Modelling and control of hybrid renewable energy system connected to AC grid

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***Abstract*—This paper discusses the development of new control and supervision method for the optimum operation of hybrid renewable energy system (HRES) connected to AC grid. The hybrid system consists of wind generator (WG), diesel generator (DG), and flywheel energy storage system (FESS). These subsystems are based on permanent magnet synchronous machines (PMSM) which are controlled by sliding mode control. A supervisor control is designed to determine the energy transfer type of flywheel energy storage system (charging / discharging / no transfer energy), to take decision on diesel generators ON/OFF status, and to determine the reference powers for these two subsystems. The supervisor inputs are the power requested by AC grid, the power generated by wind generator, and the energy stored in flywheel. The objectives of the control and supervision for hybrid renewable energy system are to satisfy the power requested by AC grid, to manage the energy transfer between hybrid system and AC grid, to optimize the use of wind energy, and to reduce fuel of diesel generator. The system is simulated with Matlab – Simulink software and it gave good results.**

Keywords-Control and Supervision; Hybrid Renewable Energy System; Wind Generator; Flywheel Energy Storage System; Diesel Generator; Permanent Magnet Synchronous Machine; Sliding mode control.

I. INTRODUCTION

Currently, following the progressive reduction of energy resources, the wind energy appears clearly to complete the used energy. The wind generators are decentralised sources, their production of electricity varies quickly according to wind speed which is very fluctuating in very short time. The studies of Al Aimani [1] and Cimuca [2] showed that their connection to network pause many problems, such as the unbalances of consumption-production, and absence of frequency-power and voltage adjustment, what causes a bad quality of wind energy and limits their rate of penetration to networks, to guarantee their stability.The combination of wind generator with other energy sources in hybrid system can reduce these problems, and optimize to maximum this generator technically and economically. Many solutions of hybrid systems which collects wind generator with other renewable energy sources such as wind - photovoltaic system [3-4-5], and wind - hydraulic system [6], these systems require geographical places which can provide these types of sources. Other solutions of hybrid systems which does not depend on the geography, and collect wind generator with controllable sources such as wind - diesel system [7-8], which is very significant to improve wind power quality. Association in addition to storage energy system with wind - diesel system, can provide a reserve of energy which is used for various adjustments. An energy storage system allows the increasing of the value of the electric power generated by providing energy for the peak periods, and by accumulating energy during the period when the energy requested is reduced. Among storage system, the flywheel energy storage system is well adopted because of its raised dynamics, its good efficiency, and its long period of life to store energy for short periods [2]. In particular flywheel energy storage system is most profitable if the period of storage does not exceed 10mn [2].

In this work, we proposed a hybrid renewable energy system which collects wind generator (WG) with diesel generator (DG), and flywheel energy storage system (FESS). The unit is based on permanent magnet synchronous machines (PMSM), this type of machine is very recommended in the wind power conversion systems. The hybrid system is connected to AC network by using power electronic. We developed control methods for each subsystem (wind generator, diesel generator, flywheel energy storage system) and we applied the sliding mode control for the permanent magnet synchronous machine, it is a robust method for very disturbed models and it can be well chosen for wind renewable energy systems of production which are very fluctuating in very short time. The system control requires also the development of a supervisor. This supervisor decides the energy transfer type of flywheel energy storage system (charging / discharging / no transfer energy), take decision on diesel generators ON/OFF status, and determine the reference powers for these two subsystems. The supervisor inputs are the reference power of hybrid system (power requested by AC grid), the power generated by wind generator, and the energy stored in flywheel. The objectives of the control and supervision of hybrid system are to satisfy the reference power of hybrid system, to manage the energy transfer between hybrid system and AC grid, to optimize the use of wind energy, and to reduce fuel of diesel generator. The system is simulated with Matlab – Simulink software and it gave good results.

II. SYSTEM COMPONENTS

The figure 1 shows the structure of hybrid renewable energy system. This structure is consisted of wind generator (WG), diesel generator (DG), and flywheel energy storage system (FESS), which are based on permanent magnet synchronous machines (PMSM). The AC/DC converters are used to connect the system elements to DC link voltage, and to control machines, and that put with flywheel energy storage system is bidirectional converter. The DC link voltage and AC grid are connected via condenser, DC/AC converter and RL filter.

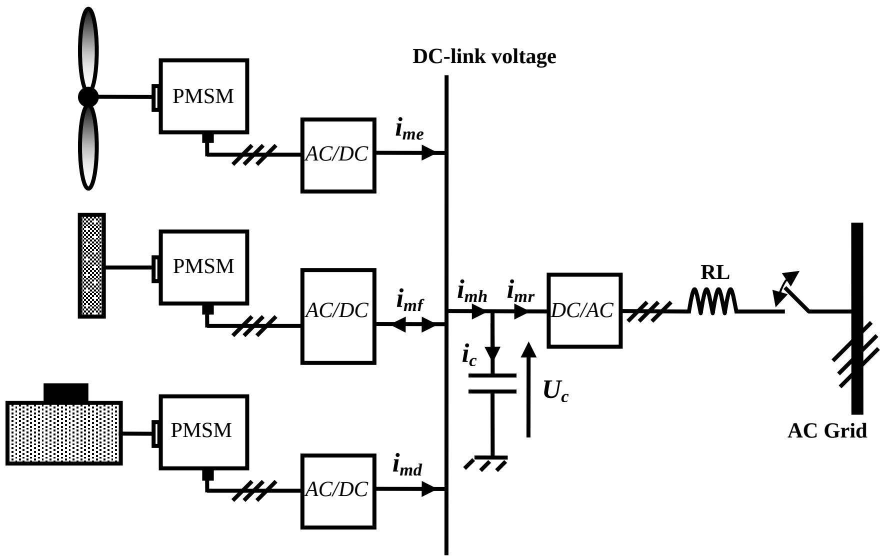

Figure 1. Hybrid renewable energy system configuration.

III. HYBRID SYSTEM MODELLING

A. Wind turbine modelling

The aerodynamic power on the rotor of the wind turbine is given by the following equation:

$$P_m = \frac{1}{2} \rho \pi R^2 v^3 C_p \qquad (1)$$

ρ is the density of the air, $\rho = 1.22 Kg/m^2$, R is the length of the blade (m), v is the wind speed (m/s). C_p is the power coefficient. It represents the aerodynamic efficiency of the turbine and depends on the specific speed λ and the orientation angle of the blades β.

The dynamic fundamental equation determines the mechanical speed evolution of the synchronous generator. The simplified model of this equation is given by:

$$J \frac{d\Omega_m}{dt} = T_m - T_{em} - f \cdot \Omega_m \qquad (2)$$

Where J is the total inertia (turbine and generator), T_m is the mechanical torque, T_{em} is the electromagnetic torque, Ω_m is the mechanical speed of the rotor and f is a coefficient of various.

B. Flywheel energy storage system modelling

The flywheel energy storage system is based on the kinetic energy of the wheel such as:

$$E_c = \frac{1}{2} J_f \cdot \Omega_f^2 \qquad (3)$$

Where J_f *and* Ω_f are respectively the inertia moment and the speed of the wheel.

The dynamic fundamental equation is given by:

$$J' \frac{d\Omega_f}{dt} = T_f - T_{em} - f \cdot \Omega_f \qquad (4)$$

C. Diesel generator modeling

Once the fuel is injected in the cylinders of the engine, there will be a delay before the torque is produced on the rotor [7-9]. This delay depends on the phenomenon of combustion. It depends also on the number of cylinders of the engine, and the rotation speed [7-9-10]. The torque produced by the engine is given by the following equation:

$$T_{di}(s) = \frac{K}{\tau s + 1} Y(s) \qquad (5)$$

τ is the time delay of the combustion and K is a gain that adapts the torque and the fuel consumption. The engine is speed controlled by an outer loop. It drives a PMSM attached to an AC/DC converter.

The dynamic fundamental equation is given by:

$$J'' \frac{d\Omega_{di}}{dt} = T_{di} - T_{em} - f \cdot \Omega_{di} \qquad (6)$$

D. Permanent magnet synchronous machine modelling

The generally used model of the PMSM is the model of Park. By considering only the fundamental harmonic of the field distribution in the air-gap of the machine and by neglecting the homopolar component, the theory of the vector of space gives the dynamic equations of the stator currents such as:

$$\begin{cases} \dfrac{di_{Sd}}{dt} = \dfrac{1}{L_d}(V_{Sd} - R_S i_{Sd} + p\Omega_m L_q i_{Sq}) \\ \dfrac{di_{Sq}}{dt} = \dfrac{1}{L_q}(V_{Sq} - R_S i_{Sq} + p\Omega_m L_d i_{Sd} - p\Omega_m \phi_m) \end{cases} \qquad (7)$$

The electromagnetic torque produced is expressed by:

$$T_{em} = p(\phi_m i_{sq} + (L_d - L_q) i_{Sd} i_{Sq}) \qquad (8)$$

Where R_S is the phase resistance of the stator, L_d and L_q are respectively cyclic inductances of d and q axis, ϕ_m is the field induced by the permanent magnet, V_{Sd} and V_{Sq} are respectively the d and q axis components voltages of the stator, i_{Sd} and i_{Sq} are respectively the d and q axis components currents of the stator, *p* is the pairs poles number.

IV. HYBRID SYSTEM CONTROL STRATEGY

A. *Sliding mode control of PMSM*

The implementation of this control method requires three stages necessary: the sliding surface, the condition of convergence and the law of order.

The general form of the sliding surface proposed by JJ Slotine [11] is:

$$S(x) = \left(\frac{\partial}{\partial t} + \lambda_x\right)^{r-1} e(x) \qquad (9)$$

Where:

$e(x) = x_{ref} - x$: Variation of the variable to be regulated

λ_x : Positive constant which interprets the band-width of desired control.

r : Relative degree, equal to the number of times that it is necessary to derive the output to reveal the order.

$S(x) = 0$: A linear differential equation whose single solution is: $e(x) = 0$.

The general form of the order is $U = U_{eq} + U_{nl}$

U_{eq} : equivalent order, it is the solution of the equation $\dot{S}(X) = 0$,and it can be interpreted as the overage value of the order *U* which makes it possible to maintain the state of the system on the sliding surface [12-14].

U_{nl} : nonlinear order, it is given to guarantee the attractivity of the variable to be controlled towards the sliding surface and to satisfy the condition of convergence, the simplest function is in the form of relay $U_{nl} = K.signS(X)$, where *K* a positive constant [12-13].

For the permanent magnet synchronous machine PMSM, the vector consisted by the errors of regulation of the stator currents is:

$$\begin{cases} y_1 = I_{sd\_ref} - i_{sd} \\ y_2 = I_{sq\_ref} - i_{sq} \end{cases} \qquad (10)$$

From the system of equation (7), the first derivative of the system (10) can lead to the system (11):

$$\begin{cases} \dot{y}_1 = \dot{I}_{sd\_ref} + \frac{1}{L_d}\left[R_s i_{sd} - pL_q\Omega_m i_{sq}\right] - \frac{1}{L_d}V_{sd} \\ \dot{y}_2 = \dot{I}_{sq\_ref} + \frac{1}{L_q}\left[R_s i_{sq} - p\frac{L_d}{L_q}\Omega_m i_{sd} + p\phi_m\Omega_m\right] - \frac{1}{L_q}V_{sq} \end{cases} \qquad (11)$$

The relative degree of the system $r = 1$ since the variables of order appear in the first derivation of the variables to be controlled. From system of equation (11) we can deduce:

$$\begin{cases} \dot{y}_1 = B_1 + A_1 V_{sd} \\ \dot{y}_1 = B_2 + A_2 V_{sq} \end{cases} \qquad (12)$$

Where:

$$\begin{cases} B_1 = \dot{I}_{sd\_ref} + \dfrac{1}{L_d}\left[R_s i_{sd} - pL_q\Omega_m i_{sq}\right] \\ A_1 = -\dfrac{1}{L_d} \\ B_2 = \dot{I}_{sq\_ref} + \dfrac{1}{L_q}\left[R_s i_{sq} - pL_d\Omega_m i_{sd} + p\phi_m\Omega_m\right] \\ A_2 = -\dfrac{1}{L_q} \end{cases} \quad (13)$$

S_1 and S_2 are respectively the two sliding surfaces of the exits variables i_{sd} and i_{sq} :

$$\begin{cases} S_1 = y_1 \\ S_2 = y_2 \end{cases} \quad (14)$$

The solution of equation $\dot{S} = 0$ leads to the equivalent order

$$\begin{cases} \dot{S}_1 = 0 \\ \dot{S}_2 = 0 \end{cases} \Rightarrow \begin{cases} \dot{y}_1 = 0 \\ \dot{y}_2 = 0 \end{cases} \quad (15)$$

What gives :

$$\begin{cases} V_{sd\_eq} = -\dfrac{B_1}{A_1} \\ V_{sq\_eq} = -\dfrac{B_2}{A_2} \end{cases} \quad (16)$$

The nonlinear order is given in the following form:

$$\begin{cases} V_{sd\_nl} = K_d \, signS_1 \\ V_{sq\_nl} = K_q \, signS_2 \end{cases} \quad (17)$$

The order $U = \left[V_{sd} V_{sq}\right]^T$ is the sum of equivalent order and nonlinear order:

$$\begin{cases} V_{sd} = L_d \dot{I}_{sd\_ref} + R_s i_{sd} - pL_q\Omega_m i_{sq} + K_d \, signS_1 \\ V_{sq} = L_q \dot{I}_{sq\_ref} + R_s i_{sq} - pL_d\Omega_m i_{sd} + p\phi_m\Omega_m + K_q \, signS_2 \end{cases} \quad (18)$$

The permanent magnet synchronous machines PMSM are controlled by the choice of references currents values, I_{sd_ref} and I_{sq_ref}. The d-axis reference current is maintained to zero (to minimize the Joule losses), the electromagnetic torque of equation (8) becomes:

$$T_{em} = p.\phi_m.i_{sq} \quad (19)$$

B. Wind generator control

The permanent magnet synchronous machine of wind generator is controlled by maximum power point tracking (MPPT). Using the mechanical characteristic of the wind turbine for various wind speed shown in figure 2, it possible to calculate the reference of electromagnetic torque deduced graphically by maximum power point $\left(\Omega_{m\_\max}, T_{m,\max}\right)$.

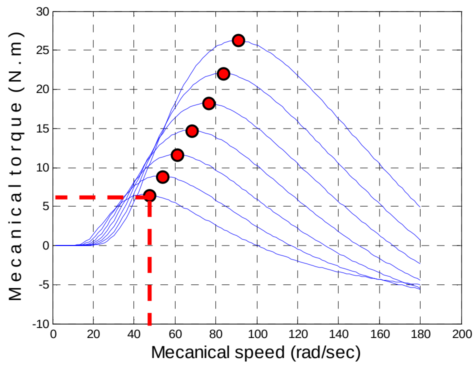

Figure 2. Mechanical characteristic of wind turbine.

The reference current I_{sq_ref} can be deduced by equation (2) in permanent mode and equation (19):

$$I_{sq\_ref} = \frac{T_{m\_max} - f.\Omega_{m\_max}}{p.\phi_m} \qquad (20)$$

The figure 3, shows the diagram of control

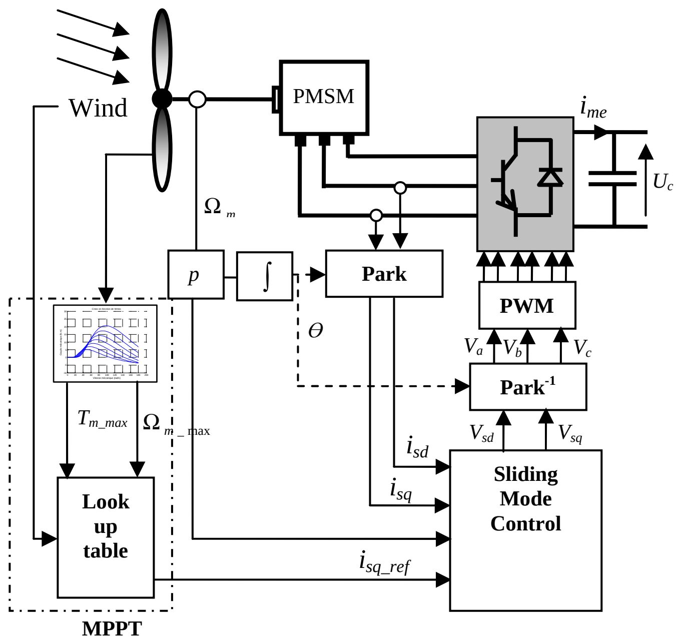

Figure 3. Diagram of wind generator control.

C. Flywheel energy storage system control

For the flywheel energy storage system, the q-axis reference current of permanent magnet synchronous machine is determined by:

$$I_{sq\_ref} = k_{sign} \frac{T_{em\_ref}}{p.\phi_m} \qquad (21)$$

Where:

$k_{sign} = -1$: When the FESS is in charging mode, transfer of energy from DC-link voltage to flywheel;

$k_{sign} = 1$: When the FESS is in discharging mode, transfer of energy from flywheel to DC-link voltage;

$k_{sign} = 0$: When the FESS is in no-transfer mode, No transfer of energy between flywheel and DC-link voltage.

The equation (4) in permanent mode and equation (21) gives:

$$I_{sq\_ref} = k_{sign} \frac{\frac{P_{f\_ref}}{\Omega_{f\_ref}} - f.\Omega_{f\_ref}}{p.\phi_m} \qquad (22)$$

P_{f_ref} is the reference power of flywheel energy storage system; it can be calculated as follows:

$$P_{f\_ref} = P_{ref} - P_{wind} \qquad (23)$$

Where P_{ref} and P_{wind}, are respectively the reference power of hybrid system, and the generated wind power. The reference speed of flywheel energy storage system Ω_{f_ref} can be calculated as follows:

$$\Omega_{f\_ref} = \sqrt{\frac{2}{J_f} \cdot E_{c\_ref}^2} \qquad (24)$$

Where E_{c_ref} is the reference value of kinetic energy, it can be calculated us follows:

$$E_{c\_ref} = E_{c0} + \int_{t_1}^{t_2} P_{f\_ref}\, dt \qquad (25)$$

The figure 4 shows the diagram of control.

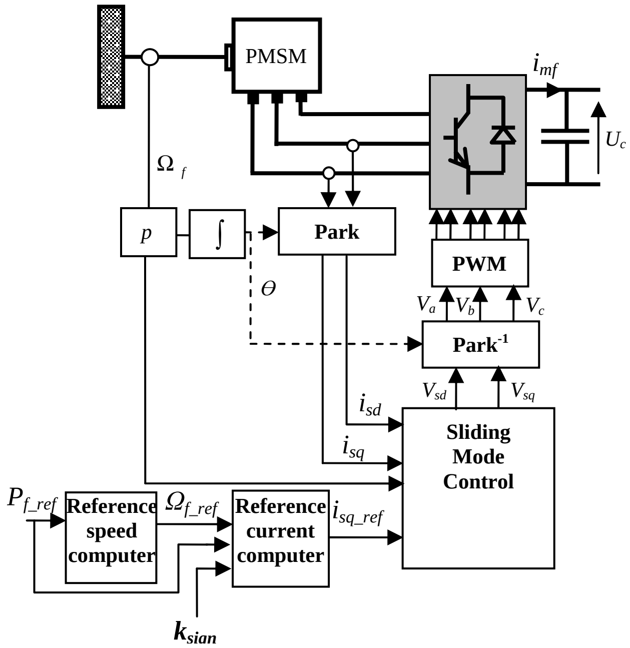

Figure 4. Diagram of FESS control.

D. Diesel generator control

The PMSM of diesel generator is also controlled by the same strategy, the q-axis reference current of permanent magnet synchronous machine is determined by:

$$I_{sq\_ref} = k_{stat} \frac{T_{em\_ref}}{p.\phi_m} \qquad (26)$$

Equation (6) in permanent mode and equation (26) gives:

$$I_{sq\_ref} = k_{stat} \frac{\frac{P_{di\_ref}}{\Omega_{di\_ref}} - f.\Omega_{di\_ref}}{p\phi_m} \qquad (27)$$

Where k_{status}, is the diesel generator ON/OFF status, it can be 0 (OFF) or 1(ON).
The diagram of diesel generator control is shown on the figure 5.

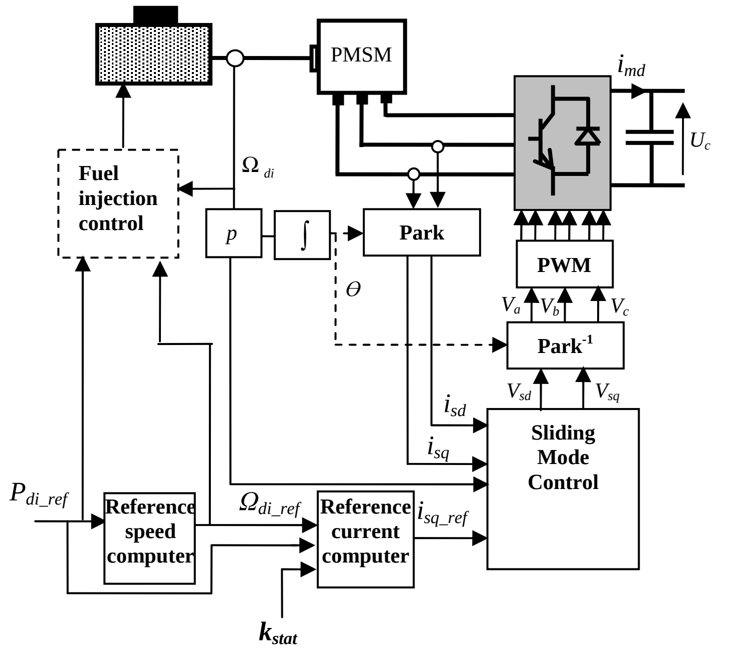

Figure 5. Diagram of diesel generator control.

E. Supervisor control for hybrid renewable energy system

The control of the flywheel energy storage system requires the determination of energy transfer sign k_{sign} and its reference power value P_{f_ref} depending on the state of the global system. The permanent magnet synchronous machine will be controlled in motor (**k_{sign} = -1:** energy transferred from DC-link voltage to flywheel), in generator (**k_{sign} = 1:** Energy transferred from flywheel to DC-link voltage), or it can be not controlled (**k_{sign} = 0:** No energy transferred between DC-link voltage and flywheel). The diesel generator control uses diesel generator ON/OFF status k_{stat} (**k_{stat} = 0:** for **OFF**/ **k_{stat} = 1:** for **ON**), and reference power value P_{di_ref}. A supervisor (figure 6) is developed then to determine k_{sign}, P_{f_ref}, K_{stat}, and P_{di_ref}. The supervisor's inputs are the reference power value of hybrid renewable energy system P_{ref}, the generated wind power P_{wind} , and the energy stored in flywheel E_{stock}; this energy is not represented by a value it is represented by X parameter which describes its limits, and can be 0 or 1, it is calculated as follows:

$$X = 0 \text{ if } E_{stock} < E_{stock\_\min} \text{ or } E_{stock} > E_{stock\_\max}$$

$$X = 1 \text{ if } E_{stock\_\min} \le E_{stock} \le E_{stock\_\max}$$

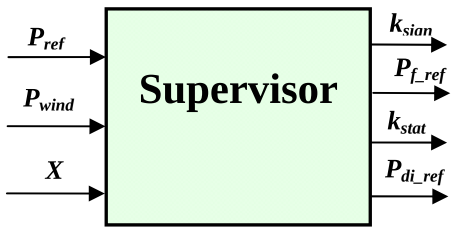

Figure 6. Supervisor control of hybrid system.

The organisation chart of supervisor is shown in figure 7.

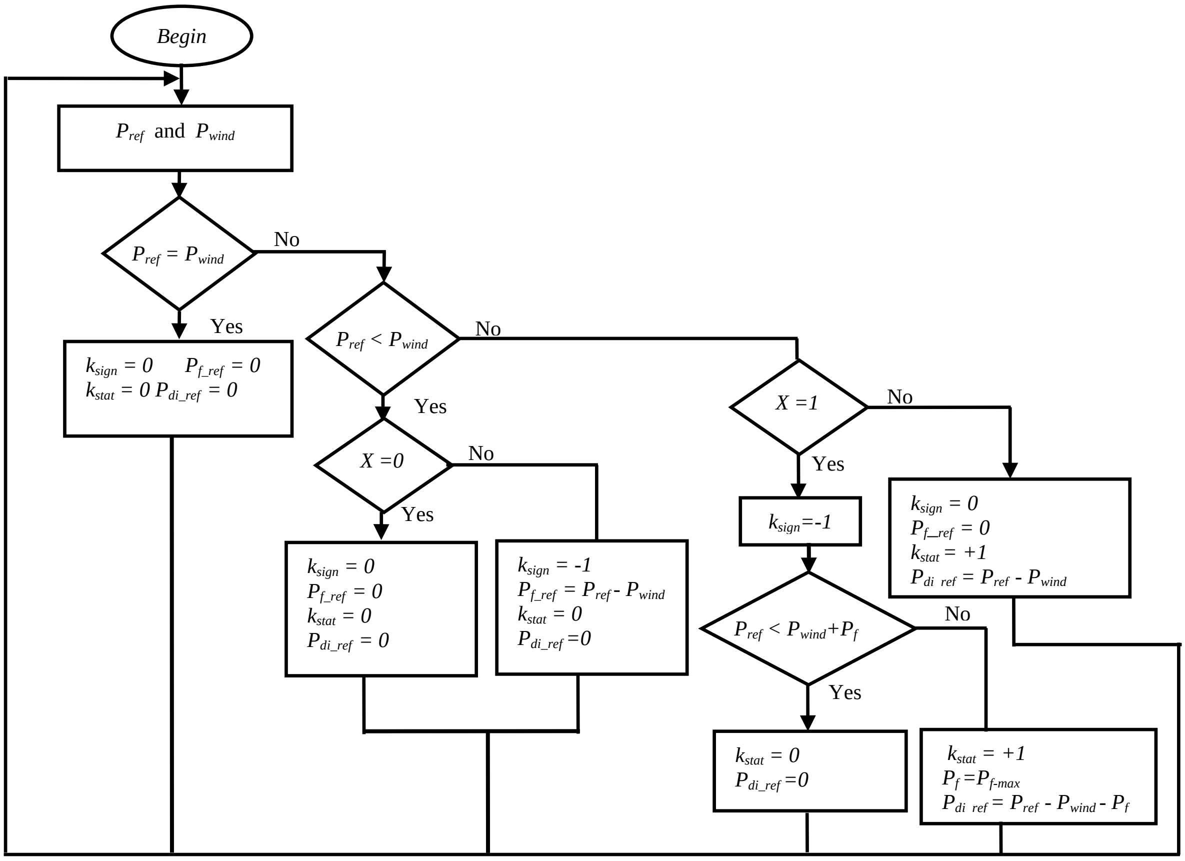

Figure 7. Organisation chart of supervisor.

V. SIMULATION RESULTS

To simulate the system we used a wind profile which is applied to the turbine and is shown on the figure 8a, the wind generator produces then a power P_{wind} which is shown on the figure 8b. The negative sign represents physically the generated power. We still proposed a reference power for hybrid renewable energy system P_{ref} shown on figure 9, its total generated power P_{gen} is shown on the same figure. The evolution of the flywheel energy storage system during this operation is shown by the energy transfer sign k_{sign} shown on the figure 10a (**k_{sign} = -1:** energy transferred from DC-link voltage to flywheel / **k_{sign} = 1:** Energy transferred from flywheel to DC-link voltage), and generated power P_f shown on the figure 10b. The figures 11a and 11b show the diesel generator ON/OFF status k_{stat} and the diesel generator power, the diesel generator is always OFF (k_{stat} = 0) and its generated power P_{di} is null, that because the reference power of hybrid renewable energy system is satisfied by the wind generator and the flywheel energy storage system without the intervention of diesel generator.

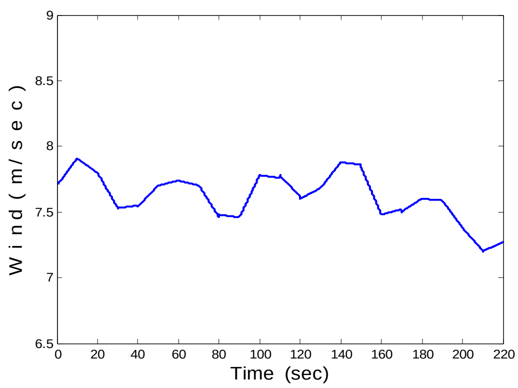

Figure 8a. Wind speed.

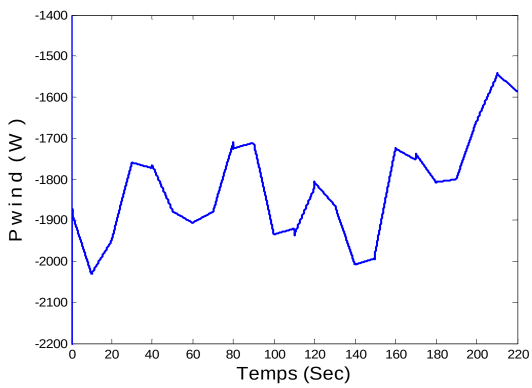

Figure 8b. Generated wind power.

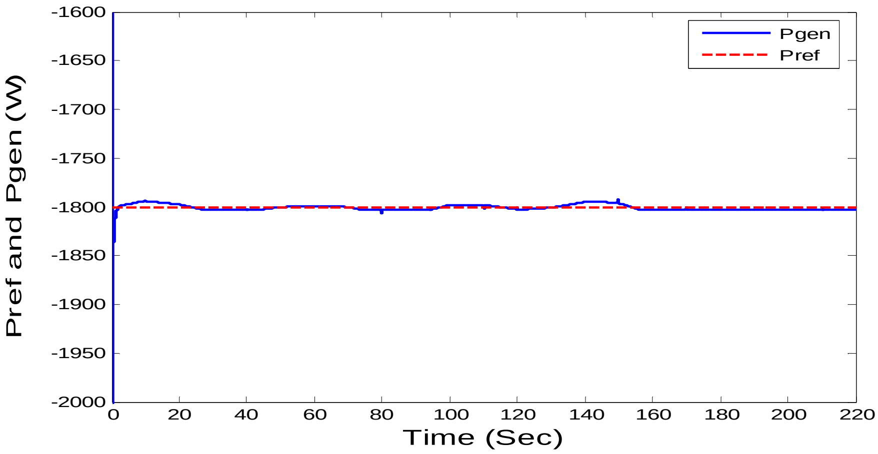

Figure 9. Reference and generated powers.

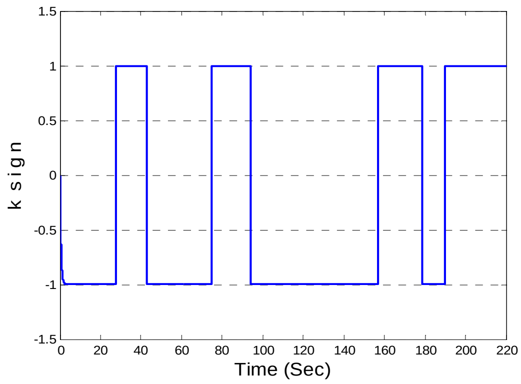

Figure 10a. Energy transfer sign of FESS.

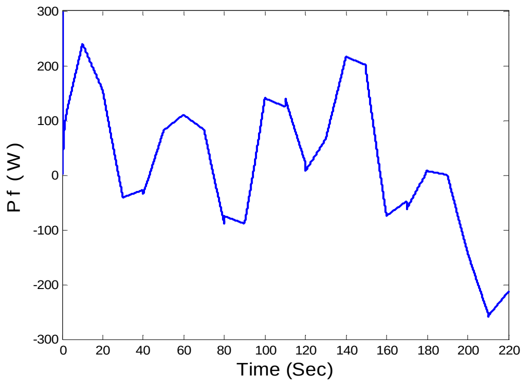

Figure 10b. Power of FESS.

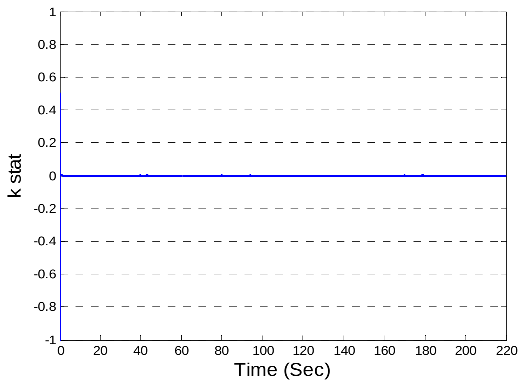

Figure 11a. Diesel generator ON/OFF status.

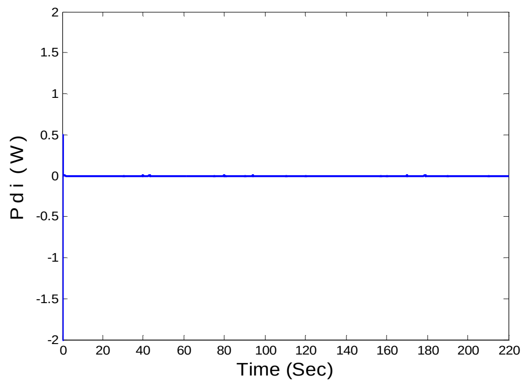

Figure 11b. Diesel generator power.

For the second simulation the reference power is variable (figure 12). The energy transfer sign of flywheel energy storage system k_{sign} (**k_{sign} = -1:** energy transferred from DC-link voltage to flywheel / **k_{sign} = 1:** Energy transferred from flywheel to DC-link voltage / **k_{sign} = 0:** No energy transferred between DC-link voltage and flywheel) the diesel generator ON/OFF status k_{stat} (0 for OFF and 1 for ON), and its generated powers are shown respectively on the figures 13a, 13b, 14a, and 14b. Initially diesel generator is deactivate, the reference power of hybrid renewable energy system is satisfied without its intervention, then it is activated to supplement the missed power, at this time wind generator and flywheel energy storage system cannot satisfy the reference power. The starting of the diesel generator is slow what made a delay on the generated power (figure 12).

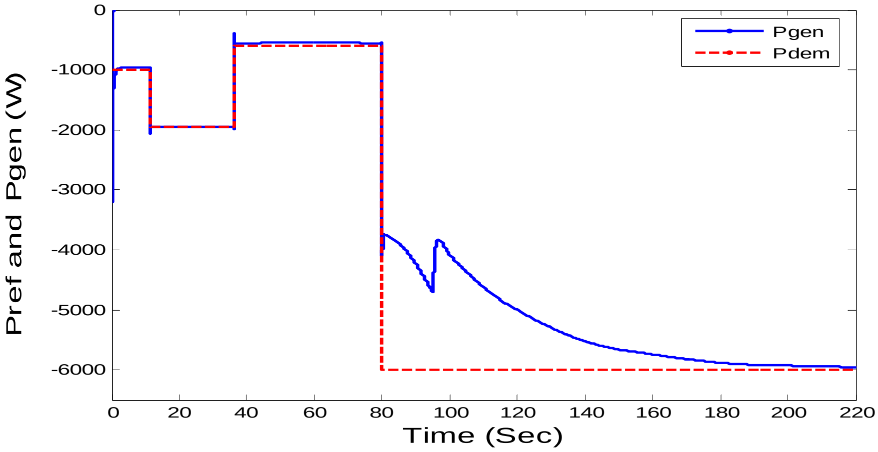

Figure 12. Reference power and generated power.

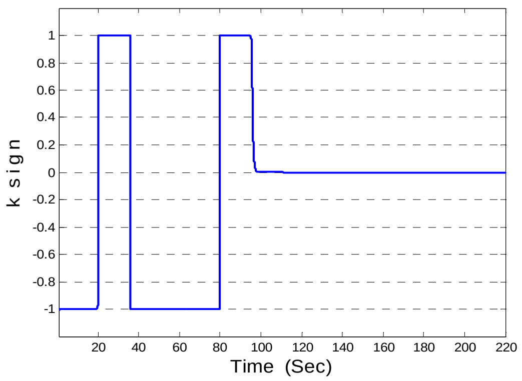

Figure 13a. Energy transfer sign of FESS.

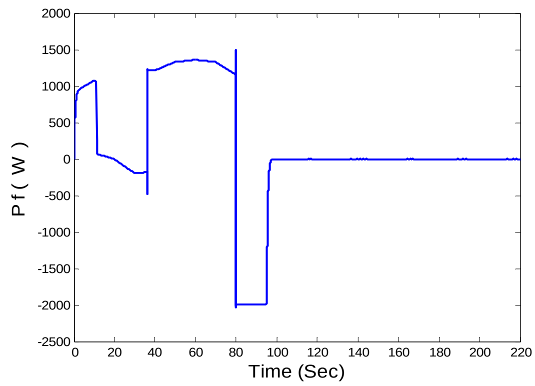

Figure 13b. Power of FESS.

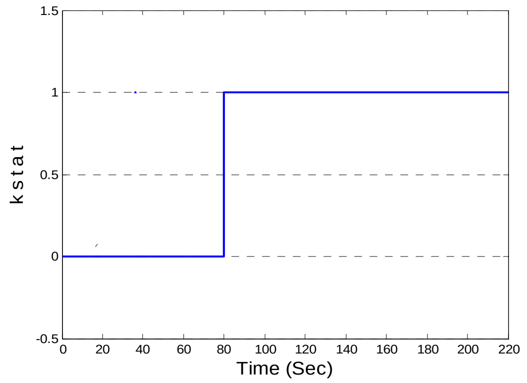

Figure 14a. Diesel generator ON/OFF status.

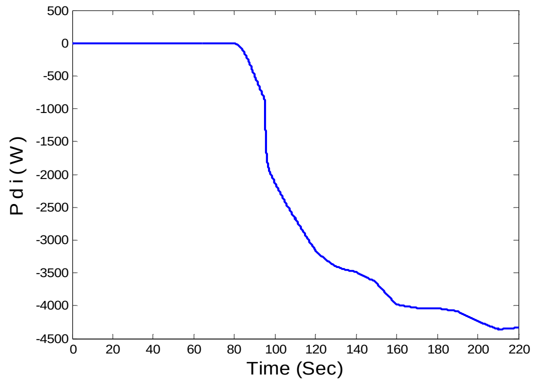

Figure 14b. Diesel generator power.

VI. CONCLUSION

In this paper, local controls methods are determined for the energy production subsystems which constitute the hybrid renewable energy system proposed and modelled. A supervisor is also developed for system control and to satisfy the power requested by AC grid, to manage the energy transfer between hybrid system and AC grid, to optimize the use of wind energy, and to reduce fuel of diesel generator. Thereafter the laws of control are validated with Matlab simulink software. The simulation Results show the advantages of hybrid renewable energy system and its control as solution for the consumption-production problem allocated to wind generators which are decentralized production sources. This solution improves the wind power quality and increases the penetration of wind generators in the electrical supply networks without causing any risk to disturb their stability.

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