*, then the rotor speed should be maintained to the optimal speed

(ω_{opt}) **[3],[13],[16]**.

The action of the speed corrector must achieve two tasks:

- It must control mechanical speed Ω_{mec} with its reference Ω_{mec_ref} **[7] ,[14],[15].**

It must attenuate the action of the wind torque which constitutes an input disturbance **[8]**. The simplified representation in the form of diagram blocks is given in Fig.3. We can use different technologies of correctors by in our work we opt for PI regulator to control our model.

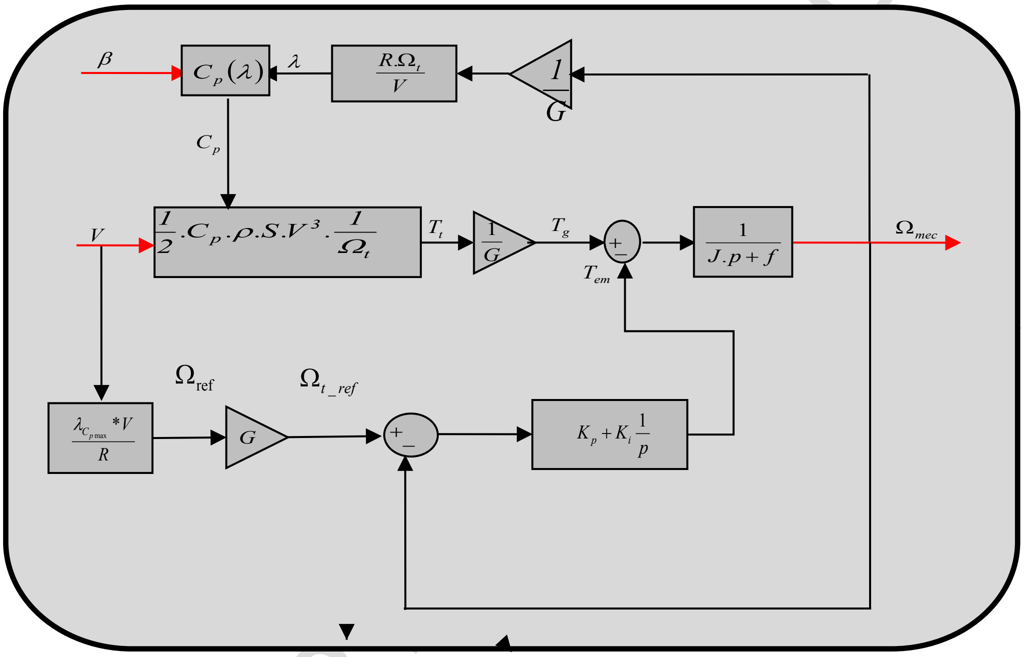

Fig. 3.Block diagram of control speed

Using the compensation of slow pole method we determinate the parameters in Eq.12.

The system to regulate is presented in Fig.4:

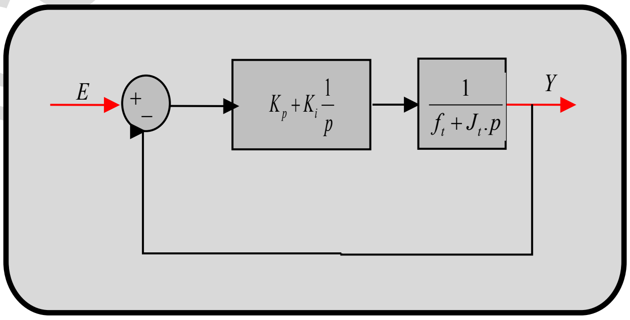

Fig. 4. Scheme of the PI with system

E: System Input

Y: System Output

The gain PI is in the form:

$$C(p) = \frac{K_i}{p}\left(1 + \frac{K_p}{K_i}.p\right) \tag{8}$$

We suppose: $A = \frac{1}{f}$ $T = \frac{J}{f}$

where:

$$P(p) = \frac{1}{f + Jp} \tag{9}$$

We can compensate the zero introduced by PI with the pole in open loop of the system.

$$H(p)_{ol} = \left(K_p + K_i.\frac{1}{p}\right)\left(\frac{1}{f + J.p}\right) \tag{10}$$

$$\Rightarrow \frac{K_p}{K_i} = \frac{J}{f}$$

In closed loop we obtain:

$$H(p)_{cl} = \left(\frac{1}{1 + \frac{f}{K_i}.p}\right) \tag{11}$$

We obtain:

$$K_i = \frac{f}{\tau} \qquad K_p = \frac{J}{\tau} \tag{12}$$

With : τ : is the response time.

3. ANT COLONY OPTIMIZATION:

The main idea of ant colony optimization is to model the problem to search the best path corresponding to the minimum cost. This algorithm is inspired from real ant colony. ACO borrows its features from the ability of some ant species to find, collectively, the shortest path between two points. This ability is explained by the fact that ants communicate in an indirect way by laying trails of pheromone. Ants randomly choose their path, but the probability of choosing a direction depends on pheromone trails on the ground **[9].**Let us now specify the behavior of the whole colony. At all times t , each Ant selects a destination city according to a defined choice. All the ants are placed at the moment $t + 1$ in a city of their choice. An iteration of the algorithm is called the set of displacements of the whole colony between the instant t and the instant $t + 1$. Thus, after n iterations, the set of the colony will have performed a Hamiltonian circuit on the graph. In this way all the ants will start and finish their turn at the same time [10].

The expression of the state's transition probability is given the following equation :

$$P_{ij}^{k}(t) = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^{\alpha}.\eta_{ij}^{\beta}}{\sum\limits_{l \in N_i^k}\left[\tau_{il}(t)\right]^{\alpha}.\eta_{il}^{\beta}} & si \quad j \in N_i^k \\ 0 & \sin on \end{cases} \tag{13}$$

Where the set N_i^k as the set of cities which the ant k , placed on the node i , has not yet visited at time t in the current cycle, α is the relative importance of the pheromone trace in the problem, and β shows the importance that given to visibility value. The value of α is a factor that allow to the ant to select the previous traversed path and β it reflects the relative importance of the heuristic information witch guides the ants in the search process **[11],[10],[12].**

η_{ij} is the heuristic factor represent the visibility value between (i, j) corners.

τ_{ij} Represent the amount of pheromones in the path. At the end of each cycle (each ant has traversed the n peaks that make up the graph), the pheromone variables are updated according to the formula

$$\tau_{ij}(t+n) = (1+\rho).\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{14}$$

The pheromones are evaporated in order to prevent infinite accumulation of pheromone. ρ is the pheromone evaporation factor in the range $[0,1]$ and $(1+\rho)$ is the residue factor.

The quantity of pheromones deposited by this ant on the arc (i, j) in this same interval of time. It is defined as follows:

$$\Delta\tau_{ij}^k = \left\{ \frac{Q}{L_k} \right\} \tag{15}$$

Where Q is a constant.

It can be seen here that pheromones are regulated as a function of the quality of the solution obtained because more $L_k(t)$ is weak plus the arc will be updated in pheromones.

We can now define the $\Delta\tau_{ij}(t)$ of the pheromone update formula as follows **[5], [10]**:

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \tag{16}$$

The Equation (16)can be implemented as:

$$\Delta\tau_{ij}^k(t) = \begin{cases} \zeta \dfrac{F_{best}}{F_{worst}}; if \quad (i,j) \in Global \quad best \quad tour \\ 0; \qquad\qquad Otherwise \end{cases} \tag{17}$$

Where F_{worst} worst is the worst value and F_{best} is the best value of the objective function among the paths taken by the k ants, and ζ is a parameter used to control the scale of the global updating of the pheromone. The larger the value of ζ , the more pheromone deposited on the global best path, and the better the exploitation ability. The aim ofEq.17 is to provide a greater amount of pheromone to the tours (solutions) with better objective function values **[5],[17],[18].**

The ACO based approach to find the global maximum value of objective function as shown in Fig. 5.The PI controller is a good controller in control of wind turbine, but the problem is the mathematical model of the plant must be known. In order to solve problems in the overall system, several methods have been introduced to tuning PI controller. Our proposed method uses the ACO to optimize the maximum power point tracking; the ACO is utilized off line to determine the controller parameters (Kp and Ki) of the wind turbine. The performance of the Wind turbine varies according to PI controller gains and is evaluated by the value of integral time absolute error (ITAE). The performance index sum (ITAE) Eq.18 is chosen as objective function. The aim of this algorithm is to minimize the objective function **[12],[19],[20].**

$$ITAE = \int_{0}^{\infty} t\left|e\left(t\right)\right|.dt \tag{18}$$

The steps follow to defined Algorithm of Ant colony
Step 1: Create population of ‘N’ ants, Initialize the pheromone and parameters.
Step 2: For every individual ant, evaluate fitness function (ITAE).
Step 3: Determine the best solution for each ant;
Step 4: Update the pheromone.
Step 5: Chesck if convergence is satisfied (all ants must have the same value of solution);
The objective function for ACO is to minimize the error function between speed reference and speed of the machine.

The algorithm is developed in the flowchart in Fig. 5.

in this proposed algorithm the criteria chosen stop the computing when all ant have the same value (best solution).

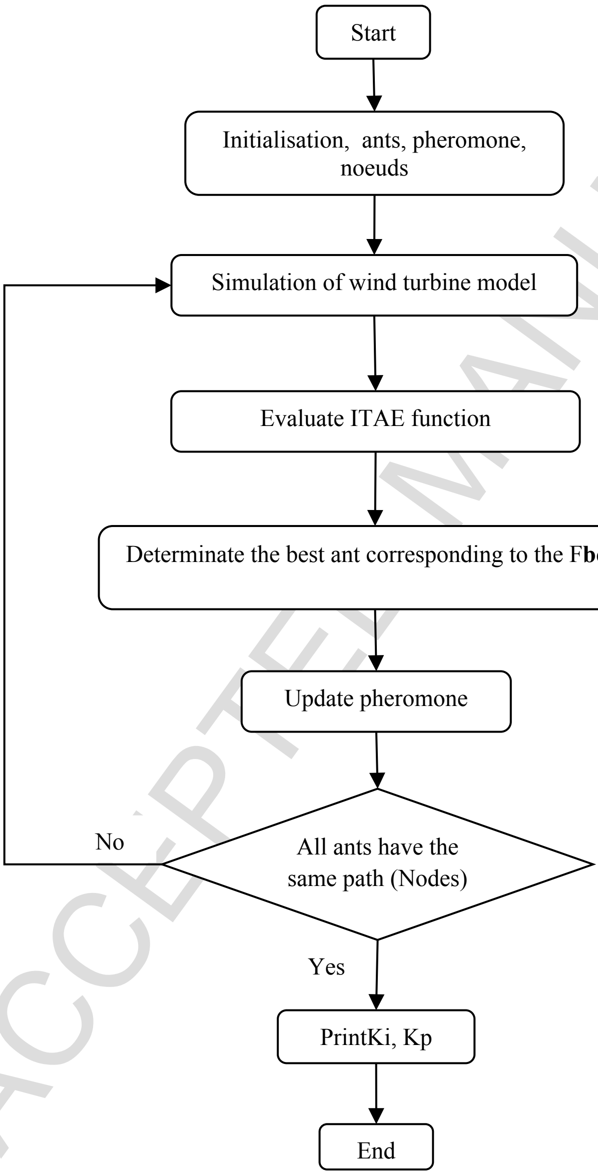

Fig. 5.The flowchart of the ACO–PI control system

The bloc diagram using ant colony algorithm is given in Fig.6.

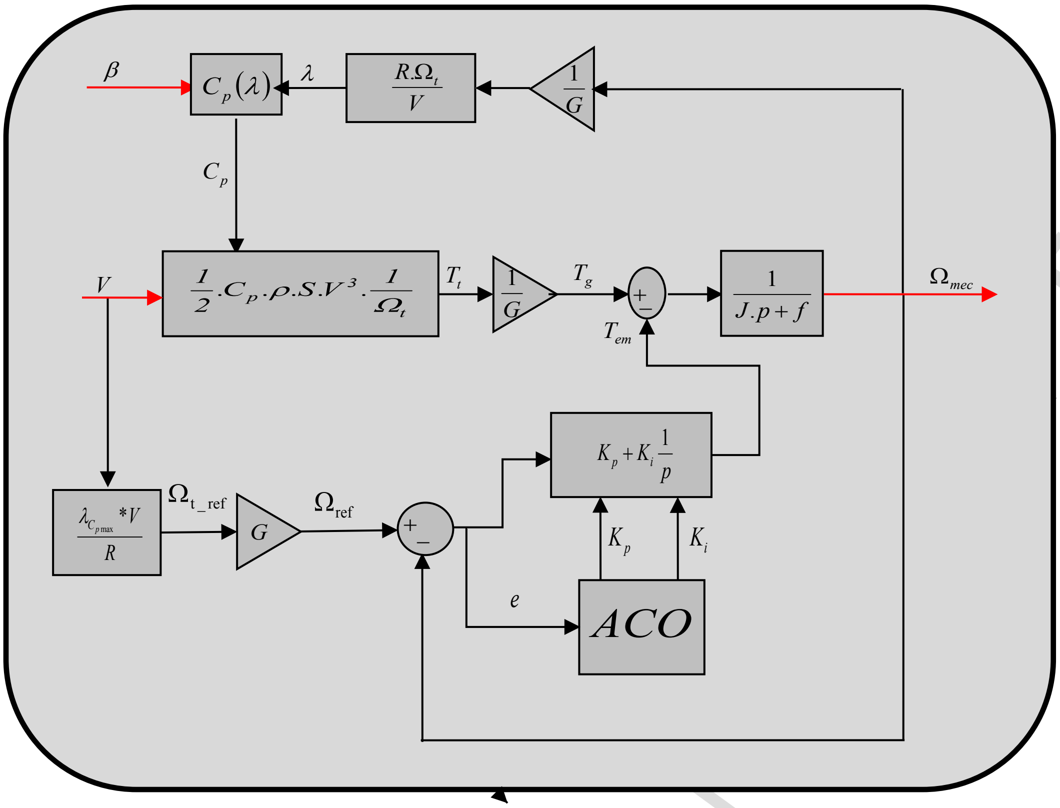

Fig. 6.Block diagram of control speed with ACO

4. SIMULATION RESULTS

In this section, we present the numerical results to improve the performance of the proposed solution algorithm. All the computation is implemented with Matlab/Simulink. The values of the parameters in ACO are:

Table 1

Values of the parameters in ACO

Number of ants	k = 100
Pheromone degree	α = 3
Visibility parameter	β = 0.1
Evaporation Rate	ρ = 0.5
Number of iteration	n_iter=500

The doubly fed induction generator shown in Fig. 7 was identified in the laboratory using the following steps:

- No load test at synchronous speed.
- Short-circuit test with blocked rotor.
- Transformer test.

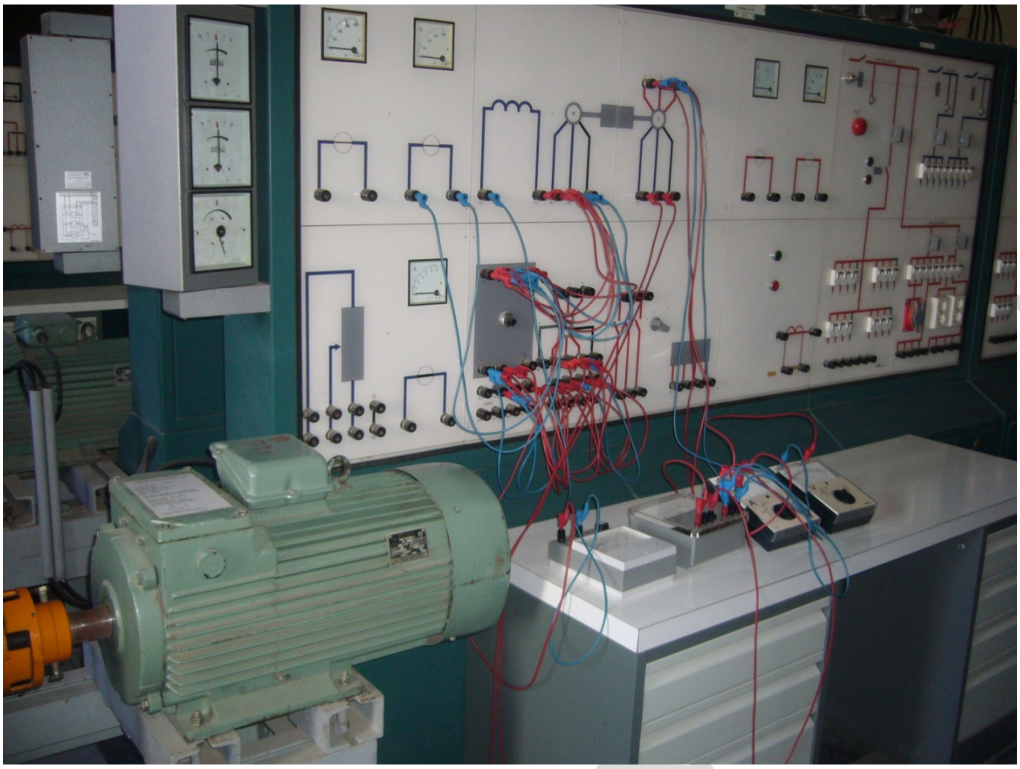

Fig. 7. DFIG indentified in the laboratory

DFIG parameters obtained are listed in Table 2.

Table 2.

DFIG parameters

Parameters	Values
Nominal power P_N	15 kW
Stator resistanceR_s	0.272 Ω
Stator inductance L_s	36.4 mH
Magnetization inductance L_m	34.9 mH
Friction f	0.073 N.m.s/rad
Inertia J	2.555 kg.m²
Pair pole number	2

Wind turbine parameters used are given in the below table (Table3.)

Table 3.

Wind Turbine parameters

Parameters	Values
blade radius R	4.85 m
Gearbox G	12.6

The wind profile chosen in this study is presented in Fig. 8. At the time 4s a wind profile applied of 2m/s and 10m/s at the time 10s, after that, we applied a constant profile of wind 10m/s from 8s until 11s. Others values of wind had been applied also between 11s and 12s corresponding to 10m/s and 6.8m/s. and we applied 6.8m/s until 8.3m/s between 15s and 16s. in the intervals [12s,15s] and [15s,20s] we applied a constant wind profile 6.8m/s, then 8.3m/s.

The power coefficient C_p obtained by the control of speed with proportional and integral controllers and the ant colony optimization algorithm, is represented in Fig.9. It is clear (Fig.10.) that the results obtained with ACO present a better optimization and the power coefficient in this case is more than the power coefficient obtained by using the classical regulators for the speed control.

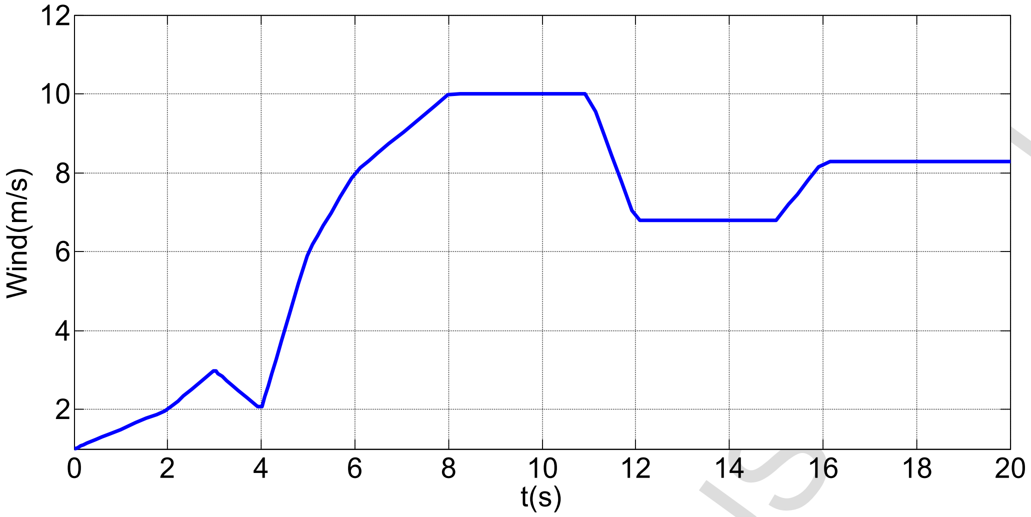

Fig. 8. Wind profile

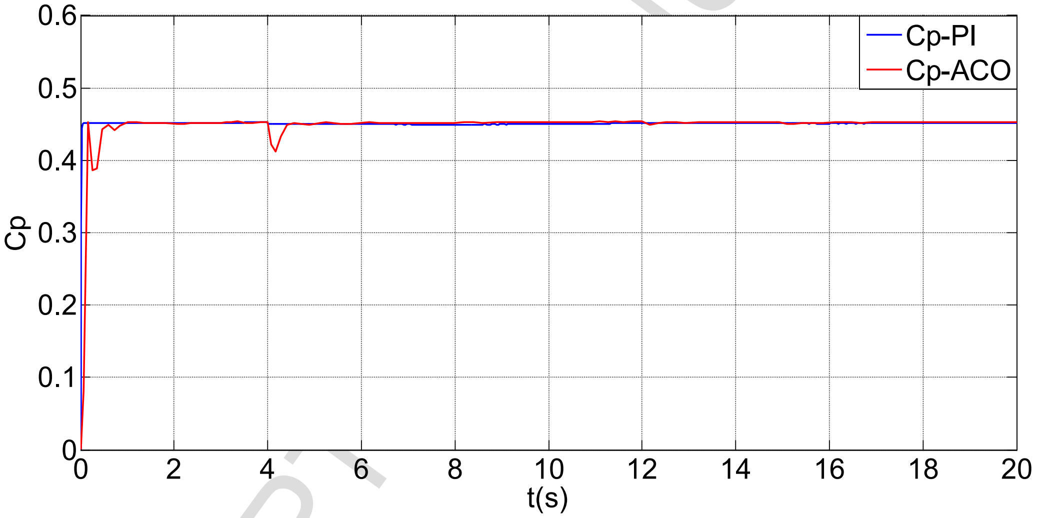

Fig. 9. Power coefficient using PI regulator and ACO

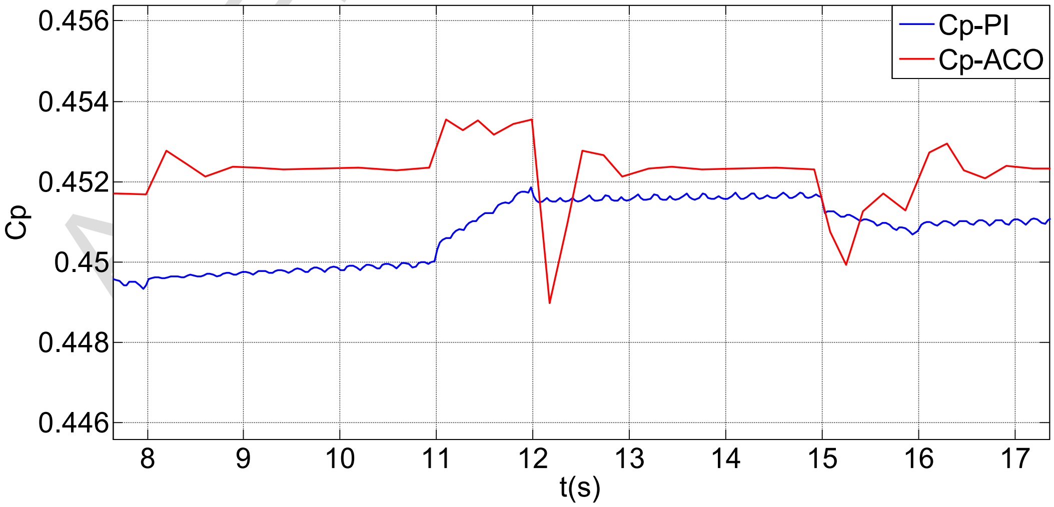

Fig. 10. Zoom on power coefficient

In the times intervals [8s,11s], [12s,15s] and [16s,20s], It is clearly seen that the power coefficient obtained using ACO [0.452,0.453] is greater than in the case of classical speed control with proportional integral controllers [0.449,0.4518], and this during each time interval (Fig.11).

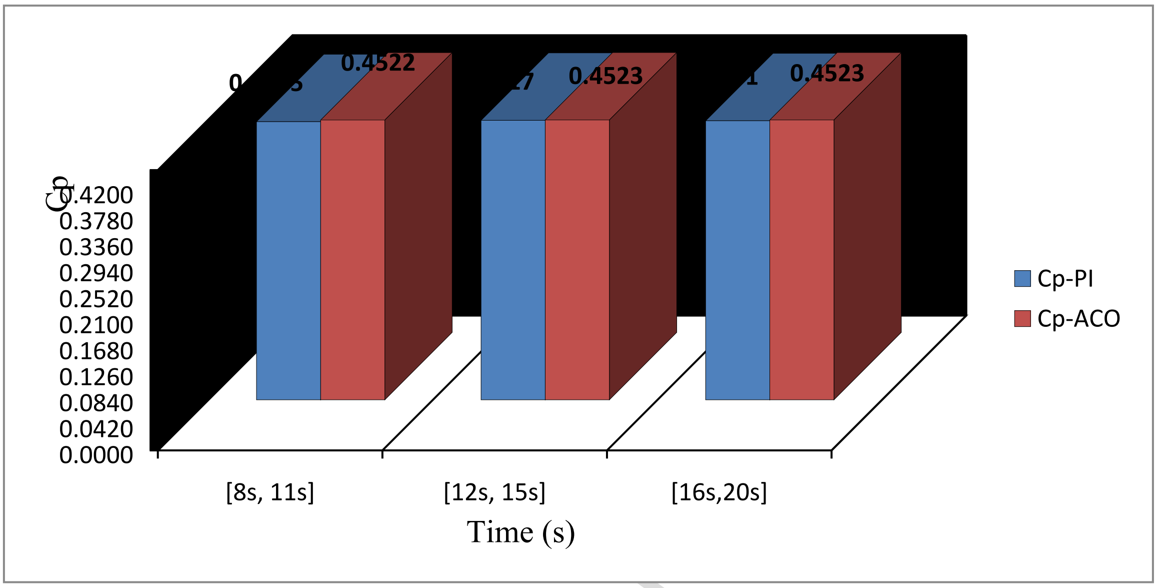

Fig.11.Obtained C_p with PI and ACO

We note that, in the other intervals of transition the value of C_p change and return.

In the fact, the power extract is maximized as shown in Figs.12-13., where it is clearly noticed that there is more power extract with ant colony optimization. In the times intervals [8s,11s], [12s,15s] and [16s,20s] it is also noticed that the power extracted with ant colony optimization speed control is more than the power extracted by using the classical method. In the interval [8s,11s] the amount of power with ACO is 20400 W and with classical is 20250 W, in the interval [12s,15s] the power with ACO is 6413 W and with classical is 6402 W, in the interval [16s,20s] the amount of power with ACO is 11556 W and with classical method is 11522 W.

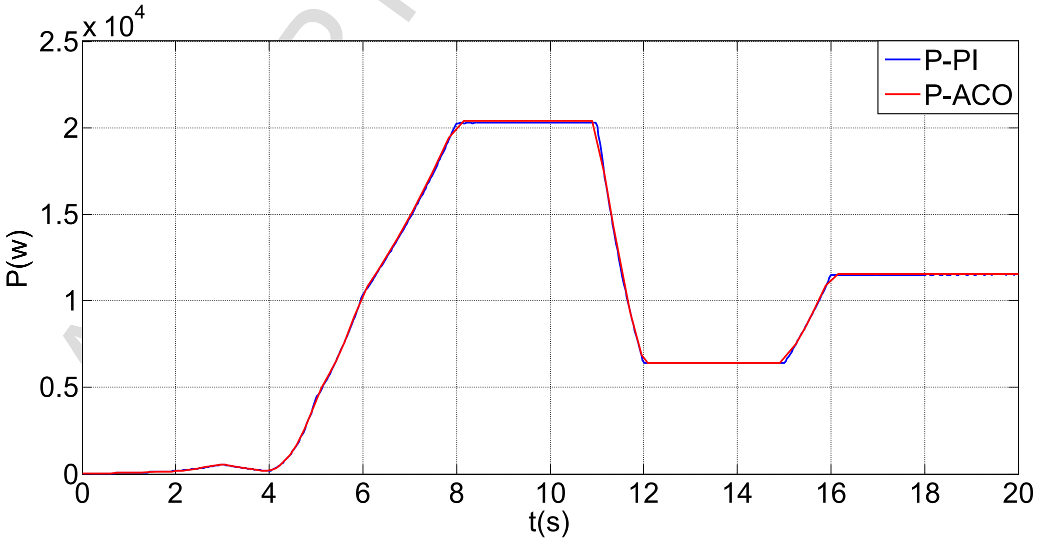

Fig. 12. Extract power using PI regulator and ACO

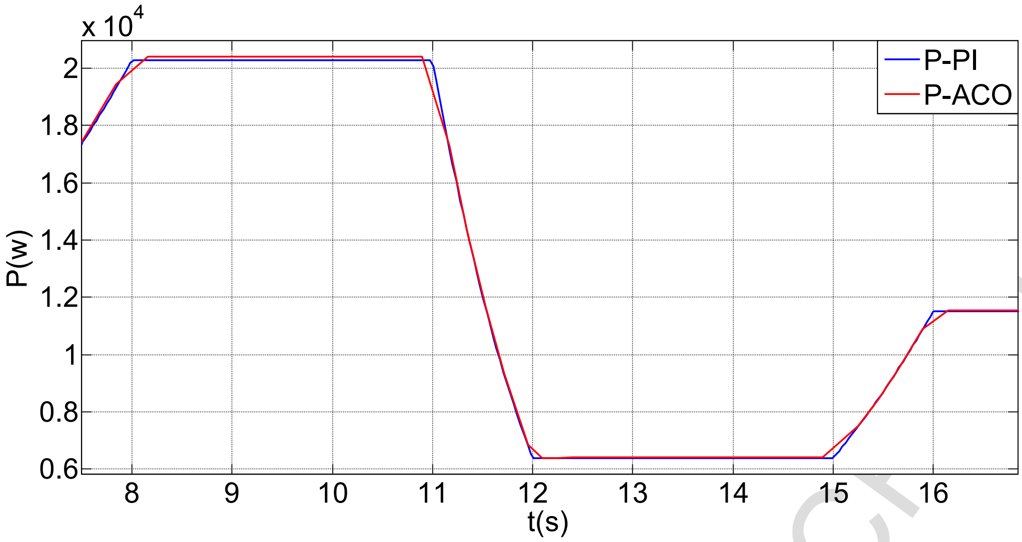

Fig. 13. Zoom on extract power

In Fig.14., the Tip speed ratio had been presented. The optimal ratio obtained with ant colony optimization is $\lambda_{opt-ACO} = 7.9$ and the value obtained by the classical method of speed control is $\lambda_{opt-PI} = 7.8$. These values give a logic interpretation of the previews results in Figs.9-10 and 12., where the speed ratio change in the aim to give the maximum C_p at each instant.

In Figs15- 16, the fitness function and K_i, K_p gains are shown. It is noticed that the function become constant from the second 3rditeration and fixed at 693.3 using ITAE function. In Fig.16.the gains K_p start to be fixed at the 7th iteration and K_i at the 16thIteration. At the 16th iteration, the algorithm start to give the same solution until that all the ants takes the same path (nodes). The algorithm stop at the 18th iteration and the convergence condition has been verified.

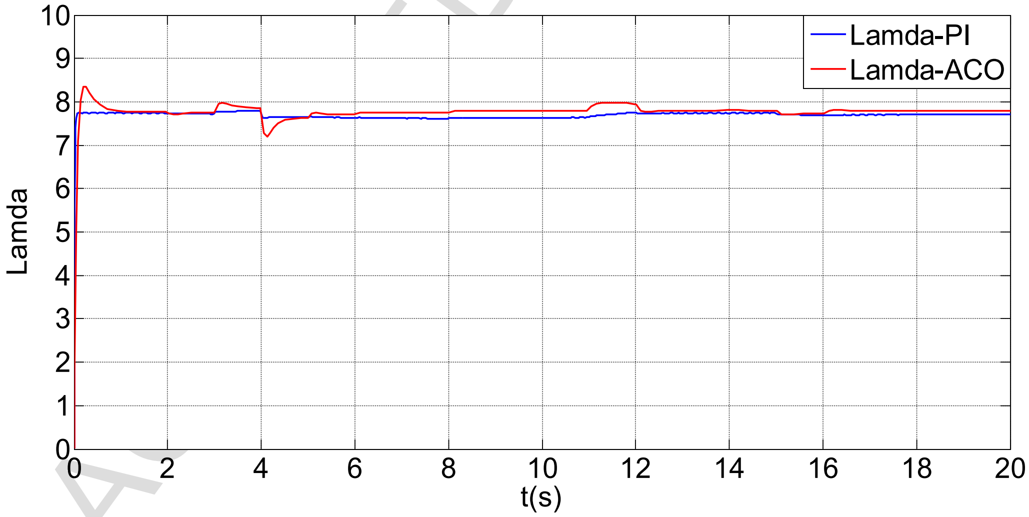

Fig. 14. Speed ratio using PI regulator and ACO

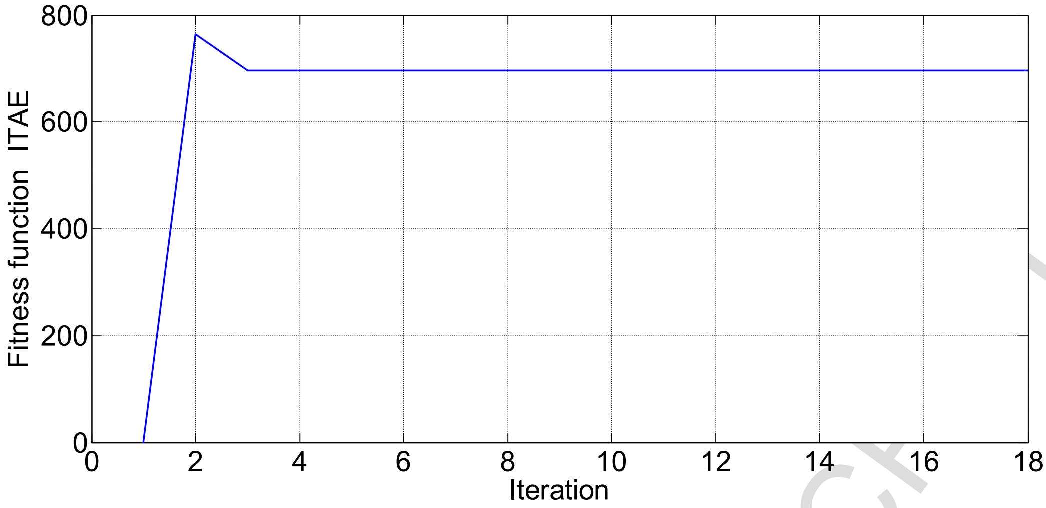

Fig. 15. Objective function values variation

The system parameters is optimized and achieved a final fitness value of 700 as it is shown in Fig. 15.

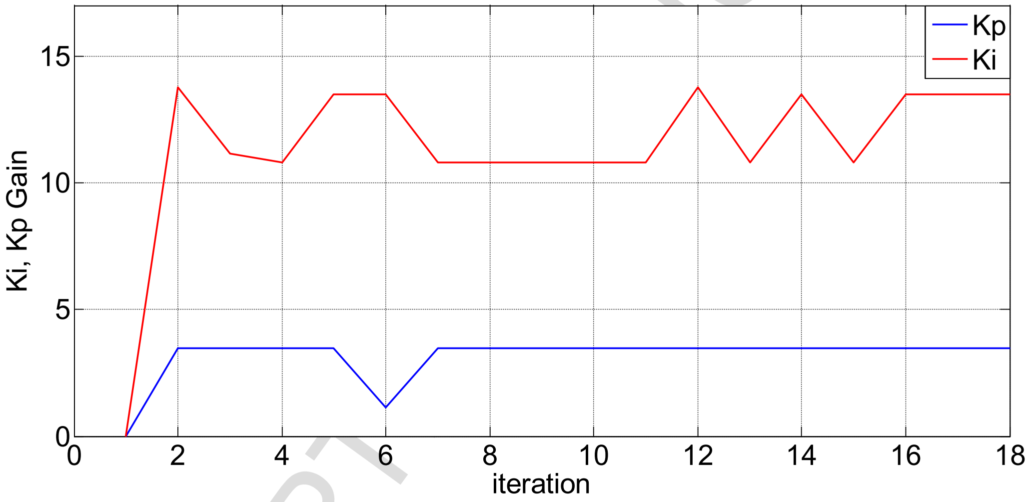

Fig. 16.Proportional and integral gain variation

5. CONCLUSION

In this work, a Maximum Power Point Tracking Using Ant Colony has been applied to wind energy conversion system connected to a Doubly Fed Induction Generator. The power coefficient has been maximized by using a metahuristic method of Ant colony optimization, and also used for extracting the wind power. The ACO algorithm has been used to optimize the parameters of proportional integral controllers in the speed control of the induction machine. This algorithm had the advantage to reach and find the best parameter without knowing induction machine parameters.

The obtained results have been compared to the classical calculation with proportional integral regulator, and, it is clearly that the algorithm of ant colony optimization gives better parameters reached, in the results we get better power coefficient than classical control of speed, in the fact, more power extracted from wind turbine.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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High Performance of Maximum Power Point Tracking Using Ant Colony Algorithm in wind turbine

1/- Achieve high efficiency in wind power systems using maximum power point tracking (MPPT) of a variable-speed turbine.

2/- Develop and improve a maximum power tracking control strategy using metaheuristic methods.

3/- Ant colony optimization (ACO) algorithm

4/-Determine the optimal PI controller parameters for speed control.