FUZZY CONTROL STRATEGY OF THE EXCITATION CAPACITOR FOR WATER PUMPING SYSTEM OPTIMIZATION

M. OUALI, S. SALLEM,

University of Sfax, CMERP-ENIS, Rte Sokra Km 3.5, BP 1173-3038, Sfax 3052, Tunisia
manel_zouhir_ouali@yahoo.fr, souhirsallem@gmail.com

M. CHAABENE, M.B.A KAMOUN
University of Sfax, CMERP-ENIS, Rte Sokra Km 3.5, BP 1173-3038, Sfax 3052, Tunisia
maher.chaabane@isetsf.rnu.tn, mba.kamoun@enis.rnu.tn

Abstract: *This paper presents a SEIG-IM plant using a self excited induction generator driven by wind turbine and supplying an induction motor which is coupled to a centrifugal pump. A system modeling in dynamic state is established. A control strategy optimizes the quantity of the pumped water is proposed. A fuzzy controller is implemented to adjust, while wind speed variation, the actual value of the total capacitive bench to its optimal value. Following the system modeling and simulation, results discussion confirms that the use of the optimal value for the excitation capacitance improve the pump power of 10%.*

Key words: *Self Excited Induction Generator, Induction Motor, Fuzzy Logic Control, centrifugal pump, optimal excitation capacitance, wind rotor speed.*

1. Introduction

Commonly, pumping systems installed in isolated sites use diesel motors. Classified very polluting for the environment, the diesel energy tends to be replaced by renewable energy sources as: photovoltaic and wind. Wind pumping is the most adequate solution for the windy sites. There are two types of wind pumping: electric and mechanical. Mechanical pumping system is characterized by a direct conversion of wind kinetic energy into mechanical one. This system is not effective, difficult to control and must be installed near the water source [1]. However, the electric system of wind pumping is based on the energy transformation of the wind into electric power which is used to supply a pump-motor unit. Thus, the wind turbine may be sited independently of the well. Moreover, the adaptation and regulation of the wind kinetic energy is possible by using suitable electronics [2, 3, 4, 5].

This work considers a wind pumping plant composed of a Self Excited Induction Generator (SEIG) driven by a wind nacelle and supplying an induction motor which is coupled to a centrifugal pump. Many types of generators convert the wind kinetic energy into electric power: permanent magnet generator, synchronous generator, variable reluctance generator and brushless generator. The asynchronous generator remains the most solicited thanks to its low cost, its reliability, its robust construction and its easy maintenance [6]. It is also autonomous while self excited if a suitable capacitor bank is connected across its stator terminals.

In literature, various aspects of modeling and simulation of the SEIG operation are established [7, 8, 9]. Researchers are interested to the determination of the minimum values of capacity necessary to initiate the self-excitation process [10, 11]. Further control strategies to regulate voltage and frequency of SEIG according to the variation of the load and rotor speed are also developed. Certain control strategies are based on the study of the equivalent circuit by applying traditional resolution methods such as Newton Raphson [6]. Likewise, other approaches used additional series capacitors in short shunt or long shunt configuration of the SEIG [12]. More researchers adapt the duty cycle of an anti parallel GTO switch connected in parallel with a fixed capacitor [13]. Finally, non conventional approaches such as fuzzy logic are recently as well adopted [5, 8].

This paper proposes a SEIG control in order to optimize the quantity of the pumped water. A fuzzy controller adjusts the actual value of the total capacitive bench which is composed of several capacities connected in parallel and controlled by switches. The approach consists of ensuring the self excitation of the induction generator at large range of wind rotor speed variation. The capacity value is continually adjusted in order to maximize the mechanical power of the induction motor which is supplying the centrifugal pump. As the voltage and frequency fluctuations are not of great importance for the autonomous pumping systems, the SEIG regulation constraint becomes unnecessary. Nevertheless, the stators currents of the two machines are controlled so as to overtake 120% of their nominal values.

Following, section two presents the control strategy. The system modeling is given by section three. The fourth section shows the obtained results. Finally, a conclusion summarizes the developed work.

2. Control Strategy

The pumping unit, shown by figure 1, is composed of a wind turbine which converts wind kinetic energy into electricity by means of a Self Excited Induction Generator (SEIG). The produced power is used to supply an induction motor coupled to a centrifugal water pump. As the SEIG requires reactive power for its excitation, a three phase capacitor bank is connected across its stator terminals. Thus, the capacity value should be adjusted while wind speed varies so as to ensure the SEIG excitation. The IM cannot be supplied unless the SEIG stator voltage build up process occurs. For this reason an operating mode switchers selects first the no load condition (S = OFF) until the voltage build up process is accomplished. Subsequently the switcher is turned ON so as to connect the IM to the SEIG. A fuzzy control computes the switch states to control the excitation capacitance while the SEIG rotor speed varies. The self excitation of the SEIG is ensured following a wind speed change. The excitation capacitance is calculated with respect to limit the current stator at 120% of its nominal value in order to avoid destructive over current witch causes serious damage to the system equipments. Considering safety criterion in over current case, the capacitor is disconnected in order to demagnetise the SEIG and to lose itself excitation.

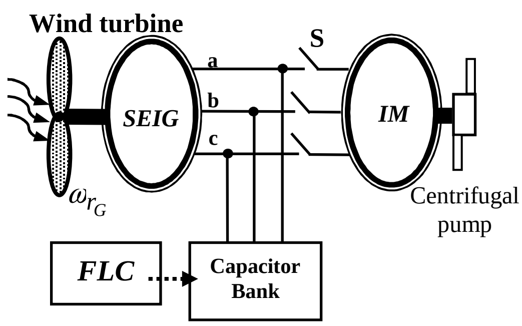

Fig.1. Wind electric pumping

Figure 2 illustrates the capacitor bank connection for each phase. Each combination of switch control gives the sum of switched ON capacitors. First S is switched OFF then switch states are computed according to SEIG rotor speed ω_{r_G}. While stator voltage is build up, the SEIG is connected to the IM. Therefore, the fuzzy controller adjusts the capacitor value to maintain the self excitation following wind speed variation and to optimize the quantity of the pumped water.

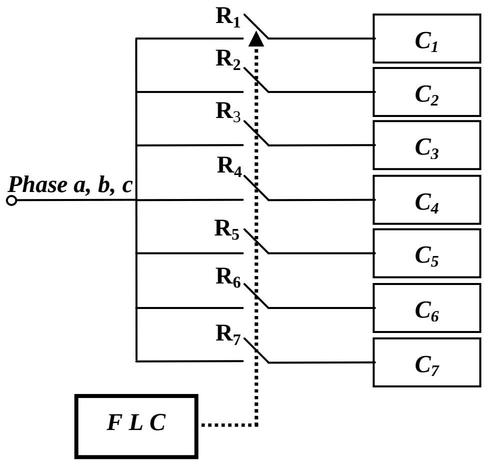

Fig.2. Capacitor banc composition

The capacitance calculation should offer a SEIG voltage around or less than its nominal value for low wind speed. For high wind speed, the SEIG voltage may reach its nominal value which can be accepted since the current stator does not exceed 120% of its nominal value. Hence, as the SEIG operation is maintained the quantity of pumped water is maximised.

In order to develop an efficient switch states calculation, a control strategy is adopted to ensure the imposed objectives and considering the safety criterion. Table 1 summarizes the switch management approach.

Table 1 : A control strategy

INPUTS : $\begin{cases}\omega_{r_G} \\ S\end{cases}$	
Criteria	***Objective***
- $I_{s_G} < 1.2\ I_{sn_G}$ - $I_{s_M} < 1.2\ I_{sn_M}$	- Ensure self excitation of SEIG for a wide range variation of wind speed - Maximize the amount of water pumped
OUTPUTS: Switches control	

3. System modeling and control

In order to develop the control strategy, a system modelling is necessary: the SEIG, the IM and the centrifugal pump.

3.1 Induction machines models

Using the generator convention, the voltage equations of SEIG are expressed as:

$$\begin{cases} \overline{V}_{s_G} + R_{s_G}\, \overline{I}_{s_G} + \dfrac{d\overline{\psi}_{s_G}}{dt} = 0 \\ R'_{r_G}\, \overline{I}'_{r_G} + \dfrac{d\overline{\psi}'_{r_G}}{dt} - j\omega_{r_G}\, \overline{\psi}'_{r_G} = 0 \end{cases} \quad (1)$$

Where, the fluxes of SEIG are giving by:

$$\begin{cases} \overline{\psi}_{s_G} = L_{s_G}\, \overline{I}_{s_G} - L_{m_G}\, \overline{I}'_{r_G} + \overline{\psi}_o \\ \overline{\psi}'_{r_G} = -L_{m_G}\, \overline{I}_{s_G} + L'_{r_G}\, \overline{I}'_{r_G} - \overline{\psi}_o \end{cases} \quad (2)$$

$\overline{\psi_o}$ represent the initial residual flux.

The generator magnetizing flux is computed by:

$$\overline{\psi}_{m_G} = \frac{L_{m_G} L'_{\sigma r_G}\, \overline{\psi}_{s_G} + L_{m_G} L_{\sigma s_G}\, \overline{\psi}'_{r_G} + L_{\sigma s_G} L'_{\sigma r_G}\, \overline{\psi}_o}{L_{s_G} L'_{r_G} - L^2_{m_G}} \quad (3)$$

In the same way and by adopting the motor convention, the voltage equations and fluxes of IM are giving respectively by:

$$\begin{cases} \overline{V}_{s_M} = R_{s_M}\, \overline{I}_{s_M} + \dfrac{d\overline{\psi}_{s_M}}{dt} \\ 0 = R'_{r_M}\, \overline{I}'_{r_M} + \dfrac{d\overline{\psi}'_{r_M}}{dt} - j\omega_{r_M}\, \overline{\psi}'_{r_M} \end{cases} \quad (4)$$

$$\begin{cases} \overline{\psi}_{s_M} = L_{\sigma s_M}\, \overline{I}_{s_M} + L_{m_M}\, \overline{I}m_M \\ \overline{\psi}'_{r_M} = L'_{\sigma r_M}\, \overline{I}'_{r_M} + L_{m_M}\, \overline{I}m_M \end{cases} \quad (5)$$

The motor magnetizing flux is computed by:

$$\overline{\psi}_{m_M} = \frac{L_{m_M} L'_{\sigma r_M}\, \overline{\psi}_{s_M} + L_{m_M} L_{\sigma s_M}\, \overline{\psi}'_{rM}}{L_{s_M} L'_{r_M} - L^2_{m_M}} \quad (6)$$

The stator voltage of both machines can be expressed as:

$$\overline{V}_{s_G} = \overline{V}_{s_M} = \overline{V_s} = \frac{1}{C}\int \overline{I}_C\, dt \quad (7)$$

$\overline{I_C}$ represents the capacity current. It is giving by:

$$\overline{I}_C = \overline{I}_{s_G} - \overline{I}_{s_M} \quad (8)$$

To take account of the non linearity of the magnetic material, the magnetization curve of both machines SEIG and IM are implemented in their models. At each sampling step, the value of a magnetic inductance is adjusted according to the magnetic flux thanks to a spline interpolation.

The mechanical equation that describes this system is:

$$\frac{d\omega_{r_M}}{dt} = \frac{p_M}{J_M}(T_{e_M} - T_{pump}) \quad (9)$$

Where,

T_{e_M} and T_{pump} represent respectively the electromagnetic torques produced by IM and the load torque of the pump.

3.2 Centrifugal pump model

Coupled to the shaft of induction motor, the centrifugal pump uses a mechanical power given by:

$$P = T_{pump}\ \omega_{r_M} \quad (10)$$

The load torque of the pump T_{pump} is expressed as [14]:

$$T_{pump} = K_p\ \omega_{r_M} \quad (11)$$

Where the coefficient K_p is computed by:

$$K_p = \frac{T_{p\max}}{\omega_{r_{\max}}} \quad (12)$$

$T_{p\,max}$ is the maximum rated torque and $\omega_{r\,max}$ is the maximum rated speed.

Due to mechanical losses, the useful power is:

$$P_u = \eta\, P = \ell_w\ g\ H\ Q \quad (13)$$

Where η represents the pump efficiency, ℓ_W is the water density (Kg/m^3), g is the gravity acceleration (m^2/s), H *is* the height of rise (*m*) and Q is the flow (m^3/s).

For a pumping period ΔT, the volume of pumped water (m^3) is computed by:

$$V = Q\ \Delta T \quad (14)$$

3.3 Fuzzy controller

Unlike conventional control strategies based on theoretical studies and mathematical models, fuzzy logic is funded on prior behaviour knowledge of the system to be addressed. For this reason, the fuzzy approach is increasingly used in the control and regulation of industrial processes. The implementation of a fuzzy control shows three main parts: fuzzification, rules and defuzzification. During the first stage a membership function is attributed to the actual value of each input. The shape of membership functions used for both input and output are triangular. The rules governing the relationships between inputs and outputs are developed. During the last step (the defuzzification) the real output is attributed to each fuzzy output. The input vector consists of two fuzzy variables: the SEIG rotor speed ω_{r_G} and the value of relay S (figure 3). Fourteen membership functions are used for the first input and two for the second input as shown respectively in figures 4 and 5. The fuzzy output vector consists of seven variables representing the seven switches; each one is associated to a capacitor of well defined value. Similarly, we use two membership functions for each relay as illustrated in figure 6.

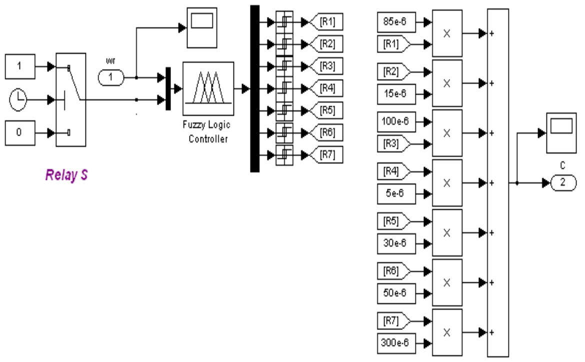

Fig.3. Simulink fuzzy control for computing the switch states to controlling the excitation capacitance.

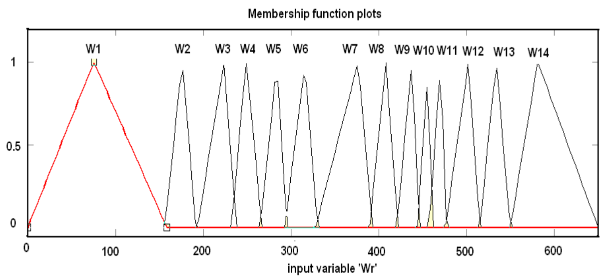

Fig.4. Membership functions for SEIG rotor speed ω_{r_G}

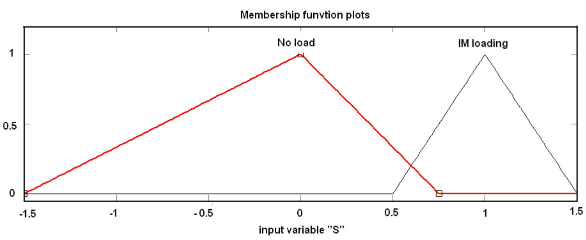

Fig.5. Membership functions for value of operating mode switchers S

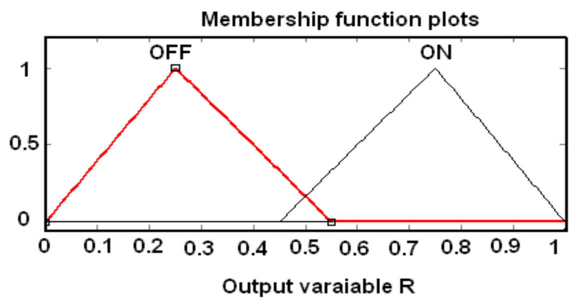

Fig.6. Output membership functions for each relay

Following, the algorithm steps are developed for no load operation and for load IM operation under constant speed drive.

- Read the wind rotor speed $\omega_{r_{G_o}}$ and the last combination of the switches states $(R_i)_{i=1..7}$.
- Read the fuzzy input S and determine the operating modes: no load or IM load. Then select the corresponding data base (note that the data bases of the two models are implemented in the models as look up tables).
- Determine the excitation capacity value C_O according to $\omega_{r_{G_o}}$ and the selected data base.
- Decide the new switches combination $(R_i')_{i=1..7}$ according to two criteria:
  - $C_o = \sum_{i=1}^{7} R_i' C_i$
  - As C_o may be obtained for different switches combinations, retain the combination that requires minimum actions on switches referring to their last value.

4. Results and discussion

The fuzzy knowledge database is established according to the static steady state. This base is composed of two sets. The first part includes the capacity values for which the SEIG stator voltage builds up occurs at no load operation. Hence, for each value of ω_{r_G} the minimal value of capacity excitation $C_{\min,\ at\ no\ load}$ is calculated. In a second stage, the IM is connected to the SEIG. Then for each speed ω_{r_G}, $C_{\min,\ at\ IM\ load}$ is determined using equation (1-9). $C_{\max}$ is calculated considering the limitation of the current stator at 120% of its nominal value to avoid destructive over current which causes serious damage to the system equipments. Consequently, C_{opt} is identified for which the IM power remains constant even if C increases. Figure 7 represents a set curves for various value of ω_{r_G} showing the variation of centrifugal pump power (P_{pump}) as a function of excitation capacitance. It is noted that for a given wind rotor speed ω_{r_G} and a variation of capacity within $[C_{\min,\ at\ IM\ Load}\ ;\ C_{\max}]$, P_{pump} increases linearly then remains constant since a certain value of C noted C_{opt}. Equations (10-14) indicate that the quantity of the pumped water is proportional to P_{pump}. Therefore to optimize this quantity it convenes to choose the capacitance adequate value that allows the optimization of the centrifugal pump power.

Figure 8 shows the variation of C_{opt}, $C_{\max}$ and

$C_{\min,\ at\ IM\ load}$ as a function of $u = \frac{\omega_{r_G}}{\omega_n}$ ($\omega_n = 100\pi\ \ rad/s$). Note that the wind rotor speed ω_{r_G} considered during simulation is less then $1.8\omega_n$ in order to respect the security criterion ($I_s \leq 1.2 I_n$).

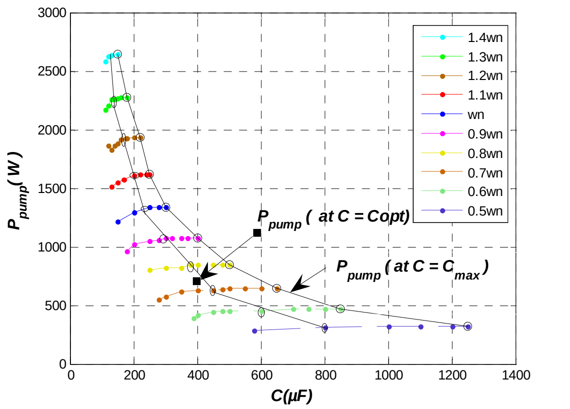

Fig.7. Variation of P_{pump} with excitation capacitance for various value of ω_{r_G} .

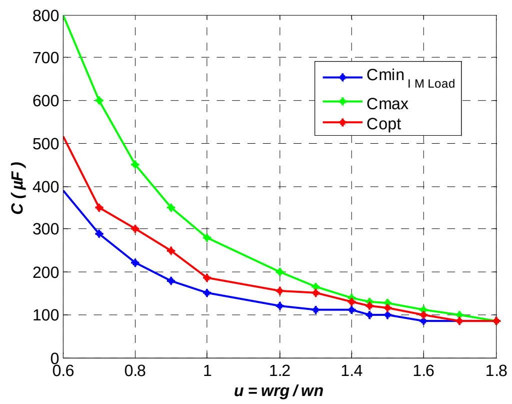

Fig.8. Variation of optimal, maximal and minimal capacitances with u.

Figure 9 illustrates the variation of P_{pump} as a function of u for the two excitation capacitances: $C_{\min,\ at\ IM\ load}$ and C_{opt} . It is noticed that for high and low rotor speed ($u \leq 0.8$ and $u \geq 1.2$), the value of C_{opt} tends to that of $C_{min,\ at\ IM\ load}$. However, while the rotor speed is around its nominal value $0.8 \leq u \leq 1.2$; C_{opt} is clearly different of $C_{\min,\ at\ IM\ load}$. This confirms the approach power improvement devalued of about 10%. In fact, by using C_{opt} instead of $C_{\min,\ at\ IM\ load}$ the power improvement is evaluated as:

$$\frac{\Delta P}{P}\% = 100\ \frac{\sum_n P_{opt} - \sum_n P_{\min}}{\sum_n P_{opt}} \qquad (14)$$

Where:

$P_{\min} = P_{pump}(\,C = C_{\min,\ at\ IM\ load}\,)$

$P_{opt} = P_{pump}(\,C = C_{opt}\,)$

This yields to value 10 %.

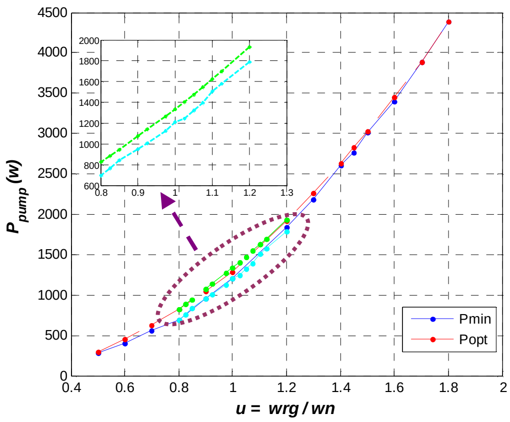

Fig.9. Variation of P_{pump} with u .

Since the data base is established, the fuzzy controller is implemented so as to control the capacitor switches. The switch combination should decide the C_{opt} value while the speed ω_{r_G} varies. The ω_{r_G} profile was chosen as indicated in figure 10.a and simulation results of SEIG-IM system are examined. Figure 10.b shows the excitation capacitance variation as a function of time during both operation phases. The time allowed in the first phase (at no load) has been chosen equal to $3s$.

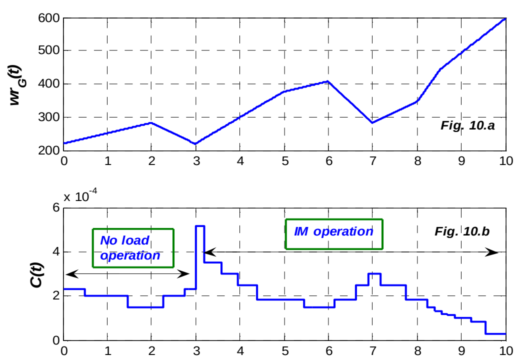

Fig. 10a & 10b SEIG rotor speed ω_{r_G} and excitation capacitance variation with time.

Figure 11 shows the variation of V_{as} , $I_{as_{Gen}}$ and $I_{ar_{Gen}}$ as a function of time. It is noted that even so a large variation of ω_{r_G} , the self-excitation is still maintained and the stator current Ias_{Gen} does not exceed 120% of its nominal value.

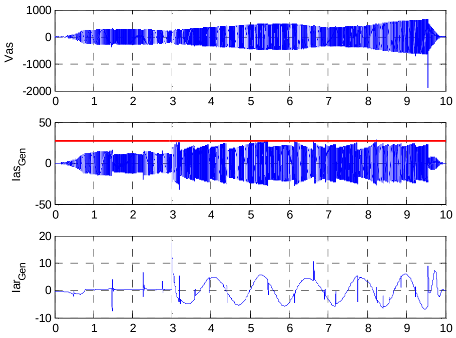

Fig.11. Stator voltage-time, stator current-time and rotor current-time characteristics of a SEIG.

As shown in figure 12, while the IM is connected ($t>3s$) it operates properly and his stator current Ias_M does not exceed 120% of its nominal value.

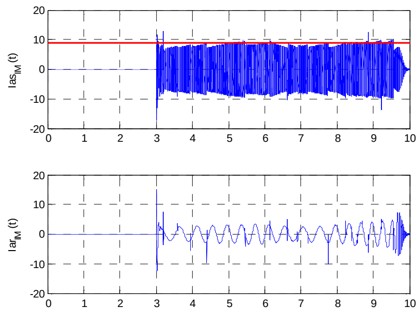

Fig.12. Stator voltage, stator and rotor current of IM as a function of time.

Figure 13 shows that for $0 \le t \le 3s$ (no load mode) the motor speed ω_{r_M} is null. However, while $3s \le t \le 9.5s$ the ω_{r_M} variation follows the wind rotor speed ω_{r_G}. The safety criterion is not verified starting $t \ge 9.5s$ since ω_{r_G} exceeds 180% of its nominal value. Therefore the fuzzy controller adjusts the value of the capacity at its minimum value to demagnetise the SEIG so as to lose its self excitation.

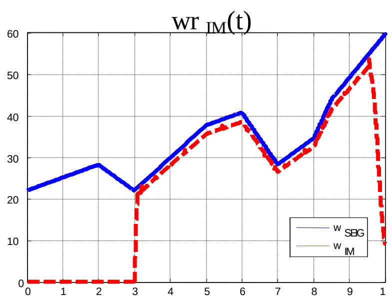

Fig.13. IM rotor speed ω_{r_M} variation

5. Conclusion

In order to optimize the quantity of the pumped water, a control strategy based on a fuzzy controller is developed. A detail base which reflects the system behaviour at no load and IM operation is established and used to adjust the actual value of the total capacitive following wind speed variation. System modelling and simulation results has been described and analysed. Simulation results demonstrate that the control approach make a pump power improvement of 10%. Actually, the approach is under implementation in a real pumping plant so as to maximize the quantity of the pumped water.

Appendix

The nominal characteristics of SEIG when acting as a motor are: $4.4\ Kw, 220/380\,V, 16.8/9.7\ A, 50Hz$

The nominal characteristics of IM are: $1.5\ Kw, 220/380\,V, 8/5.6\ A, 50Hz$

The fixed parameters of both induction machines used in simulation are:

$$R_{s_M} = 5\Omega, R'_{r_M} = 5.7\ \Omega, p_M = 2, L_{\sigma s_M} = L'_{\sigma r_M} = 0.0034H$$

$$R_{s_G} = 1.02\ \Omega, R'_{r_G} = 1.0544\ \Omega, p_G = 2, L_{\sigma s_G} = L'_{\sigma r_G} = 0.0056H$$

The magnetizing inductances of the both induction machines shown by the figure *A* are measured as a function of the magnetizing currents by performing an open circuit test in which the machines are driven at synchronous speed and a variable voltage source was applied to the stator.

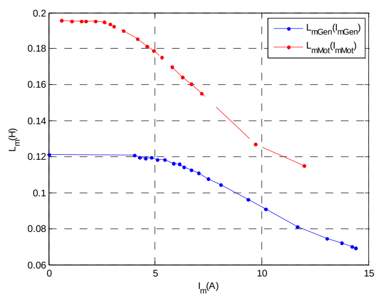

Fig.A. Magnetization characteristics of both induction machines

Nomenclature

R_s , R'_r : Stator and rotor resistances (Ω)

L_s, L'_r : Cyclic stator and rotor inductances (H)

L_m **:** Cyclic stator mutual inductance (H)

$L_{\sigma s}$, $L'_{\sigma r}$: Stator and rotor leakage inductances(H)

C : Excitation capacitor (F)

p_M : Number of poles pairs of IM

ω_r : Rotor electrical angular speed (rad/s)

J_M : Inertia moment of IM (Kg/m^2)

Superscript $'$ denotes the transformed rotor quantities based on the stator. Indices s and r stand for stator and rotor respectively, while G and M stand for induction generator and induction motor respectively.

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