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On -Off Control based Particle Swarm Optimization for Maximum Power Point Tracking of Variable Speed Wind Energy Conversion Systems

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***Abstract*— in recent years, there has been an evolution of electricity production based on wind energy, because its production is environmentally friendly. In this paper, Particle Swarm Optimization (PSO) is proposed to generate an On-Off Controller. On-Off Controller based maximum power point tracking is proposed to control a squirrel-cage induction generator (SCIG) of wind energy conversion system .Simulation studies are made with Matlab / Simulink to verify the effectiveness of the purposed method.**

***Keywords*— Wind Energy Conversion System (WECS),Maximum Power Point Tracking, On-Off Control, Particle Swarm Optimization (PSO).**

I. INTRODUCTION

Electrical energy is increasing in recent years and the constraints related to its production, such as the effects of pollution, the research lead to the development of renewable energy sources. In this context, Wind energy conversion systems (WECS) offer a very competitive solution. To overcome the problem of efficiency for maximum performance, it is necessary to optimize the design of all parts of the WECS [1].

In addition, it is necessary to optimize the tip speed ratio in order to extract the maximum power and thus run the generator at its point of maximum power (MPP) using a MPPT controller (maximum power point tracking), consequently, achieve maximum electromagnetic torque in the variation of wind [2].

A significant number of MPPT control technology have been developed for years, starting with simple techniques such as MPPT controllers based on the feed back of the power and generator speed to get the optimal tip speed ratio [3].

On-Off control is a robust control method aiming at captured power maximization for a low power fixed-pitch SCIG-based wind turbine. This method superposes the tracking of the optimal torque value and the tracking of the optimal tip speed ratio [4].

The particle swarm optimization (PSO) is an evolutionary computation technique developed by Eberhart and Kennedy in 1995 inspired by social behaviour of bird flocking [5].

The PSO algorithm is an optimization tool based on population, and the system is initialized with a population of random solution. It can search for optima by the updating of generations [6].

There is a certain difficulty about the On-Off control, concerning the definition of a switched component (following the sign of the tip speed ratio error) with guaranteed properties of attractiveness and stability [7].

In this paper, we propose an On-Off control based on particle swarm optimization (PSO) algorithm. By the PSO algorithm, the parameters of a switched component function are optimized for maximum power point tracking of wind energy conversion system.

II. WIND TURBINE MODELING

The wind conversion system, which is shown in Figure 1, consists of: a turbine, a Gear box, a SCIG and Compensating capacitors.

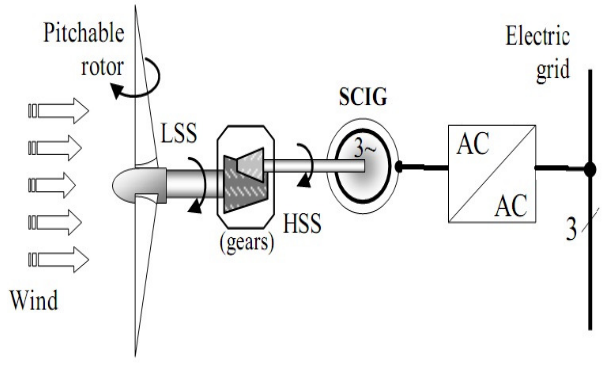

Fig.1 A wind energy conversion scheme

The turbine converts the kinetic energy of wind into mechanical energy and the total kinetic power available from the turbine of a wind turbine is given by:

$$P_a = \frac{1}{2}\rho S v^3 \qquad (1)$$

According to Betz theory, the mechanical power harvested by a wind turbine P_a is expressed as:

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

Where R is the blade radius of the wind turbine, ρ is the air mass density, v is the wind speed, λ is the tip speed ratio, β is the pitch angle, C_p is the wind turbine energy coefficient.

The tip speed ratio is defined as:

$$\lambda = \frac{w_r R}{v} \qquad (3)$$

w_r is a wind turbine rotor speed.

The $C_p - \lambda$ characteristics, for different values of the pitch angle β , are illustrated in Figure 2. This figure indicates that there is one specific λ at which the turbine is most efficient. Normally, a variable-speed wind turbine follows the $C_{P\max}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt} .

The rotor power (aerodynamic power) is also defined by

$$P = w_r T_a \qquad (4)$$

Moreover

$$C_q(\lambda) = \frac{C_p(\lambda)}{\lambda} \qquad (5)$$

It, thus, follows that the aerodynamic torque is given by

$$T_a = \frac{1}{2}\pi \rho R^3 C_q(\lambda) v^2 \qquad (6)$$

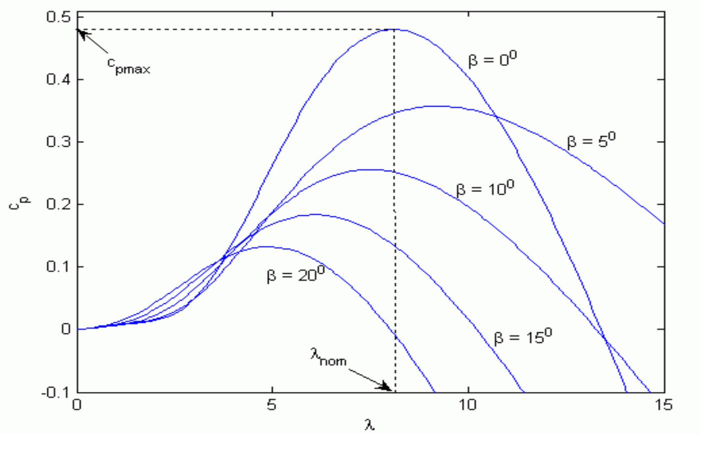

Fig.2 $C_p(\lambda, \beta)$ curve.

III. MODELLING OF SCIG

A mathematical model of a Squirrel-Cage Induction Generator (SCIG) in *d-q* rotating coordinate system is established.

The rotor of the squirrel-cage asynchronous generator is short circuit. So in the *d-q* rotation coordinate system, the voltage equation of the squirrel-cage asynchronous generator is as follows [8-9]:

$$\begin{bmatrix} u_{ds} \\ u_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_1 L_s & L_m p & -\omega_1 L_m \\ \omega_1 L_s & R_s + L_s p & \omega_1 L_m & L_m p \\ L_m p & 0 & R_r + L_r p & 0 \\ \omega_s L_m & 0 & \omega_s L_r & R_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \qquad (7)$$

The flux equations of stator are as follows:

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \qquad (8)$$

The torque equations of vector controlling are as follows:

$$T_e = n_p \frac{L_m}{L_r} i_{sq} \psi_r \qquad (9)$$

$$\psi_r = \frac{L_m}{T_r p + +1} i_{sd} \qquad (10)$$

Where ψ_r is the rotor flux, ω_1 the stator electricity angular velocity , ω_s is the slip angular velocity, L_s is stator inductance, L_r is the rotor inductance, L_m is the excitation circuit reactance. In the expression of components and rotor flux $T_r = L_r / R_r$.

IV. ON-OFF CONTROL FOR MAXIMUM POWER POINT TRACKING OF WECS

For ensuring the optimal energy conversion an On-Off supposes that the WECS reacts sufficiently fast to variation of the low-frequency wind speed.

An On-Off controler can be used in order to zeroing the difference between the optimal tip speed ratio and the actual tip speed ratio σ [10]:

$$\sigma = \lambda_{opt} - \lambda \tag{11}$$

On-Off objective is to make the difference between the optimal tip speed ration and the actual tip speed ratio as small as possible with regulate the rotor speed according to the wind speed [11].

The control law u has two components:

$$u = u^{eq} + u^{n} \tag{12}$$

Where the equivalent control u^{eq} as defined:

$$u^{eq} = 0.5\pi.\rho.R^{3}.v_{s}^{2}.\frac{C_{p}(\lambda_{opt})}{i.\lambda_{opt}} = A.v_{s}^{2} \tag{13}$$

With: $A = 0.5\pi.\rho..R^{3}\,\frac{C_{p}(\lambda_{opt})}{i.\lambda_{opt}}$ and i is the gear box ratio, u^{n} is an alternate, high-frequency component, which switches between two values, $-\alpha$ and $+\alpha, \alpha > 0$:

$$u^{n} = \alpha.sign(\sigma) \tag{14}$$

Component u^{eq} makes the system operated in the optimal point, whereas u^{n} has the role of stabilising the system behaviour around this point, once reached.

In (10), the rotor flux ψ_r, only has a relationship with i_{sd} which is the excitation component of stator current.

When the rotor flux ψ_r is constant, the generator torque T_e is only for the stator current torque component to decide. So through the control of i_{sq}, we can control the electromagnetic torque of the generator.

The proposed generator electromagnetic torque control strategy is shown by Fig.3.

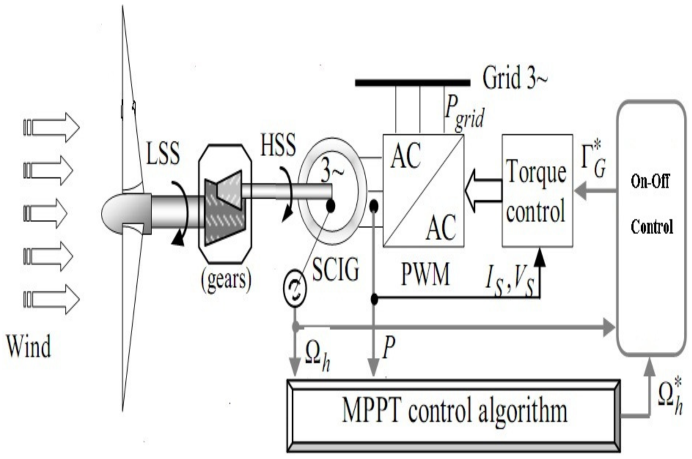

Fig.3. On-Off control based MPPT scheme.

V. PARTICULE SWARM OPTIMIZATION

Evolutionary algorithms have been successfully applied to solve many complex optimization engineering problems. Together with genetic algorithms, the PSO algorithm, proposed by Kennedy and Eberhart [12].

PSO is an algorithm based on the behaviour of individuals (i.e. particles) of a swarm. It has been perceived that members within a group seem to share information among them, a fact that causes to increased efficiency of the group. An individual in a swarm approaches to the optimum by its present velocity, previous experience, and the experience of its neighbours.

Iteration is defined as the following two equations in this study:

$$\begin{cases} V_{iD}^{t+1} = k \cdot \left(V_{iD}^{t} + c_1 r_1 (P_{iD}^{t} - z_{iD}^{t}) + c_2 r_2 \left(g_{i}^{t} - z_{iD}^{t}\right)\right) \\ z_{iD}^{t+1} = p_{iD}^{t} + z_{iD}^{t} \end{cases} \tag{15}$$

where, i = 1, ..., n and n is the size of the swarm, D is dimension of the problem space, c_1 and c_2 are positive constants, k is the momentum or inertia, r_1 and r_2 are random numbers which are uniformly distributed in [0, 1], t determines the iteration number, p_i represents the best previous position (the position giving the best fitness value) of the ith particle, and g represents the best particle among all the particles in the swarm. The algorithm of PSO can be depicted as follows:

- **Step 1**: Initialize a population (array) of particles with random positions and velocities V on d dimension in the problem space. The particles are generated by randomly selecting a value with uniform probability over the dth optimized search space $\left[z_d^{\min}, z_d^{\max}\right]$.
- **Step 2:** Evaluate desired optimization fitness function in D variables for each particle.
- **Step 3:** Compare particles fitness evaluation with x_{pbest}, which is the particle with best local fitness value. If the current value is better than that of x_{pbest}, then set xpbest equal to the current value and x_{pbest} locations equal to the current locations in d dimensional space.
- **Step 4:** Identify the particle in the neighborhood with the best fitness so far, and assign its index to the variable g.
- **Step 5:** Update velocity and position of the particle according to Equation (23).
- **Step 6:** Loop to **Step 2**, until a criterion is met, usually a good fitness value or a maximum number of iterations (generations) *m* is reached.

VI. PSO LERNING ALGORITHM

To accelerate the convergence of PSO, it was proposed to find a better solution in a minimum computation time and accuracy, we calculate the best solution, on minimizing a certain criterion (objective function) is the mean square error (MSE) calculated by the following equation:

$$MSE = Fit = \frac{1}{nT}\sum_{i=1}^{n} e(K)^2 \qquad (16)$$

Where: $e(k)$ is the total number of samples and T the sampling time, $e(k)$ =T_{ref}-Te is the difference between value of the electromagnetic torque reference and the value of the electromagnetic torque under On-Off control.

According to Fig. 4, after determining the initial values like swarm size and initial velocity of particles, PSO calculates the parameters of On-Off controller for each particle and stores the MSE. Then according to the MSE the best position of each particle is calculated and the best particle among the all particles in population is selected. This process is iterated while the number of iterations is equal with max iteration number and the best particle is selected after final iteration. In fact, the best particle contains the optimal On-Off controller parameters which are corresponding to the minimum MSE.

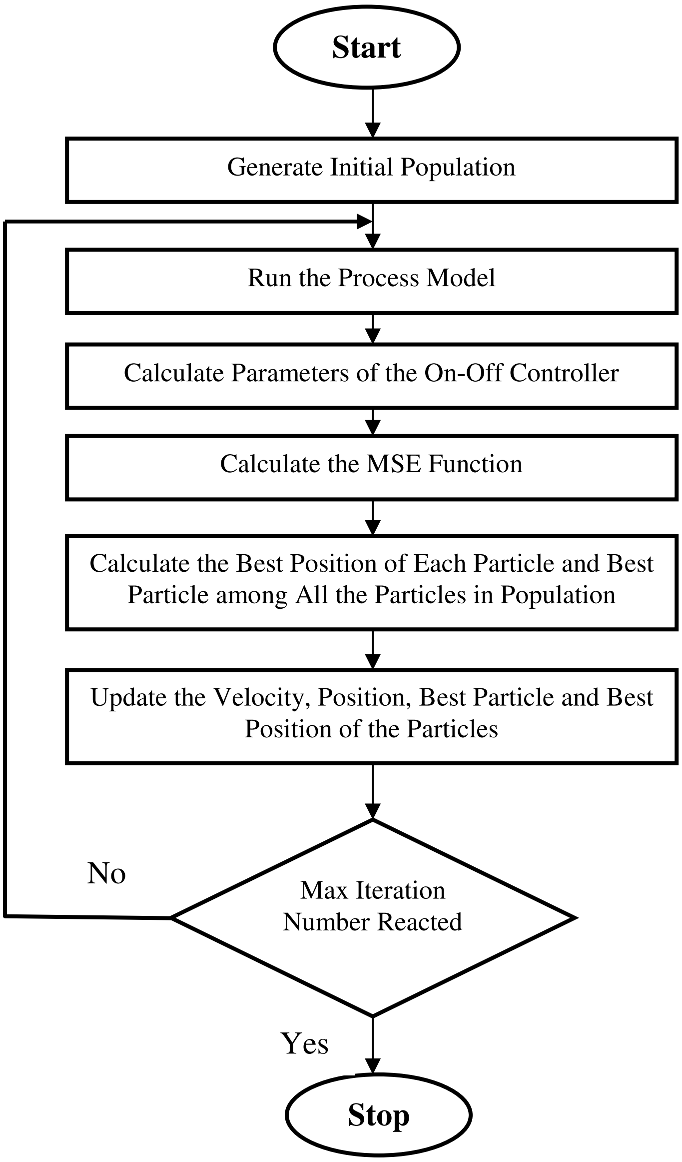

Fig.4. Flowchart of the PSO approach for optimizing On-Off controller.

VII. SIMULATION RESULTS AND INTERPRETATION

The simulation results in the study state were carried out with Matlab/Simulink in order to verify the effectiveness of the considered system using On-Off control for the designed WECS with squirrel-cage asynchronous generator.

Wind speed is common to assume that the mean value of the wind speed is constant for some intervals.

To simulate the wind velocity v can be expressed as:

$$v = x.(1-0.09.\sin(\frac{2\pi t}{20})-0.09.\sin(\frac{2\pi t}{60})) \qquad (16)$$

Where x is a chosen number. To simulate wind gusts, the magnitude and frequency of the sinusoidal fluctuations is increased.

Some of the parameters of PSO that is used to find the optimal parameters values of the On-Off controller are shown in Table 1.

The parameters of the wind turbine are shown in Table 2.

The generator parameters are shown in Table 3.

Parameters	**Values**
Swarm size	20
Max iteration	50
Inertia weight factor (w)	0.9
Confidence coefficient	c_1=0.12 and c_2=1.2

TABLE 1.PARAMETERS OF PSO

Parameters	**Values**
The air density	$1.25 kg / m^3$
The blade radius	2.5 m
The maximum wind power conversion coefficient	0.47
The optimal tip speed ratio	7

TABLE 2.PARAMETERS OF WIND TURBINE

Parameters	**Values**
The rated voltage	220 V
The rated frequency	50 Hz

The stator winding resistance	1.265 Ω
The rotor winding resistance	1.430 Ω
The stator winding self-inductance	0.1452 mH
The transformer between the stator winding and equivalent rotor winding	0.1397 mH
The rotor inertia	3 kgm^2

TABLE 3.GENERATOR PARAMETERS

In order to evaluate the control method aiming at captured power maximization for a low power fixed-pitch SCIG-based wind turbine by means of a Particle swarm optimization based On-Off controller, MATLAB is used to carry out the simulation.

The wind speed is simulated in figure 5.

The simulation results are shown in Figs.6, 7, 8, 9 and 10 respectively.

Fig. 6 is the rotor power coefficient C_p . In Fig. 6, it can be seen that when the system is stable, C_p is stable down, it is located basically in 0.47.

From Fig. 7, it can be seen that the tip speed ratio λ is closed to its optimal value $\lambda_{opt} = 7$.

Fig. 8 is the actual electromagnetic torque and its reference. From Figs.8, it can be seen that the electromagnetic torque can kept up with reference value quickly.

Fig. 9 shows the stator voltage and Fig.10 show the stator current.

These figures demonstrate the effectiveness of the proposed robust controller. During the change of the wind speed, the stator voltages remain stable in steady state.

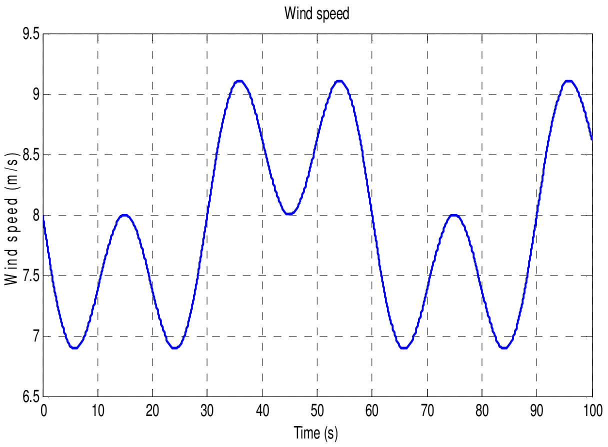

Fig.5 Wind speed

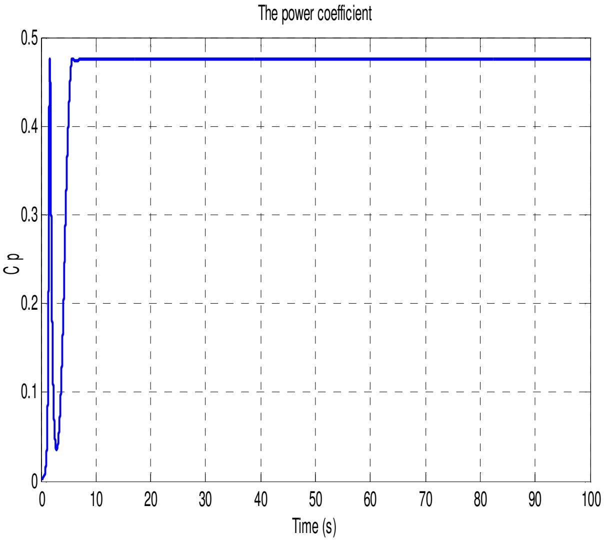

Fig.6 The power coefficient Cp

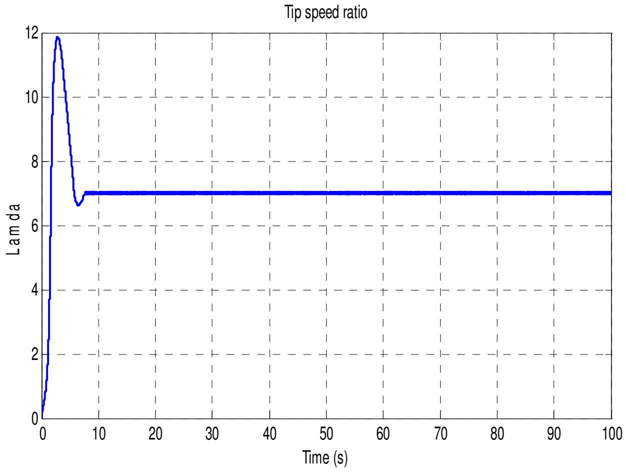

Fig.7 Actual tip speed ratio λ

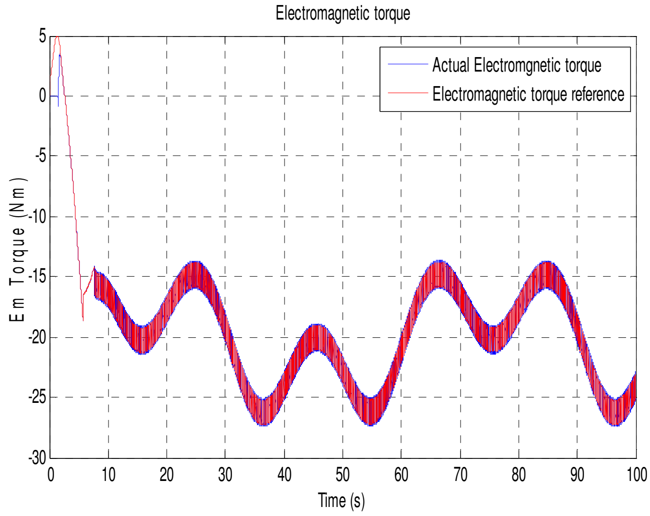

Fig.8 Actual electromagnetic torque and its reference

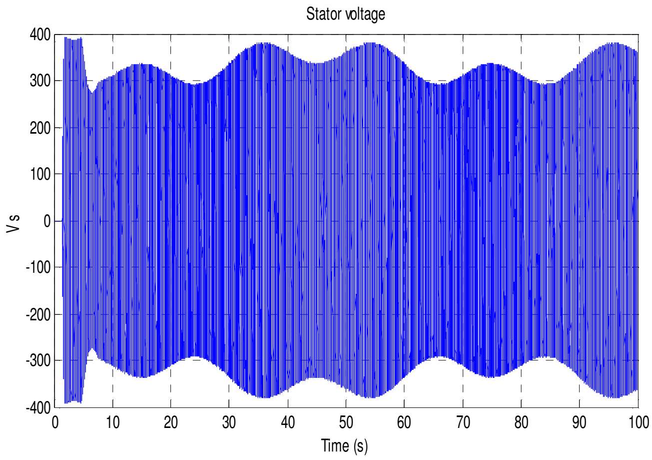

Fig.9 Stator Voltage

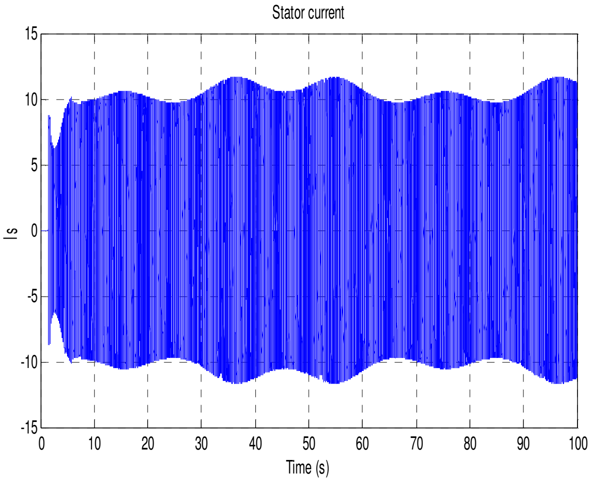

Fig.10 Stator current

VIII. CONCLUSIONS

In this paper, we have presented an On-Off control based particle swarm optimization for maximum power point tracking of a wind conversion system equipped with a squirrel-cage induction generator (SCIG).

After modeling the system, we have developed a controller for electromagnetic torque, using an On-Off control based particle swarm optimization.

With an appropriate selection of controller parameters, the results we obtained are useful for the application of wind energy in order to ensure robustness and quality of the energy produced.

In addition, the proposed controller based particle swarm optimisation can improve the performance of the system.

NOMENCLATURE

v	Wind speed (m/sec)
ρ	Air density (kg/m^3)
R	The blade radius of the wind turbine
P_a	Aerodynamic power (W)
T_a	Aerodynamic torque (Nm)
λ	Tip speed ratio
λ_{opt}	The optimal value of λ
β	Pitch angle (deg)
C_p	Power coefficient
C_q	Torque coefficient
$C_p^{'}(\lambda)$	the derivative of the power coefficient
$C_{p\max}$	the maximum wind power conversion coefficient
w_r	Wind Turbine rotor speed (rad/sec)
T_e	Generator electromagnetic torque (Nm)
ψ_r	The rotor flux
ω_1	The stator electricity angular velocity (rad/s)
ω_s	The slip angular velocity (rad/s)
L_s	The stator inductance (H)
L_r	The rotor inductance (H)
L_m	The excitation circuit reactance (H)
S	The sliding surface
u	The control variable
u^{eq}	Equivalent control variable
u^n	Switching control

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