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1	<b>PSO-based MPPT Control of Wind-driven Self-Excited</b>
2	Induction Generator for Pumping System
3	Mohamed. Ali Zeddini <sup>1</sup> , Remus Pusca <sup>2</sup> , Anis Sakly <sup>1</sup> , M. Faouzi Mimouni <sup>1</sup>
4	(1) Research unit: Industrial Systems Study and Renewable Energy (ESIER), National Engineering School of Monastir
5	(ENIM), University of Monastir, Tunisia.
6	(2) Artois University, EA4025, Laboratory of Electrical Systems and Environment (LSEE), Bethune, F-62400, France.
7	zeddini_med_ali_enim@yahoo.fr
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.

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

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

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

#### 25 1. Introduction

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

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

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

Other works have focused on architectures and methods for maximizing the wind power. Among them, various regulating schemes have been adopted to extract the maximum power from the wind turbine [13-15]. Consequently, the SEIG is operating at variable frequency, which needs a single power controller. However, this scheme is gaining importance for stand-alone wind power applications, in particular for water pumping systems with Induction Motor (IM) where the variation of the electrical 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 proposed in [18,19]. However, this technique which minimizes the oscillation needs to use the generator 55 56 rotor speed variation (as complementary information) to provide the correct direction to the Maximum 57 Power Point (MPP).

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

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

The whole paper is organized as follows: section 2 describes the dynamic modeling of the SEIG pumping system, section 3 is devoted to presents the principle of MPPT control strategies. Simulation results performed with Matlab/Simulink are discussed and presented in section 4. The location of the MPP is calculated for different wind speed values to show the robustness and the efficiency of the propose PSO MPPT algorithm. Experimental results are presented in section 5 with measurements on a
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 mechanical break to emulate the centrifugal pump model, a frequency controller based on Thyristor 78 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.



Fig.1. Schematic block diagram of the experimental test-bench of the wind turbine energy conversionsystem.

# 85 2.1. Modeling of Wind Turbines Curve

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

88

97

99

$$P_w = \frac{1}{2} \rho A V_w^3 \tag{1}$$

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 
$$P_m = \frac{1}{2} \rho A C_p(\beta, \lambda) V_w^3$$
(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 
$$C_{p}(\lambda,\beta) = 0.5179(116\lambda_{i} - 0.4\beta + 5)e^{-21\lambda_{i}} + 0.068\lambda$$
(3)

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

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

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

$$\lambda = \frac{R_w \Omega_r}{V_w} \tag{5}$$

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 
$$\Gamma_{w} = \frac{P_{m}}{\Omega_{r}} = \frac{R_{w}}{2\lambda} \rho A V_{w}^{2} C_{p}(\beta, \lambda)$$
(6)

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

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





Fig. 2 Variation of (a) mechanical power curves and (b) power coefficient of the wind turbine fordifferent wind speeds.

# 109 2.2. Modeling of the Self Excited Induction Generator

For the modeling and analysis of the SEIG, the stationary reference frame model is used. Moreover, the following differential equations describing the global generator model including the IG currents ( $i_{sd}^{G}, i_{sq}^{G}, i_{rq}^{G}, i_{rq}^{G}, i_{rq}^{G}$ ) which integrated the auto-excitement capacitor *C* and the IM currents ( $i_{sd}^{M}, i_{sq}^{M}$ ) are developed as:

$$114 \qquad \frac{d}{dt} \begin{pmatrix} i_{sd}^{G} \\ i_{sq}^{G} \\ i_{rq}^{G} \\ i_{rq}^{G} \\ v_{sd} \\ v_{sd} \end{pmatrix} = \frac{1}{D^{G}} \left\{ \begin{bmatrix} L_{r}^{G}R_{s}^{G} & -L_{m}^{G^{2}}\omega_{r}^{G} & -L_{m}^{G}R_{r}^{G} & -L_{m}^{G}L_{r}^{G}\omega_{r}^{G} & -L_{r}^{G} & 0 \\ L_{m}^{G^{2}}\omega_{r}^{G} & L_{r}^{G}R_{s}^{G} & L_{m}^{G}L_{r}^{G}\omega_{r}^{G} & -L_{m}^{G}R_{r}^{G} & 0 & -L_{r}^{G} \\ -L_{m}^{G}R_{s}^{G} & L_{m}^{G}L_{s}^{G}\omega_{r}^{G} & L_{s}^{G}R_{r}^{G} & L_{s}^{G}L_{r}^{G}\omega_{r}^{G} & L_{m}^{G} & 0 \\ -L_{m}^{G}L_{s}^{G}\omega_{r}^{G} & -L_{m}^{G}R_{s}^{G} & -L_{s}^{G}L_{r}^{G}\omega_{r}^{G} & L_{s}^{G}R_{r}^{G} & 0 & L_{m}^{G} \\ \frac{1}{C} & 0 & 0 & 0 & \frac{1}{C} & 0 \\ 0 & \frac{1}{C} & 0 & 0 & 0 & \frac{1}{C} & 0 \\ 0 & \frac{1}{C} & 0 & 0 & 0 & \frac{1}{C} \end{bmatrix} \begin{pmatrix} i_{sd}^{G} \\ i_{sq}^{G} \\ i_{rq}^{G} \\ i_{sd}^{M} \\ i_{sd}^{M} \end{pmatrix} - \omega_{r}^{G} \begin{pmatrix} -L_{m}^{G} \\ -L_{m}^{G} \\ L_{s}^{G} \\ L_{s}^{G} \end{pmatrix} \phi_{0} \right\}$$
(7)

115 where,  $L_s^G = l_s^G + L_m^G \ L_r^G = l_r^G + L_m^G$ , and  $D^G = L_m^{G^2} - L_s^G L_r^G$ 

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  $\Gamma^G_{em} = \frac{3}{2} \left(\frac{p}{2}\right) \left[ i^G_{rd} i^G_{sq} - i^G_{sd} i^G_{rq} \right]$ (8)

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

125
$$\begin{cases}
J\frac{d\Omega_{r}^{G}}{dt} + \Gamma_{f} = \Gamma_{\omega} - \Gamma_{em}^{G} \\
\Gamma_{\omega} = \frac{P_{w}}{\Omega_{r}^{G}}
\end{cases}$$
(9)

where  $\Gamma_w$  represents the torque which acts on the SEIG shaft by means of the blades,  $\Gamma_f$  is the friction 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  $(v_{sd} \text{ and } v_{sq})$  are developed as:

$$\frac{d}{dt} \begin{pmatrix} i_{sd}^{M} \\ i_{sq}^{M} \\ i_{rq}^{M} \\ i_{rq}^{M} \end{pmatrix} = \frac{1}{D^{M}} \begin{vmatrix} -pL_{m}^{M} \Omega_{r}^{M} & -L_{r}^{M} r_{s}^{M} & -pL_{m}^{M} L_{r}^{M} \Omega_{r}^{M} & -L_{m}^{M} r_{r}^{M} \\ -L_{r}^{M} r_{s}^{N} & pL_{m}^{M^{2}} \Omega_{r}^{M} & -L_{m}^{M} r_{r}^{M} & pL_{m}^{M} L_{r}^{M} \Omega_{r}^{M} \\ pL_{m}^{M} L_{s}^{M} \Omega_{r}^{M} & L_{m}^{M} r_{s}^{M} & pL_{s}^{M} L_{r}^{M} \Omega_{r}^{M} & L_{s}^{M} r_{r}^{M} \\ L_{m}^{M} r_{s}^{M} & -pL_{m}^{M} L_{s}^{M} \Omega_{r}^{M} & L_{s}^{M} r_{r}^{M} & pL_{s}^{M} L_{r}^{M} \Omega_{r}^{M} \\ L_{m}^{M} r_{s}^{M} & -pL_{m}^{M} L_{s}^{M} \Omega_{r}^{M} & L_{s}^{M} r_{r}^{M} & pL_{s}^{M} L_{r}^{M} \Omega_{r}^{M} \\ 1 & \begin{bmatrix} -L_{r}^{M} & 0 \\ 0 & -L_{r}^{M} \end{bmatrix} (v_{sd}) \end{vmatrix} \tag{10}$$

131

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

132 where,  $L_s^M = l_s^M + L_m^M L_r^M = l_r^M + L_m^M$  and  $D^M = L_m^{M^2} - L_s^M L_r^M$ ,

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 
$$\Gamma^{M}_{em} = \frac{3}{2} \left(\frac{p}{2}\right) \left[ i^{M}_{rd} i^{M}_{sq} - i^{M}_{sd} i^{M}_{rq} \right]$$
(11)

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

139  

$$\begin{cases}
J \frac{d\Omega_r^M}{dt} + \Gamma_f = \Gamma_{em}^G - \Gamma_{pump} \\
\Gamma_{pump} = \frac{P_{pum}}{\Omega_r^M} = k_n \Omega_r^{M^2}
\end{cases}$$
(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  $C_0 = 75 \ \mu F$ 

and a fixed self inductance  $L_0 = 335 \text{ mH}$ . A per phase circuit of TCR circuit is shown in Fig. 3.



Fig. 3. Per phase equivalent circuit of TCR system and open loop control scheme for frequencyregulation.

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

149 
$$i_{L0} = \begin{cases} \frac{V_s}{\pi . L_0 \omega} \sqrt{2} [\cos(\psi) - \cos(\omega . t)] & \psi < \omega . t < \psi + \sigma \\ 0 & \psi + \sigma < \omega . t < \pi \end{cases}$$
(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 
$$I_1 = \frac{\sigma - \sin(\sigma)}{\pi L_0 \omega} V_s = B(\sigma) V_s$$
(14)

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

The TCR system is controlled by adjusting a fundamental frequency susceptance whose reactive power is balanced according to the requirement current in the SEIG. However, the reactive power  $Q_{TCR}$ generated by a TCR system is equal to the difference between the capacitor power  $Q_{C0}$  and the inductance power  $Q_L$  as:

159 
$$Q_{TCR} = Q_{C0} - Q_{L0} = 3(C_0\omega - B(\sigma))V_s^2$$
(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 possible power, the wind turbine aloud be operates at this speed. During the constant wind speed is possible to control the rotational speed of the wind turbine by changing the reactive power.

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

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



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

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  $\omega_{ropt}$ .

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

In the proposed PSO algorithm, as the rotor speed  $\omega_r$  can be modified by changing the capacity value, a 189 vector of capacitor  $C_j^k$  is used as initial value. j is the index of evolving parameters ( $j = 1, 2, ..., N_p$ ) called 190 191 particles and their values change at each iteration k. For each iteration, these j values of the capacity are sent to the TCR system, which imposes to the SEIG a frequency  $f_j^k$  and a rotor speed  $\omega_{rj}^k$ . The wind 192 turbine emulator use a characteristic wind curve memorized in a look-up table and a rotor speed 193 estimator to calculate  $P_{opt}$ . In the test bench is used a power loop control for DC motor under a PWM 194 chopper to generate the corresponding mechanical power to the SEIG shaft. After the sending of the first 195 capacity value  $C_i^k$  and the establishment of the permanent regime of mechanical and electrical 196 197 quantities in the generator, voltage and current sensors are used to measure the electrical power and to estimate the mechanical power ( $P_{wj}^k$ ) applied at the SEIG shaft. In the same iteration k the TCR system 198 receives the second reference of the capacity value  $C_{j+1}^k$ , which imposes to the DC machine a new 199 mechanical shaft power  $P_{wj+1}^k$ . The last value of the capacity for the iteration k is  $C_{N_n}^k$ . Each time 200 necessary to establish the permanent regime and to measure electrical variables  $(U_{DC} \text{ and } I_{DC})$  for  $C_j^k$ 201 202 depends on the global inertia system, parameters of the SEIG and requires for presented system approximately 200 ms. For practical implementation the number of particles  $N_p$  must be limited (  $N_p \le 4$ ). In presented application the global iteration time is near to 800 ms and this cycle will be repeated continuously until the real mechanical power achieves the maximum power points (MPP). It can be noticed in Fig.4.b that for a real wind turbine the proposed PSO algorithm does not need to 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, it randomly produces  $N_p$  particles in searching space, where each particle is characterized by a position 210  $X_j^k$  in the searching space, and a velocity  $V_j^k$  [26, 28]. Each position of particle  $X_j^{(k)}$  (in this case the 211 capacity  $C_j^k$ ) represents a solution of the problem and the "velocity"  $V_j^{(k)}$  its displacement (variation of 212  $\Delta C_i^k$ ) in the searching space (between  $C_{\min}$  and  $C_{\max}$ ). The particles have memory to keeps track of 213 its previous best particle called  $P_{best}$  which corresponds to an optimal fitness function  $Fit_{opt}$  (a 214 215 mathematical function where the objective is to be minimized by changing the particles) obtained for iteration k. After the second iteration (k+1) is memorized (between  $P_{best_k}$  and  $P_{best_{k+1}}$ ), the particle gives 216 the minimized value of the  $Fit_{opt}$ . This particle (capacity in presented application) is called  $G_{best}$ . This 217 218 concept considers a random weighted acceleration at each time step [28]:

219 
$$\begin{cases} V_{j}^{(k+1)} = \mu V_{j}^{(k)} + \delta_{1} rand [0,1] (P_{best} - X_{j}^{(k)}) + \delta_{2} rand [0,1] (G_{best} - X_{j}^{(k)}) \\ X_{j}^{(k+1)} = X_{j}^{(k)} + V_{j}^{(k+1)} \end{cases}$$
(16)

where,  $j = 1, 2, ..., N_p$  is the index of particles,  $\mu$  is the momentum or inertia ( $\mu = 0.5$ ),  $\delta_1$  and  $\delta_2$  are a positive constant ( $\delta_1 = \delta_2 = 0.5$ ), *rand* is random numbers which are uniformly distributed in [0, 1], and k is the iteration number. A typical movement of particles in the optimization process is shown in Fig. 5.



#### 224

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

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

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

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

236 
$$X_{j}^{(k)} = V_{j}^{(k)} = C_{j}^{k} = \frac{C_{\max} - C_{\min}}{N_{p} - 1} (j - 1) + C_{\min}$$
(17)

237 
$$j = 1, 2, ... N_p$$

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

242 
$$Fit = \min \Delta P = \left| P_{nom} - P_w(C_j^k) \right|$$
(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 
$$\begin{cases} \Delta C_{j}^{(k+1)} = \mu \Delta C_{j}^{(k)} + \delta_{1} rand [0,1] (C_{jPbest}^{k} - C_{j}^{(k)}) + \delta_{2} rand [0,1] (C_{jGbest}^{k} - C_{j}^{(k)}) \\ C_{j}^{(k+1)} = C_{j}^{(k)} + \Delta C_{j}^{(k+1)} \end{cases}$$
(19)

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

248 
$$C_{jPbest}^{k} = \begin{cases} C_{j}^{k} \text{ for } P_{w}(C_{j}^{(k)}) > P_{w}(C_{j-1}^{(k)}) \\ C_{j-1}^{k} \text{ for } P_{w}(C_{j}^{(k)}) < P_{w}(C_{j-1}^{(k)}) \end{cases}$$
(20)

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

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

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

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

This capacity  $C_{jGbest}^k$  gives the minimal value for fitness function at iteration k and it makes it possible to extract more power from the wind turbine. We note that, in order to avoid the disconnection of the SEIG, limitations of the capacity value must be imposed ( $C_{\min} < C_j^k < C_{\max}$ ). Taking this constraint into consideration the new capacity can be expressed by:

258 
$$C_{j}^{k+1} = \begin{cases} C_{\min} \text{ for } C_{j}^{(k)} + \Delta C_{j}^{(k+1)} < C_{\min} \\ C_{j}^{(k)} + \Delta C_{j}^{(k+1)} \text{ for } C_{\min} < C_{j}^{(k)} + \Delta C_{j}^{(k+1)} < C_{\max} \\ C_{\max} \text{ for } C_{j}^{(k)} + \Delta C_{j}^{(k+1)} > C_{\max} \end{cases}$$
(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 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 261 262 correlated with the system inertia and in this application limited to N<sub>p</sub>=4. In Fig. 6.a, the four initial particles are marked with circular points and for each point there is one capacitor value. Each capacitor 263 imposes a rotor speed  $(\omega_{r_1}^k, \omega_{r_2}^k, \omega_{r_3}^k, \omega_{r_4}^k)$  which corresponds to a mechanical power  $(P_{w_1}^k, P_{w_2}^k, P_{w_3}^k, P_{w_4}^k)$ . 264 We can notice here that  $C_3^k$  is the best particle in the first iteration k, which gives the best power value ( 265  $P_{best} = P_{w3}^k$  ), corresponding to maximum mechanical power at the first iteration. 266

For the second iteration (iteration k+1), the particle updating is realized using equation 17. It is 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 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 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 particles between the latest and the previous iterations corresponding to the greater best power  $P_{w3}^{k+1}$ .

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 the subsequent iteration, due to very low velocity, the value of the rotor speed  $(\omega_{r_1}^{k+2}, \omega_{r_2}^{k+2}, \omega_{r_3}^{k+2}, \omega_{r_4}^{k+2})$  is 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

27**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 is estimated at approximately 2.4s (4x200 ms x3). If the wind speed applied changes the PSO algorithm 283 284 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:  $\left|C_{j}^{(k+1)}-C_{j}^{(k)}\right| < \varepsilon_{1}$
- 287 sudden change in the fitness function.  $\left|P_{\omega}(C_{j}^{k+1}) P_{\omega}(C_{j}^{k})\right| > \varepsilon_{2}$

Here the first condition imposes a small variation capacity between two iteration steps, error  $\varepsilon_1$  and the second condition imposes a minimum power variation for a new "initialize particles" step, error  $\varepsilon_2$ . The flowchart of this algorithm is given in Fig. 7 where the delay time  $\Delta T$  is estimated at 200 ms.



292

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

#### 296 4. Simulation Results and Discussion

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

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



304

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

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

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

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 m/s and back to 10 m/s.

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

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

In Fig.16 the first line currents of the  $I_{SEIG}$ , the first line current  $I_{TCR}$  of the TCR system and those of the pump are shown. We can notice that the  $I_{TCR}$  changing during each considered interval ( $V_w=12m/s$ ,

324  $V_w=10$  m/s,  $V_w=13$  m/s) when the reactive power is changed and so the  $\omega_r$  respectively the frequency.

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

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.



Fig. 10. Variations of optimal capacitor during step wind speed variation; V=13m/s and V=12m/s.
340







341

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



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



349

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



355

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

5 Instantaneousfirst line currents (A) 0 -5 15 5 10 20<sub>Time(sec)</sub>25 30 5 5 -**i**seig 0 0  $-5 \\ 12.5$ -5 7.5 -5 17.5 7.52 12.52 17.52

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



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



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



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



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

367



371

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

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

- power-controlled DC motor drive which is used to emulate the characteristics of the wind turbine
  and to gives P<sub>w</sub> at the SEIG shaft.
- 2[kW] squirrel-cage induction motor which is mechanically coupled to a break to emulate the
   centrifugal pump system, a TCR system converter connected in parallel with the SEIG output

terminals for the control of the reactive power, and a dSPACE controller board which isinterfaced 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**

The performance of the MPPT control strategy was validated experimentally using a laboratory test bench composed of an IG which feeds an IM loaded by a specific break characteristic in order to assure a pump emulator. Different wind speed operating conditions are created by a DC motor which receives a power control in order to assure a constant power  $P_w$  at the SEIG shaft making it possible to investigate the dynamic characteristics of a SEIG-Pump system and to find the maximum of the power 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 reference presented in Fig. 23. For experimental induction machines characterized by the parameters 407 408 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  $V_w = 13$ m/s to  $V_w = 12$  m/s and return to 13 m/s. 414 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.



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

The RMS voltage variation measured at the SEIG output is presented in Fig. 25. Here during the wind variation the voltage changes between 308V at 284V with the low overtaking caused by the wind

426 power variation (regulation) at the SEIG shaft.



427



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



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

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



443



For this case the power estimation  $P_{MPP}$  obtained by the proposed algorithm and the measured power absorbed by the pump  $P_{pump}$  are presented in Fig. 28. The reference power  $P_{ref}$  is a step signal changing between 1640W and 1870W. Taking into consideration the DC motor and the IG losses we can notice the identical variation for  $P_{pump}$  and  $P_{MPP}$ . The difference during the transitory interval between  $P_{MPP}$  and  $P_{w}$  can be justified by regulation power at the SEIG shaft.

451





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

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



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

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



465

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

We can observe in Fig. 30 an increasing of the voltage and the current signals (top lines) for  $V_w = 13$ m/s and a increase of the I<sub>L</sub> current consumed by inductance L<sub>0</sub> in order to decrease the reactive power in the system. For the second case considered the wave forms of the current and voltage signals are presented in the following pictures. Fig. 31 gives the signals for wind speed V<sub>w</sub>=10m/s and Fig. 32 for V<sub>w</sub>=13m/s.





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



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



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

To conclude all steady state analyses results, a summary of the SEIG performance is tabulated inTable 1.

	Simulation Results			Experimental Results		
V <sub>w</sub> (m/s)	12	10	13	12	10	13
V <sub>s</sub> (V)	285.5	274.4	303	284	278	308
f(Hz)	47	45	50	47.4	45.1	50
P <sub>MPPT</sub> (W)	1660	1598	1880	1640	1580	1870
P <sub>Pump</sub> (W)	1352	1250	1462	1335	1247	1460
Losses(W)	308	348	418	305	333	410
η (%)	81.5	78.2	77.7	81.4	78.9	78

#### 486 Tab.1 Steady state results

 $487^{-}$ 

### 488 **6.** Conclusion

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

In this paper a new MPPT control algorithm involving PSO technique without use of a rotor speed sensor is proposed. The wind turbine in operation delivers the maximum mechanical output power for a 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  $\omega_{ropt}$ .

A proposed PSO-MPPT based algorithm is presented in this work as a case study. The advantage of the proposed method is that it does not require the knowledge of wind speed, air density or turbine parameters. The MPPT controller generates at its output the optimum capacitor command  $C_{opt}$  for rotor 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
В	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	$L^G_m$ and $L^M_m$	Magnetizing inductances of the IG and IM
$C_j^k$	j <sup>th</sup> capacitor at iteration k	$L_0$	Big fixed self inductance.
C <sub>Gbest</sub>	Global best capacitor of each group	$N_p$	Number of particles
C <sub>opt</sub>	Optimal capacitor	р	Pair of poles
$C_p$	Power coefficient of the wind turbine	$P_{jref}^k$	j <sup>th</sup> reference mechanical power at iteration k
$C_{pbest}^{k}$	Best capacitor of j <sup>th</sup> particle until iteration k	$P_{wj}^k$	j <sup>th</sup> mechanical power at iteration k
$f_j^k$	j <sup>th</sup> 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 <sub>MPP</sub>	Maximum power extracted from the wind turbine
G <sub>best</sub>	Global best particles	P <sub>best</sub>	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 <sup>th</sup> iteration	rand	Random numbers which are uniformly distributed in interval [0, 1]
k <sub>n</sub>	Torque-rotor speed coefficient	$U_{DC}$ and $I_{DC}$	DC voltage and current
$V_j^k$	Velocity of jth particles at iteration k	$\delta_{\!_1}$ and $\delta_{\!_2}$	Positive constants
$V_w$	Wind speed	$\lambda_{opt}$	Optimum Tip Speed Ratio.
V <sub>s</sub>	RMS of the SEIG terminal voltage	λ	Tip Speed Ratio.
$X_j^k$	Position of j <sup>th</sup> particles at iteration k	μ	Momentum or inertia
β	Blade pitch angle	$\omega_r^G$ and $\omega_r^M$	Electrical rotor speed of IG and IM
$\Gamma^{G}_{em}$ and $\Gamma^{M}_{em}$	Electromagnetic torque developed by the IG and IM	$\omega_{rj}^k$	j <sup>th</sup> rotor speed at iteration k
$\Gamma_f$	Friction torque	$\omega_{ropt}$	Optimum rotor speed
$\Gamma_w$	$\Gamma_w$ Mechanical torque of the wind turbine		Optimal rotor speed

### 511 Appendix 1

512 The considered induction generator is characterized by:

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

515 The considered induction motor is characterized by:

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

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