Maximum Power Point Tracking of Wind Energy Conversion System Using Multi-objective Grey Wolf Optimization of Fuzzy-Sliding Mode Controller

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Abstract- Ongoing electricity demand and the increasing growth of population have become necessary to provide alternative and clean sources of energy. Wind energy is one of the most important sustainable energies but the irregular characters of the primary source, which is characterized by a random wind speed variation, makes the process of control is difficult in order to maximize the power. This paper presents a multi objective grey wolf optimization (MOGWO) of fuzzy sliding mode controller in order to maximize the power captured by wind turbine; meanwhile, the mechanical loads are alleviated for variable speed wind energy conversion system (VS-WECS); firstly, Fuzzy logic theory based sliding mode control is developed by collecting the sliding surface data to reduce the chattering effect caused by the SMC, then the Grey Wolf Optimization is introduced to solve multi-objectives functions of WECS which are extracting the maximum power and alleviation the mechanical loads in order to find the optimal parameters of Fuzzy-Sliding mode controller to drive the conversion system to the optimal operating point. The obtained results are compared with those given by Sliding mode controller and Fuzzy-Sliding mode controller in which our proposed method can ensure a better dynamic behavior of the WECS.

Keywords Wind Energy Conversion System WECS, Maximum Power Point Tracking MPTT, Sliding mode control, Fuzzy Logic Control, MO-GWO.

1. Introduction

Nowadays, the growing demand for electrical energy throughout the world presents a serious problem to meet energy needs. Faced with this demand, most of the fossil energy resources are exploited compared to renewable energies [1, 2]. So we have to find another alternative is to use renewable energy, which offer the possibility to generate electricity cleanly. Today, after hydro, wind turbine becomes competitive in terms of production costs. It is currently contributing to the reduction emissions of greenhouse gases [3].

In the past, the majority of wind turbines installed were fixed speed. [4] These turbines nevertheless have many drawbacks: low energy efficiency, insofar as they are not optimized for an operating point and a short-lived because of the important forces to their structure. In addition, these turbines generate considerable fluctuations in the voltage and network power during wind gusts.

The variable wind speed turbines were then introduced to provide solutions to these problems. Power fluctuations are mitigated beings with a device which allows varying rotation speeds and thus store energy gusts as kinetic energy in the large rotating masses. Thus, the annual energy output of a variable speed wind turbine is increased by 5 to 10% compared to a fixed wind speed [5]. It was also shown that control strategies can have a major effect on the loads of the wind turbine and the electrical system [6], and regardless of the type of wind, the key factor remains the method of control.

The objectives of a wind turbine control law with variable speed based on [4]:

- Generation of maximum power below rated power in low winds.
- Maintain a satisfactory quality power above the rated power (instrong winds).
- Minimize the forces to the rotor blades and the drive device.

Much work in the field of wind energy conversion system (WECS) control. The development of these commands is mainly based on Linear Time invariant (LTI) models of wind systems. Conventional controllers PI, PID type have been widely used, but also a set of linear controllers were developed by Ekelund [7] to a variable speed wind turbine and fixed pitch, including LQ and LQG controls [7,8].

The LQG approach was duplicated by Ma [9] and Muteanu [10], to try to make improvements. H∞ was applied in [11] to control design for a stall regulated wind turbine drive system operating at variable speed operation while a sequencing approach gain scheduling is presented in [12] considering the wind turbine model in the context of Linear Parameters Varying (LPV) systems.

The synthesis of these commands is made from the linearized model of wind turbine; performance will degrade significantly when we are facing a real wind profile [13]. This is due to the nonlinear nature of the wind turbine system. To account for the non-linearity, some non-linear controllers have been proposed. Mullane et al suggest a non-linear control with an adaptive approach for estimating the aerodynamic torque [14].Nevertheless, the hypothesis of access to wind speed to calculate the reference speed which optimizes the production. This is also the case of the non-linear control proposed by Song [15]. However, none of these techniques studied the performance of the operator in case of disturbances or measurement noise. Two other known control techniques to be used frequently in the literature are the indirect speed control (ISC) [16] and the feedback control of the aerodynamic torque [7]. They use the assumption that the wind works in stabilized regime around any operating point of maximum efficiency curve. The control torque is calculated in this case from the instantaneous measurement of the rotor speed, but only in the steady state.

The sliding mode control is part of the family of controllers with variable structure, i.e. controls switching between several different control laws. The importance of sliding mode controllers lies in: the high accuracy, fast dynamic response, stability, simplicity of implementation, and robustness for changes in internal or external parameters [17] [18].

The principle of the sliding mode control is to constrain the trajectories of the system to achieve a given sliding surface, and then stay there. However, the control by sliding mode induced in practice high frequency switching known as the chattering. These switches can excite unwanted dynamics that risk to destabilizing, damage or even destroy the system studied.

There are deferent methods to reduce the phenomenon of chattering which is to replace the sign function with a continuous approximation in the sliding surface (saturation function or sigmoid function) [19], [20]. But this solution is only a special case of the fuzzy-sliding mode controller, hence the need to use a controller that combines fuzzy logic theory and sliding mode control to achieve a robust and smooth control. Another method is to use the high order sliding mode control [19], [20], [21], whose principle is to reject the discontinuities in higher derivatives of the system input.

The combination between the two control laws, the nonlinear fuzzy logic control and sliding mode controls one of the promising solutions to handle systems uncertainty, as well as nonlinearity situations, that is to say, the fuzzy controller for its speed and easy implementation, and the sliding mode for its reassuring theoretical foundations the stability and robustness standpoint. This combination benefits between the invariance uncertainties and perturbations of sliding mode control with those of speed and good track of fuzzy logic control.

In order to extract the maximum power from the WECS, the control objective can be formulated as an optimization problem, and there is a certain difficulty to find the controller parameters.

The optimization problems can be solved using meta-heuristic optimization methods. Some of these approaches include genetic algorithm (GA) [22], bacterial foraging (BF) [23], differential evolution (DE) [24], gravitational search algorithm (GSA) [25], particle swarm optimization (PSO) [26, 27], firefly algorithm (FA) [28], and cuckoo search (CS) [29].

In the last years, many researchers have focused on the optimization problems which aim at extracting the maximum power and alleviation the mechanical. J S González et al proposed an optimization of an overall production by individual setting of turbines operation. [30].X Gao et al. [31] proposed a multi-population genetic algorithm (MPGA) program in a wind farm for MPPT in a minimum investment cost. Kahla et al. [32] proposed PSO to optimize the parameters of an On-Off control scheme to control the rotor side converter in order to maximize the power of wind turbine equipped with DFIG connected to the grid with battery storage.

Grey Wolf Optimization (GWO) is recently developed meta-heuristics algorithm inspired from theleadership hierarchy and hunting mechanism of gray wolves in nature [33].GWO has been successfully applied for solving the engineering optimization problems [34,35].

In this paper Grey Wolf Optimization is introduced to solve multi-objectives functions of WECS such as extracting the maximum power and the mechanical loads are alleviated in order to find the optimal parameters of Fuzzy-Sliding mode controller. The plant model that modeled the dynamic behavior of the wind turbine is proposed, in which its strong non-stationeries are considered. Furthermore, the robust controller synthesized from combining the fuzzy logic theory and Sliding mode control strategies is proposed to reduce the chattering effect caused by SMC.

The present paper is structured as follows. In Section 2,a brief description of the proposed system with variable wind speed will be presented. In Section3, a modeling step of the wind energy conversion system will be given. In Section 4, a Fuzzy-sliding mode control strategy of the wind energy conversion system and robustness analysis will be discussed in details. Mathematical equations of the grey wolf optimization are given In Section 5. In Section 6, a MOGWO of Fuzzy-Sliding mode in order to find the optimal parameters of the controller is detailed. Simulation results will be proved. Finally, it is ended by a conclusions and numerical data of the proposed system.

2. System Modelling

The wind energy conversion system (WECS) under consideration in this paper is depicted in Fig. 1.The proposed system consists of the WECS based upon induction generator. The stator winding is connected to electrical grid. However the rotor, which is driven by the wind turbine, is connected back-to-back (AC-DC-AC) voltage source converter.

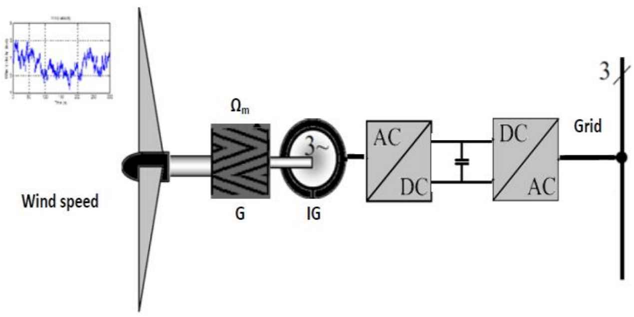

Fig. 1. Schematic diagram of the WECS equipped with the induction generator.

3. Modeling step of the WECS equipped with the induction generator

3.1. Wind turbine modelling

Wind energy comes from the kinetic energy of the wind. Indeed, if we consider an air mass (m) that moves with the velocity (v), the kinetic energy of this mass is expressed by

$$E_k = \frac{1}{2}mv^2 \tag{1}$$

Tthe wind velocity and the air mass which passes through a disc in time unit. It is defined as

$$m = \rho Sd \tag{2}$$

Where ρ, S and d denote respectively, the density of the air, the area swept by the rotor blades and the distance travelled by the wind. Moreover, the power available from the turbine is defined by [36]

$$P_w = \frac{1}{2}\rho\pi R^2 v^3 \tag{3}$$

From Betz theory, the mechanical power harvests by wind turbine is given by [37, 38]

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta) \tag{4}$$

WhereR, λ and β, C_p are respectively, the blade radius, tip speed ratio, pitch angle and the power coefficient or the wind turbine. The tip speed ratio is defined by

$$\lambda = \frac{\Omega_t R}{v} \tag{5}$$

Where$\Omega_t$denotes rotor speed of the wind turbine. Noticing that, several numerical approximations exist for$C_p(\lambda)$; the power coefficient can be described by a polynomial function of the tip speed ratio λ [39]:

$$C_p(\lambda) = a_6.\lambda^7 + a_5.\lambda^6 + a_4.\lambda^5 + a_3.\lambda^4 + a_2.\lambda^3 + a_1.\lambda^2 + a_0 \tag{6}$$

With polynomial coefficients $a_6 : a_0$

$$\begin{cases} a_6 = -4.54.10^{-7} \\ a_5 = 1.3027.10^{-5} \\ a_4 = -6.5416.10^{-5} \\ a_3 = -9.7477.10^{-4} \\ a_2 = 0.0081 \\ a_1 = -0.0013 \\ a_0 = 0.0061 \end{cases}$$

The $C_p - \lambda$ characteristics, for different values of the top speed ratio, are illustrated in Fig. 2.

Fig.2 shows curves of the power coefficient for different values ofλ . This gives a maximum power coefficient of $C_{pmax} = 0.475$ for a tip speed ratio λ which is 7 (λ_{opt}).

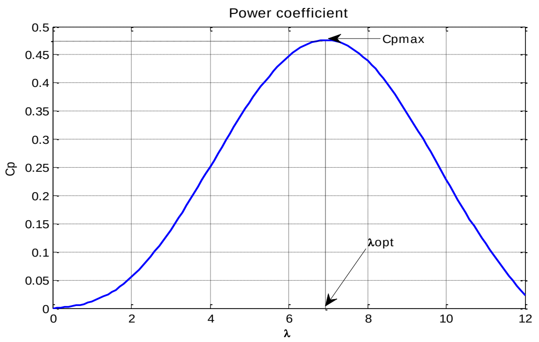

Fig. 2. $C_p(\lambda)$ curve.

Therefore, the aerodynamic torque Γ_t is determined through the ratio between both mechanical power $P_m$and rotation speed of the bladesΩ_t, yields also [40]

$$\Gamma_t = \frac{P_m}{\Omega_t} \tag{7}$$

$$\Gamma_t = \frac{1}{2}.\pi.\rho.v^2.R^3.C_\Gamma(\lambda) \tag{8}$$

Where$C_\Gamma(\lambda) = C_p(\lambda)/\lambda$ is the torque coefficient.

Moreover, the relationship between the aerodynamic torque$\Gamma_t$and the mechanical torque$\Gamma_g$applied on the generator shaft, is defined by [38]

$$\Gamma_g = \frac{\Gamma_t}{G} \tag{9}$$

Where G is the gearbox. The resulting mechanical equation is given as follows:

$$\Gamma_e - J\frac{d\Omega_m}{dt} = \Gamma_g + f\Omega_m \tag{10}$$

Where$f$ and J denote the friction coefficient and the system moment of inertia respectively. Furthermore, the mechanic generator speed $\Omega_m$is defined by

$$\Omega_m = \Omega_t G \tag{11}$$

From Equations (7-11), the plant model of mechanic system that established from the wind turbine and the speed multiplier with MPPT algorithm is shown in Fig.3.

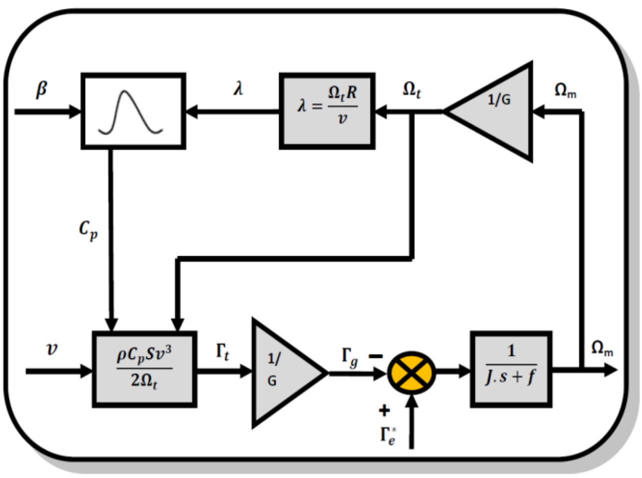

Fig.3. The obtained plant model of the mechanic system.

3.2. On the modeling step of the induction generator

The model of the induction generator, expressed in d−q frame, is given by the following voltage system equations [41]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} - \omega_s \varphi_{ds} \\ 0 = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - \omega_r \varphi_{qr} \\ 0 = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} - \omega_r \varphi_{dr} \end{cases} \tag{12}$$

It is defined also by the following stator and rotor flux that expressed by [40]

$$\begin{cases} \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \varphi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \tag{13}$$

Where $v_{ds}$and v_{qs}represent the stator voltages in (d, q) axis;$i_{ds}, i_{qs}, i_{dr}, i_{qr}$ are the currents components of the stator and rotor respectively; while $\varphi_{ds}, \varphi_{qs}, \varphi_{dr}, \varphi_{qr}$ are the stator and rotor (d, q) components; $R_s, R_r$are the stator and rotor phase resistances; L_s, L_r and L_m are stator, rotor and respectively mutual winding inductance.

The process output to be controlled presents the electromagnetic torque of the induction machine, it is expressed as

$$\Gamma_e = \frac{3}{2} p L_m \left(i_{qs}\, i_{dr} - i_{ds}\, i_{qr}\right) \tag{14}$$

The rotor field is oriented on the d-axis; this implies the cancellation of the φ_{qr} component ($\varphi_{qr} \backsimeq 0$) and a new expression for the torque, as in the following expression:

$$\Gamma_e = \frac{3}{2} p \frac{L_m}{L_r} i_{qs} \varphi_{dr} \tag{15}$$

In Appendix.Tab.1summarizes the signification of each induction machine parameter, as well as Tab. 2 gives the numerical data for each parameter of wind turbine.

4. On the Fuzzy Sliding mode Synthesis Controller

The main goal of the Fuzzy-Sliding mode controller is a wisely chosen sliding surface which allows the turbine to operate more or less close to the optimal regimes characteristic (ORC). The proposed design controller shown in Fig.4 solves the chattering problem of above control strategy using the fuzzy logic control strategy in the switched component. In order to compute the sliding surface and the control law, the state equations are given by the following expression:

$$\dot{x} = f(x,t) + B(x,t).u \tag{16}$$

Where:

$$f(x,t) = \begin{bmatrix} \frac{\Gamma_t}{(J_t.G)} - \frac{\Gamma_e}{J_t} \\ -\frac{\Gamma_e}{T_G} \end{bmatrix} \tag{17}$$

$$B(x,t) = \begin{bmatrix} 0 \\ \frac{1}{T_G} \end{bmatrix} \quad (18)$$

Then, the state equations of the study system are given by:

$$\begin{bmatrix} \dot{\Omega}_m \\ \dot{\Gamma}_e \end{bmatrix} = \begin{bmatrix} \frac{\Gamma_t}{(J_t.G)} - \frac{\Gamma_e}{J_t} \\ -\frac{\Gamma_e}{T_G} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{T_G} \end{bmatrix}.u \quad (19)$$

Where $x = [\Omega_m \quad \Gamma_e]$,$u = \Gamma_e^*$,$J_t$ is the inertia of the high-speed shaft and $T_G$is the time constant of the electromagnetic subsystem. By applying the existence condition of the equivalent control input ($\frac{\partial\sigma}{\partial x}.B(x,t) \neq 0$), the sliding surface is given by the following expression [42] :

$$\sigma = d_1.J_h.\Omega_m + \Gamma_e.(1 + d_2.J_h) - \Gamma_t/G \quad (20)$$

With d_1, d_2 are the inverse of the time constant and the static gain respectively given by the following expressions:

$$d_1 = -1/T_{sm} \quad (21)$$

$$d_2 = -\frac{d_1\Omega_{mopt}}{\Gamma_{eopt}} \quad (22)$$

Where J_h being the equivalent inertia rendered at the high-speed shaft and T_{sm} is a time constant.

From Equation (19), one can obtain

$$\Gamma_e = \frac{1}{1+d_2.J_h}.(\frac{\Gamma_t}{G} - d_1.J_h.\Omega_m) \quad (23)$$

The control lawu is the sum of the equivalent component and switching control component:

$$u = u^{eq} + u^n \quad (24)$$

The following relations used to compute the equivalent control input, [43]:

$$u^{eq} = -\left[\frac{\partial\sigma}{\partial x}.B\right]^{-1}.\left[\frac{\partial\sigma}{\partial t} + \frac{\partial\sigma}{\partial x}.f(x,t)\right] \quad (25)$$

Where:

$$\frac{\partial\sigma}{\partial x}.B = \begin{bmatrix} \frac{\partial\sigma}{\partial\Omega_m} & \frac{\partial\sigma}{\partial\Gamma_e} \end{bmatrix}.\begin{bmatrix} 0 \\ \frac{1}{T_G} \end{bmatrix} = \frac{1}{T_G}.\frac{\partial\sigma}{\partial\Gamma_e} \quad (26)$$

The partial derivative of the sliding surface in relation to the electromagnetic torque and the rotor speed are given respectively by the following expressions:

$$\frac{\partial\sigma}{\partial\Gamma_e} = 1 + d_2.J_h \quad (27)$$

$$\frac{\partial\sigma}{\partial\Omega_t} = d_1.J_h - \frac{1}{G}.\frac{\partial\Gamma_t}{\partial\Omega_t} \quad (28)$$

From Equation (8), the partial derivative of the wind torque in relation to the rotor speed:

$$\frac{\partial\Gamma_t}{\partial\Omega_t} = \frac{1}{2}.\pi.\rho.v^2.R^3.\frac{\partial C_\Gamma(\lambda)}{\partial\Omega_t} = \frac{Kv^2R}{G}\left(\frac{\dot{C}_p(\lambda).\lambda - C_p(\lambda)}{\lambda^2}\right) \quad (29)$$

With $K = 0.5.\pi.\rho.R^2$,$\dot{C}_p(\lambda)$is the derivative of the power coefficient in relation to λ. Equation (28) can rewrite:

$$\frac{\partial\sigma}{\partial\Omega_t} = d_1.J_h - A(\lambda, v) \quad (30)$$

$$A(\lambda, v) = K.v.R^2.\left(\frac{\dot{C}_p(\lambda).\lambda - C_p(\lambda)}{\lambda^2.G^2}\right) \quad (31)$$

Then the expression of the equivalent control input u^{eq} is given by:

$$u^{eq} = \Gamma_e - \frac{T_G}{1+d_2J_h}(d_1.J_h.\Omega_m + d_2.J_h.\Gamma_e)(d_1 - A(\lambda, v)) \quad (32)$$

The alternate high-frequency component u^n is obtained by choosing the Lyapunov function, which is switched between $-\tau$ and $+\tau$ where $\tau > 0$, is given by

$$u^n = \tau.\mathrm{sign}(\sigma) \quad (33)$$

Noticing that u^{eq}makes the system operated in the optimal point. However, the Component u^n has the role of stabilizing the system behavior around this point, once reached. As previously mentioned, the disadvantage of the sliding mode controller appears in the switching component step. To avoid this problem the term $\mathrm{sign}(\sigma)$ in the alternate high-frequency component$u^n$is substituted by the fuzzy control inputu^f, yields also the following control law:

$$\Gamma_e^* = u^{eq} + u^f \quad (34)$$

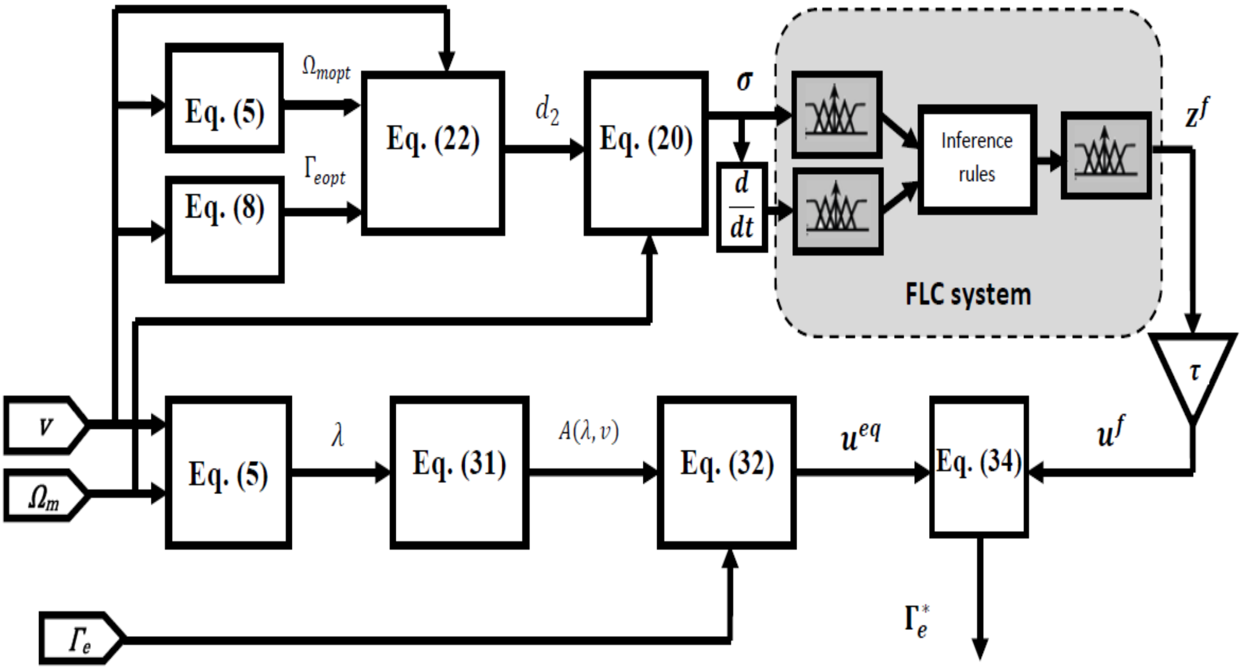

Fig.4. The Proposed fuzzy sliding mode control for MPPT.

The fuzzy logic theory is introduced hereto reduce the effect of the chattering problem of the switched component. Fuzzy logic theory has been introduced in many researches as an alternative to conventional control techniques that are based on complex mathematical models. The basic idea behind FLC is to combine the "expert experience" of a human operator with the design of the controller that does not need any mathematical model.

The Fuzzy controller comprises three main steps namely, fuzzification, rule evaluation, and defuzzification. Two inputs of the fuzzy controller areσ and its derivative$\dot{\sigma}$, as well as, the fuzzy system output is given byz^f. In the fuzzification stage, the seven triangular membership functions are given for the inputs (σ and $\dot{\sigma}$) and outputz^f.Moreover; the fuzzy input-output system is linked by the rule base, which commonly obtained from expert knowledge. It contains a collection of fuzzy conditional statements expressed as the set of if − then rules such as

$$R^{(i)}: \text{if}(y_1 \text{ is } F_1) \text{ and } (y_2 \text{ is } F_2) \text{ and } \cdots (y_n \text{ is } F_n)$$

$$\text{then } \left(H \text{ is } W^{(i)}\right), i = 1, \dots M \quad (35)$$

$(y_1, y_2, \dots y_n)$ are the input variables vector, His the output variable, M is the number of rules, n is the number of the fuzzy variables, $(F_1, F_2, \dots F_n)$are the fuzzy sets.

Table.1 shows the rules base when each pair $(\sigma, \dot{\sigma})$determines the output level of the corresponding variable u^f.The following abbreviations are used in Table.1 as

NB:Negative Big.NM: Negative Medium. NS : Negative Small.ZR:Zero.PS : Positive Small. PM : Positive Medium. PBis Positive Big. The fuzzy system is described by the following expression:

$$u^f = \tau.\frac{\sum_{j=1}^{49}\left(\bar{z}^j.\mu_{\sigma_j}.\mu_{\dot{\sigma}_j}\right)}{\sum_{j=1}^{49}\left(\mu_{\sigma_j}.\mu_{\dot{\sigma}_j}\right)} \quad (36)$$

Where $\bar{z}^j$ is the singleton control in j^{th}rule, $\mu_{\sigma_j}$is the member function value ofσ, and $\mu_{\dot{\sigma}_j}$ is thermember function value of $\dot{\sigma}$ in j^{th} rule.

Table 1. Fuzzy rule

z^f							
σ \ $\dot{\sigma}$	**NB**	**NM**	**NS**	**ZR**	**PS**	**PM**	**PB**
NB	*NB*	*NB*	*NB*	*NB*	*NM*	*NS*	*ZR*
NM	*NB*	*NB*	*NB*	*NM*	*NS*	*ZR*	*PS*
NS	*NB*	*NB*	*NM*	*NS*	*ZR*	*PS*	*PM*
ZR	*NB*	*NM*	*NS*	*ZR*	*PS*	*PM*	*PB*
PS	*NM*	*NS*	*ZR*	*PS*	*PM*	*PB*	*PB*
PM	*NS*	*ZR*	*PS*	*PM*	*PB*	*PB*	*PB*
PB	*ZR*	*PS*	*PM*	*PB*	*PB*	*PB*	*PB*

5. Grey Wolf Optimization Algorithm

The GWO algorithm simulates the natural behavior of a group of wolves to hunt their prey [33]. Within the different wolves categories like alpha, kappa, delta and omega are distinguished for the simulation. The mechanism that follows is simple. The first groups of alpha wolves are the leaders of the pack and, therefore, influence in a more forceful way in the search space. At the end of the execution, the best individual is going to be the one associated with the alpha wolf. The Fundamental stages of grey wolf hunting are tracking, chasing, pursuing, encircling, and attacking the prey.

Firstly, the following equations are proposed for the modeling of encircling the prey [44]:

$$\vec{D} = |\vec{C}.\vec{X}_p^t - \vec{A}.\vec{X}^t| \quad (37)$$

$$\vec{X}^{t+1} = \vec{X}_p^t - \vec{A}.\vec{D} \quad (38)$$

Where t is the current iteration, $\vec{X}_p$ is the position vector of the prey, and $\vec{X}$ indicates the position vector of a grey wolf.$\vec{A}$ and $\vec{C}$ are vectors that have three different random numbers and that help the candidate solutions by moving them into the search space calculated as follows:

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \quad (39)$$

$$\vec{C} = 2.\vec{r}_2 \quad (40)$$

The parameter $\vec{a}$ is the exploration factor that starts with a value of 2 and decreases over the course of iterations until it reaches 0 and r_1, r_2 are random vectors in [0, 1].Fig.5 shows the 2D position of prey at (X^*, Y^*) and grey wolf at (X, Y) with its possible next locations.

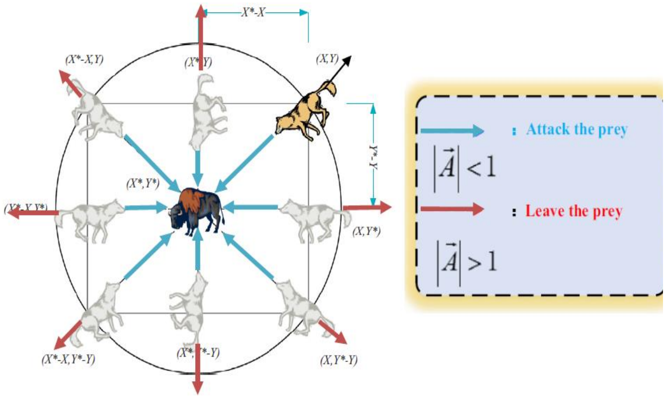

Fig. 5. 2D position vectors and their possible next locations.

The position of the best search agents can be calculated by the following equations:

$$\begin{cases} \vec{D}_\alpha = |\vec{C}_1.\vec{X}_\alpha - \vec{X}| \\ \vec{D}_\kappa = |\vec{C}_2.\vec{X}_\kappa - \vec{X}| \\ \vec{D}_\delta = |\vec{C}_3.\vec{X}_\delta - \vec{X}| \end{cases} \quad (41)$$

$$\begin{cases} \vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.\vec{D}_\alpha \\ \vec{X}_2 = \vec{X}_\kappa - \vec{A}_2.\vec{D}_\kappa \\ \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.\vec{D}_\delta \end{cases} \quad (42)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (43)$$

When$|A| < 1$, the wolves attack towards the prey, which represents an exploitation process.

6. MOGWO of Fuzzy sliding mode controller

GWO was proposed to achieve quickly a good overall solution without the need for large memory or significant computing capabilities; we calculate the best parameters of the controller, on minimizing the two objectives functions in order to maximize the power captured by WECS; meanwhile, the mechanical loads are alleviated. The following equations presented the two objectives functions:

$$\begin{cases} Fit1 = \frac{1}{n_1 T_s} \sum_{l=1}^{n_1} e_1(k_1) \\ Fit2 = \frac{1}{n_2 T_s} \sum_{l=1}^{n_2} e_2(k_2) \end{cases} \quad (44)$$

Where: $T_s$is the sampling time.

$e_1 = \Gamma_e^* - \Gamma_e$ is the difference between value of the electromagnetic torque reference and the value of the electromagnetic torque .

$e_2 = C_{pmax} - C_p$ is the difference between value of the maximum power coefficient and the value of actual power coefficient.

The proposed optimization of the fuzzy sliding mode controller is shown in Fig. 6.

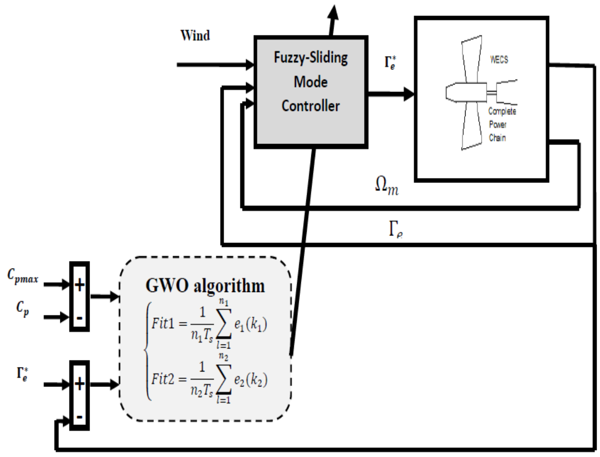

Fig.6. Multi-objective GWO of Fuzzy-Sliding mode controller.

7. Results and Discussions

In order to analyze the performance of the proposed MOGWO of Fuzzy-Sliding mode controller, simulation results are carried out using Matlab–Simulink package; Figure.7 shows the test wind profile limits (5m/s-8m/s) of the wind turbine with mean wind speed of 7 m/s.

Numerical values for the parameters of the Multi-objective Grey wolf optimization are given in Tab.3 in Appendix.

The evolution of the power coefficient for MOGWO of Fuzzy-Sliding mode control, Fuzzy-Sliding mode control and Sliding mode control are depicted in Fig.8.It should be noted that$C_{p_{max}} = 0.475$ for the wind turbine in this simulation. It can be seen from Figure.8that the proposed method of control is able to track quickly the maximum power coefficient better than the other methods of control.

In Fig.9, one can see that the effectiveness of the proposed MOGWO of Fuzzy-Sliding mode control to more accurately maintain the tip speed ratio around the optimal value as compared with the Fuzzy-sliding mode and Sliding mode methods.

Fig.10 shows the generator speed waveforms obtained by the different control strategies. These results confirm that the disturbance of the wind speed variation is strongly deflecting the generator speed to its optimal trajectory particularly, between the time interval 56 to 62 s for the Fuzzy-Sliding mode and Sliding mode control. This deviation has obvious consequences for the capture of wind energy, counter to MOGWO of Fuzzy sliding mode control which manages to assure the optimal speed tracking.

Fig.11 shows the performance of the proposed method, one could remark the operating point distribution around optimal regimes characteristic in speed-power plane (Fig.11.a) and in tip speed ratio-electromagnetic torque plane (Fig.11.b). Both figures show a better performance of the control law the torque follows the reference given by the control and allows us to reduce the torque ripples compared with Fuzzy-Sliding mode control (Fig.12) and Sliding mode control (Fig.13).

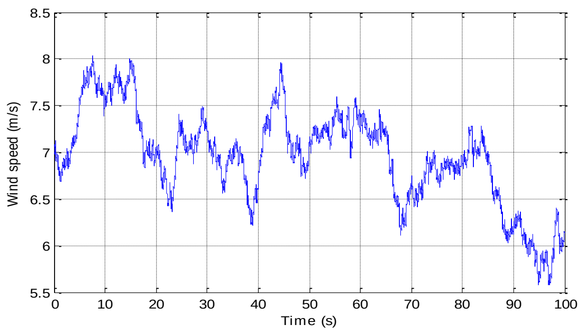

Fig.7. Wind speed profile

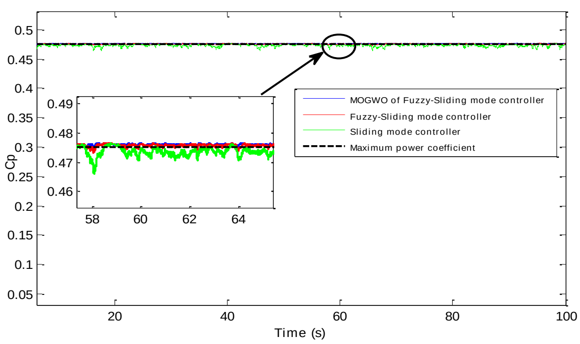

Fig.8. The power coefficient

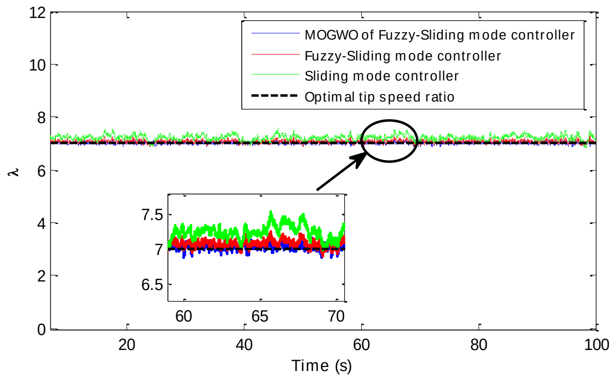

Fig. 9. Tip speed ratio

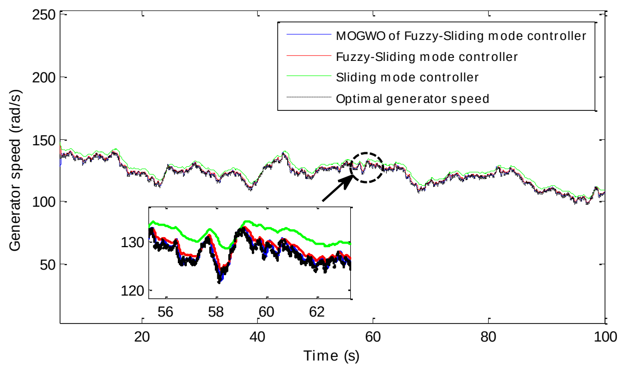

Fig.10. Generator speed

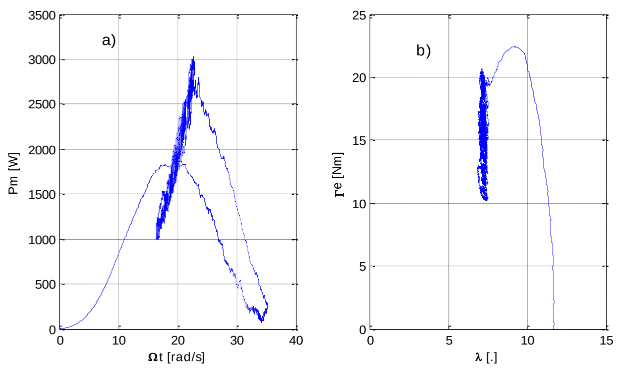

Fig.11. Performance of MOGWO Fuzzy-Sliding mode control

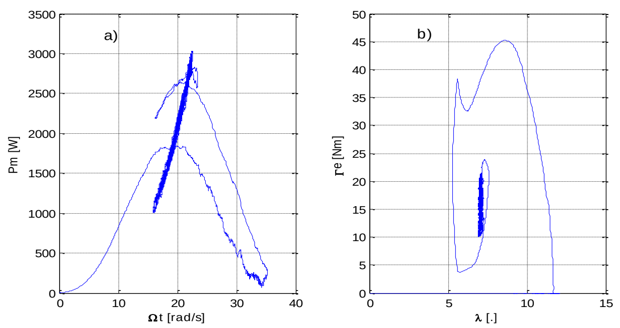

Fig.12. Performance of Fuzzy-Sliding mode control

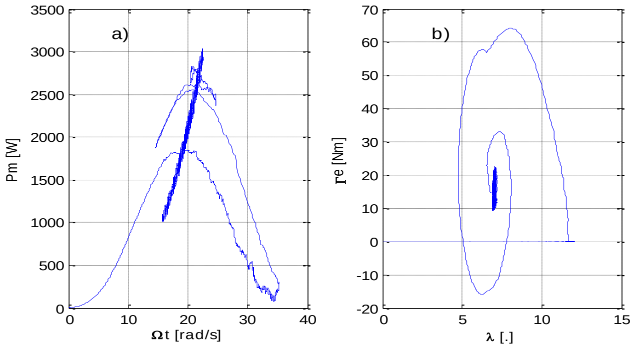

Fig.13. Performance of sliding mode control

The efficiency of the proposed control structure can be evaluated in terms of energy which equals the ratio between the captured energy$E_{capt}$and the optimalenergyE_{opt}, denoted by:

$$\eta = \frac{E_{capt}}{E_{opt}} = \frac{\int_{t_0}^{t_f} 0.5\pi R^2 v^3(t) C_p(\lambda) dt}{\int_{t_0}^{t_f} 0.5\pi R^2 v^3(t) C_p(\lambda_{opt}) dt} \quad (45)$$

The MOGWO of Fuzzy-Sliding mode control efficiency (0.998) is a little higher than the Fuzzy-Sliding mode control efficiency (0.985), and is higher than the Sliding mode control efficiency (0.955). The dynamic performance of the proposed method is accomplished for fast wind speeds variations.

8. Conclusion

This paper has presented a new meta-heuristic called Grey wolf optimization to find the optimal parameters of fuzzy-sliding mode controller applied to an induction generator used in a wind energy conversion system connected to the grid. Firstly, the different parts of the proposed WECS have been modeled separately and the Fuzzy-Sliding mode control aims at reducing the effect of the chattering in the alternate high-frequency component caused by the sliding mode control, while limiting the electromagnetic torque ripples. Based on two objectives criteria in order to maximize the power captured by WECS; meanwhile, the mechanical stress are alleviated, MO-GWO is employed to selection the controller parameters .The obtained results of the proposed controller compared with Fuzzy-Sliding mode control and Sliding mode control was really encouraging in the application of wind energy in order to ensure the robustness and quality of the energy produced.

Appendix

Table 1. Induction generator parameters.

Parameters	Values
Number of search agents	25
Maximum number of iterations	100

Table 2. Wind turbine parameters.

Parameters	Values
Rated voltage	220 V
Rated frequency	50 Hz
Stator winding resistance	1.265 Ω
Rotor winding resistance	1.430 Ω
Stator winding self-inductance	0.1452 mH
Transformer between the stator winding and equivalent rotor winding	0.1397 mH

Table 3. GWO parameters.

Parameters	Values
The air density	1.25 kg/m^3
The blade radius	2.5 m
The maximum wind power conversion coefficient	0.475
The optimal tip speed ratio	7
Rotor inertia	3 $kg.m^2$

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