ENERGY MANAGEMENT AND BATTERIES LIFESPAN ESTIMATION IN A PHOTOVOLTAÏC SYSTEM WITH HYBRID STORAGE A COMPARATIVE STUDY

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***Abstract* – In this paper, a photovoltaic system with hybrid storage connected to the grid has been studied. A smart supervision algorithm based on fuzzy logic has been successfully developed. In addition, a comparative study of different hybrid storage possibilities in terms of batteries longevity has been done using rain-flow cumulative damage method.**

***Keywords* – PHOTOVOLTAIC SYSTEM, HYBRID STORAGE, ENERGY MANAGEMENT, BATTERIES LIFESPAN, RAINFLOW METHOD.**

I. INTRODUCTION

The Energy productions from renewable energy sources such as photovoltaic generators are characterized by uncertainty and intermittence. They are greatly influenced by meteorological conditions. Thus, to ensure good stability of the electric network, it is necessary to store part of the produced energy. In fact, there are several methods of storage: potential form (STEP), kinetic (flywheel), hydrogen, in an electrochemical battery (lead, lithium) or a super-capacitor [1-3].

Currently, there are several companies that sell storage solutions for network support or future integration into smart grids, such as:

- Li-ion batteries containers (Saft, Mitsubishi Heavy Industries),
- Batteries Sodium-Sulfur (NaS) (NGK),
- Hydrogen production and storage systems (CETH2 and McPhy),
- Flywheel systems (Vycon, Beacon Power),
- Super-capacitors containers (Maxwell).

However, It is rare at the moment a system dedicated to electricity network and combining these various technologies; these systems staying at the moment in development.

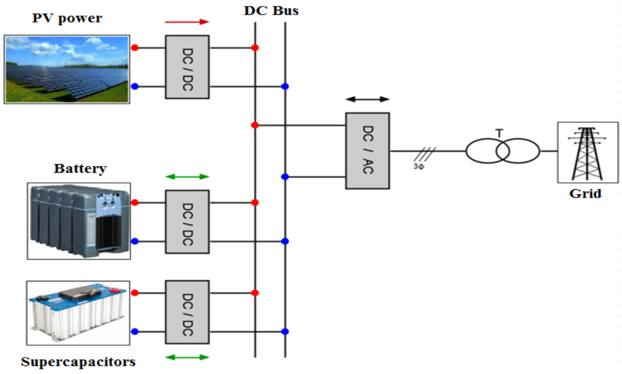
From an academic perspective, there are several works that are interested in coupling batteries and super-capacitors in particular in embedded applications [2]. We also find applications for photovoltaic systems [4-8]. For example in [7 and 8], authors propose a systematic control strategy for grid-friendly photovoltaic systems that comprise PV arrays, lead acid battery, super-capacitor, DC/DC and DC/AC power converters. The objective consists on supplying prescribed reactive and active power to the grid. However, works that combine other types of storage are rare [9-11].

In this paper, we have studied a photovoltaic system with hybrid storage. We focused on optimal system energy management using fuzzy logic and on batteries lifespan using rain-flow method for different storage combinations (batteries lithium NCA with Batteries NiMH or Li Fe PO4 or capacitors).

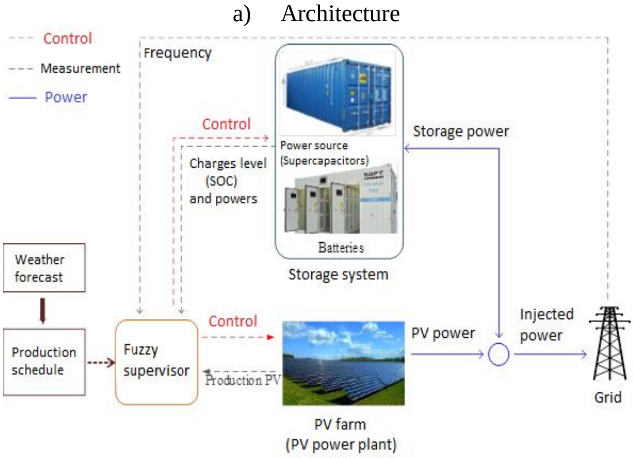
II. STUDIED PHOTVOLTAIC SYSTEM DESCRIPTION

Figure 1 presents a synopsis of the studied photovoltaic power plant and the critical role of the supervisor in the management system. Storage station is based on combination of two complementary technologies: a source of power storage (batteries NiMH or Li Fe PO4 or super-capacitors) and a source of energy storage (lithium batteries NCA with high specific energy). The main purpose of adding a source of power storage is to smooth the power flow in case of intermittency of photovoltaic source and to increase the lifetime of the energy storage one.

Energy management is made with a multi-step fuzzy logic methodology as described is [12] and [13]. It ensure several objectives at once (constraints and network services, storage levels and availability, lifespan and aging, etc.).In our case, flow management is intend to satisfy Day-1 production planning, to participate in frequency support and to protect storage elements monitoring their state of charge.



a) Architecture



b) Management structure

Fig. 1. Block diagram of the studied system

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Table I outlines Operating specifications for fuzzy logic based supervisor:

Table I: Supervisor operating specifications

Objectives	Constraints	Actions
. Meet a production schedule ensuring injected power smoothness. . Participate in frequency support (primary and secondary supports). . Improve storage elements life by optimizing their management.	. PV production intermittency (amplitude and duration variations). . Storage elements size . Primary support in less than 500sec for 15 minutes. Response in less than 15 minutes for 30 minutes in case of secondary support. (Error of 0.5% with respect to the basic frequency 50 Hz). . The error on the production schedule : - Error margin on the production schedule: less than 10 % in middle hourly energy of the power plant compared with production program. Beyond this constraint, there is a risk that the photovoltaic producer loses his hour of production. - In case of excess or lack of energy injected according to that suited to Day-1 with the network administrator, the hour of production is lost.	. Two power storage references: - long-term (batteries), - short-term (power source: example: super-capacitors). . Degradation factor of photovoltaic production.

The block diagram of the fuzzy supervisor is shown in Figure 2.

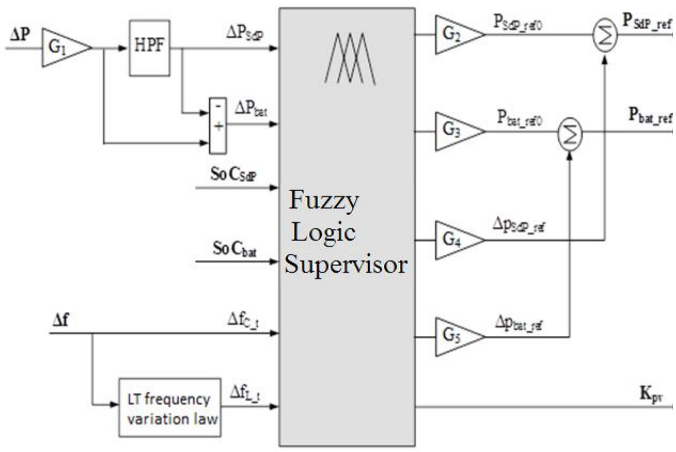


Fig.2. Block diagram of the fuzzy supervisor

$\boldsymbol{\Delta P}$: Difference between planned and actual photovoltaic power production.

$\boldsymbol{\Delta P_{bat}}$ and $\boldsymbol{\Delta P_{SdP}}$: respectively batteries and super-capacitors powers after filter separation.

$\boldsymbol{SOC_{bat}}$ and $\boldsymbol{SOC_{SdP}}$: respectively batteries and super-capacitors State Of Charge.

$\boldsymbol{\Delta f}$: Frequency variation with $\boldsymbol{\Delta f_{C\_t}}$ for short term variations and $\boldsymbol{\Delta f_{L\_t}}$ for long term ones.

$\boldsymbol{P_{bat\_ref}}$: Batteries reference power. It is the sum of two sub-outputs, initial reference $\boldsymbol{P_{bat\_ref0}}$ and secondary support power frequency $\boldsymbol{\Delta p_{bat\_ref}}$.

$\boldsymbol{P_{SdP\_ref}}$: Storage power source (super-capacitors) reference. It is the sum of two sub-outputs, initial reference P_{SdP_ref0} and primary support power frequency$\boldsymbol{\Delta p_{SdP_ref}}$.

$\boldsymbol{G_{i=1:5}}$: Normalization gains. **HPF**: high pass filter (first-order filter). **K_{pv}**: PV production degradation factor.

As described in [13], supervision strategy is based on three modes:

Normal or main mode (N1): The SOC is medium or nominal (SOC_M) and the first aim of this mode is to meet the production program planned at day-1. The storage system has to fill the gap between the instantaneous power and photovoltaic production planned in day-1 while maintaining the functionality of power smoothing and frequency support.

Overcharge mode (N2): This mode is dedicated to protecting storage system against the harmful effect of an overcharge on their lifespan. The principle is to minimize photovoltaic generation to discharge the storage elements until their nominal value.

Deep discharge mode (N3): This mode is dedicated to protecting storage system against the harmful effects of deep discharge on their lifespan. The principle is to guarantee storage capacity by well preparing storage elements to production program. Ideally charge storage organs until their nominal value. Charge may be provided by photovoltaic production on the same day before beginning the production program (e.g. in a summer day) or directly from recharging via the grid.

III. BATTERIES LIFESPAN ESTIMATION : PRINCIPLE OF BATTERIES DETERIORATION CALCULATING

To quantify the total damage produced by different storage elements charge-discharge cycles, we use the cumulative law proposed by Miner [14] as described in [15] and [16]. It is defined as follows:

$$\boldsymbol{D = \sum_{i=1}^{N} \frac{n_i}{N_i}} \qquad (\mathbf{1})$$

Where n_i : cycles number at amplitude DoD_i.

N_i : Lifespan cycles at amplitude DoD_i.

Thus, this factor allows us to assess storage elements lifespan for a degradation D limited to 70% in order to take into account calendar aging and estimation uncertainty. Figure 3 shows the principle of batteries cumulative degradation calculation.

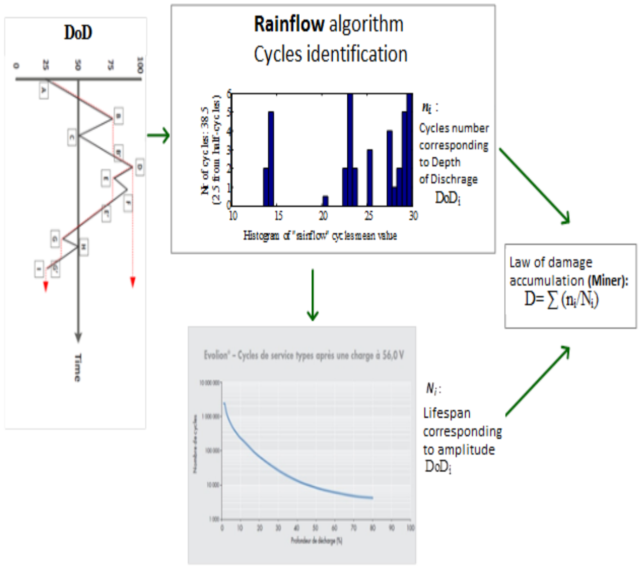
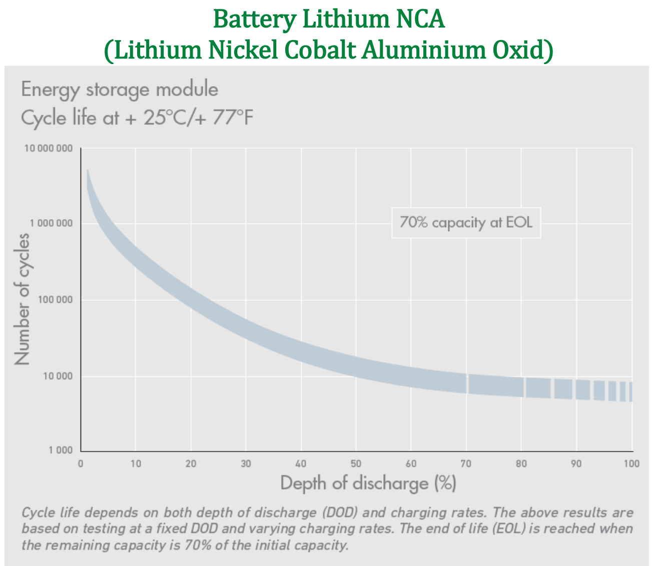
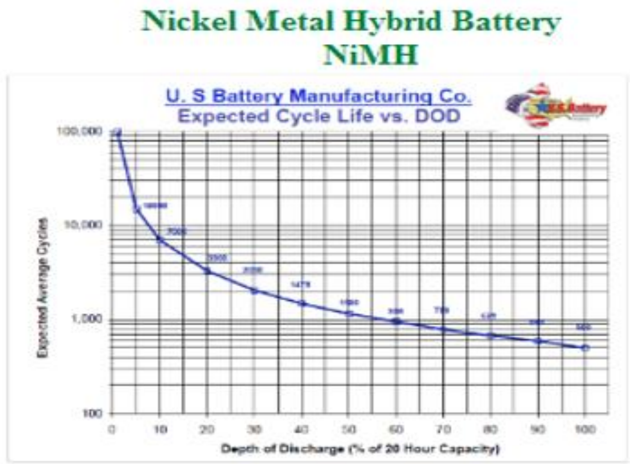


Fig. 3. Principle of batteries deterioration calculating.

This method relies on two steps. The first step is the use of a cycle counting algorithm (Rainflow) that precisely identifies the parameters of a battery lifespan (number of cycles, deep cycles, standard cycles (complete or half cycles) and the periods of the cycles). The second step consists on using the aging curve of the storage component to identify its lifespan according to the respective cycles depths found in the first step.

Figure 4 shows the aging curves of the various storage elements used in this work. Their data were extracted and interpolated with fixed-point 1-D interpolation (table lookup, “fixpt_interp1” function) under Matlab.





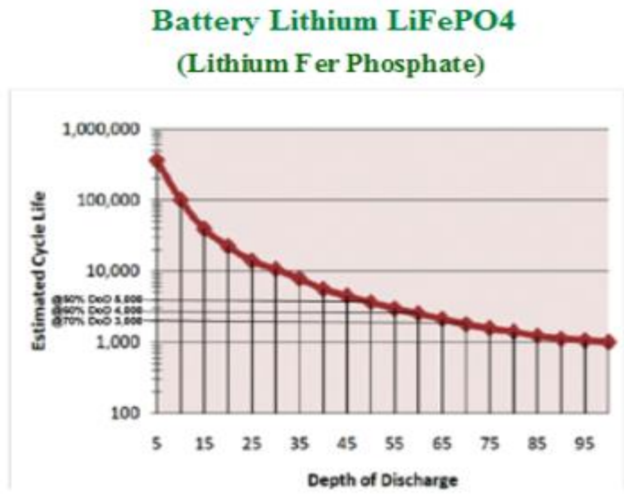


Fig. 4. Aging curves of the different storage elements used in this work.

IV.RESULTS

This section is divided into two parts whose objectives are:
- developed supervision strategy validation by simulation;
- analysis of different storage combinations in terms of batteries durability.

Scenarios of photovoltaic generated and planned power correspond to forecasts at (Day – 1) in a real site for year 2013. These data are collected on an hourly average. Realistic month profiles are considered with some modifications to incorporate effects of sudden weather changes as shown in figure 5.

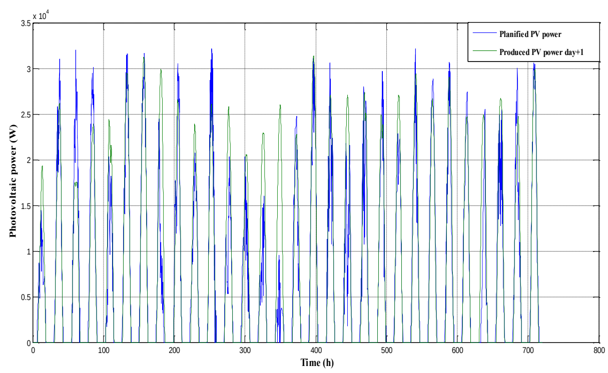


Fig. 5. Evolution of photovoltaic plant powers during 1 month.

A. Supervisor validation

Simulations are done according to these powers:
Photovoltaic source peak power: 30 kW.
Nominal NCA lithium batteries power (energy storage source): 6 kW (max power 8 KW).
Nominal power for storage power source (super-capacitors): 5kW (max power 9 KW) as transient peaks does not exceed the maximum power of 9 KW and for cost reasons.

Figure 6 shows the evolution of storage power to meet production schedule for a week. Figure 7 distinguishes the response of the two storage units. Figure 8 shows the percentage of error on production program satisfaction (MAPE score evaluated every 30 minutes). It remains below 10 % for studied case. Figure 9 shows that network support function reduces frequency variations amplitude.

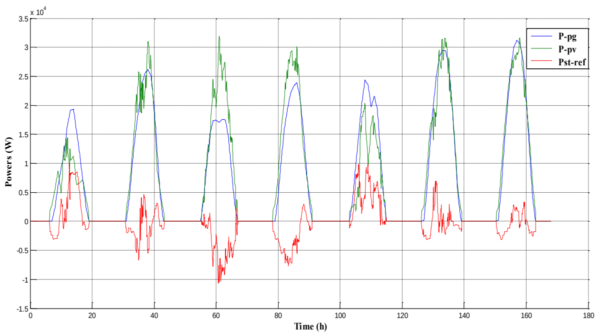


Fig.6. Evolution of PV power plant powers on a week (30 KW PV+ 6 KW of batteries + 5 KW of super-capacitors)

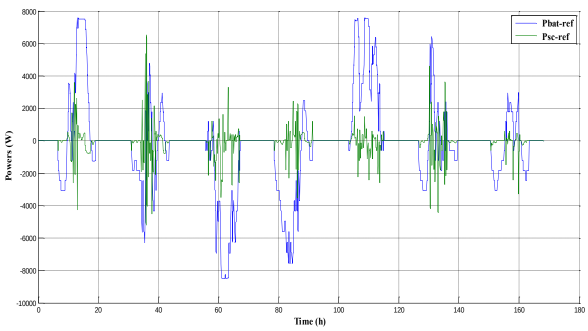


Fig. 7. Complementary operation between NCA lithium batteries and super-capacitors power storage source.

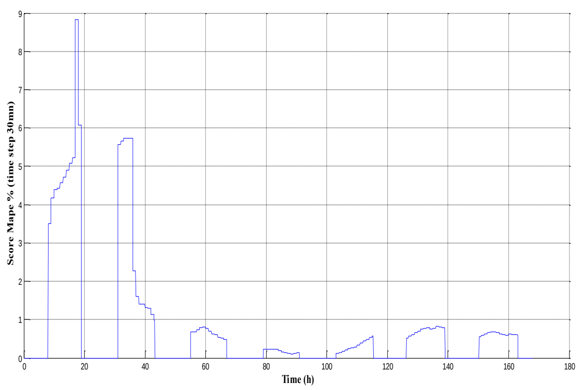


Fig. 8. Percentage of error on production program satisfaction (MAPE score evaluated every 30 minutes).

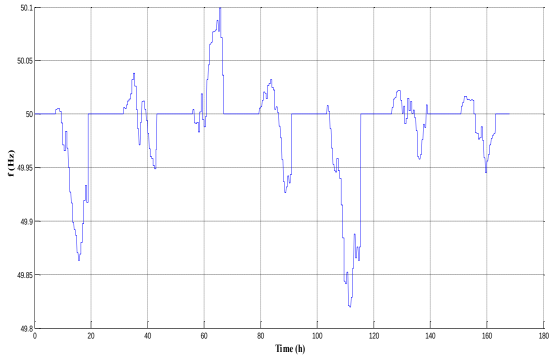


Fig. 9. Evolution of frequency every 15 minutes.

B. Storage elements lifespan assessment

To analyze the contribution of two-storage technologies combination, we propose to estimate storage system lifespan using the cumulative damage law along both configurations:

- Batteries Lithium NCA in combination with different power storage sources :
  - Batteries NiMH;
  - Batteries Lithium Li Fe PO_4;
  - SuperCaps Maxwell.

Powers: Batteries Lithium NCA of 6 kW, 7.5 KW, 15 KW and 22.5 KW and power storage source of 5 KW (max power 9 KW) as transient peaks does not exceed the maximum power of 9 KW and for cost reasons. The peak power of the photovoltaic system is 30 kW.

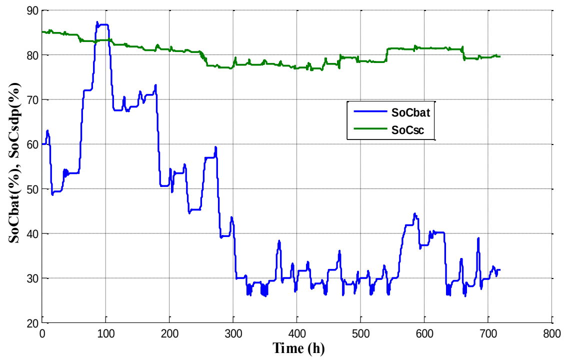
- Batteries lithium NCA only : 6 kW, 7.5 KW, 15 KW and 22.5 KW

The peak power of the photovoltaic system is 30 kW.
For this purpose, we consider the realistic scenario of a month of produced and planned photovoltaic power with irregularities as shown in Figure 5.
Figure 10 shows the evolution of the state of charge levels of lithium batteries NCA and power storage source for the two extreme cases.
When estimating storage studied elements lifespan, we initially find the number of cycles within different states of charge by the Rainflow algorithm. Figures 11 (a) and 11 (b) show the number of cycles corresponding to depths of Discharge $\boldsymbol{DoD_i}$ made respectively by lithium batteries NCA 6 kW and the power storage source 5 kW. Note that the power storage sources listed above (Batteries NiMH, Batteries Lithium Li Fe PO4, SuperCaps Maxwell, etc.) are assumed to have the same state of charge $\boldsymbol{SOC_{SdP}}$.
Secondly, using the damage cumulative law defined in equation (1) we can calculate the rate of degradation caused by different cycles. Thus, Table 2 summarizes the estimated useful lives.
Results shows that :

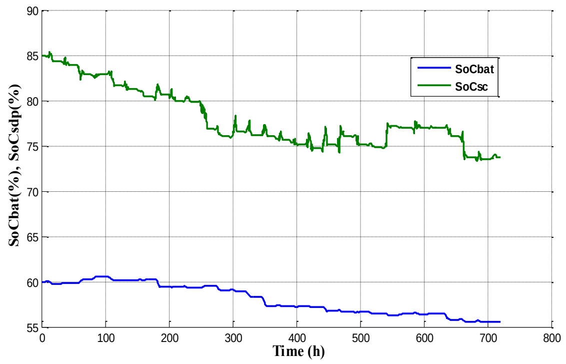
- System sizing is crucial. It influences batteries life time and frequency regulation. There must be installed a few rapid storage power for peaks and lots of batteries.
- The life of the power source decreases slightly by increasing batteries power because of more frequency regulation with primary support (refer to

period (hours / month) of tolerated frequency error (0.5%) violation in table II).

- The increase in batteries power smooths their charge discharge curve and consequently decreases their DoD thus improves their durability.
- Adding a power storage source to absorb the peaks improves batteries life but it may be better to oversize batteries than make hybridization. Unless, there must be installed a few rapid storage power for peaks and lots of batteries.
- According to the table II, to have a good frequency adjustment with respect of the production program, a power storage> = 50% installed PV power must be used.
- Batteries NIMH are not adequate for hybridization. They have a very short lifespan.
- Batteries FePO4 and super-capacitors are recommanded for hybridization. However, they have totally different lifespans and costs, so a life cycle cost analysis should be made to help designers in their choice.
- To ensure maximum battery lifespan, it is recommended to maintain its state of charge of around 60% (DoD around 40%).
- The comparative table II can be considered as a design aid tool. For example, we can opt for a system of 30 KW PV, 15 KW Batteries, 5 KW supercap. The final choice of course will require a rigorous analysis of the life cycle cost of the chosen solution.

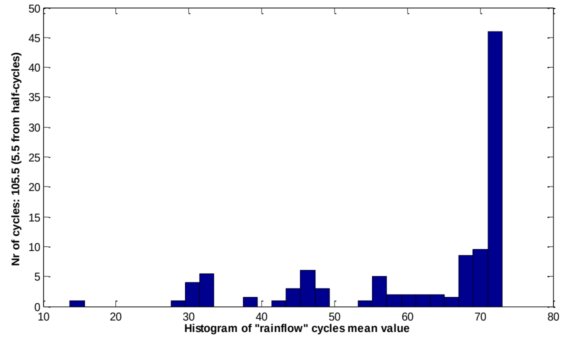


(a)

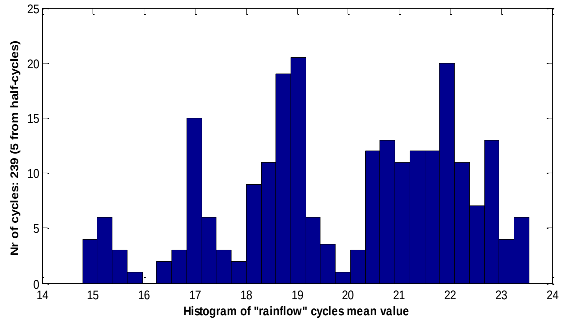


(b)

Fig. 10. Evolution of SoC level: (a) batteries lithium NCA 6 kW and power storage source 5 kW; (b) batteries lithium NCA 22.5 kW and power storage source 5 kW.



a) Number of batteries cycles vs DoD_i : batteries lithium NCA 6 KW



b) Number of batteries cycles vs DoD_i : storage power source 5 kW

Fig. 11. Number of batteries cycles vs DoD_i : (a) batteries lithium NCA 6 kW ; (b) power storage source 5 kW.

C. Conclusion

This work concerns a photovoltaic system that combines two storage technologies (one for energy needs NCA batteries and another for power needs NiMH or Li Fe PO4 batteries or SuperCaps Maxwell). A smart supervision algorithm based on fuzzy logic has been successfully developed. Simulations show that it achieves the desired objectives in terms of compliance with production program while respecting the various constraints of electric grid manager.

In addition, a comparative study of different storage configurations especially in terms of storage components lifspan has been carried out. It shows that:

- The pooling of power between storage batteries and fast storage component has an effect in batteries lifetimes. Adding a power storage source to absorb the peaks improves batteries life but it may be better to oversize batteries than make hybridization. Unless, there must be installed a few rapid storage power for peaks and lots of batteries.
- The use of super-capacitors or lithium Li Fe PO4 batteries as a power source in combination with lithium batteries (NCA energy source) appears as the most reasonable choice in terms of lifespan.
- System sizing is crucial. It influences batteries life time and frequency regulation.
- An optimal design with analysis of the life cycle cost is highly recommended.
- Finally, the results depend strongly on the photovoltaic production profile and the quality of forecasts. They should be taken with great care.

In our future work, we propose to validate the developed energy management fuzzy logic method on a test bench with a realistic reproduction in terms of powers and emulation time. We also propose to focus on the optimal design of the system taking into account the satisfaction of grid constraints in addition to life cycle economic costs and levelized cost of energy.

TABLE II
Comparative table of the different storage technologies lifespan for various hybridization scenarios

Batteries power (KW)	**Power storage sources (KW)**	**Period (hours / month) of tolerated frequency error (0.5%) violation**	**Battery Lifespan (years) (70% degrada-tion)**	**Storage source lifespan (years) (70% degradation)**
6	**0**	**56.6**	**4.9**	-------
7.5	**0**	**49.14**	**5**	-------
15	**0**	**1.5**	**11**	--------
22.5	**0**	**0**	**22.4**	--------
6	**5**	**53.6**	**5.5**	**Bat. NIMH : 0.9** **Bat. FePO4 : 6.2** **Supercap : > 25 [17]**
7.5	**5**	**44.6**	**6**	**Bat. NIMH : 0.9** **Bat. FePO4 : 6.1** **Supercap : > 25**
15	**5**	**2.5**	**13.6**	**Bat. NIMH : 0.8** **Bat. FePO4 : 5.4** **Supercap : > 25**
22.5	**5**	**0**	**25**	**Bat. NIMH : 0.8** **Bat. FePO4 : 5.1** **Supercap : > 25**

ACKNOLEDGEMENTS

The Autors want to thank the pole MEDEE in region Nord Pas De Calais, France for its finacial support.

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