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# 1 PSO-based MPPT Control of Wind-driven Self-Excited 2 Induction Generator for Pumping System

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## 8 **Abstract**

9 In recent years, much research has been done to improve the performance of a wind energy conversion  
10 system at various wind speeds using **Maximum Power Point Tracking (MPPT)** algorithms to find an  
11 efficient production of peak energy.

12 In most cases, the MPPT techniques used to maximize the turbines power coefficient neglect the effect  
13 of losses generated by the system components, which can shift the true optimal operating point of the  
14 wind turbine. Furthermore, conventional MPPT methods such as **Perturbation and Observation (P&O)**  
15 and **Incremental of Conductance (IncCond)**, need to sense both the rotor speed and the power of the  
16 wind turbine. In addition, other methods such as Fuzzy Logic and neural networks based on MPPT  
17 algorithms are proposed but these methods require knowledge of the wind speed and system parameters  
18 for the training phase.

19 In this context, a new MPPT technique is being proposed in this paper, based on **Particle Swarm**  
20 **Optimization (PSO)** for a standalone **Self-Excited Induction Generator (SEIG)** operating at variable  
21 wind speed and supplying an induction motor coupled to a centrifugal pump.

22 **Keywords** - Self Excited Induction Generator, Pumping system, Maximum Power Point Tracking  
23 Particle Swarm Optimization

## 25 **1. Introduction**

26 In the last decades, producing electricity with renewable energies such as wind and solar energy has  
27 been considered to replace conventional resources [1-3]. Particularly, in remote site it is important to  
28 limit the maintenance and to operate with minimum storage batteries, so the wind turbine pumping  
29 systems without energy storage can be an alternative solution to conventional powered pumping  
30 systems. In addition, this type of pumping systems does not pollute the environment.

31 Many types of generators are used for stand-alone power generation in remote site such as permanent  
32 magnet, brushless, synchronous, asynchronous, variable reluctance. But the **Self Excited Induction**  
33 **Generator (SEIG)** is mainly used because of its lower cost, high power density and very little  
34 maintenance required [4-6].

35 During the last decades, several works have been developed to investigating a performance analysis of  
36 the SEIG, and dynamic performance for feeding static and dynamic loads (resistive, inductive,  
37 capacitive, and induction motor) at various wind speed conditions [7-10]. Therefore, the power  
38 converter topology have been developed and various regulating schemes explored to obtain improved  
39 voltage and frequency regulation [11,12]. In this scheme, the SEIG needs to control the providing  
40 bidirectional flow of both active and reactive powers.

41 Other works have focused on architectures and methods for maximizing the wind power. Among them,  
42 various regulating schemes have been adopted to extract the maximum power from the wind turbine  
43 [13-15]. Consequently, the SEIG is operating at variable frequency, which needs a single power  
44 controller. However, this scheme is gaining importance for stand-alone wind power applications, in  
45 particular for water pumping systems with **Induction Motor (IM)** where the variation of the electrical  
46 parameters is not very critical for its use.

47 Indeed, different control strategies referred to **Maximum Power Point Tracking (MPPT)** algorithms are  
48 used to track peak power production efficiently at varying wind speeds. In this context, many techniques  
49 of MPPT controller have been applied to induction generators such as, **Perturb and Observe (P&O)** or  
50 Fuzzy logic, Neural network estimator [16-20]. The P&O technique is often proposed as solution for  
51 MPPT controller for its simplicity calculus algorithm. The disadvantage of this technique is that it  
52 introduces a continuous oscillation around the real maximum power point and have a limited ability to  
53 track this point in the transient environmental conditions [16,17]. As a solution to improve the tracking  
54 algorithm under speed-varying changes in wind speed, the Adaptive step Perturb and Observe strategy is  
55 proposed in [18,19]. However, this technique which minimizes the oscillation needs to use the generator  
56 rotor speed variation (as complementary information) to provide the correct direction to the **Maximum**  
57 **Power Point (MPP)**.

58 Other MPPT strategies are implemented using intelligent computations like Artificial Neural Networks  
59 [20] and Fuzzy logic [21, 22]. Recent improvements using a Fuzzy-Neuro based algorithm, combined  
60 with an additional measurement of wind speed, obtain excellent precision in the tracking, but increase  
61 the computational burden and cost.

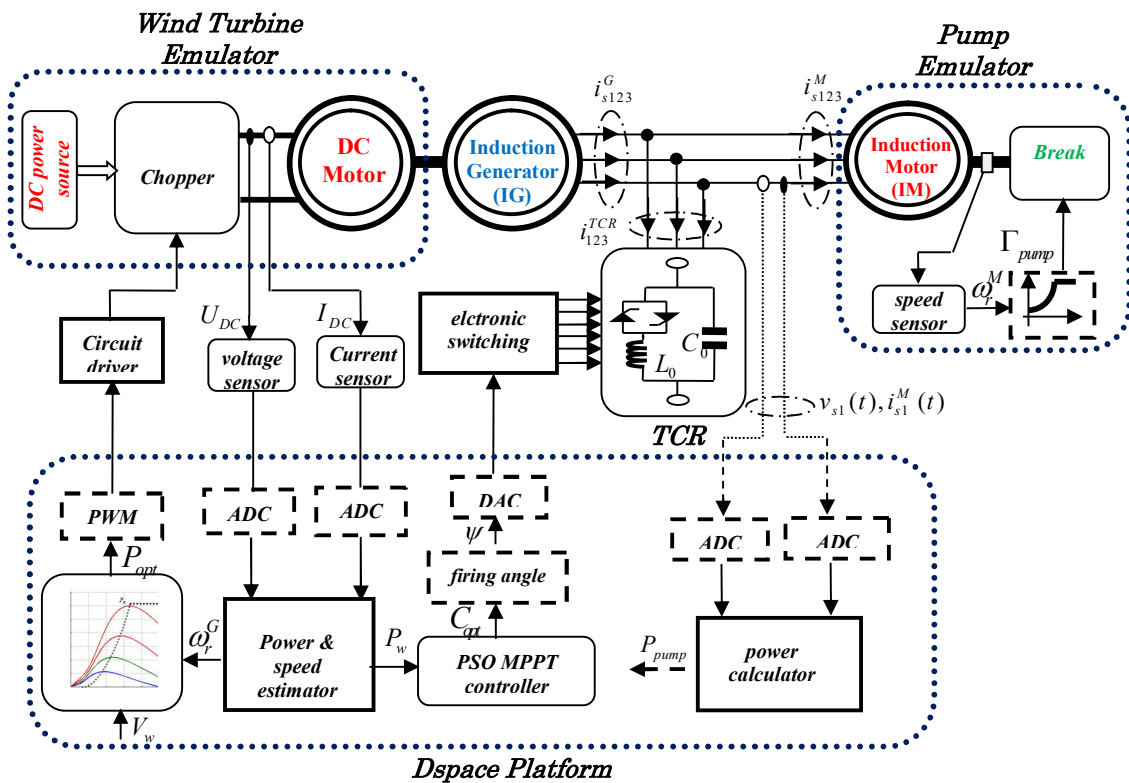
62 In this context, this paper presents a PSO-MPPT controller of wind-driven Self-Excited Induction  
63 Generator for pumping systems which have not need to measure the wind or turbine speed. A SEIG-  
64 Pump performance analysis is developed to extract the maximum power rated from the wind turbine.  
65 The frequency is reached by using a **Thyristor Controller Reactor (TCR)** to adapt the rotor speed of the  
66 SEIG at the desired value.

67 The whole paper is organized as follows: section 2 describes the dynamic modeling of the SEIG  
68 pumping system, section 3 is devoted to presents the principle of MPPT control strategies. Simulation  
69 results performed with Matlab/Simulink are discussed and presented in section 4. The location of the  
70 MPP is calculated for different wind speed values to show the robustness and the efficiency of the

71 propose **PSO MPPT** algorithm. Experimental results are presented in section 5 with measurements on a  
 72 test bench wind turbine emulator. Finally, a conclusion sums up the developed work and its features.

73 **2. Modeling of Wind Turbine Conversion System**

74 A wind turbine energy conversion system intended to work in isolated sites is shown in Fig.1. It  
 75 consists of a DC Motor controlled through a chopper to emulate the wind turbine model used to convert  
 76 wind kinetic energy , a squirrel cage **Induction Generator (IG)** to convert the mechanical power  
 77 provided from the DC motor on electrical power, an induction motor which is coupled with a  
 78 mechanical break to emulate the centrifugal pump model, a frequency controller based on Thyristor  
 79 Controller Reactor system which is used to locate the MPP from the wind turbine, and a dSPACE  
 80 controller board which is interfaced with a PC under Matlab/Simulink for the implementation of the  
 81 PSO-MPPT controller .



82  
 83 Fig .1. Schematic block diagram of the experimental test-bench of the wind turbine energy conversion  
 84 system.

85 **2.1. Modeling of Wind Turbines Curve**

86 The power delivered by the wind turbine is proportional to the cube of the wind speed and can be  
87 expressed as:

88 
$$P_w = \frac{1}{2} \rho A V_w^3 \quad (1)$$

89 where  $\rho$  is the air density,  $A$  is the area swept by blades and  $V_w$  is the wind speed. A wind turbine can  
90 only extract part of the power (maximum 59%) from the wind, which is given by the Betz limit [23].

91 Therefore, the wind turbine mechanical power extracted from the wind is given by:

92 
$$P_m = \frac{1}{2} \rho A C_p(\beta, \lambda) V_w^3 \quad (2)$$

93 where  $C_p(\lambda, \beta)$  is the power coefficient of the wind turbine. In this paper, the value of  $C_p(\lambda, \beta)$  is  
94 calculated as follows [24]:

95 
$$C_p(\lambda, \beta) = 0.5179(116\lambda_i - 0.4\beta + 5)e^{-21\lambda_i} + 0.068\lambda \quad (3)$$

96 where the parameter  $\lambda_i$  is expressed as:

97 
$$\lambda_i = \frac{1}{0.5/(\lambda + 0.08\beta) - 0.035/(\beta^2 + 1)} \quad (4)$$

98 The Tip Speed Ratio (TSR) is defined as the ratio between the blade tip speed and the wind speed:

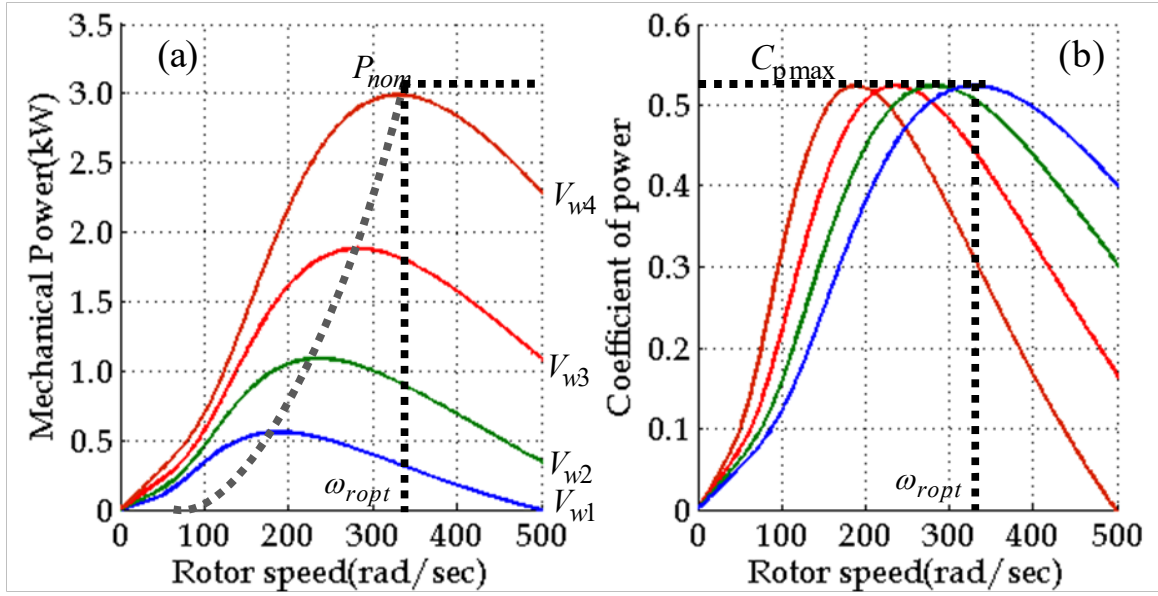
99 
$$\lambda = \frac{R_w \Omega_r}{V_w} \quad (5)$$

100 where  $\Omega_r$  denotes the rotor speed, and  $R_w$  is the radius of the wind turbine blade. The torque  
101 developed by the wind turbine is given by:

102 
$$\Gamma_w = \frac{P_m}{\Omega_r} = \frac{R_w}{2\lambda} \rho A V_w^2 C_p(\beta, \lambda) \quad (6)$$

103  $\beta$  is the blade pitch angle, and  $\lambda$  is the Tip Speed Ratio.

104 Fig. 2 shows the power coefficient and the mechanical power curves of the wind turbine as a  
105 function of the rotor speed for a pitch angle  $\beta = 0^\circ$ .



106

107 Fig. 2 Variation of (a) mechanical power curves and (b) power coefficient of the wind turbine for  
 108 different wind speeds.

109 **2.2. Modeling of the Self Excited Induction Generator**

110 For the modeling and analysis of the SEIG, the stationary reference frame model is used. Moreover, the  
 111 following differential equations describing the global generator model including the IG currents (

112  $i_{sd}^G, i_{sq}^G, i_{rd}^G, i_{rq}^G$ ) which integrated the auto-excitement capacitor  $C$  and the IM currents ( $i_{sd}^M, i_{sq}^M$ ) are

113 developed as:

$$114 \quad \frac{d}{dt} \begin{pmatrix} i_{sd}^G \\ i_{sq}^G \\ i_{rd}^G \\ i_{rq}^G \\ v_{sd} \\ v_{sq} \end{pmatrix} = \frac{1}{D^G} \left\{ \begin{array}{cccccc} L_r^G R_s^G & -L_m^G \omega_r^G & -L_m^G R_r^G & -L_m^G L_r^G \omega_r^G & -L_r^G & 0 \\ L_m^G \omega_r^G & L_r^G R_s^G & L_m^G L_r^G \omega_r^G & -L_m^G R_r^G & 0 & -L_r^G \\ -L_m^G R_s^G & L_m^G L_s^G \omega_r^G & L_s^G R_r^G & L_s^G L_r^G \omega_r^G & L_m^G & 0 \\ -L_m^G L_s^G \omega_r^G & -L_m^G R_s^G & -L_s^G L_r^G \omega_r^G & L_s^G R_r^G & 0 & L_m^G \\ \frac{1}{C} & 0 & 0 & 0 & \frac{1}{C} & 0 \\ 0 & \frac{1}{C} & 0 & 0 & 0 & \frac{1}{C} \end{array} \right\} \begin{pmatrix} i_{sd}^G \\ i_{sq}^G \\ i_{rd}^G \\ i_{rq}^G \\ i_{sd}^M \\ i_{sq}^M \end{pmatrix} - \omega_r^G \begin{pmatrix} -L_m^G \\ -L_m^G \\ L_s^G \\ L_s^G \end{pmatrix} \phi_0 \quad (7)$$

115 where,  $L_s^G = L_s^G + L_m^G$ ,  $L_r^G = L_r^G + L_m^G$ , and  $D^G = L_m^G - L_s^G L_r^G$

116  $R_s^G$  is the winding stator resistance,  $R_r^G$  the rotor resistance and  $\omega_r^G$  the rotor speed of the wind

117 induction generator.

118  $\phi_0$  is the remanant of the residual flux linkages,  $l_s^G$  the leakage inductance of the stator winding,  $l_r^G$   
 119 leakage inductance of the rotor copper arrangement referred to the stator, and  $L_m^G$  magnetizing  
 120 inductance of the IG.

121 The electromagnetic torque developed by the IG can be computed in  $d-q$  axes stator and rotor currents  
 122 as:

$$123 \quad \Gamma_{em}^G = \frac{3}{2} \left( \frac{P}{2} \right) [i_{rd}^G i_{sq}^G - i_{sd}^G i_{rq}^G] \quad (8)$$

124 The equation which represents the SEIG mechanical behavior will be assumed to be expressible as:

$$125 \quad \begin{cases} J \frac{d\Omega_r^G}{dt} + \Gamma_f = \Gamma_\omega - \Gamma_{em}^G \\ \Gamma_\omega = \frac{P_w}{\Omega_r^G} \end{cases} \quad (9)$$

126 where  $\Gamma_w$  represents the torque which acts on the SEIG shaft by means of the blades,  $\Gamma_f$  is the friction  
 127 torque,  $P_w$  is the corresponding mechanical power and  $J$  is the global inertia of the system.

### 128 2.3. Model of the Induction Motor

129 The differential equations describing the stator currents ( $i_{sd}^M$ ,  $i_{sq}^M$ ) and rotor currents ( $i_{rd}^M$  and  $i_{rq}^M$ ) of  
 130 the IM using a  $d-q$  components of stator voltage ( $v_{sd}$  and  $v_{sq}$ ) are developed as:

$$131 \quad \frac{d}{dt} \begin{pmatrix} i_{sd}^M \\ i_{sq}^M \\ i_{rd}^M \\ i_{rq}^M \end{pmatrix} = \frac{1}{D^M} \begin{bmatrix} -pL_m^M \Omega_r^M & -L_r^M r_s^M & -pL_m^M L_r^M \Omega_r^M & -L_m^M r_r^M \\ -L_r^M r_s^M & pL_m^M \Omega_r^M & -L_m^M r_r^M & pL_m^M L_r^M \Omega_r^M \\ pL_m^M L_s^M \Omega_r^M & L_m^M r_s^M & pL_s^M L_r^M \Omega_r^M & L_s^M r_r^M \\ L_m^M r_s^M & -pL_m^M L_s^M \Omega_r^M & L_s^M r_r^M & pL_s^M L_r^M \Omega_r^M \end{bmatrix} \begin{pmatrix} i_{sd}^M \\ i_{sq}^M \\ i_{rd}^M \\ i_{rq}^M \end{pmatrix} \quad (10)$$

$$+ \frac{1}{D^M} \begin{bmatrix} -L_r^M & 0 \\ 0 & -L_r^M \\ L_m^M & 0 \\ 0 & L_m^M \end{bmatrix} \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix}$$

132 where,  $L_s^M = l_s^M + L_m^M$ ,  $L_r^M = l_r^M + L_m^M$  and  $D^M = L_m^M - L_s^M L_r^M$ ,



133  $l_s^M$  is the leakage inductance of the stator winding,  $l_r^M$  leakage inductance of the rotor copper  
 134 arrangement referred to the stator and  $p$  is the pair of poles.  $r_s^M$  is the winding stator resistance,  $r_r^M$   
 135 the rotor resistance and  $\omega_r^M$  the rotor speed of the induction motor.

136 The electromagnetic torque of the IM can be computed in  $d-q$  axes stator and rotor currents as:

137 
$$\Gamma_{em}^M = \frac{3}{2} \left( \frac{p}{2} \right) [i_{rd}^M i_{sq}^M - i_{sd}^M i_{rq}^M] \quad (11)$$

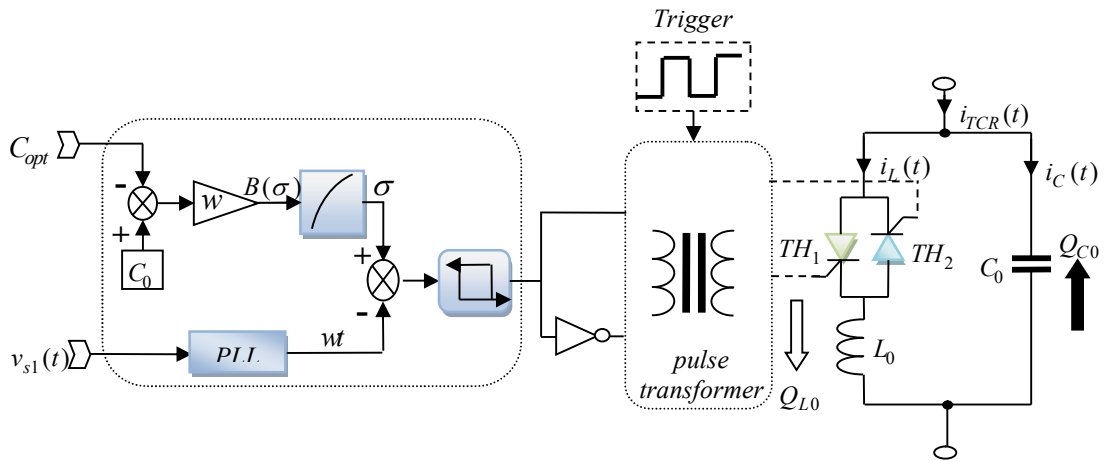
138 The equation which represents the IM mechanical behavior will be expressible as:

139 
$$\begin{cases} J \frac{d\Omega_r^M}{dt} + \Gamma_f = \Gamma_{em}^G - \Gamma_{pump} \\ \Gamma_{pump} = \frac{P_{pump}}{\Omega_r^M} = k_n \Omega_r^M \end{cases} \quad (12)$$

140 with  $k_n$  .....and  $P_{pump}$  electrical pump power

141 **2.4. Modeling of the TCR System**

142 A Thyristor Controlled Reactor circuit is basically composed of two oppositely poled thyristors and  
 143 a reactor [25,8]. The reactor is composed as two elements; a relatively big fixed capacitor  $C_0 = 75 \mu F$   
 144 and a fixed self inductance  $L_0 = 335 \text{ mH}$ . A per phase circuit of TCR circuit is shown in Fig. 3.



145  
 146 Fig. 3. Per phase equivalent circuit of TCR system and open loop control scheme for frequency  
 147 regulation.

148 The instantaneous current absorbed by the self inductance  $L_0$  is given by:

$$149 \quad i_{L_0} = \begin{cases} \frac{V_s}{\pi L_0 \omega} \sqrt{2} [\cos(\psi) - \cos(\omega.t)] & \psi < \omega.t < \psi + \sigma \\ 0 & \psi + \sigma < \omega.t < \pi \end{cases} \quad (13)$$

150 where  $\sigma$  is the thyristor conduction angle, and  $\psi$  is the thyristor firing angle.

151  $V_s$  and  $\omega$  are the RMS and the frequency of the SEIG terminal voltage respectively.

152 The fundamental component is found by Fourier analysis, and is given by:

$$153 \quad I_1 = \frac{\sigma - \sin(\sigma)}{\pi L_0 \omega} V_s = B(\sigma) V_s \quad (14)$$

154 where  $B(\sigma)$  is an adjustable fundamental frequency susceptance.

155 The TCR system is controlled by adjusting a fundamental frequency susceptance whose reactive  
156 power is balanced according to the requirement current in the SEIG. However, the reactive power  $Q_{TCR}$   
157 generated by a TCR system is equal to the difference between the capacitor power  $Q_{C_0}$  and the  
158 inductance power  $Q_L$  as:

$$159 \quad Q_{TCR} = Q_{C_0} - Q_{L_0} = 3(C_0 \omega - B(\sigma)) V_s^2 \quad (15)$$

160 The generated firing pulses for the thyristors are obtained by a pulse transformer and a trigger which  
161 is synchronized with the line voltages using a PLL system.

### 162 **3. Analysis of the Proposed MPPT Controller**

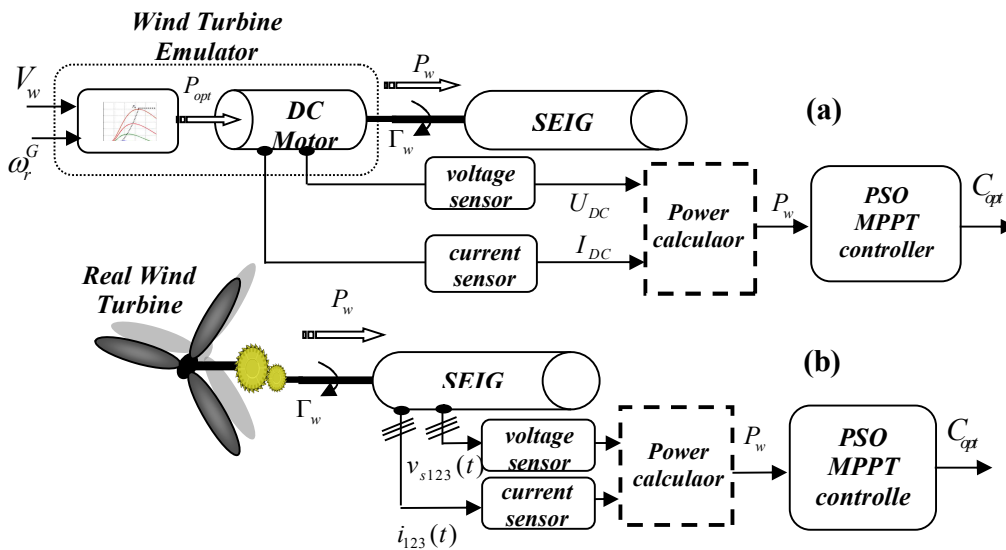
#### 163 **3.1. MPPT Controller Principle**

164 Considering the mechanical power curves presented in Fig. 2.a we can note that the power of a wind  
165 turbine is maximum for a rotor speed called optimum rotor speed  $\omega_{ropt}$ . So in order to extract maximum

166 possible power, the wind turbine should be operated at this speed. During the constant wind speed is  
 167 possible to control the rotational speed of the wind turbine by changing the reactive power.

168 Note that the operating slip of the induction generator is a small value. Therefore, for operating at  
 169 **Maximum Power Point (MPP)**, the rotor speed can be controlled by adjusting the capacitor value which  
 170 also influences the frequency value of the SEIG. In a classical P&O algorithm, the MPP can be obtained  
 171 by measuring two parameters: electrical power ( $P_w$ ) and rotor speed  $\omega_r$ . The particularity of the  
 172 proposed PSO algorithm is that it uses only electrical power ( $P_w$ ) parameter as reference to estimate the  
 173 optimal value of the capacitor which leads to  $\omega_{opt}$ .

174 For the wind turbine emulation, the proposed PSO-MPPT controller is based on measurement of  
 175 electrical variables ( $U_{DC}$  and  $I_{DC}$ ) as is shown in Fig. 4a. In a real wind turbine, the measurement of the  
 176 mechanical power is complex or not always available. So it is possible to maximize the electrical power  
 177 extracted from the SEIG considering the measured power at the SEIG output as the image of the  
 178 mechanical power at the SEIG shaft. This case is shown in Fig. 4b and proposed in the presented PSO  
 179 algorithm.



180  
 181 Fig. 4. Schematic diagram of power estimation: a) wind emulator and power estimation using DC motor  
 182 electrical signals b) power estimation using SEIG electrical signals.

183  
184 In this case the losses are considered constants and the maxima values of electrical and mechanical  
185 powers obtained having the same optimal rotor speed value  $\omega_{opt}$ .

186 For experimental bench a realistic wind turbine curve and a rotor speed estimator are used to calculate  
187 the optimal reference mechanical power  $P_{opt}$  for the DC motor. It will be controlled under a PWM  
188 chopper to generate the corresponding mechanical power  $P_w$  to the SEIG shaft.

189 In the proposed PSO algorithm, as the rotor speed  $\omega_r$  can be modified by changing the capacity value, a  
190 vector of capacitor  $C_j^k$  is used as initial value.  $j$  is the index of evolving parameters ( $j = 1, 2, \dots, N_p$ ) called  
191 particles and their values change at each iteration  $k$ . For each iteration, these  $j$  values of the capacity are  
192 sent to the TCR system, which imposes to the SEIG a frequency  $f_j^k$  and a rotor speed  $\omega_{rj}^k$ . The wind  
193 turbine emulator use a characteristic wind curve memorized in a look-up table and a rotor speed  
194 estimator to calculate  $P_{opt}$ . In the test bench is used a power loop control for DC motor under a PWM  
195 chopper to generate the corresponding mechanical power to the SEIG shaft. After the sending of the first  
196 capacity value  $C_j^k$  and the establishment of the permanent regime of mechanical and electrical  
197 quantities in the generator, voltage and current sensors are used to measure the electrical power and to  
198 estimate the mechanical power ( $P_{wj}^k$ ) applied at the SEIG shaft. In the same iteration  $k$  the TCR system  
199 receives the second reference of the capacity value  $C_{j+1}^k$ , which imposes to the DC machine a new  
200 mechanical shaft power  $P_{wj+1}^k$ . The last value of the capacity for the iteration  $k$  is  $C_{N_p}^k$ . Each time  
201 necessary to establish the permanent regime and to measure electrical variables ( $U_{DC}$  and  $I_{DC}$ ) for  $C_j^k$   
202 depends on the global inertia system, parameters of the SEIG and requires for presented system

203 approximately 200 ms. For practical implementation the number of particles  $N_p$  must be limited (  
 204  $N_p \leq 4$ ). In presented application the global iteration time is near to 800 ms and this cycle will be  
 205 repeated continuously until the real mechanical power achieves the maximum power points (MPP) . It  
 206 can be noticed in Fig.4.b that for a real wind turbine the proposed PSO algorithm does not need to  
 207 measure or estimate the rotor speed.

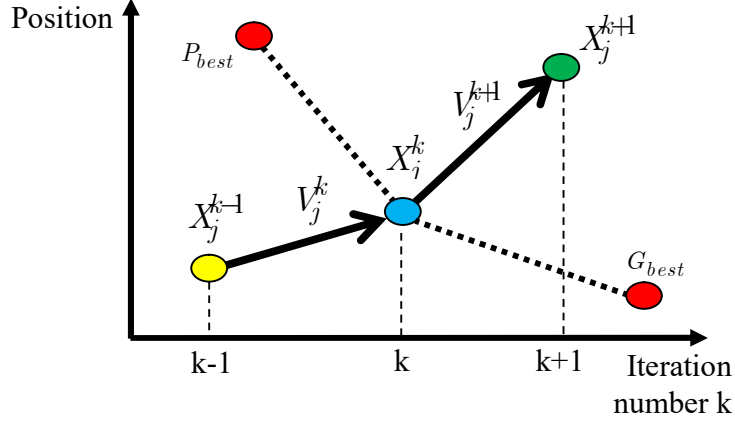
### 208 3.2. PSO Overview

209 The Particle Swarm Optimization (**PSO**) is a population-based searching algorithm. In general cases,  
 210 it randomly produces  $N_p$  particles in searching space, where each particle is characterized by a position  
 211  $X_j^k$  in the searching space, and a velocity  $V_j^k$  [26, 28]. Each position of particle  $X_j^{(k)}$  (in this case the  
 212 capacity  $C_j^k$ ) represents a solution of the problem and the "velocity"  $V_j^{(k)}$  its displacement (variation of  
 213  $\Delta C_j^k$ ) in the searching space (between  $C_{\min}$  and  $C_{\max}$ ). The particles have memory to keeps track of  
 214 its previous best particle called  $P_{best}$  which corresponds to an optimal fitness function  $Fit_{opt}$  (a  
 215 mathematical function where the objective is to be minimized by changing the particles) obtained for  
 216 iteration k. After the second iteration (k+1) is memorized (between  $P_{best_k}$  and  $P_{best_{k+1}}$ ), the particle gives  
 217 the minimized value of the  $Fit_{opt}$ . This particle (capacity in presented application) is called  $G_{best}$ . This  
 218 concept considers a random weighted acceleration at each time step [28]:

$$219 \begin{cases} V_j^{(k+1)} = \mu V_j^{(k)} + \delta_1 rand[0,1](P_{best} - X_j^{(k)}) + \delta_2 rand[0,1](G_{best} - X_j^{(k)}) \\ X_j^{(k+1)} = X_j^{(k)} + V_j^{(k+1)} \end{cases} \quad (16)$$

220 where,  $j = 1, 2, \dots, N_p$  is the index of particles,  $\mu$  is the momentum or inertia ( $\mu = 0.5$ ),  $\delta_1$  and  $\delta_2$  are a  
 221 positive constant ( $\delta_1 = \delta_2 = 0.5$ ),  $rand$  is random numbers which are uniformly distributed in  $[0, 1]$ ,

222 and  $k$  is the iteration number. A typical movement of particles in the optimization process is shown in  
 223 Fig. 5.



224

225 Fig. 5. Typical movement of particles in the searching space or optimization process.

226 In this figure the general spatial evolution case (between two iterations  $k$ , and  $k+1$ ) of particles  $X_j^{(k)}$  to  
 227  $X_j^{(k+1)}$  is presented. It takes in consideration the velocity evolution from  $V_j^k$  to  $V_j^{k+1}$ . The best  $X_j^{(k)}$   
 228 value for the  $j$  particles which give a minimal value for  $Fit$  function at iteration  $k$  is memorized with  
 229 the name  $P_{best}$  (local best value) and the best value between all realized iterations is memorized with the  
 230 name  $G_{best}$  (global best value). In the presented PSO algorithm a scalar particles evolution is considered  
 231 where the particles are capacity values ( $C_1^{(k)}, C_2^{(k)}, C_3^{(k)}, C_4^{(k)} \dots$ ) and the velocity evolution are the  
 232 capacity variation  $\Delta C_1^k, \Delta C_2^k, \Delta C_3^k, \Delta C_4^k \dots$ .

### 233 3.3. Application of PSO Algorithm for MPPT

234 In this paper, the initial  $N_p$  particles ( $N_p = 4$ ) are chosen to be uniformly distributed between  $C_{min}$  and  
 235  $C_{max}$ . So, the value of particles and the corresponding velocity at the first iteration ( $k=1$ ) are defined as:

$$236 \quad X_j^{(k)} = V_j^{(k)} = C_j^k = \frac{C_{max} - C_{min}}{N_p - 1} (j - 1) + C_{min} \quad (17)$$

$$237 \quad j = 1, 2, \dots, N_p$$

238 where, for the presented algorithm,  $C_{\min} = 35\mu F$  and  $C_{\max} = 110\mu F$  are the low bound and the upper  
 239 bound values of the optimal capacitor  $C_{\text{opt}}$ . The objective of the PSO algorithm is to maximize the  
 240 generated power of the wind turbine ( $P_w(C_j^{(k+1)}) > P_w(C_j^{(k)})$ ) consequently to minimize the fitness  
 241 function  $Fit$  described by the following equation:

$$242 \quad Fit = \min \Delta P = |P_{nom} - P_w(C_j^k)| \quad (18)$$

243 The updating of the particles  $C_j^{(k)}$  and each capacity variation  $\Delta C_j^{(k)}$ , are given by the following  
 244 equation [26]:

$$245 \quad \begin{cases} \Delta C_j^{(k+1)} = \mu \Delta C_j^{(k)} + \delta_1 rand[0,1](C_{jPbest}^k - C_j^{(k)}) + \delta_2 rand[0,1](C_{jGbest}^k - C_j^{(k)}) \\ C_j^{(k+1)} = C_j^{(k)} + \Delta C_j^{(k+1)} \end{cases} \quad (19)$$

246 where,  $C_{jPbest}^k$  and  $C_{jGbest}^k$  are the local and global best capacity solution which lead to a minimal value  
 247 of the  $Fit$ . The best local capacity solution is obtained using the following relationship:

$$248 \quad C_{jPbest}^k = \begin{cases} C_j^k & \text{for } P_w(C_j^{(k)}) > P_w(C_{j-1}^{(k)}) \\ C_{j-1}^k & \text{for } P_w(C_j^{(k)}) < P_w(C_{j-1}^{(k)}) \end{cases} \quad (20)$$

249 At latest iteration k the best local power is obtained for the best capacity value:

$$250 \quad P_w^k = P(C_{jPbest}^k) \quad (21)$$

251 For the global best capacity solution, considering all realized iterations  $C_{jGbest}^k$  is defined by the best  
 252 solution under latest and previous iteration. It is given as:

$$253 \quad C_{jGbest}^k = \begin{cases} C_{jPbest}^k & \text{for } P_w(C_{jPbest}^{(k)}) > P_w(C_{jPbest}^{(k-1)}) \\ C_{jPbest}^{k-1} & \text{for } P_w(C_{jPbest}^{(k-1)}) > P_w(C_{jPbest}^{(k)}) \end{cases} \quad (22)$$

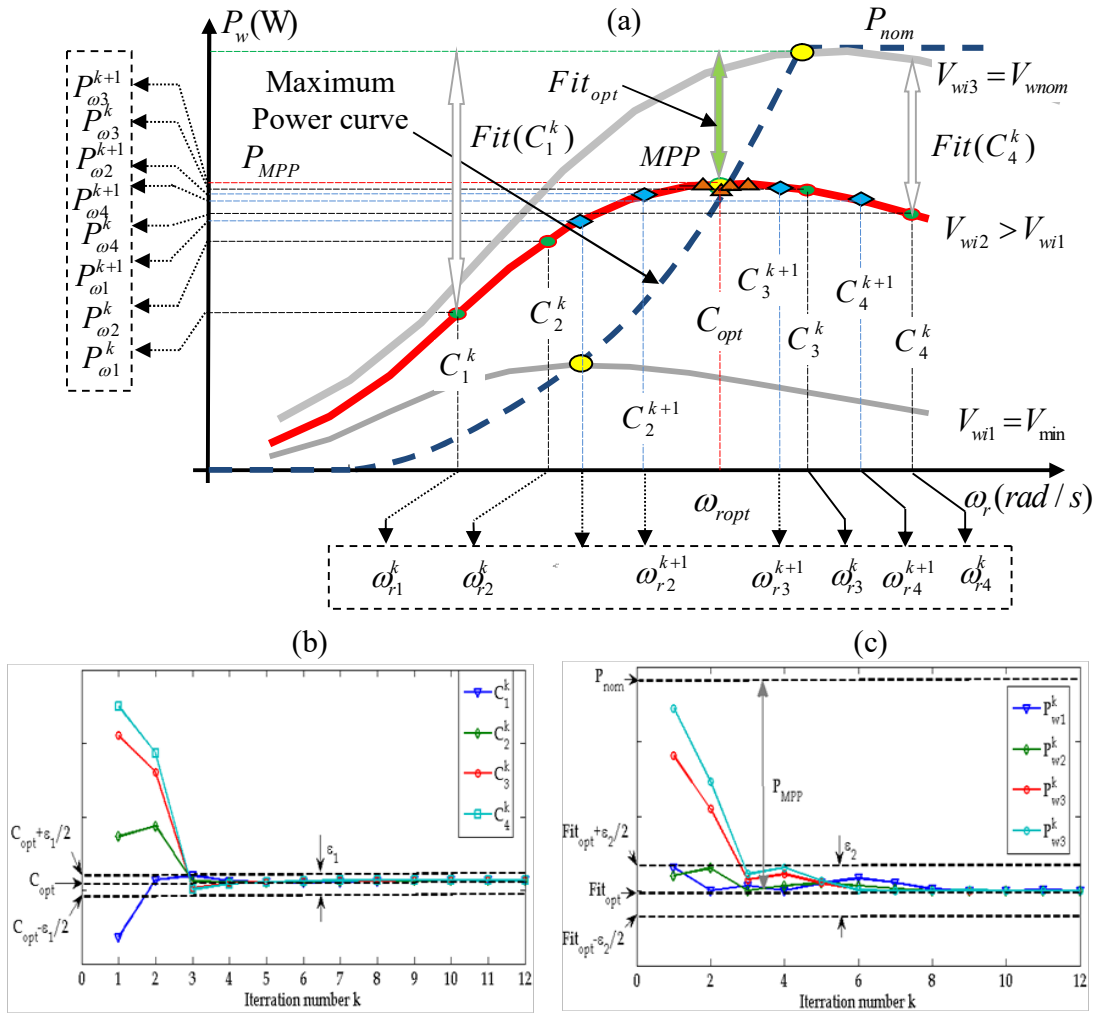
254 This capacity  $C_{jGbest}^k$  gives the minimal value for fitness function at iteration k and it makes it possible to  
 255 extract more power from the wind turbine. We note that, in order to avoid the disconnection of the

256 SEIG, limitations of the capacity value must be imposed ( $C_{\min} < C_j^k < C_{\max}$ ). Taking this constraint into  
 257 consideration the new capacity can be expressed by:

$$258 \quad C_j^{k+1} = \begin{cases} C_{\min} & \text{for } C_j^{(k)} + \Delta C_j^{(k+1)} < C_{\min} \\ C_j^{(k)} + \Delta C_j^{(k+1)} & \text{for } C_{\min} < C_j^{(k)} + \Delta C_j^{(k+1)} < C_{\max} \\ C_{\max} & \text{for } C_j^{(k)} + \Delta C_j^{(k+1)} > C_{\max} \end{cases} \quad (23)$$

259 Fig.6.a illustrates the application of the PSO algorithm in tracking the MPP, using a first vector of  
 260 capacitor with four particles. To start the optimization process (iteration k), the algorithm transmits to  
 261 the TCR system four capacitor reference values ( $C_1^k, C_2^k, C_3^k, C_4^k$ ). The number of the particles must be  
 262 correlated with the system inertia and in this application limited to  $N_p=4$ . In Fig. 6.a, the four initial  
 263 particles are marked with circular points and for each point there is one capacitor value. Each capacitor  
 264 imposes a rotor speed ( $\omega_{r1}^k, \omega_{r2}^k, \omega_{r3}^k, \omega_{r4}^k$ ) which corresponds to a mechanical power ( $P_{w1}^k, P_{w2}^k, P_{w3}^k, P_{w4}^k$ ).  
 265 We can notice here that  $C_3^k$  is the best particle in the first iteration k, which gives the best power value (  
 266  $P_{best} = P_{w3}^k$ ), corresponding to maximum mechanical power at the first iteration.  
 267 For the second iteration (iteration k+1), the particle updating is realized using equation 17. It is  
 268 calculated new capacitor vector  $C_1^{k+1}, C_2^{k+1}, C_3^{k+1}, C_4^{k+1}$ . These new particles are marked with square points  
 269 in Fig. 6.a. A new best personal particle  $C_3^{k+1}$  is found and the best power is obtained at  $P_{w3}^{k+1}$ , which  
 270 corresponds to best rotor speed  $\omega_{r3}^{k+1}$ . In fact, it is a global best ( $C_{Gbest} = C_3^{k+1}$ ), which represents the best  
 271 particles between the latest and the previous iterations corresponding to the greater best power  $P_{w3}^{k+1}$ .  
 272 In the third iteration (iteration k+2), all capacitor particles ( $C_1^{k+2}, C_2^{k+2}, C_3^{k+2}, C_4^{k+2}$ ) come near to MPP. In  
 273 the subsequent iteration, due to very low velocity, the value of the rotor speed ( $\omega_{r1}^{k+2}, \omega_{r2}^{k+2}, \omega_{r3}^{k+2}, \omega_{r4}^{k+2}$ ) is  
 274 approaching to optimal rotor speed  $\omega_{ropt}$ . Therefore, the wind turbine power will be maintained at the  
 275 maximum power ( $P_{MPP}$ ), and the oscillation around it diminishes.





276

277 **F** Fig. 6. Curves of a) MPP evolution on the wind turbine power, b) capacity and c) fitness optimization.

278 This sequence will be repeated continuously until the particles gradually come close to achieving MPP.

279 This algorithm is realized during a constant wind speed. Fig. 6.b and Fig.6.c present the evolution of the

280 capacity and fitness function for different iteration numbers. We can notice that after  $k=3$  iterations the

281  $Fit$  is minimized and the turbine works at MPP. The time necessary to detect the MPP is dependent on

282 the global system inertia of the machine. In presented test bench, the global time to detect the new MPP

283 is estimated at approximately 2.4s ( $4 \times 200$  ms  $\times 3$ ). If the wind speed applied changes the PSO algorithm

284 must be reinitialized automatically to search again a new maximal power point. In this case two

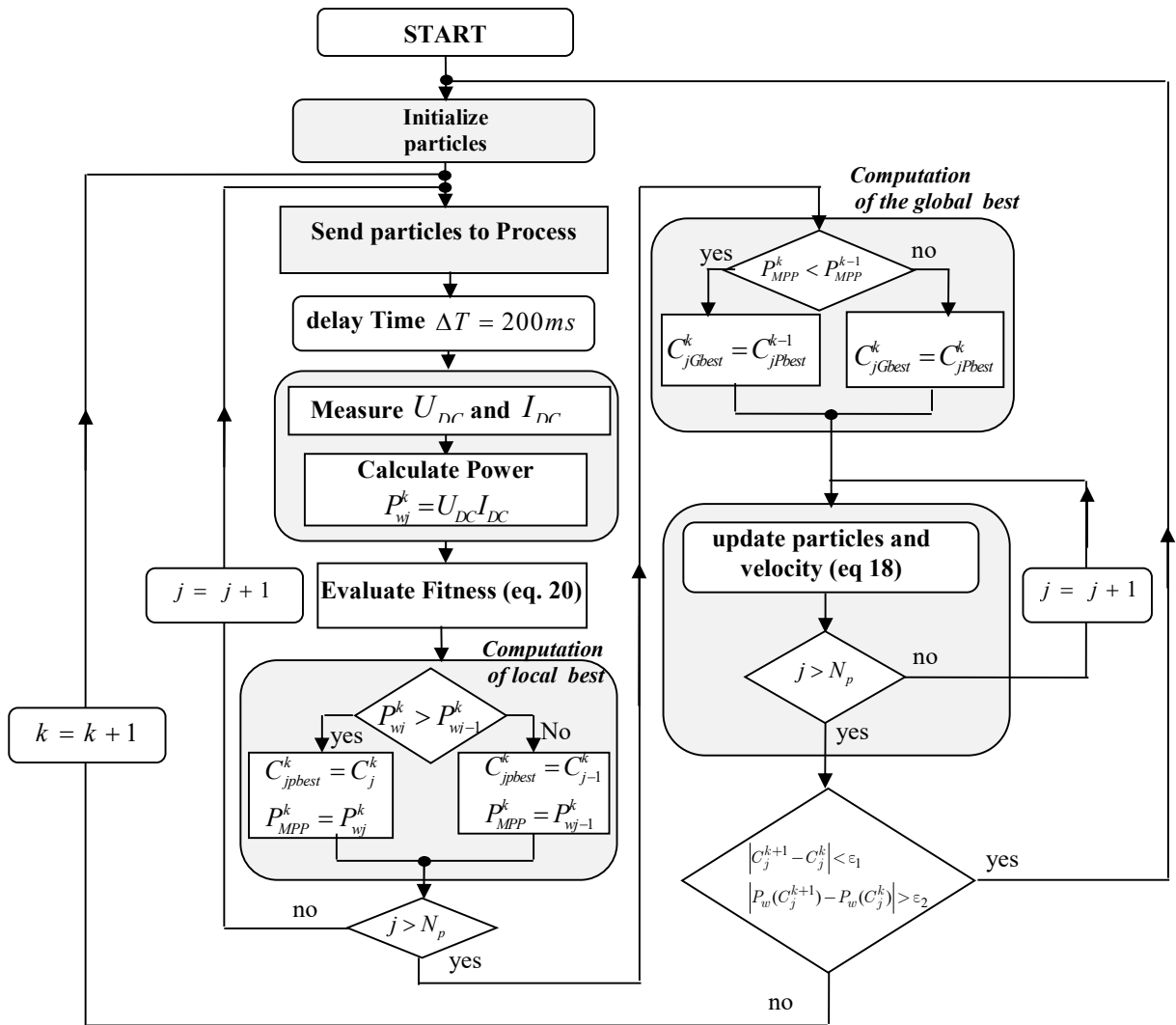
285 following simultaneous conditions must be respected to reinitialize the MPPT controller:

- 286 - particle convergence detection:  $|C_j^{(k+1)} - C_j^{(k)}| < \varepsilon_1$
- 287 - sudden change in the fitness function.  $|P_w(C_j^{k+1}) - P_w(C_j^k)| > \varepsilon_2$

288 Here the first condition imposes a small variation capacity between two iteration steps, error  $\varepsilon_1$  and the

289 second condition imposes a minimum power variation for a new “initialize particles” step, error  $\varepsilon_2$ . The

290 flowchart of this algorithm is given in Fig. 7 where the delay time  $\Delta T$  is estimated at 200 ms.



291

292

293 Fig. 7. Flowchart of PSO -MPPT proposed algorithm.

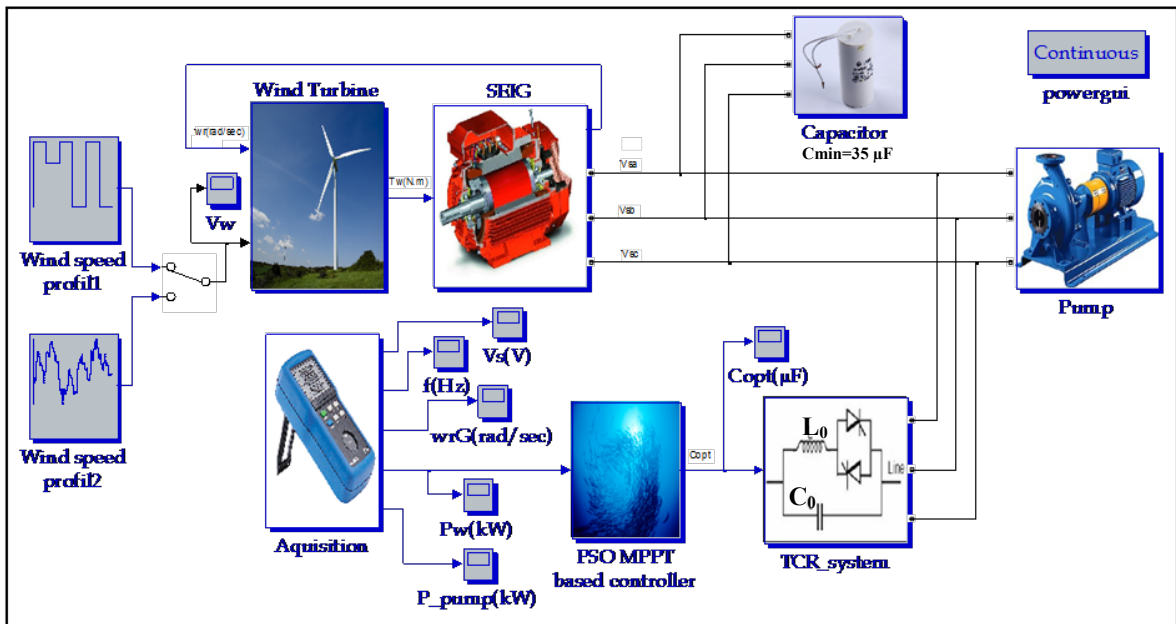
294

295

296 **4. Simulation Results and Discussion**

297 The simulations are carried out using Matlab/Simulink mathematical analysis software package. The  
 298 system component parameters are presented in Appendix 1.

299 A TCR system composed of a fixed big capacitor  $C_0 = 75\mu F$  and a fixed big inductance  $L_0 = 335mH$   
 300 is used, whose principle is to adjust SEIG rotational speeds according to an optimal reference speed  
 301 obtained from an MPPT controller. The simulink program begins with small initial voltage in the d and  
 302 q axes of the stator due to residual magnetism. The block diagram of the global simulated system is  
 303 shown in Fig. 8.



304  
 305 Fig. 8. Global simulink model for the wind turbine energy conversion system.

306 Initially, the SEIG start up process without pump, until the priming of the SEIG is reached. During this  
 307 time, we hang the pump and the regulation system. Simulation was carried out for two wind speed  
 308 profiles applied to the wind turbine, incorporating the proposed MPPT controller.

309 However, to validate the dynamic performance of the proposed MPPT controller, a step wind speed  
 310 profile shown in Fig. 9 was applied to the wind turbine. In this case, the wind speed has been changed

311 from 13 m/s to 12 m/s and back to 13 m/s. The wind profile was to be changed again from 10 m/s to 13  
312 m/s and back to 10 m/s.

313 The simulated waveforms of optimal capacitor, ( $C_{opt}$ ), Fig. 10, rotor speed ( $\omega_r^G$ ) Fig. 11, shaft  
314 power of wind turbine ( $P_w$ ) Fig. 12 and pump ( $P_{pump}$ ), wind turbine curve  $f(P_w, \omega_r^G)$  Fig. 13  
315 terminal RMS phase voltage ( $U_s$ ) and frequency( $f$ ) Fig. 14 are presented for the step change of the  
316 wind speed ( $V_w$ ). It can be seen from Fig. 11 that the real rotor speed ( $\omega_r^G$ ) is converged to the optimal  
317 rotor speed ( $\omega_{r_{opt}}^G$ ) obtains by the PSO MPPT algorithm. Furthermore, the wind turbine power ( $P_w$ ) is  
318 maintained at the maximum power ( $P_{MPP}$ ). In fact, the proposed MPPT controller has managed to track  
319 the MPP for different values of wind speed (Fig. 13).

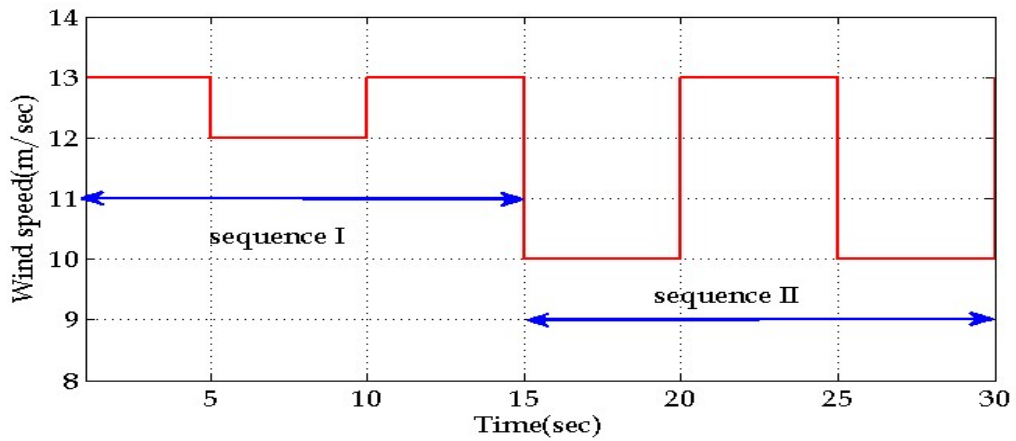
320 To observe the performance of the proposed MPPT algorithm, the instantaneous wave forms of the  
321 first line voltage of the SEIG and those of the TCR system is shown and zoomed in Fig.15.

322 In Fig.16 the first line currents of the  $I_{SEIG}$ , the first line current  $I_{TCR}$  of the TCR system and those of  
323 the pump are shown. We can notice that the  $I_{TCR}$  changing during each considered interval ( $V_w=12\text{m/s}$ ,  
324  $V_w=10\text{m/s}$ ,  $V_w=13\text{m/s}$ ) when the reactive power is changed and so the  $\omega_r$ , respectively the frequency.

325 Furthermore, to assess the successful working of the proposed MPPT controller for a large value of  
326 wind speed, a more realistic wind speed profile illustrated in Fig.17 was applied to the wind turbine.  
327 Simulation results represent the optimal capacitor variation ( $C_{opt}$ ). Fig. 18, the rotor speed ( $\omega_r^G$ ), Fig.  
328 19 the active power of wind turbine ( $P_w$ ), pump ( $P_{pump}$ ), estimation power by MPP algorithm  $P_{MPP}$ , Fig.  
329 20, terminal RMS voltage ( $U_s$ ) and frequency ( $f$ ) Fig. 21, gives the time evolution of presented  
330 parameters.

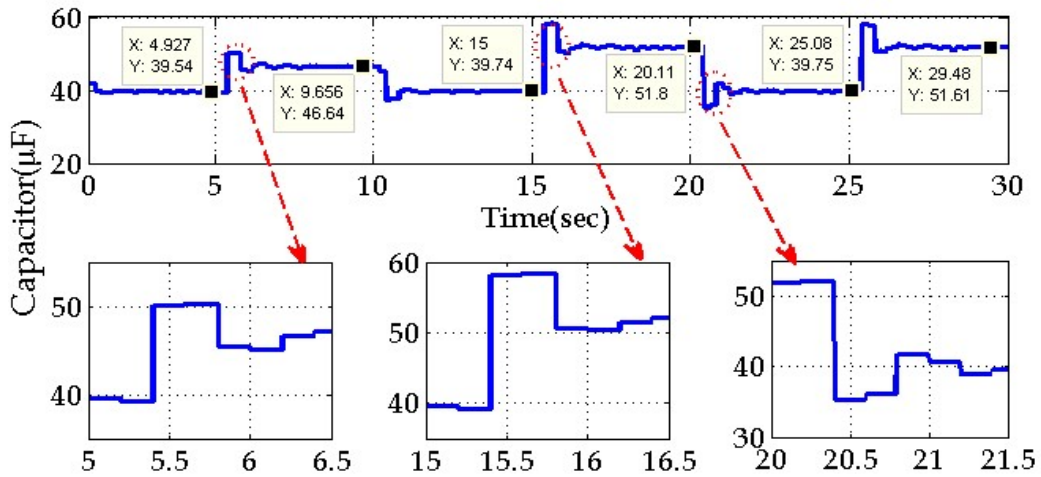
331 It can be seen from this figure that the maximum value of power of the turbine ( $P_w$ ) shown in Fig.12  
 332 is already reached, and it was equal to the MPP power found by the MPPT controller. It can therefore be  
 333 observed from the simulation results a good tracking capability of the proposed MPPT controller.

334 The first and the second test involve increasing or decreasing the reference speed keeping the torque  
 335 constant. The aim of this case is to evaluate the performance of the proposed PSO-MPPT controller.



336

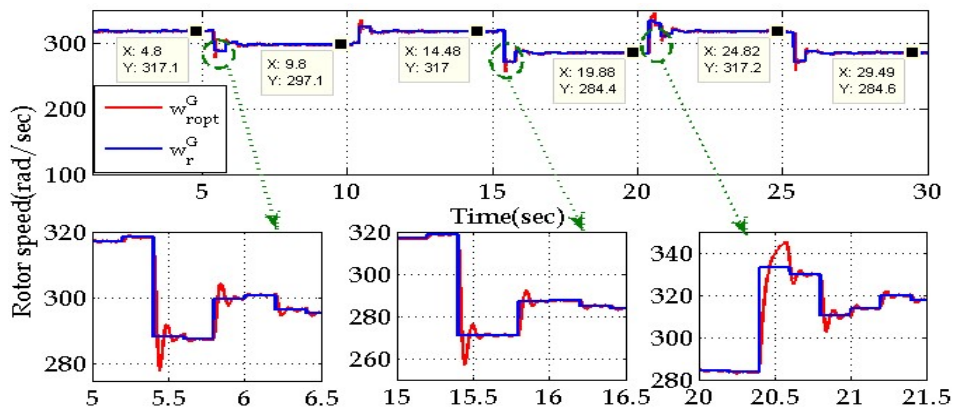
337 Fig . 9. Step wind speed profile for simulation tests.



338

339 Fig. 10. Variations of optimal capacitor during step wind speed variation;  $V=13\text{m/s}$  and  $V=12\text{m/s}$ .

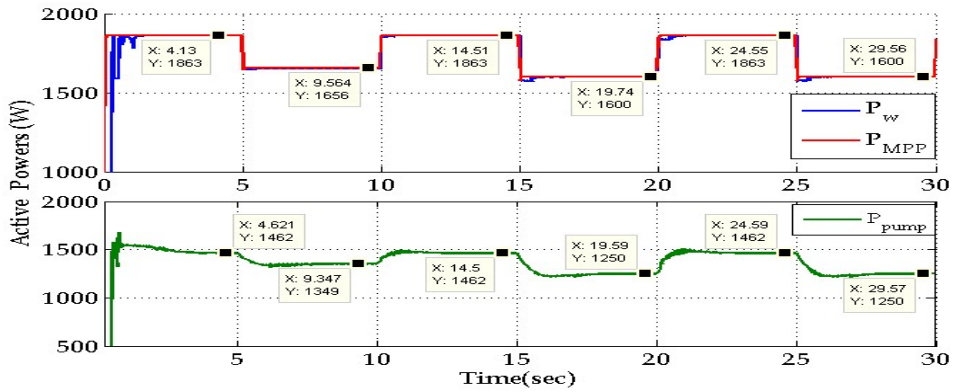
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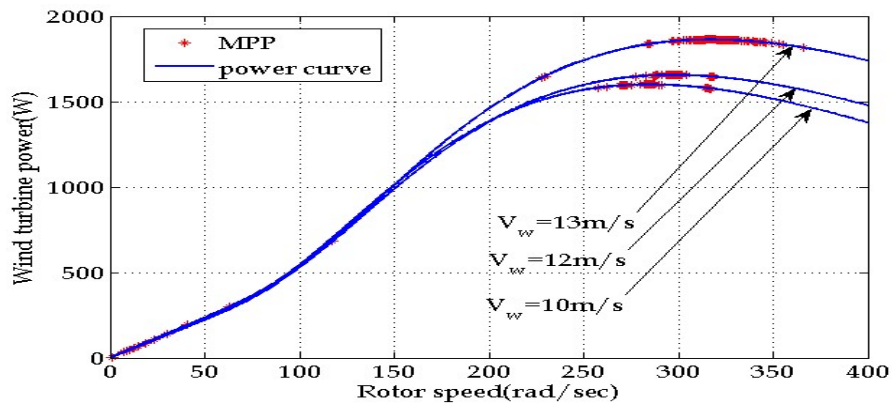
342 Fig. 11. Variations of optimal rotor speed and measured rotor speed during wind speed variation.

343



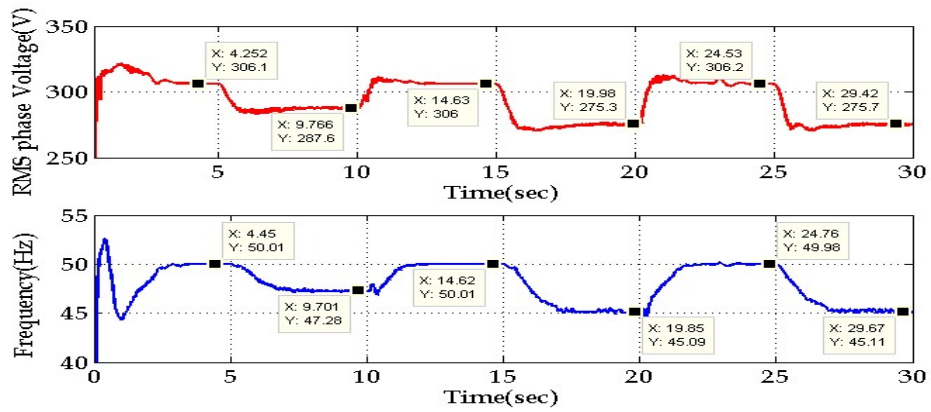
344

345 Fig. 12. Variations of active power of wind turbine  $P_w$ , active power of pump  $P_{pump}$  and estimated power  
346  $P_{MPP}$  during wind speed step variation.



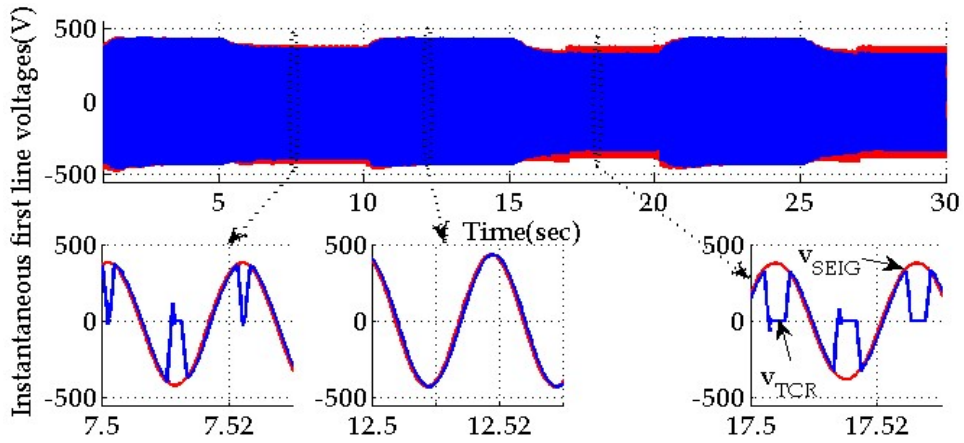
347

348 Fig. 13. Mechanical power of wind turbine characteristics and estimated power by MPP algorithm.



349

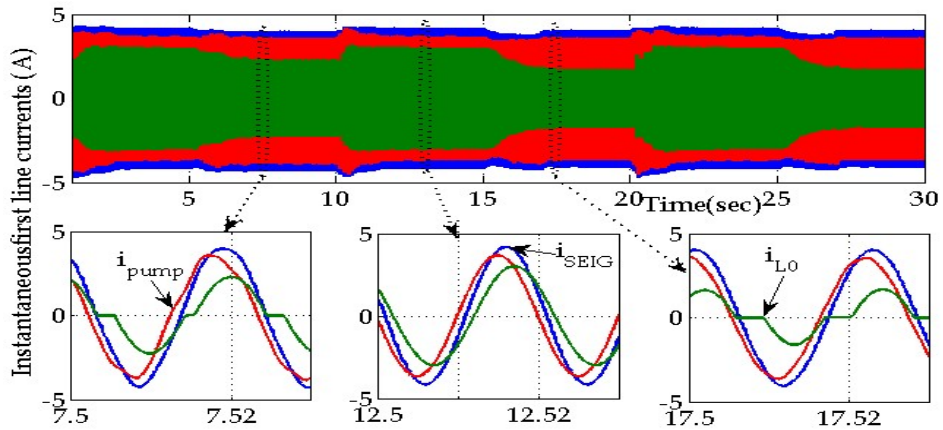
350 Fig. 14. Variations in RMS phase line voltage and frequency of the SEIG during wind speed step  
351 variation.



352

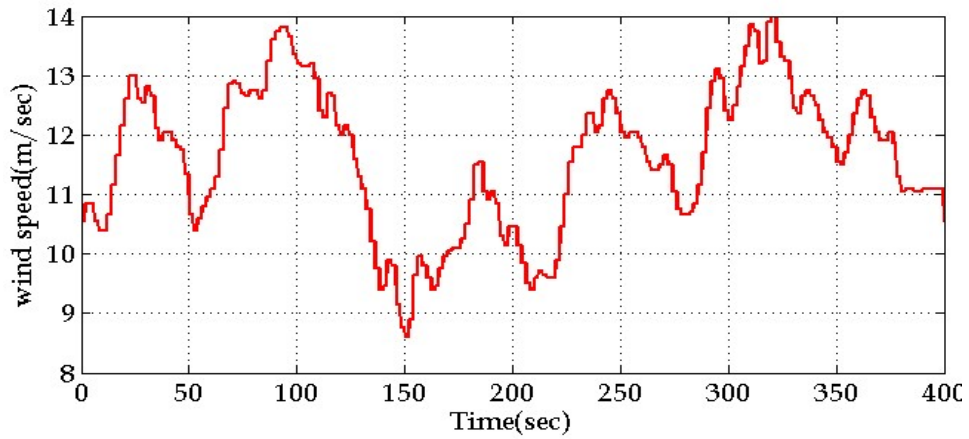
353 Fig. 15. Instantaneous first line voltage of the SEIG and TCR system during wind speed step  
354 variation.

355

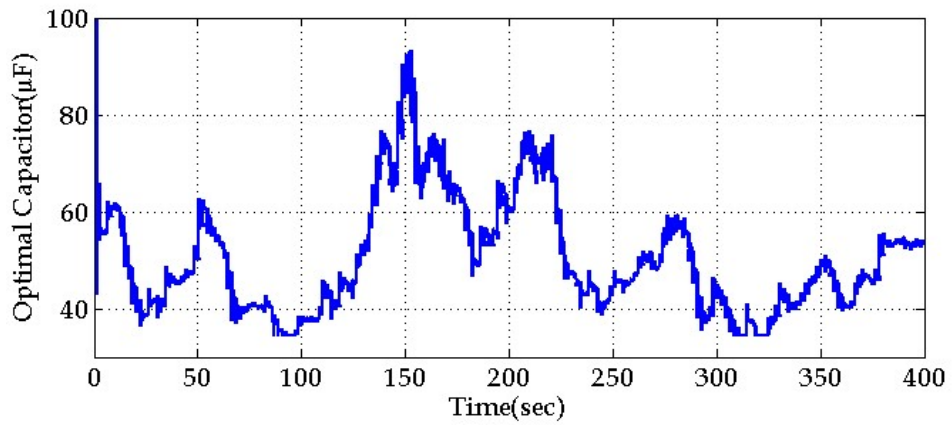


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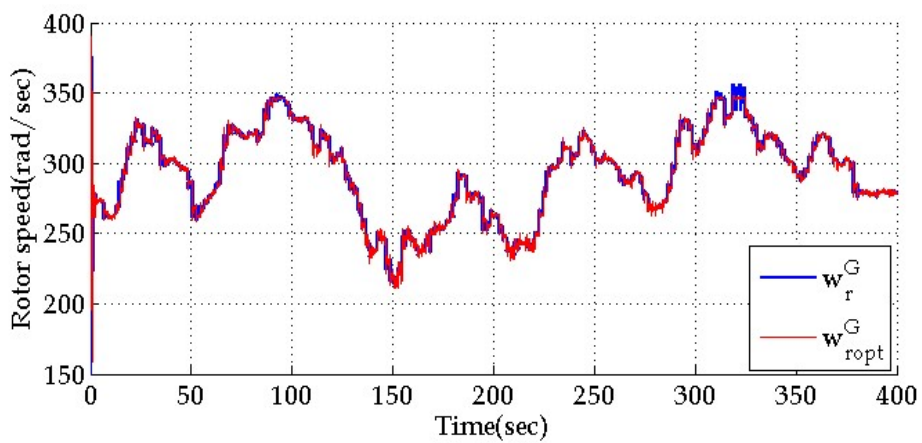
357 Fig. 16. Instantaneous first line currents of a) SEIG, b) TCR system and c) IM (pump) under wind  
358 speed perturbations.



359  
 360 Fig. 17. Realistic wind speed profile used in the second simulation tests.



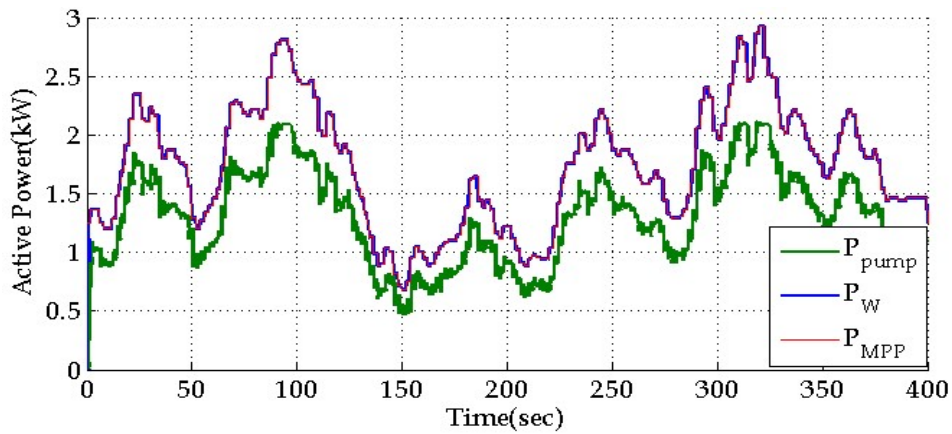
361  
 362 Fig. 18. Variations of optimal capacitor during wind speed variation.



364  
 365 Fig. 19. Variations of optimal rotor speed and measured rotor speed during wind speed variation.

366

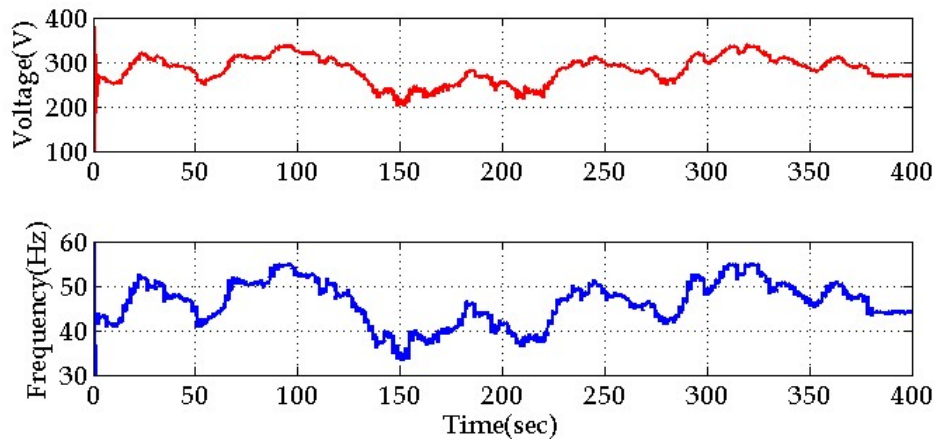




367

368 Fig. 20. Variations of wind turbine active power, active pump, and estimated power during wind speed  
 369 variation.

370



371

372 Fig. 21. Variations of line RMS voltage and frequency of the SEIG during wind speed variation.

### 373 5. Experimental Results and Discussion

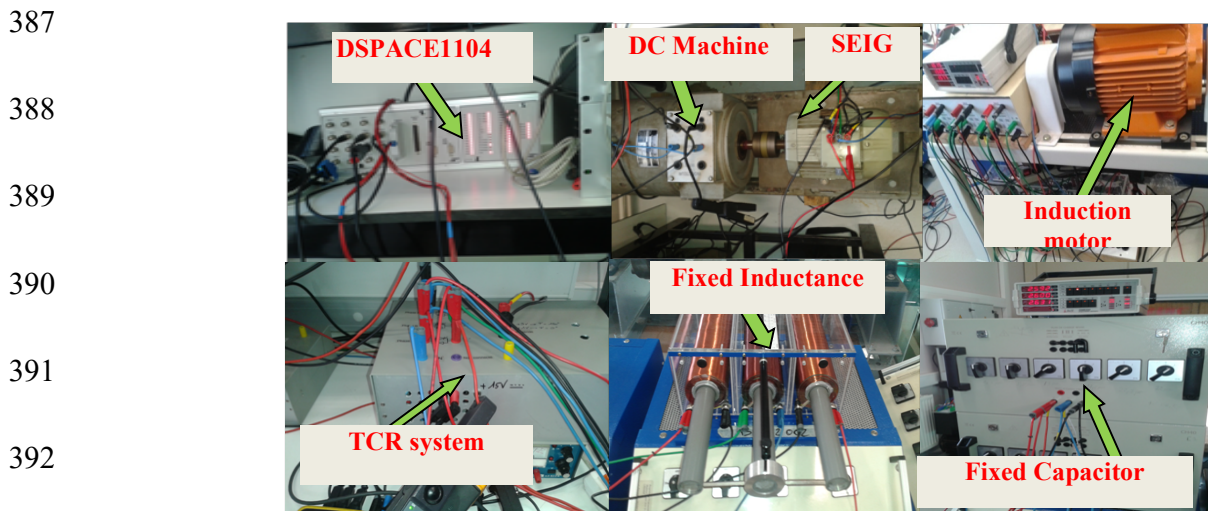
#### 374 5.1. Experimental Setup

375 The configuration of the experimental test bench is shown in Fig. 22. The proposed MPPT algorithm  
 376 is implemented using a digital controller based on a dSPACE unit. The system components are:

- 377 - power-controlled DC motor drive which is used to emulate the characteristics of the wind turbine  
 378 and to gives  $P_w$  at the SEIG shaft.
- 379 - 2[kW] squirrel-cage induction motor which is mechanically coupled to a break to emulate the  
 380 centrifugal pump system, a TCR system converter connected in parallel with the SEIG output

381 terminals for the control of the reactive power, and a dSPACE controller board which is  
382 interfaced with a PC under Matlab/Simulink.

383 The output signals of the voltage and current transducers are sampled in dSPACE DSP under  
384 DS1104-ADC blocks. Low pass filters are used in measuring units to eliminate the unwanted high-  
385 frequency noise. The PWM pulses from the dSPACE are sampled under a DS1104-DSP-PWM block to  
386 generate standard 10 kHz fixed-frequency PWM pulses.



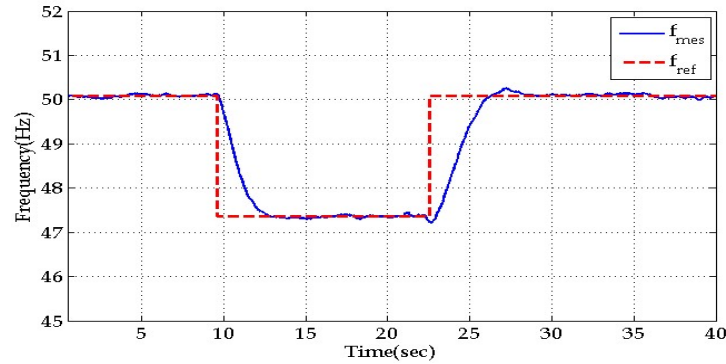
393 Fig. 22. Constituting elements of the experimental test bench.

## 394 5.2. Experimental Results

395 The performance of the MPPT control strategy was validated experimentally using a laboratory test  
396 bench composed of an IG which feeds an IM loaded by a specific break characteristic in order to assure  
397 a pump emulator. Different wind speed operating conditions are created by a DC motor which receives  
398 a power control in order to assure a constant power  $P_w$  at the SEIG shaft making it possible to  
399 investigate the dynamic characteristics of a SEIG-Pump system and to find the maximum of the power  
400 with the proposed method.

401 Experimental tests were carried out considering two speed profiles applied to the wind turbine, the  
402 first considers a decrease and the second an increase of the wind speed turbine. These profiles are used

403 to test the performances of the new proposed PSO MPPT controller algorithm and to analyze the signal  
 404 variations. During the tests, a step wind (power) variation is considered. The following tree pictures  
 405 (Fig. 23, Fig. 24 Fig. 25) shown the evolution of specific parameters during the decreasing wind speed.  
 406 As the frequency is dependent on the rotor speed the step reference is highlighted by the frequency  
 407 reference presented in Fig. 23. For experimental induction machines characterized by the parameters  
 408 presented in Appendix 1, the frequency 50 Hz corresponds to 13 m/s wind speed and the frequency 47.4  
 409 Hz to 12 m/ s wind speed. The transitory time includes the inertia of the SEIG-Pump system and also of  
 410 the wind turbine emulator which uses a power control loop.

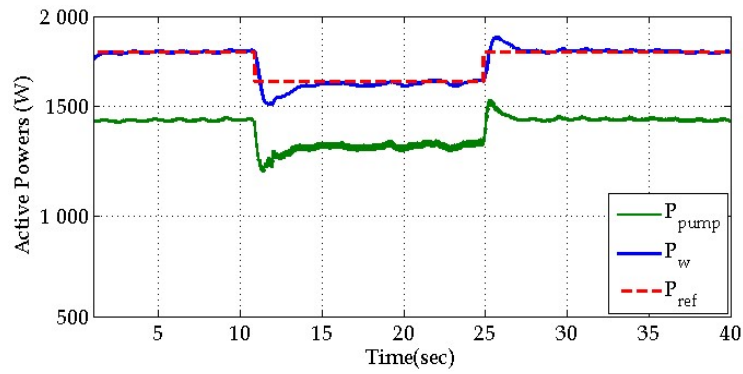


411

412 Fig. 23. Wave forms of reference frequency  $f_{ref}$  and SEIG measured frequency  $f_{mes}$  for wind speed  
 413 switching from  $V_w = 13\text{m/s}$  to  $V_w = 12\text{ m/s}$  and return to 13 m/s.

414

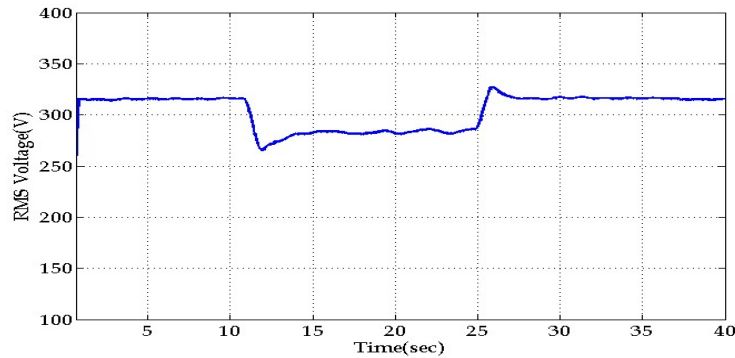
415 The reference power  $P_{ref}$  applied at the SEIG, the estimated power obtained from PSO algorithm and  
 416 a power consumed by the pump  $P_{pump}$  are shown in Fig. 24. For MPP reaching an adjustment of the  
 417 SEIG excitation capacitor is applied using a TCR system. We can notice a good power estimation  
 418 obtained by the proposed algorithm compared to  $P_w$  power reference applied to the PWM converter  
 419 (Fig.1). The difference between  $P_{pump}$  and  $P_w$  corresponds to the DC motor and IG losses.



420

421 Fig. 24 . Wave forms of reference power  $P_{ref}$ , estimated power  $P_w$  obtained by PSO-MPP algorithm and  
 422 the power consumed by the pump  $P_{pump}$  for wind speed switching from  $V_w = 13\text{m/s}$  to  $V_w = 12\text{ m/s}$  and  
 423 return to  $13\text{ m/s}$ .

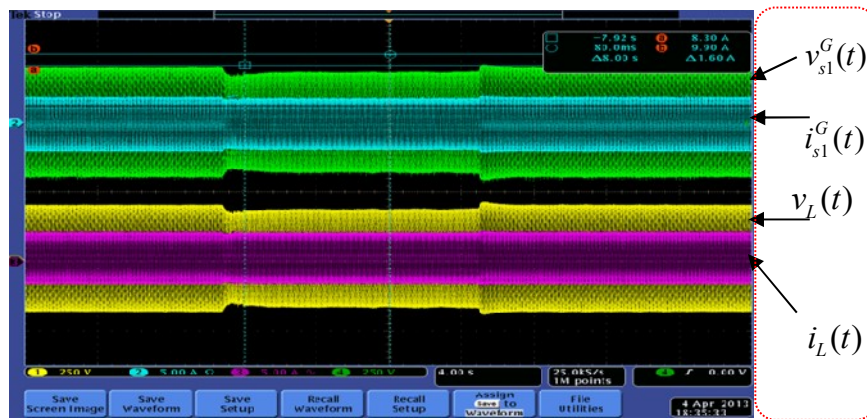
424 The RMS voltage variation measured at the SEIG output is presented in Fig. 25. Here during the  
 425 wind variation the voltage changes between  $308\text{V}$  at  $284\text{V}$  with the low overtaking caused by the wind  
 426 power variation (regulation) at the SEIG shaft.



427

428 Fig. 25. Measured phase RMS voltage at the SEIG output for wind speed switching from  $V_w = 13\text{m/s}$  to  
 429  $V_w = 12\text{ m/s}$  and return to  $13\text{ m/s}$ .

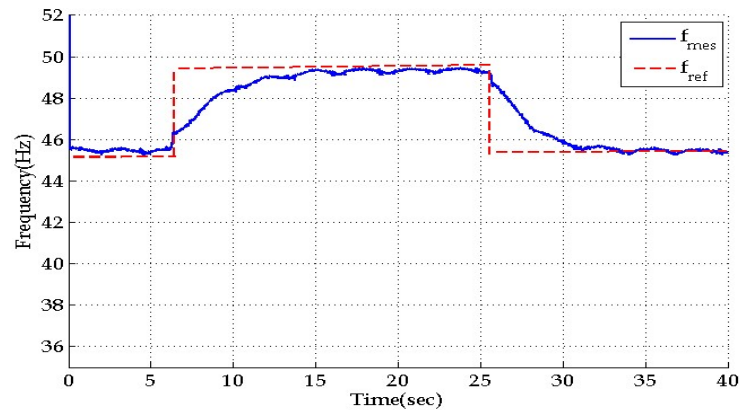
430 For considered speed (power) variation the wave forms of recording signals are presented in Fig. 26.  
 431 Here the top recording lines show the voltage and the current measured at the SEIG output and the  
 432 bottom lines the voltage and the current measured at the TCR input. We can notice the voltage  
 433 decreasing with a very low influence of the currents.



434

435 Fig. 26. Wave forms of recording signals : top lines show voltage and current lines measured at the  
 436 SEIG output, bottom lines show voltage and current lines of TCR system for wind speed switching  
 437 from  $V_w = 13\text{m/s}$  to  $V_w = 12\text{ m/s}$  and return to  $13\text{ m/s}$ .

438 The following tree pictures show the signal variations ( frequency, power, voltage, ) in the second  
 439 case when the wind speed increases from  $V_w = 10\text{m/s}$  to  $V_w = 13\text{ m/s}$  and returns to  $10\text{ m/s}$ . The  
 440 frequency target and the real frequency variations are presented in Fig. 27. We can notice in this case a  
 441 frequency value close to the reference with different transitory interval time for increasing and  
 442 decreasing of the wind speed.



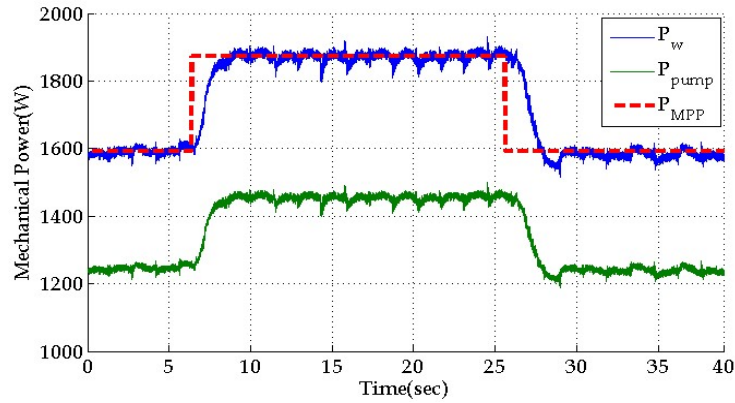
443

444 Fig. 27. Wave forms of reference frequency  $f_{ref}$  and SEIG measured frequency  $f_{mes}$  for wind speed  
 445 switching from  $V_w = 10\text{m/s}$  to  $V_w = 13\text{ m/s}$  and return to  $10\text{ m/s}$ .

446 For this case the power estimation  $P_{MPP}$  obtained by the proposed algorithm and the measured power  
 447 absorbed by the pump  $P_{pump}$  are presented in Fig. 28. The reference power  $P_{ref}$  is a step signal changing

448 between 1640W and 1870W. Taking into consideration the DC motor and the IG losses we can notice  
 449 the identical variation for  $P_{\text{pump}}$  and  $P_{\text{MPP}}$ . The difference during the transitory interval between  $P_{\text{MPP}}$  and  
 450  $P_w$  can be justified by regulation power at the SEIG shaft.

451

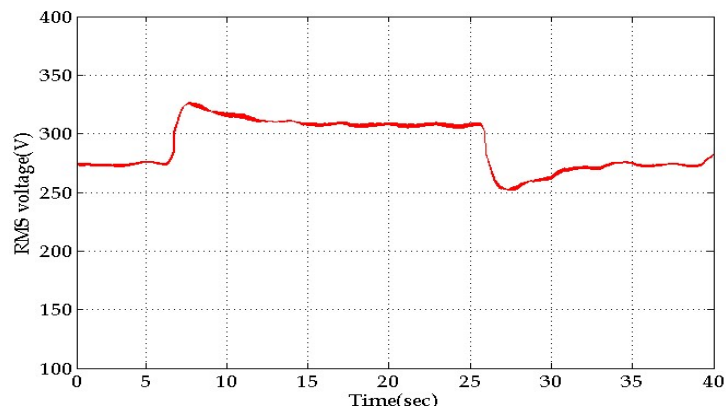


452

453 Fig. 28. Wave forms of reference power  $P_{\text{ref}}$ , estimated power  $P_w$  obtained by PSO algorithm and the  
 454 power consumed by the pump  $P_{\text{pump}}$  from  $V_w = 10\text{m/s}$  to  $V_w = 13\text{ m/s}$  and return to  $10\text{ m/s}$ .

455 The variation of the RMS voltage measured at the SEIG output for wind speed switching from  $V_w =$   
 456  $10\text{m/s}$  to  $V_w = 13\text{ m/s}$  and return to  $10\text{ m/s}$  is presented in Fig. 29. Here during the steady state the  
 457 voltage takes the values 278V and 308V respectively.

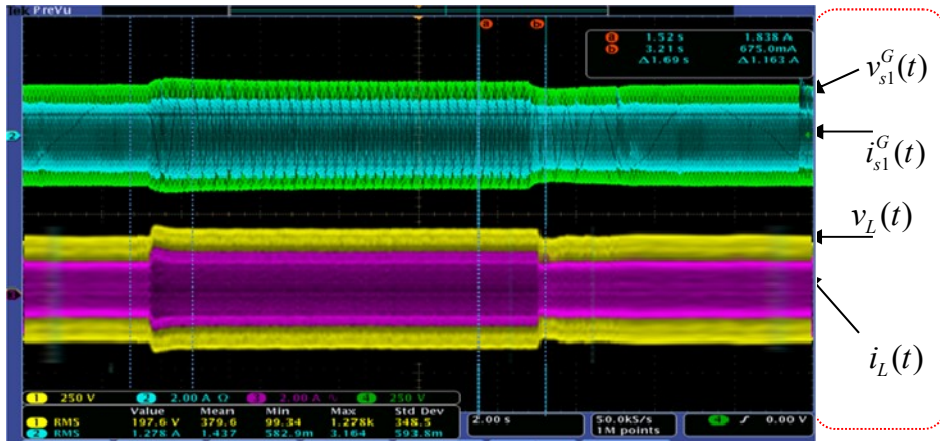
458



459 Fig. 29. Wave forms of the SEIG RMS voltage for wind speed switching from  $V_w = 10\text{m/s}$  to  $V_w = 13$   
 460  $\text{m/s}$  and return to  $10\text{ m/s}$ .

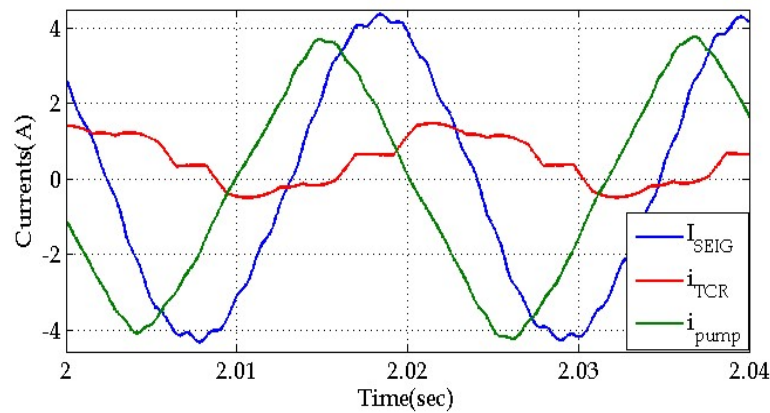


461 In the presented figures (Fig. 28 and Fig. 29) the  $P_{\text{pump}}$  and RMS voltage are reconstituted signals  
 462 obtained from instantaneous recording signals of current and voltage measured at the SEIG output and  
 463 the  $P_w$  is the estimated power obtained by the proposed the PSO algorithm. The wave forms of recorded  
 464 signals are presented in Fig. 30.

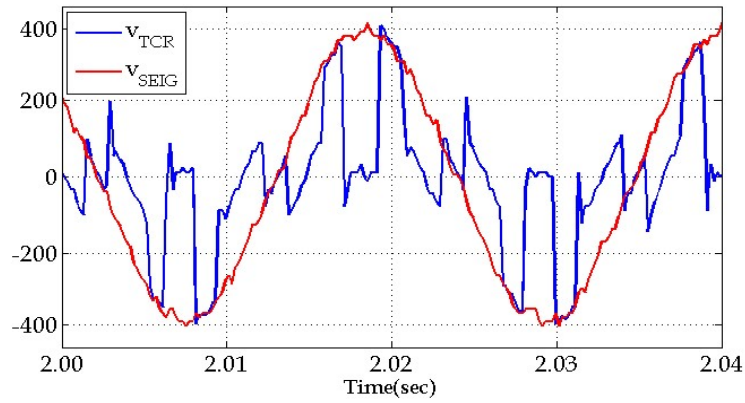


465 Fig. 30 . Wave forms of recording signals : top lines show voltage and current lines measured at the  
 466 SEIG output, bottom lines show voltage and current lines of TCR system for wind speed switching  
 467 from  $V_w = 10\text{m/s}$  to  $V_w = 13\text{ m/s}$  and return to  $10\text{ m/s}$ .  
 468

469 We can observe in Fig. 30 an increasing of the voltage and the current signals (top lines) for  $V_w = 13$   
 470 m/s and a increase of the  $I_L$  current consumed by inductance  $L_0$  in order to decrease the reactive power  
 471 in the system. For the second case considered the wave forms of the current and voltage signals are  
 472 presented in the following pictures. Fig. 31 gives the signals for wind speed  $V_w=10\text{m/s}$  and Fig. 32 for  
 473  $V_w=13\text{m/s}$ .



474  
 475 a)  $I_{\text{SEIG}}$  current,  $I_{\text{pump}}$  current and  $I_{\text{TCR}}$  current



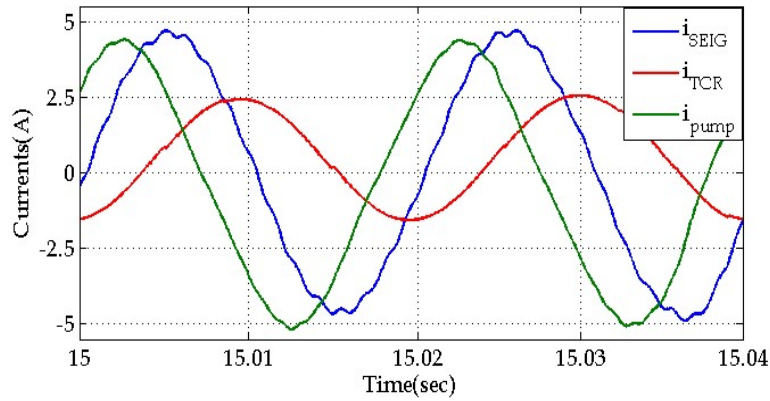
476

477

b) first line voltage of SEIG, and first line voltage of TCR system

478

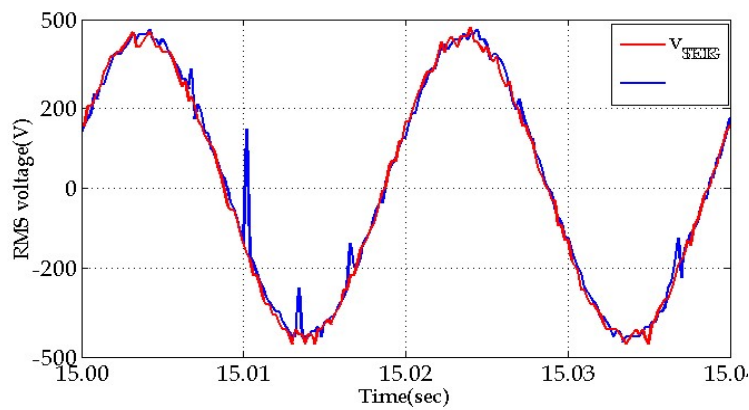
Fig. 31. Zoomed wave forms of a) current and b) voltage for  $V_w=10\text{m/s}$  wind speed.



479

480

a)  $I_{SEIG}$  current,  $I_{pump}$  current and  $I_{TCR}$  current



481

482

b) first line voltage of SEIG, and first line voltage of TCR system

483

Fig. 32. Zoomed wave forms of a) current and b) voltage for  $V_w=13\text{m/s}$  wind speed.



484 To conclude all steady state analyses results, a summary of the SEIG performance is tabulated in  
 485 Table 1.

486 Tab.1 Steady state results

	Simulation Results			Experimental Results		
$V_w(\text{m/s})$	<b>12</b>	<b>10</b>	<b>13</b>	<b>12</b>	<b>10</b>	<b>13</b>
$V_s(\text{V})$	<b>285.5</b>	<b>274.4</b>	<b>303</b>	<b>284</b>	<b>278</b>	<b>308</b>
$f(\text{Hz})$	<b>47</b>	<b>45</b>	<b>50</b>	<b>47.4</b>	<b>45.1</b>	<b>50</b>
$P_{\text{MPPT}}(\text{W})$	<b>1660</b>	<b>1598</b>	<b>1880</b>	<b>1640</b>	<b>1580</b>	<b>1870</b>
$P_{\text{Pump}}(\text{W})$	<b>1352</b>	<b>1250</b>	<b>1462</b>	<b>1335</b>	<b>1247</b>	<b>1460</b>
Losses(W)	<b>308</b>	<b>348</b>	<b>418</b>	<b>305</b>	<b>333</b>	<b>410</b>
$\eta$ (%)	<b>81.5</b>	<b>78.2</b>	<b>77.7</b>	<b>81.4</b>	<b>78.9</b>	<b>78</b>

487

## 488 6. Conclusion

489 This paper presents the performance of a Self Excited Induction Generator Pumping system used in  
 490 the case of variable wind speed. The system is able to track a maximum power using a generated power  
 491 as input. The Maximum Power Point Tracking controller sets the generator to work at the optimal rotor  
 492 speed command, which is achieved through a frequency control loop by changing the reactive power.  
 493 The proposed system has been implemented in a real-time application, using two Induction Machine  
 494 (generator and pump) and a DC motor for emulator of the wind turbine behavior. Simulation and  
 495 experimental results show the appropriate behavior of the system.

496 In this paper a new MPPT control algorithm involving PSO technique without use of a rotor speed  
 497 sensor is proposed. The wind turbine in operation delivers the maximum mechanical output power for a  
 498 given wind velocity. It is considered that the slip of the SEIG is very small. Therefore, when operating

499 the induction generator with wide rotor speeds achieving MPPT, the frequency of the SEIG is controlled  
 500 to reach the optimal rotor speed  $\omega_{ropt}$  .

501 A proposed PSO-MPPT based algorithm is presented in this work as a case study. The advantage of  
 502 the proposed method is that it does not require the knowledge of wind speed, air density or turbine  
 503 parameters. The MPPT controller generates at its output the optimum capacitor command  $C_{opt}$  for rotor  
 504 speed control loop using only the instantaneous active power as input signal.

505 From, the analyses results, the PSO based MPPT has been proved to be useful in tracking the  
 506 maximum power point and it is able to respond to the changes of wind speed and power coefficients.

507 However, the global time for tracking of the MPP is dependent by the global inertia of the system  
 508 and SEIG parameters and can take few second time delay.

## 509 Nomenclature

Variable	Designation	Variable	Designation
$A$	Area swept by blades	$l_s^G$ and $l_s^M$	Leakage inductance of the stator winding of IG and IM
$B$	Fundamental frequency susceptance		
$C_0$	Big fixed capacitor	$l_r^G$ and $l_r^M$	Leakage inductance of the rotor copper of IG and IM
$C_{min}$ and $C_{max}$	Low bound and upper bound values of the optimal capacitor	$L_m^G$ and $L_m^M$	Magnetizing inductances of the IG and IM
$C_j^k$	$j^{\text{th}}$ capacitor at iteration k	$L_0$	Big fixed self inductance.
$C_{Gbest}$	Global best capacitor of each group	$N_p$	Number of particles
$C_{opt}$	Optimal capacitor	p	Pair of poles
$C_p$	Power coefficient of the wind turbine	$P_{jref}^k$	$j^{\text{th}}$ reference mechanical power at iteration k
$C_{pbest}^k$	Best capacitor of $j^{\text{th}}$ particle until iteration k	$P_{wj}^k$	$j^{\text{th}}$ mechanical power at iteration k
$f_j^k$	$j^{\text{th}}$ frequency at iteration k	$P_w, P_{pump}$	Mechanical powers of the wind turbine respectively the pump
$Fit, Fit_{opt}$	Fitness function and Optimal Fitness function	$P_{MPP}$	Maximum power extracted from the wind turbine
$G_{best}$	Global best particles	$P_{best}$	Local best particles
$j$	Index of particles	$Q_{TCR}, Q_{C0}$ and $Q_L$	Reactive powers of the TCR system, the capacitor and the inductance
$J$	Global inertia of system.	$R_w$	Radius of the wind turbine blade

$k$	$k^{\text{th}}$ iteration	$rand$	Random numbers which are uniformly distributed in interval [0, 1]
$k_n$	Torque-rotor speed coefficient	$U_{DC}$ and $I_{DC}$	DC voltage and current
$V_j^k$	Velocity of $j^{\text{th}}$ particles at iteration $k$	$\delta_1$ and $\delta_2$	Positive constants
$V_w$	Wind speed	$\lambda_{opt}$	Optimum Tip Speed Ratio.
$V_s$	RMS of the SEIG terminal voltage	$\lambda$	Tip Speed Ratio.
$X_j^k$	Position of $j^{\text{th}}$ particles at iteration $k$	$\mu$	Momentum or inertia
$\beta$	Blade pitch angle	$\omega_r^G$ and $\omega_r^M$	Electrical rotor speed of IG and IM
$\Gamma_{em}^G$ and $\Gamma_{em}^M$	Electromagnetic torque developed by the IG and IM	$\omega_{rj}^k$	$j^{\text{th}}$ rotor speed at iteration $k$
$\Gamma_f$	Friction torque	$\omega_{ropt}$	Optimum rotor speed
$\Gamma_w$	Mechanical torque of the wind turbine	$\omega_{ropt}^G$	Optimal rotor speed

510

## 511 Appendix 1

512 The considered induction generator is characterized by:

513  $380/660V$ ,  $7.3/4.2A$ ,  $1420\text{ rpm}$ ,  $f = 50\text{Hz}$ ,  $\cos(\varphi) = 0.8$ ,  $p = 2$ ,  $R_s^G = 8.66\ \Omega$ ,  $R_r^G = 3\ \Omega$ ,  
514  $l_s^G = 24.24\text{ mH}$ ,  $l_r^G = 36.3\text{ mH}$ ,  $L_m^G = 534\text{ mH}$ ,  $L_s^G = 558.24\text{ mH}$ ,  $L_r^G = 570.3\text{ mH}$ ,  $\Gamma_f = 1.3\text{ N.m}$

515 The considered induction motor is characterized by:

516  $380/660V$ ,  $5.2/3A$ ,  $1420\text{ rpm}$ ,  $f = 50\text{Hz}$ ,  $\cos(\varphi) = 0.89$ ,  $p = 2$ ,  $r_s^M = 3.7\ \Omega$ ,  $r_r^M = 2.72\ \Omega$ ,  
517  $l_s^M = 20.78\text{ mH}$ ,  $l_r^M = 14.8\text{ mH}$ ,  $L_m^M = 436.6\text{ mH}$ ,  $L_s^M = 457.38\text{ mH}$ ,  $L_r^M = 451.4\text{ mH}$ ,

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