J. Automation & Systems Engineering

Regular paper

Sensorless Control of a Flywheel Energy Storage System Associated to an Isolated Hybrid Energy Production Unit

Ghada Boukattaya, Lotfi Krichen and Abderrazak Ouali

The aim of this paper is to ensure the sensorless control of an inertial storage system associated to an isolated Hybrid Energy Production Unit (HEPU). This isolated HEPU comprises two sources solar/diesel, a Flywheel Energy Storage System (FESS) and a load. The exceeded generated power than required by the load is diverted towards a pump. To maintain the wheel speed in the normal operating range, a supervision strategy must be envisaged, thus ensuring the production control. The nonlinear control with exact linearization for the flywheel squirrel induction machine is proposed. Indeed, this control makes it possible to have a better decoupling between the two controlled variables which are the mechanical speed and the rotor flux. The developed adaptive observer was integrated into the induction machine control with an accurate stability study. Good performances in static and dynamic modes were observed by simulation of the suggested structure.

Keywords: Photovoltaic generator, diesel generator, flywheel storage system, non linear control, adaptive observer, fuzzy logic supervisor.

1. INTRODUCTION

Environmental concerns have been motivating increased interest in the use of renewable energy sources [1]. Two main reasons to be interested in renewable energy sources are, diminishing of fossil fuel sources and the negative affect on the environment [2]. Also for many years electricity of remote and isolated areas have been solely supplied by conventional power plants [3, 4]. The hybrid renewable energy systems have received much attention over the past decade. In particular, the integrated approach makes a hybrid system to be most appropriate for isolated communities such as remote islands [5]. The system controller provides supervisory control of all power system elements as well as protection. In general, hybrid power systems are divided for two different categories: stand-alone systems and grid-connected systems [4]. The stand-alone systems must, therefore, have some means of storing energy, which can be used later to supply the load during the periods of low or no power output. Flywheels are used as energy buffers in order to store or retrieve energy into a stand-alone load or small generation system.

Both induction (IM) and permanent-magnet (PM) machines are appropriate for flywheel storage and power smoothing applications. The IM is, therefore, a good candidate for flywheel drives, especially at higher powers, being robust and cheap. The control of the flywheel induction motor requires precise speed information. Therefore, a speed sensor, such as a resolver or an encoder, is usually adhered to the shaft of the motor to measure the motor speed. However, a speed sensor increases the cost and requires a connection line between the control system and the motor, thereby preventing the stable operation of the control system due to interference from the signal line. Furthermore, an exact servo control performance is sometimes required in an operating environment where the attachment of a

University of Sfax, National School of Engineering, Department of Electrical Engineering BP W, 3038, Sfax, Tunisia. boukettayaghada@yahoo.fr, lotfi.krichen@enis.rnu.tn, abderrazak.ouali@enis.rnu.tn.

speed sensor is impossible. Accordingly, the sensorless control of induction motors knows a real development since the 90's. The most effective sensorless control techniques mentioned in the literature are MRAS [6, 7, and 8] and the Luenberger observer [6, 9]. In MRAS, speed is estimated using the difference between the reference model's output and the adjustable model's output [10, 11]. Schauder [12] inserted a linear transfer function in the form of high pass filter in both the reference and the adjustable models. Tajima and Hori [11] improved Schauder's work by proposing a robust flux observer of which the poles are designed in function of rotor speed and rotor time constant. Adaptive observer introduced by [13] has been a powerful prolongation of initial sensor based observer [14]. However, some operation limits of conventional observers were quickly highlighted [15]. The drive stability can't be guarantee when this type of observer is associated with a field oriented control.

The studied system is a hybrid diesel-photovoltaic production installation. These electric generation hybrid systems are usually more reliable than the systems that use a single source of energy. When designing a hybrid system, both the sizing of the elements and the most adequate control strategy must be obtained. The diesel generator is assumed to be equipped with both voltage-control and frequency- control loops. This diesel engine is associated to a synchronous generator and only requested as a last resort. An inertial storage system is associated to the structure to control the power provided by the two sources. In fact, the excess energy with respect to the load requirement has been stored as flywheel to generate electricity during low sunshine periods. The exceeded generated power than required by the load is diverted towards a pump. Thus, there is no more a loss or lack of energy.

In this paper, an adaptive observer associated to the FESS is developed with a new strategy of computation of the gain matrix observer. Then, the simultaneous rotor flux and mechanical speed of the flywheel observers are presented. These observers are tested in association with the non linear control structure.

2. SYSTEM DESCRIPTION

The studied Hybrid Energy Production Unit (HEPU) consists of a 4 kW (peak) PV array as primary energy source and a diesel engine of a 2 kW. The excess energy with respect to the load requirement has been stored as flywheel to generate electricity during low sunshine periods. In this work, the power consumption of the isolated load is predicted around an average of 1.5 KW. The studied HEPU in this paper is represented in figure 1.

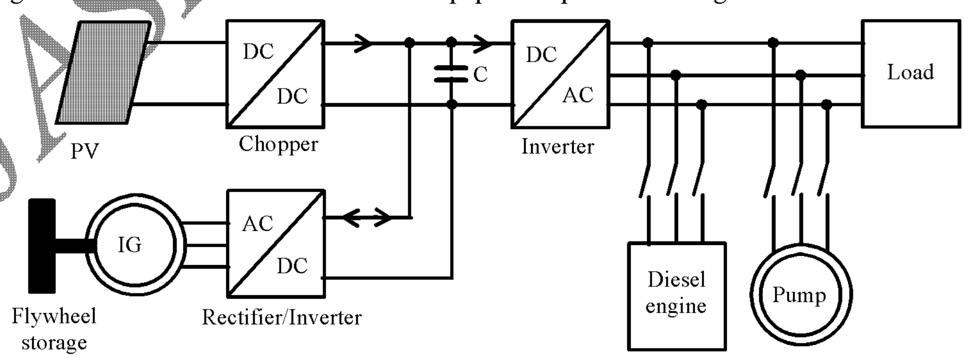

Figure 1: Configuration of the studied hybrid generation system

The PV subsystem made up of several panels is connected to the DC bus via a filter and a DC/DC converter, which controls the operating point of the panels and therefore the generated power. The flywheel subsystem comprises a flywheel, an induction machine and an AC/DC converter (rectifier/inverter), which controls the speed of the flywheel and therefore the exchanged power. The DC bus collects the energy generated by these two subsystems and supplies it through a converter DC/AC and a filter to a primary load or to a pump as optional load. The diesel engine is activated only as a last resort to supply the primary load.

3. MODELING OF THE HEPU

3.1. Modeling of the PV panel

The typical structure of a PV system is constituted by a high number of modules arranged in a parallel and series structure in order to obtain the desired level of voltage and current output [16].

The power of a single module varies between 50 and 100 W in accordance with the number of single series cells. The electric power generated by a photovoltaic panel is unstable according to the irradiation level and the temperature. So the solar power generation for any solar radiation can be predicted by using the formula given below:

$$P_{pv} = aE^2 + bE + c \qquad (1)$$

where: E : the solar radiation $\left[W/m^2\right]$, P_{pv} : the PV power generation $[W]$

a , b and c are constants, which can be derived from measured data. By using the above formula, solar power generation at any solar radiation can be predicted. This is also useful in estimating the suitable solar photovoltaic panels for many required load.

3.2. Modeling of the diesel engine

The developed torque T_{diesel} associated to the diesel engine is proportional to the fuel rack position Y which is delayed by the time delay τ_d of the fuel combustion process [17]:

$$T_{diesel} = Y e^{-\tau_d s} \qquad (2)$$

The fuel rack position is proportional to the applied fuel rate F which is delayed by the electro hydraulic time constant τ_c [17]:

$$Y = \frac{F}{1+\tau_c s} \qquad (3)$$

The fuel consumption of the diesel generator is expressed by [18]:

$$FC = \eta_{fuel}(P_{diesel} - P_{diesel,rated}) + FC_{rated} \qquad (4)$$

where $FC(l/h)$ is the fuel consumption, $P_{diesel}(W)$ is the actual power of the diesel generator, $P_{diesel,rated}(W)$ is the rated power of the diesel generator, η_{fuel} is the fuel consumption efficiency, and FC_{rated} is the diesel generator fuel consumption at rated power.

3.3. Modeling of the pump

Ghoneim [19] use a detailed theoretical analysis to determine the characteristics of the motor and the centrifugal pump. The model is briefly summarized in the following. In this model, the head can be represented by using the affinity laws, which relates the head $H(m)$ to the pump speed $N(rpm)$ and the flow rate $Q(l\,/\,s)$ as:

$$H = p_2 N^2 + p_1 N Q - p_0 Q^2 \tag{5}$$

where (p_2, p_1, p_0) are constant coefficients at the reference condition.

3.4. Modeling of the flywheel storage system

The operating point of the flywheel energy storage is based on the stored flywheel energy E_c given by [20]:

$$E_c = \frac{1}{2} J_f \Omega_f^2 \tag{6}$$

with $J_f(kg.m^2)$ and $\Omega_f(rd\,/\,s)$ are the inertia moment and the flywheel speed, respectively.

If we consider a photovoltaic generator supplying between 6 hours AM up to 6 hours PM, the flywheel must be able to store a quantity of energy approximately equal to 12 KWh. To satisfy this condition, the rated power of the induction machine P_{n-MAS} driving the flywheel is equal to 3KW. As well, the flywheel inertia moment is defined by [21]:

$$J_v = \frac{2\ P_{n-MAS}\ \Delta t}{\Omega_{f\max}^2 - \Omega_{f\min}^2} \tag{7}$$

with: $\Omega_{f,\min}$ and $\Omega_{f,\max}$ represent the minimal speed limit and the maximal speed limit of the flywheel, respectively. $\Delta t(s)$ is the storage period.

The non linear control of the flywheel induction machine will be applied to the level of inverter by imposing control references. In the stator reference frame and by considering the rotor field oriented control with the d-axis, the state equation of the FESS can be described as:

$$\begin{aligned} \dot{x} &= f(x) + g_a v_{sd} + g_b v_{sq} \\ y &= h(x) \end{aligned} \tag{8}$$

where:

$$f(x) = \begin{pmatrix} \dfrac{pL_m}{JL_r}\psi_r i_{sq} - \dfrac{C_r}{J} - \dfrac{f}{J}\Omega \\ \dfrac{L_m}{\tau_r} i_{sd} - \dfrac{1}{\tau_r}\psi_r \\ -\gamma_1 i_{sd} + \dfrac{\gamma_2}{\tau_r}\psi_r + \omega_s i_{sq} \\ -\gamma_1 i_{sq} - \omega_s i_{sd} - p\Omega\gamma_2\psi_r \end{pmatrix},\quad g_a = \begin{pmatrix} 0 \\ 0 \\ \dfrac{1}{\sigma L_s} \\ 0 \end{pmatrix},\quad g_b = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \dfrac{1}{\sigma L_s} \end{pmatrix},\quad \gamma_1 = \frac{\dfrac{L_m^2}{L_r^2} R_r + R_s}{\sigma L_s} \quad \text{and}$$

$$\gamma_2 = \frac{L_m}{L_r L_s \sigma}.$$

L_r, L_s : rotor and stator inductances ; $x = [\Omega \;\; \psi_r \; i_{sd} \; i_{sq}]^T$ is the state vector

L_m : mutual inductance ; $[v_{sd} \;\; v_{sq}]^T$ is the stator voltage vector

R_r, R_s : rotor and stator resistances ; $[i_{sd} \;\; i_{sq}]^T$ is the stator current vector

p :number of pole pairs ; $y = [h_1(x) \; h_2(x)]^T = [\Omega \;\; \psi_r]^T$ is the outputs vector

J : rotor moment of inertia ; Ω is the mechanical speed ; $\psi_r = \phi_r^2$ is the square of the rotor flux

$\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$: leakage coefficient ; $\tau_r = \dfrac{L_r}{R_r}$: rotor speed constant

The stator pulsation is defined by:

$$\omega_s = p\Omega + \frac{L_m}{\tau_r}\frac{i_{sq}}{\psi_r} \tag{9}$$

4. NON LINEAR CONTROL OF THE FLYWHEEL INDUCTION MOTOR

We suppose that all the state is measurable and that the control system outputs are the rotor flux square ψ_r , and the mechanical speed Ω . By using variable change defined by:

$$\begin{aligned} z_1 &= \Omega \\ \dot{z}_1 &= z_2 \\ z_3 &= \psi_r \\ \dot{z}_3 &= z_4 \end{aligned} \tag{10}$$

and after two necessary Lie derivation of the outputs vector, such as:

$$L_f h(x) = \sum_{i=1}^{n} \frac{\partial h}{\partial x_i}(x) f_i(x) \tag{11}$$

The system described by equations (8), becomes:

$$\begin{pmatrix} \ddot{\Omega} \\ \ddot{\psi}_r \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} L_f^2 h_1(x) \\ L_f^2 h_2(x) \end{pmatrix} + \begin{pmatrix} L_{ga} L_f h_1(x) & L_{gb} L_f h_1(x) \\ L_{ga} L_f h_2(x) & L_{gb} L_f h_2(x) \end{pmatrix} \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} = \Delta_0(x) + \Delta(x) \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} \tag{12}$$

with :

$L_{ga} L_f h_1(x) = 0$;

$L_{gb} L_f h_1(x) = \dfrac{p L_m}{J L_r L_s \sigma} \psi_r$;

$L_{ga} L_f h_2(x) = \dfrac{2 L_m}{\sigma \tau_r L_s} \psi_r$;

$L_{gb} L_f h_2(x) = 0$;

$$L_f^2 h_1(x) = -a_1\psi_r i_{sq} - a_2 i_{sd}\Omega\psi_r - a_3\Omega\psi_r^2 + a_4\Omega\,;$$
$$L_f^2 h_2(x) = b_1(i_{sd}^2 + i_{sq}^2) - b_2\psi_r i_{sd} + b_3\psi_r^2 + b_4\psi_r i_{sq}\Omega$$

$$a_1 = \frac{pL_m}{JL_r}\left(\frac{1}{\tau_r} + \gamma_1 + \frac{f}{J}\right),\ a_2 = \frac{p^2 L_m}{JL_r},\ a_3 = \gamma_2 a_2,\ a_4 = \frac{f^2}{J^2}\ ,$$

$$b_1 = \frac{2L_m^2}{\tau_r^2},\ b_2 = \frac{6L_m}{\tau_r^2} + \frac{2\gamma_1 L_m}{\tau_r},\ b_3 = \frac{2L_m\gamma_2 - 4}{\tau_r^2},\ b_4 = \frac{2pL_m}{\tau_r}$$

The state of the nonlinear feedback is then given by:

$$\begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} = -\Delta(x)^{-1}\Delta_0(x) + \Delta(x)^{-1}\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \alpha(x) + \beta(x)\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \tag{13}$$

In order to ensure a perfect speed and flux continuation, flow their respective reference Ω_{ref} and $\psi_{r\,ref}$, the new linear state system (12) is then identified with the following equations:

$$\begin{aligned} v_1 &= -k_{11}(\Omega - \Omega_{ref}) - k_{12}(\dot{\Omega} - \dot{\Omega}_{ref}) + \ddot{\Omega}_{ref}\,. \\ v_2 &= -k_{21}(\psi_r - \psi_{r\,ref}) - k_{22}(\dot{\psi}_r - \dot{\psi}_{r\,ref}) + \ddot{\psi}_{r\,ref} \end{aligned} \tag{14}$$

5. CONTROL STRATEGIES OF THE HEPU

The purpose of the proposed system is to supply an isolated load. In [22], a fuzzy logic supervisor is designed as a power management system for a PV/diesel/flywheel storage hybrid power system to guarantee the required load power under irradiation level variations. In this case, the flywheel inverter must control the DC bus voltage [21] i.e. maintaining constant the continuous bus voltage following any change of the transited power. If we neglect the power losses, the power assessment is defined by:

$$P_{PV} + P_{diesel} + P_{flywheel} = P_{load} + P_{pump} \tag{15}$$

with: P_{PV} is the produced PV power, P_{diesel} is the produced diesel power, $P_{flywheel}$ is the storage or generate flywheel power, P_{load} is the load demand power and P_{pump} is the pump power.

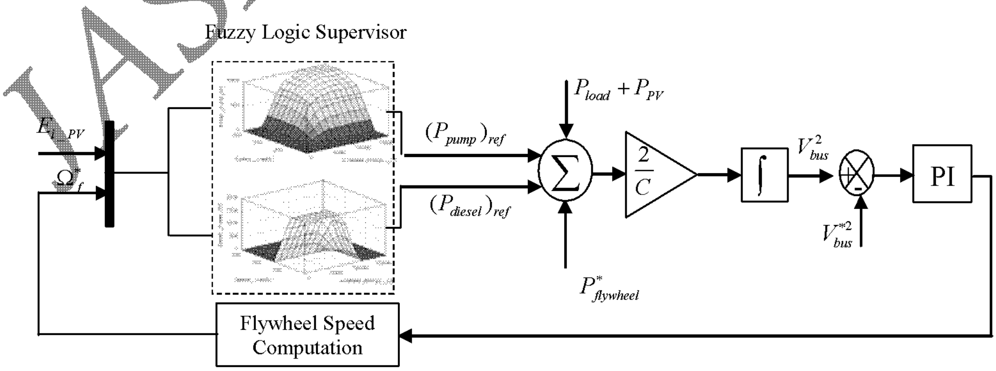

Figure 2: Block diagram of the storage system control loop

The management of the flywheel power ensures the control of the DC bus voltage. The

Control strategies of the HEPU are represented in figure 2. In order to ensure the PV-diesel production control and to maintain the storage system in his correct operating zone, a supervisor should be considered [22]. The supervisor will determine the pump consumed power and the diesel produced power according to the available instantaneous photovoltaic energy E_{i-PV} and the flywheel speed Ω_f. This speed is considered as a reference witch will be applied to the control of the flywheel motor. The reference flux is imposed by:

$$\psi_{r\,ref} = \begin{cases} \sqrt{3}\,\dfrac{L_r v_{sn}}{L_m \omega_{sn}} & if \quad \Omega_f \leq \Omega_n \\ \dfrac{P_n L_r}{p L_m i_{sq\max} \Omega_f} & if \quad \Omega_f > \Omega_n \end{cases} \tag{16}$$

with for the flywheel motor: v_{sn} is the nominal stator voltage, ω_{sn} is the nominal stator pulsation, P_n is the nominal power, $i_{sq\max}$ is the maximum stator q current and Ω_n is the nominal speed.

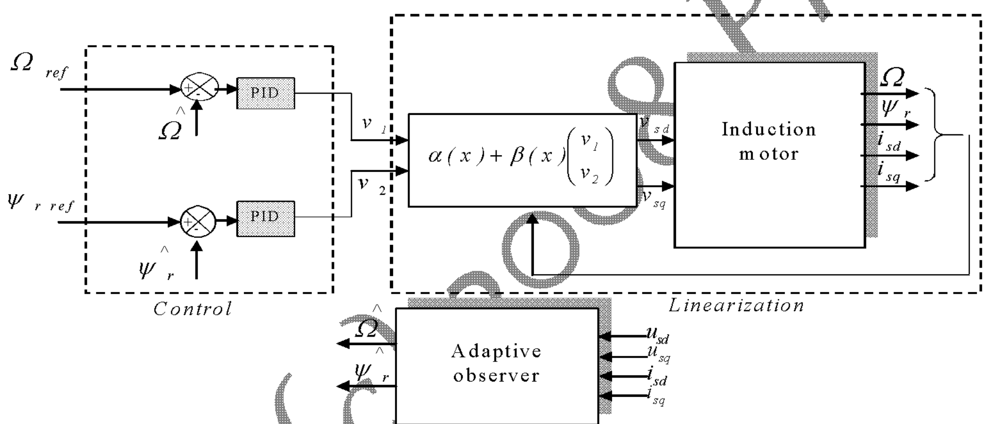

Figure 3: Block diagram of the sensorless control of the flywheel induction motor

6. OBSERVER DESIGN

According to the previous study, our main is to estimate the flux and the mechanical speed of the asynchronous machine. The fixed stator reference frame is used, thus the state matrix will depend only on mechanical speed. The studied sensorless control of the flywheel induction motor in this paper is represented in figure 3.

The established adaptive observer construction is based on the search of a Lyapunov particular function [9,10,12,23]. The Luenberger observer (full order adaptive state observer) is constructed using the equations of the induction machine in stationary reference frame [24] by adding an error compensator.

The motor model in the stationary reference frame (α, β) and the observer model are successively represented by:

$$\begin{aligned} \dot{X} &= A(\Omega)X + BU \\ Y &= CX \end{aligned} \tag{17}$$

and

$$\hat{X} = A(\hat{\Omega})\,\hat{X} + G(\hat{Y} - Y) + BU$$
$$\hat{Y} = C\,\hat{X} \tag{18}$$

with : $X = [i_{s\alpha}\ \ i_{s\beta}\ \ \psi_{r\alpha}\ \ \psi_{r\beta}]^T$ is the state vector, $U = [v_{s\alpha} v_{s\beta}]^T$ is the controlled vector of known inputs, Y is the vector of outputs, $\hat{X}$: the estimated state vector, $\hat{Y}$ the estimated outputs vector, G is the matrix gain observer and where:

$$A(\Omega) = \begin{pmatrix} -\gamma_1 & 0 & \dfrac{\gamma_2}{\tau_r} & \gamma_2 p\Omega \\ 0 & -\gamma_1 & -\gamma_2 p\Omega & \dfrac{\gamma_2}{\tau_r} \\ \dfrac{L_m}{\tau_r} & 0 & -\dfrac{1}{\tau_r} & -p\Omega \\ 0 & \dfrac{L_m}{\tau_r} & p\Omega & -\dfrac{1}{\tau_r} \end{pmatrix}, B = \begin{pmatrix} \dfrac{1}{\sigma L_s} & 0 \\ 0 & \dfrac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \text{ and}$$

$$G = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \\ g_{31} & g_{32} \\ g_{41} & g_{42} \end{pmatrix}.$$

The estimation error vector is defined by:

$$e = \hat{X} - X = [e_{is\alpha}\ e_{is\beta}\ e_{\psi r\alpha}\ e_{\psi r\beta}]^T \tag{19}$$

The differential equation representing the state estimation error is then obtained from the two equations (17) and (18):

$$\dot{e} = (A(\hat{\Omega}) + GC)\,e + (A(\hat{\Omega}) - A(\Omega))\,\hat{X}$$
$$\varepsilon = C\,e \tag{20}$$

To determine the stability of the error dynamics of the observer, we can use Lyapunov's stability theorem, which gives a sufficient condition for the form asymptotic stability of a non-linear system by using a Lyapunov function V [23,24] . This function must be continuous, differentiable, and positive definite. To obtain a stable system, the adaptation mechanism is derived by using the state error dynamic equations together with Lyapunov's stability theorem. States are continuously corrected by using a feedback correction scheme. This correction term contains the weighted difference of some of the measured and estimated output signals (the difference is multiplied by the observer feedback gain G).

Thus, the adaptive observer construction objective is in the determination of the matrix G coefficients and in the determination of the law defining $\hat{\Omega}$ to have a system with asymptotic stability.

$\Delta\Omega$ is define such as:

$$\Delta\Omega = \hat{\Omega} - \Omega \tag{21}$$

To determine the control law of estimate mechanical speed, we define the Lyaponuv function:

$$V = e^T P e + \lambda(\Delta\Omega)^2 \tag{22}$$

where λ is a constant and P is a symmetrical positive definite matrix .

The stability condition of system (20) is verified if the time derivative Lyapunov function is negative definite. We have then:

$$2e^T P\dot{e} + 2\lambda\Delta\Omega \frac{d}{dt}\hat{\Omega} < 0 \tag{23}$$

The development of the last equation (23) gives:

$$\begin{aligned} &e^T((A(\hat{\Omega}) + GC)^T P + P(A(\hat{\Omega}) + GC))e - \varsigma_1 p\Delta\Omega(e_{is\beta}\hat{\psi}_{r\alpha} - e_{is\alpha}\hat{\psi}\, r\beta) \\ &+\varsigma_2 p\Delta\Omega(e_{\psi_{r\beta}}\hat{\psi}_{r\alpha} - e_{\psi_{r\alpha}}\hat{\psi}_{r\beta}) + 2\lambda\Delta\Omega\frac{d}{dt}\hat{\Omega}\} < 0 \end{aligned} \tag{24}$$

Where ς_1 and ς_2 are positives constants.

To ensure stability, two conditions are then selected. The first Lyapunov condition is:

$$e^T \left\{(A(\hat{\Omega}) + GC)^T P + P(A(\hat{\Omega}) + GC)\right\} e < 0 \tag{25}$$

The second Lyapunov condition is:

$$\{\varsigma_2 p\Delta\Omega(e_{\psi_{r\beta}}\hat{\psi}_{r\alpha} - e_{\psi_{r\alpha}}\hat{\psi}_{r\beta}) - \varsigma_1 p\Delta\Omega(e_{is\beta}\hat{\psi}_{r\alpha} - e_{is\alpha}\hat{\psi}_{r\beta}) + 2\lambda\Delta\Omega\frac{d}{dt}\hat{\Omega}\} = 0 \tag{26}$$

If $(A(\hat{\Omega}) + GC)$ is stable, then there are two matrixes $P = P^T > 0$ and $Q = Q^T > 0$ such as:

$$(A(\hat{\Omega}) + GC)^T P + P(A(\hat{\Omega}) + GC) = -Q < 0 \tag{27}$$

The condition (25) is then also verified.

The error dynamics are described by the eigenvalues of $(A(\hat{\Omega}) + GC)$ and these are usually used to design a stable observer (gain matrix). In this paper a new simple strategy of computation of the matrix observer is presented.

The state matrix developed observer A_O is:

$$A_O = A(\hat{\Omega}) + GC \tag{28}$$

The A_O distribution is defined by:

$$A_O = \begin{pmatrix} A_{O1} & A_{O2} \\ A_{O3} & A_{O4} \end{pmatrix} \tag{29}$$

with :

$$A_{O1} = \begin{bmatrix} -\gamma_1 + g_{11} & g_{12} \\ g_{21} & -\gamma_1 + g_{22} \end{bmatrix},\ A_{O2} = \begin{bmatrix} \frac{\gamma_2}{\tau_r} & \gamma_2 p\Omega \\ -\gamma_2 p\Omega & \frac{\gamma_2}{\tau_r} \end{bmatrix},\ A_{O3} = \begin{bmatrix} \frac{L_m}{\tau_r} + g_{31} & g_{32} \\ g_{41} & \frac{L_m}{\tau_r} + g_{42} \end{bmatrix} \text{ and}$$

$$A_{O4} = \begin{bmatrix} -\frac{1}{\tau_r} & -p\Omega \\ p\Omega & -\frac{1}{\tau_r} \end{bmatrix}$$

As A_{O4} is stable, then to guaranty the stability of A_O, two necessary and sufficient conditions are established: first to guarantee that A_{O1} is stable and second to cancel A_{O3}.

A judicious choice of the parameters which guarantee the stability of A_{O1} is such as:

$$g_{11} = g_{22} < 0 \text{ et } g_{12} = g_{21} = 0 \tag{30}$$

The cancellation of A_{O3} gives:

$$g_{31} = g_{42} = -\frac{L_m}{\tau_r} \qquad g_{32} = g_{41} = 0 \tag{31}$$

The resolution of the Lyapunov second condition (26), gives the adapted law:

$$\frac{d}{dt}\hat{\Omega} = k_1 f_1(X, \hat{X}) + k_2 f_2(\psi_r, \hat{\psi}_r) = \varsigma_1 \frac{1}{2\lambda} p(e_{is\beta}\hat{\psi}_{r\alpha} - e_{is\alpha}\hat{\psi}_{r\beta}) - \varsigma_2 \frac{1}{2\lambda} p(e_{\psi_{r\beta}}\hat{\psi}_{r\alpha} - e_{\psi_{r\alpha}}\hat{\psi}_{r\beta}) \tag{32}$$

Knowing that the established observer output is:

$$\varepsilon = Ce = [e_{is\alpha} e_{is\beta}]^T \tag{33}$$

The second term of the equation (32) is then regarded as being a disturbance. To cancel the effect of this disturbance, a Proportional Integral regulator is used, as shown in figure 4.

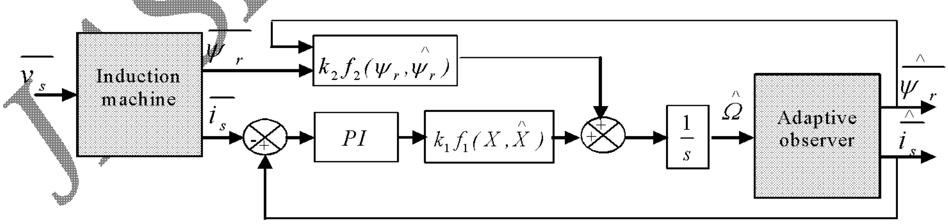

Figure 4: Block diagram of the designed observer associated to the flywheel induction motor

7. SIMULATION RESULTS

The simulation is done during 72 hours. It's corresponding to three different situations of PV power generation as shown in figure 5. In the first day (0h-24h) the production is typical, in the second day (24h-48h) the PV production is low and in the third day (48h-72h) the production is high.

Figure 6 shows the speed waveforms when the sensorless vector control was performed using the proposed method. The good performance in static mode of the proposed observer is shown in figure 7. This figure shows that the reference rotor speed, the real rotor speed and the estimated rotor speed are practically the same. The good performance in dynamic mode of the proposed observer is shown in figure 8.

We note that the estimated speed was in accord with the real speed and the reference speed. Figure 9 depicts the active power stored (negative) or generated (positive) by the flywheel system corresponding to his speed. Figures 10, 11 and 12 show the current error, the speed error and the flux error, respectively. Figures 13 and 14 show that the reference rotor flux, the real rotor flux and the estimated rotor flux are confused. The rotor flux curve follows rightly the evolution of the flywheel speed curve.

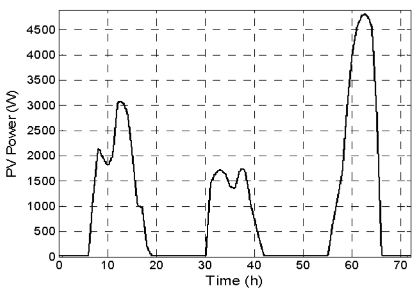

Figure 5: PV power.

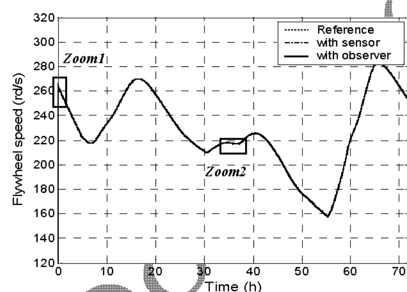

Figure 6: Flywheel speed

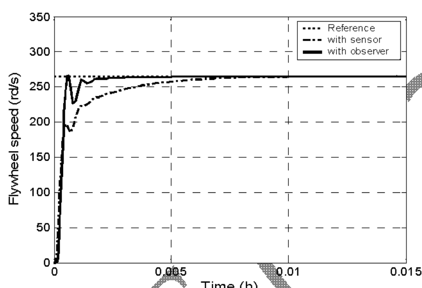

Figure 7: Flywheel speed-Zoom 1.

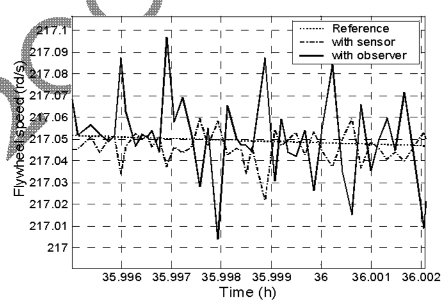

Figure 8: Flywheel speed-Zoom 2

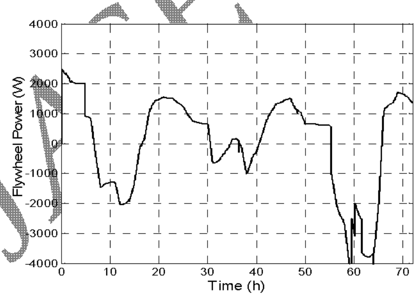

Figure 9: Flywheel power.

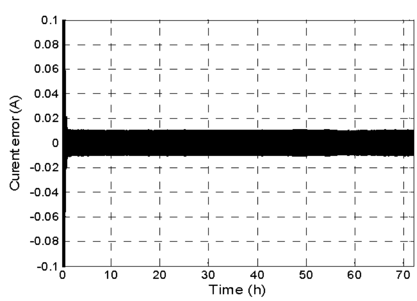

Figure 10: Current error

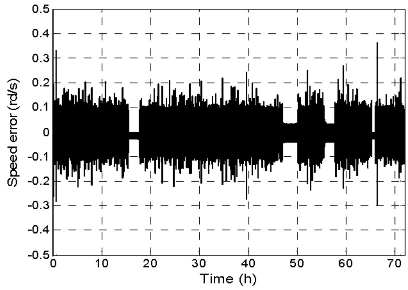

Figure 11: Speed error.

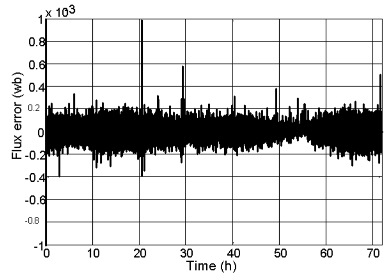

Figure 12: Flux error

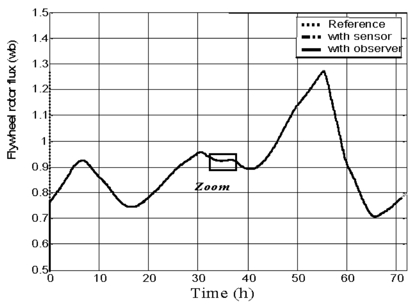

Figure 13: Flywheel rotor flux.

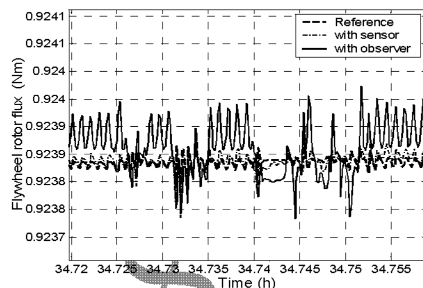

Figure 14: Flywheel rotor flux-Zoom

8. CONCLUSION

The main of this article is the design of an adaptive speed and rotor flux observer of an induction machine used in an isolated hybrid energy production unit. The proposed adaptive speed observer is simple and according to the simulation results is effective. In this presented method, the stator current is used as state variable for estimating the speed. The new proposed design of the gain matrix guaranty the stability of the adaptive observer, without complex computation us in linearization or in eigenvalues determination. This observer is successfully implemented in a direct rotor flux oriented IM drive with non linear control. Simulation results show the good performances of the controller associated to the studied observer.

Acknowledgment

This study, achieved in the National School of Engineering of Sfax, Tunisia, in the research unit "Advanced Control and Energy Management" ACEM, enters in the setting of the research project federated sustained by the State Secretariat to the Scientific Research and Technology and coordinated by the National Management Energy Agency. We thank the ENIS, the SERST and the ANME.

REFERENCES

[1] F. Benjamin and Jon G.Mccowan, An Analytical Study of Hybrid Wind Passive Solar System,Solar Energy, Vol.32, N°3,PP.405-415,1984

[2] S.R. Bull, Renewable Energy today and tomorrow, proceeding of the IEEE, Vol89, No8, August 2001.

[3] J. D. Maclay, J. Brouwer, G. Scott Samuelsen,Dynamic modeling of hybrid energy storage systems coupled to photovoltaic generation in residential applications, ELSIVIER, Journal of Power Sources 163 (2007) 916–925

[4] G. O'Sullivan, Trimode power converteroptimizes PV, diesel andBattery energy sources,1994 IEEE First WCPEC; Dec. 5-9, 1994; Hawaii

[5] Bonarino, A. Consoli, A. Baciti, B. Morgana, and U. Nocera, Transient analysis of integrated dieselwind- photovoltaic generation systems, IEEE paper No.PE-425-EC-104, July 1998.

[6] B.K. Bose, Modern Power Electronics and AC Drives, Prentice Hall, Upper Saddle River, 2002.

[7] R.D. Lorenz, Tuning of field oriented induction motor controllers for highperformance applications, IEEE Industry Appl. Soc. Annu. Meet. (1985) 607–612.

[8] C.C. Chan,W.S. Leung, C.W. Ng, Adaptive decoupling control of induction motor drives, IEEE Trans. Indust. Electr. 37 (1) (1990) 41–47.

[9] H. Kubota, K. Matsuse, T. Nakano, DSP-based speed adaptive flux observer of induction motor, IEEE Trans. Industry Appl. 29 (2) (1993) 344–348.

[10] S. Tamai, H. Sugimoto, M. Yano, Speed sensorless vector control of induction motor with model reference adaptive system, Conf. Record of the 1985 IEEE-IAS Annual Meeting, pp. 613–620.

[11] H. Tajima, Y. Hori, Speed sensorless field-orientation control of the induction machine, IEEE Trans. Industry Appl. 29 (1) (1993) 175– 180

[12] C. Schauder, Adaptive speed identification for vector control of induction motor without rotational transducers, IEEE Trans. Ind. Appl. 28 (5) (1992) 1054–1061.

[13] G. Yang and T. Chin, Adaptive-speed identification scheme for a vector-controlled speed sensorless inverter-induction motor drive, IEEE Transactions on industrial electronics, vol. 29, no 4, 1993.

[14] G.C. Verghese and S.R Sanders. Observers for flux estimation in induction machines. IEEE Transactions on industrial electronics,vol. 35, no 1, 1988.

[15] H. Kubota, L. Sato, Y. Tamura, K. Matsuse, H. Ohta, and Y. Hori, Stable operation of adaptive observer based sensorless induction motor drives in regenerating mode at low speeds, Conf. Rec. IAS Annual Meeting, 2001.

[16] S. A. Daniel and N. A. Gounden, A Novel Hybrid Isolated Generating System Based on PV Fed Inverter-Assisted Wind-Driven Induction Generators, IEEE Trans. Energy Conversion, vol. 19, no. 2, pp. 416-422, June 2004.

[17] E.S. Abdin, A.M. Oiheibn, M.M. Kater, Modeling and optimal controllers design for a stand alone photovoltaic diesel generating unit, IEEE Transactions on Energy Conversion, Vol. 14, No. 3, September 1999.

[18] A. Al-Alawi, S.M. Al-Alawi , S. M.Islam, Predictive control of an integreted PV-diesel water and power supply system using an artificial neural network, ELSIVIER, Renewable Energy 32(2007), pp. 1426-1439.

[19] A.A. Ghoneim, Design optimisation of photovoltaic powered water pumping systems, ELSIVIER, Energy Convertion and Management 47 (2006),pp. 1449-1463.

[20] L. Leclercq, B .Robyns, J.M. Grave, Control based on fuzzy logic of a flywheel energy storage system associeted with wind and diesel generators, Math. and Comput. in Sim. 63(2003), pp 271-280.

[21] G.O. Cimuca, C .Saudemont, B. Robyns, M.M. Radulescu, Control and Performance Evaluation of a Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator, IEEE Tran. on Ind. Elect., Vol.53, Issue 4, June 2006, pp. 1074-1085.

[22] G. BOUKETTAYA , L. KRICHEN, A. OUALI, A Fuzzy Logic Supervisor for Power Control of an Isolated Hybrid Energy Production Unit, International Journal of Electrical and Power Engineering 1(3): 279-285,2007

[23] N. Bensialia, C. Chaigne, S. Tnami, Erik Etien and G. Champenois, Optimal Observer design for Sensorless control of induction motor in regenerating mode, IEEE, 1-4244-0194, pp. s4:6-11, 2006.

[24] A. Paladugu, B.H. Chowdhury, Sensorless control of inverter-fed induction motor drives, ELSIVIER, Electric Power Systems Reaserch 77 (2007), pp. 619–629.