Improved sizing method of storage units for hybrid wind-diesel powered system

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Abstract: **This paper deals with the segmentation of frequency domain to achieve DC bus stability by efficient design of storage and control principle. The wind energy disturbances measured on DC link are actively filtered by flywheel and battery storages to provide smoothed and secured behaviour of diesel engine. This is obtained by cascaded low pass filters applied to currents control when the dc link voltage is assumed constant. Thus, the templates, the degree of filters selectivity influence the sizing of storage units. This study focuses on the flywheel and battery sizing taking in to account wind energy path dynamics. Simulation results provide first step considerations for energy management tied to energy periodicity and system effectiveness.**

Keywords: **Battery management systems (BMS). DC power supply. Flywheel system. Energy system management. Energy storage. Renewable energy systems. Wind generator systems.**

I. INTRODUCTION

Energy storage device sizing techniques are studied first. These techniques are used to design a hybrid system which includes wind turbine, diesel engine, flywheel, battery, capacitor and emulated load. The maximum power of the wind turbine and the load is respectively 15kW and 76 kW.

According to energy storage issue, the properties of available technologies can be spread on dual energy-power definition related to time horizon of effectiveness.

From 10 to 100kw output power depending on energy amount to be stored, we have proposed the following Storage Units Frequency Allocation Table (SUFAT) [1]

TABLE 1
Storage Units Frequency Allocation Table (SUFAT)

Frequency range	low	Medium	high
technology	battery	flywheel	capacitor

The aim of storage elements and diesel engine coupling is based on the frequency that each source can support with long lifetime guarantee. An overview of known models of single path or element of the system is presented. The energy management strategy based on a frequency approach is explained for each section. Filtering principle is presented and Storage elements (battery and flywheel) are then sized according to adopted energy management strategy. Batteries lifetime prediction is included as a sample case.

II. WIND SPEED MODEL

The wind speed is considered, as usual, as a random process. This process is assumed to have low frequency components and the turbulence components.
The method used for the modelling of the wind speed is the wind spectral characteristic of Van Der Hoven [2]. Wind speed is obtained by means of direct discretization of the power spectral characteristic S_{vv}.
The wind speed $v(t)$ is the sum of the harmonics characterised by the magnitudes A_i, the pulsation w_i and the phase φ_i generated randomly.

$$v(t) = v_l(t) + v_t(t)$$
$$= \frac{2}{\pi}\sum_{i=0}^{N_l} A_i \cos(w_i t + \varphi_i) + \frac{2}{\pi}\sum_{N_t}^{N} A_i \cos(w_i t + \varphi_i) \quad (3)$$

N_l are Samples for the slow component $v_l(t)$ and N-N_t are Samples for the component of turbulence $v_t(t)$.

III. POWER SOURCES MODELS

A. Wind turbine model

We have considered that the blades are rigidly attached to the wind turbine; consequently the pitch angle of the blades is constant. The wind turbine characteristics modelling have been made by a six order polynomial regression [2]. The power coefficient characteristic Cp is a function of tip speed ratio λ and in this case is given by:

$$C_p(\lambda) = \sum_{i=0}^{n} a_i \lambda^i \quad (4)$$

$$\lambda = R\Omega / v \quad (5)$$

Where R is the radius of the rotor, Ω is the mechanical angular velocity of the rotor and v is the wind speed.
The a_i parameters $(i=0...6)$ are determined by a Matlab computing program [2]. The output power of the wind turbine is calculated from the following equation:

$$P_t = (1/2)\rho A v^3 C_p(\lambda) \quad (6)$$

where ρ is air density in kg/m^3 and A is the frontal area of the wind turbine in m^2. The torque developed by the wind turbine is expressed by :

$$\Gamma_t = \frac{P_t}{\Omega} = (1/2)\rho A R v^2 C_\Gamma(\lambda) \quad (7)$$

Where $\frac{C_p(\lambda)}{\lambda}$ is the torque coefficient.

B. Wind turbine Control strategy

The generator torque is controlled assuming that the permanent magnet generator torque is proportional to the current (8). Consequently, The current reference frame of the wind generator (9) is calculated. For the steady state points the turbine and the generator torques are equals (8).

$$\Gamma_{t\_opt} = \Gamma_g = \frac{3}{2} p\Phi_{\max} I_s \tag{8}$$

$$I_{dc\_ref} = \sqrt{\frac{3}{2}\left(\frac{1}{3} p\Phi_{\max}\right) C_\Gamma\left(\lambda_{opt}\right)\rho\pi R^3 v^2} \tag{9}$$

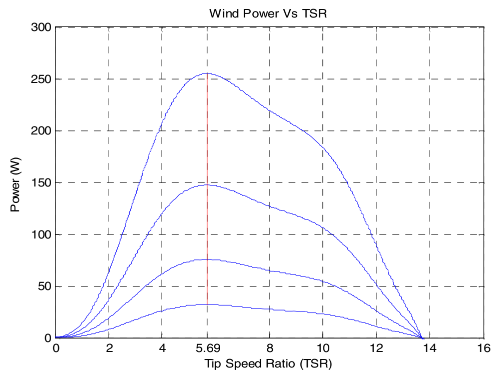

Fig. 1 Power characteristics versus turbine rotational speed

C. Diesel engine model

The diesel engine includes a gasoline engine and an electric generator. The torque produced by the engine is given by the following equation:

$$T_d = \frac{K}{\tau_1 p + 1} X(p) \tag{10}$$

τ_1 is the time constant 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 synchronous generator (GAP) attached to a rectifier-filter-chopper path.

IV. Energy storage devices

The hybrid system presented in figure 2 is DC bus linked. Flywheel and battery are used as storage devices.
The flywheel energy storage system is based on switched reluctance machine (SRM). In the SRM, phase flux linkage is a function of phase current and rotor position. This is the result of inherent stator and rotor salient poles and iron saturation that impose the flux linkage to be a nonlinear function of both position and current. The phase flux linkage ψ is related to the inductance L and the current i as

$$\psi_k(i_k,\theta) = L(i_k,\theta) i_k \tag{11}$$

Where θ is the rotor position. The calculation of the inductance is obtained using polynomial interpolation;
The instantaneous voltage across the terminals of each SRM phase (k=1, 2, 3, …m) is given by [3]:

$$v_k = r_k i_k + \frac{d\psi(i_k,\theta)}{dt} \tag{12}$$

$$\Gamma(i_k,\theta) = \sum_{k=1}^{3} \frac{\partial W_k'(y_k,i_k)}{\partial\theta} \tag{13}$$

The co-energy is defined by

$$W_k'(\psi_k,i_k) = \int_0^{I_k} \psi(i_k,\theta) di_k \tag{14}$$

The converter supplying the SRM is H-hybrid asymmetric bi-directional converter. This converter allows operating the SRM in motor or generator modes.

$$J\frac{d\Omega}{dt} = \Gamma(i_k,\theta) - f\Omega \tag{15}$$

The flywheel associated with static converter is linearized into a first order transfer function $G_{SRM}(p)$ [3] presented to the equation (16).

$$G_{SRM}(p) = \frac{K_{SRM} e^{-\gamma p}}{\tau_{SRM} p + 1} \tag{16}$$

With, K_{SRM} The process gain, τ_{SRM} the time constant and γ the delay time.
The impedance spectroscopy shows that at low frequencies (f <1 hertz), the impedance of the battery can be represented by a resistor and a capacitor in series [4]. Therefore, the battery can be modelled by an internal source E_{bat}, in series with a capacity C_{bat} and a resistor R_{bat}.

$$G_{bat}(p) = \frac{pC_{bat}}{1 - \tau_{bat} p} \tag{17}$$

With $\varepsilon = Vbat - Ebat$ and the time constant $\tau_{bat} = R_{bat} C_{bat}$.

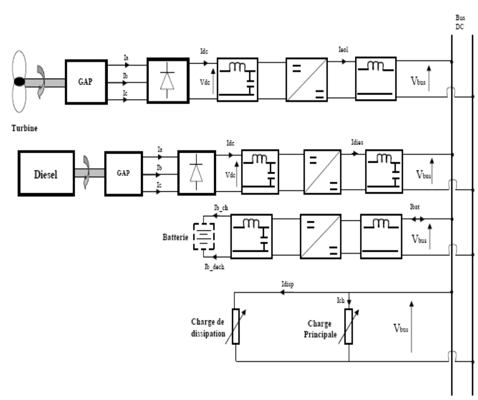

Fig 2. hybrid system WITHOUT FLYWHEEL

V. Hybrid system without flywheel

The hybrid system is shown in Figure 2, the principle of regulating the voltage bus, and energy transfer between the components described in the next paragraph.

Batteries are used to smooth the interactions of frequencies above the dynamics of diesel generator, according to an outline of the figure 2.

Reflected currents exchanged between the turbine, diesel and load are presented in Figure 3.
With this configuration, power demand from the load is satisfied and DC bus voltage is regulated as well (fig.4).

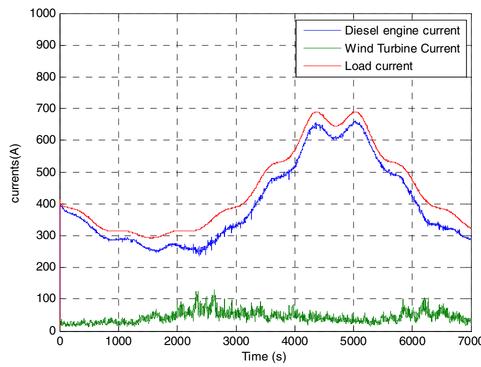

Fig. 3. Currents from the diesel, the wind generators and the load

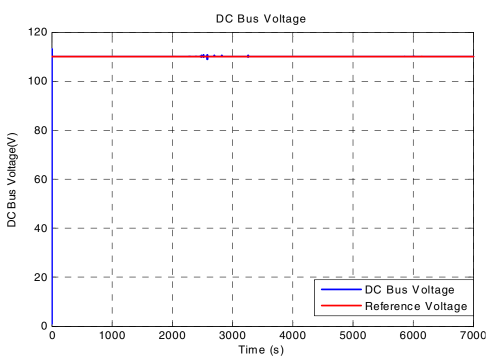

Fig.4 Dc bus voltage

A. Storage devices sizing

A good design of storage devices requires definition of periodicity of the energy to be stored. To show feasibility, the proposed approach in this paper is to process the signal from storage device (flywheel, battery) and to make the signal periodicity match the window of data collected. The used computer capability must be considered to avoid data overflow.

Pure fluctuating value $\tilde{i}(t)$ (i.e. zero mean value) of instantaneous reference current can be calculated by equation (24).

$$\tilde{i}(t) = i(t) - mean(i(t)) \tag{18}$$

Equation (24) allows calculating the magnitude of stored energy variations of each storage unit in the assumed period.
Energy exchanged by storage device with DC bus is expressed as:

$$e(t) = \int v(t) * i(t) * dt \tag{19}$$

With $v(t)$ and $i(t)$ are voltage and current of the storage source.

Equation (26) allows calculating the energy capacity of the storage units.

$$Energy = Max(e(t)) - Min(e(t)) \tag{20}$$

Equations (19) and (20) are used to calculate battery exchanged energy that is presented in figure 5 for 2h simulation of system operation considered as wind turbine period. Most important consideration is that the energy level at the beginning and at the end of assumed period is the same.
The energy Ah capacity of the battery and capacitor bus continuous tension are reported in Table 2.

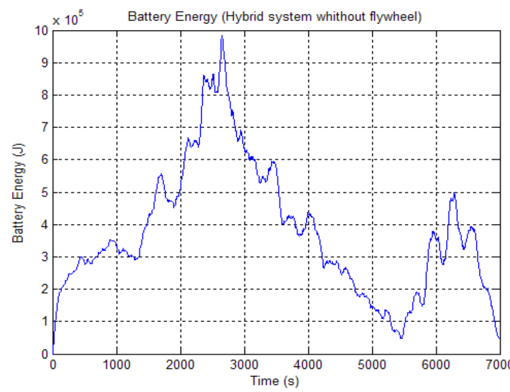

Fig.5. Battery stored energy

TABLE 2.
Storage units capacities.

	Battery	**Capacitor (35mF)**
Capacity (Ah)	57	0.0283

Batteries are one of the key weak links in the long-term operation of fluctuating power systems, such as renewable energy sources or locomotives. They act not only on the performance and operation of the system, but also greatly on the life cycle cost of the system.

Indeed, the performance of the battery is affected by degradation more or less strong as profiles of energy absorbed, resulting in longer or shorter life [4][5][6].

B. Lifetime estimation

To estimate the battery lifetime the Umass battery lifetime model [4] is used. This model incorporates the main mechanisms of degradation of the battery and uses the method of counting cycles, known as rainflow cycle counting, usually applied in calculating the fatigue of materials. The assumption is that the battery lifetime impact factor is similar to fatigue in material subjected to vibrations.

From battery charges and discharges currents (powers), the lifetime model calculates the time series of state of charge, which will undergo two treatments. A first algorithm is used to identify extreme values (peaks and valleys). This gives a new but short-time series in which a second algorithm is applied to determine the individual cycles. The total discharge range is divided into equal size in 16 to 20 bins, with the final bin corresponding to complete discharge and recharge from a full battery. The cycles determined are classified by bin, the number of cycles per bin calculated and coefficients are used to estimate the lifetime.

So, two independent models are used to estimate the lifetime of the battery: the wind - diesel hybrid system model and the battery lifetime model. The first model (fig.2) allows the calculation of the battery power which will serve as an input to the lifetime model.

Standard hybrid system simulation results show the battery power capacity (fig. 6) that will be used in lifetime model. The battery life is estimated this case to 1.0726 years.

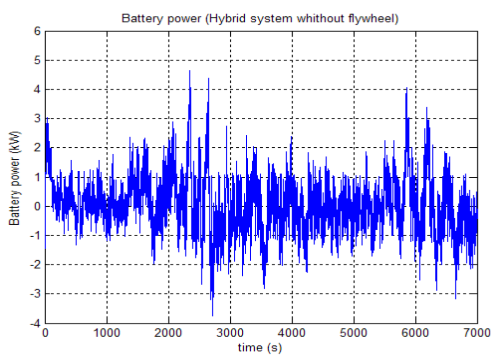

Fig.6. Battery power

Figure 7 shows that the cycles of energy at low amplitudes are the most numerous and that the maximum amplitude is about 10% of the energy capacity of the battery.

The battery is thus subjected to partial charges and discharges cycles that can affect its lifetime.

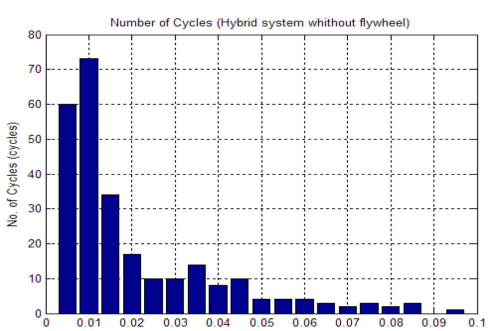

Fig.7 Battery number of cycles

The optimal operation of a wind-diesel hybrid system is characterized by the satisfaction of the load demand, almost constant tension of the DC bus and optimization of lifetime (and therefore cost) of storage devices.

To optimise battery lifetime, a new configuration of the hybrid system is proposed in the following study. It involves inserting a flywheel and makes a frequency distribution.

V. Hybrid System with flywheel

The strategy for managing energy transfer obviously depends on the intrinsic characteristics of each source. As shown in figure 6, energy storage devices are classified according to their energy density, their power density and according to the dynamics they provide [7][8]. Batteries are actual energy sources providing few slow dynamic cycles (1000 cycles). Figure 3 shows the state of the art in the field of relevant storage technologies, gathered in the Ragone plots. This can be use to indicate theoretically and approximately frequency capabilities of the devices.

Figure 7 shows the Nyquist plan of a lead-acid battery impedance and frequency distribution of degradation mechanisms [5]. The main physical effects which affect the lifetime of the battery are the electrical and chemical effects (very fast effects), the effects of operating principles, such as the effects of mass transport and double-layer effects and long - term effects caused by operating systems (ageing, stratification, SOC,…).

The best way for improving their lifetime is to prevent them from fast dynamic currents and high number of cycles [4][5][6]. On the opposite, flywheels and capacitors are capable of absorbing currents with fast dynamics, and to provide a significant number of cycles (50000 cycles) [7][9].

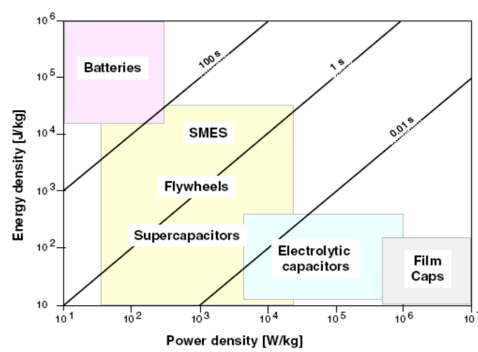

Fig.6. Ragone plots

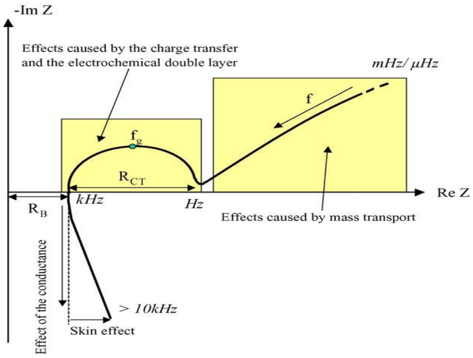

Fig.7 typical Nyquist plot for a lead-acid battery

An optimised configuration of hybrid system including a flywheel is proposed in Figure 8. Development of the strategy of energy transfer presented here follows previous work in [1] [10]. References [8] [11] apply a similar principle in order to make a division between energy sources frequency, storage devices and load. The high frequencies are handled by a SMES in [8] and a super capacitor in [11].

Ref. [11] applies the strategy to a system whose storage capacity is initially defined, which entails the use of fuzzy logic to prevent saturation and depletion of energy. The diesel may be sought by high frequencies Ref [8]. The sizing process of storage devices takes into account batteries and super capacitors efficiency factors.

The design principle presented in this paper is based on the quantification of energy exchanges. It is assumed that the first case is ideal case without any critical damage. A simulation is carried out over a period of wind speed and battery power is used in a second system that integrates the stress factors and calculates the lifetime of the battery.

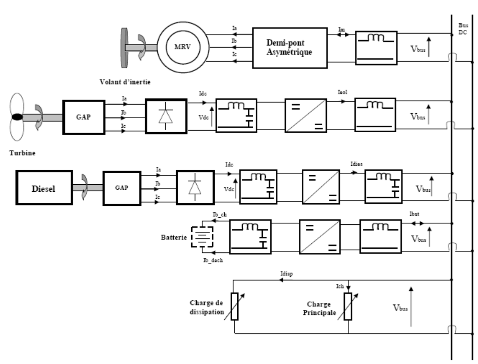

Fig 8. hybrid system with flywheel

The strategy for regulating the DC bus voltage and energy transfer between different components is based on the filtering of the current supplied on DC bus by the wind turbine assuming that it is the main source of disturbances.

VI. Filtering principle

Two first order low-pass filters are used to generate the current reference frames of storage devices. The transfer function of a first order low pass filter is expressed by the equation (21).

$$H_{LPF}(p) = \frac{1}{1 + p\tau_c} \tag{21}$$

With, $fc = \frac{1}{2\pi\tau_c}$ the filter cut-off frequency and τ_c the time constant.

The coupling principle of sources on DC bus is depicted in Figure 9.

The low-pass filters transfer functions $H_{LPF1}(p)$ and $H_{LPF2}(p)$ in the respective cut-off frequencies f_{c1} and f_{c2} can generate the references of flywheel and battery regulator current, with $f_{c1} > f_{c2}$. The cut-off frequency of the filter is equal to the maximum frequency currents that will be covered by the battery and the filter frequency is related to the dynamics of diesel and will correspond to the allocated maximum frequency currents. This principle I based on cascaded filtering of wind turbine measured current I_{wind_opt} .

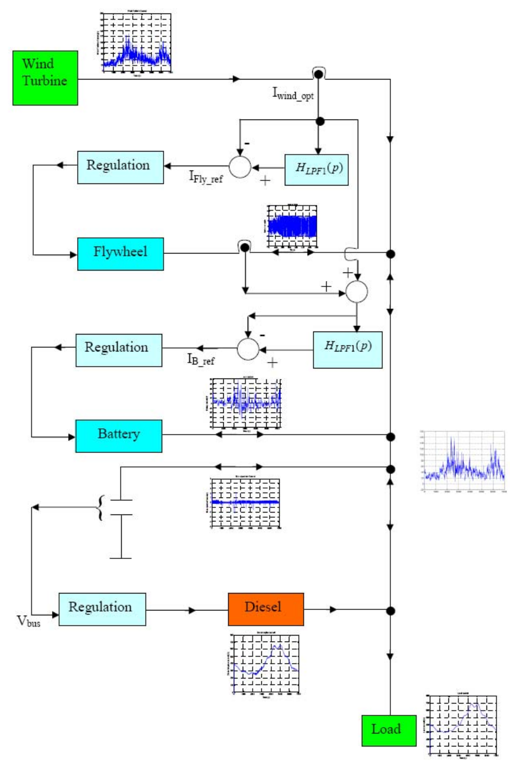

Fig.9. filtering principle

We must keep in mind that very high frequencies are absorbed instantly by the capacitors without a special need of control.

The wind turbine current is forced to maximum I_{wind_opt} on the DC bus. The current is measured and filtered through the low pass filter $H_{LPF1}(p)$. This filter output is subtracted from I_{wind_opt} to get the reference frame current I_{Fly_ref} of the regulator of flywheel. Thus the current I_{Fly_ref} contains only high frequency fluctuations devoted to flywheel compensation. Assuming that the final operation is effective, the difference between the actual wind generator current and the I_{Fly_ref} , provides the reference frame I_{bat_ref} of the battery regulator.

Currents exchangeable by the flywheel and battery with the DC bus have expressions (22) and (23).

$$I_{Fly}(p) = G_{SRM}(p) * I_{Fly\_ref}(p) \quad (22)$$

$$I_{bat}(p) = G_{bat}(p) * I_{bat\_ref}(p) \quad (23)$$

Reference currents are presented by equations (24) and (25).

$$I_{Fly\_ref}(p) = I_{eol\_opt}(p) * (1 - H_{LPF1}(p)) \quad (24)$$

$$I_{bat\_ref}(p) = I_{eol\_opt}(p) * \left[1 - G_{SRM}(p) * (1 - H_{LPF1}(p))\right] * (1 - H_{LPF2}(p)) \quad (25)$$

The resulting current I_{eol_BF} from the smoothing of wind turbine current fluctuations by the DC bus capacitor and storage elements contains low frequencies components.

$$I_{eol\_BF}(p) = I_{eol\_opt}(p) * \left[1 - G_{bat}(p) * \left[1 - G_{SRM}(p) * (1 - H_{LPF1}(p))\right] * (1 - H_{PLF2}(p))\right] \quad (26)$$

Diesel compensates the difference between the load demand and the current I_{eol_BF} supplied by the turbine while maintaining DC bus voltage almost constant (fig. 4).
Resulting currents exchanged between the turbine, diesel and load are presented in Figure 3.
After the implementation of an efficient strategy of transfer of energy in a hybrid system across a DC bus, we introduce a method of sizing of the storage units based on simulation results.

Simulation results

In our study case, battery allocated band is assumed to be between 0.0013Hz and 0.02 Hz. Lower frequencies are devoted to the diesel engine compensation, high frequencies to the flywheel one, and higher frequencies to the capacitors. Wind turbine is controlled to operate at maximum power point all the time.
Figure 10 shows the spectra of electricity produced by wind and the load divided into four frequency bands supported by diesel, battery, flywheel and capacitors. There is a wide swath of high-frequency; very high frequencies do not appear because of their very low magnitude. The flywheel sizing requires quantification of energy resulting from such wide fluctuations to ensure stability of the bus voltage and energy availability on load side.

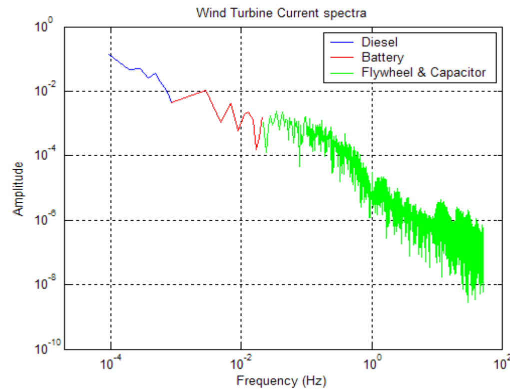

Fig.10. wind turbine current spectrum

Equations (19) and (20) are used to calculate battery and flywheel exchanged energy that are presented respectively in figure 11 and 12 for 2h simulation of system operation considered as wind turbine period. Most important consideration is that the energy level at the beginning and at the end of assumed period is the same.

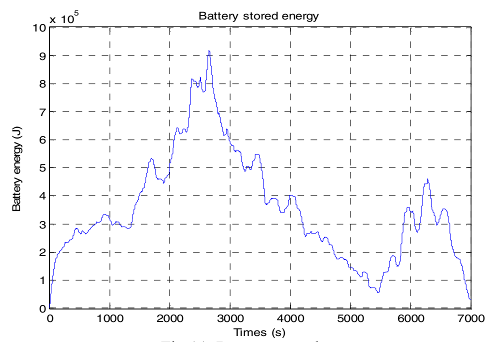

Fig.11. Battery stored energy

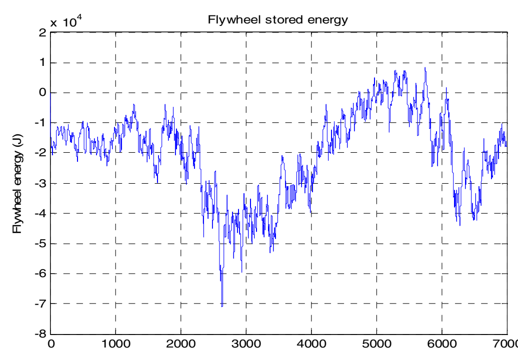

Fig.12. Flywheel stored energy

With used wind velocity profile, required storage devices capacities are presented by table 1.

TABLE 3.
Storage units capacities.

	Battery	Flywheel ($0.5kgm^2$)	Capacitor (35mF)
Capacity (Ah)	53	10	0.0283

The allocation of frequency assignments of storage devices aims to optimize their lifetime.
The power resulting from the battery (Fig. 13) is simulated in the Umass model and the lifetime is estimated to 4.3129 years.

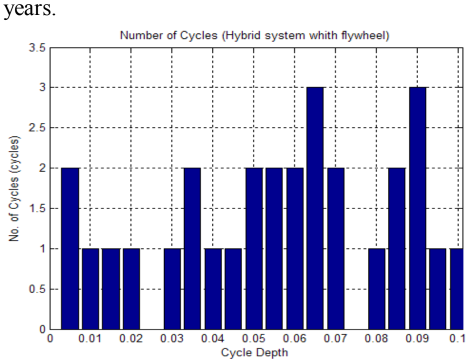

Fig.14. Battery number of cycles (Hybrid system with flywheel)

Differently from the previous case "without flywheel" the battery is characterized by a smaller number of partial energy cycles with larger amplitudes (Fig. 14), multiplying the battery lifetime by four (4).
Thus, the battery lifetime is affected by the number and magnitude of partial cycles. Large number of cycles and small amplitudes reduce battery lifetime.

VIII. Conclusion

Energy management strategy presented in this study gives the opportunity of discussion on energy storage units sizing procedure. It has been demonstrated the interest of the use of flywheel to increase the lifetime of the battery which is known to be affected by the magnitude and the number of partial cycles of charges and discharges.

We have considered a hybrid system including diesel engine, wind turbine, flywheel, battery, and capacitor with DC point of common coupling. To emphasis the smoothing effect of the wind disturbances, the measurement of the current is a rather original step of management of the transfer of energy and compensation of fluctuations in such a system. Despite its effectiveness, this method includes some limitations which will be analyzed in a next future study. The main subject will be the examination of uncertainties on the evaluation of periodicities and the selectivity of frequency bands of the filter tied to experimental dynamics of devices.

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