Hybridization of electrical energy storage for intelligent integration of photovoltaics in electric networks

Azeddine Houari*, Dhaker Abbes*, Antoine Labrunie**, Benoit Robyns*

* L2EP, HEI, 13 Rue de Toul, 59800, Lille Cedex France
** GB SOLAR, 25-27 rue de la Clef - 75005 PARIS Cedex France
E-mail : dhaker.abbes@hei.fr

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Keywords

« Photovoltaic System », « Hybrid Storage », « Energy Management », « Batteries Lifespan», « Rainflow Method ».

Abstract

In this paper, a photovoltaic system with super capacitors and batteries hybrid storage connected to the grid has been studied. A smart supervision algorithm based on fuzzy logic has been successfully developed. In addition, contribution of storage hybridization on batteries longevity has been proved using rain-flow cumulative damage method.

Introduction

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 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),
- Supercapacitors 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 [4-6]. However, works that combine other types of storage are rare [7-9].
In this paper, we have studied a photovoltaic system with super capacitors and batteries hybrid storage. We focussed on optimal system energy management using fuzzy logic and we proved the benefit of hybridization on batteries lifespan using rain-flow method.

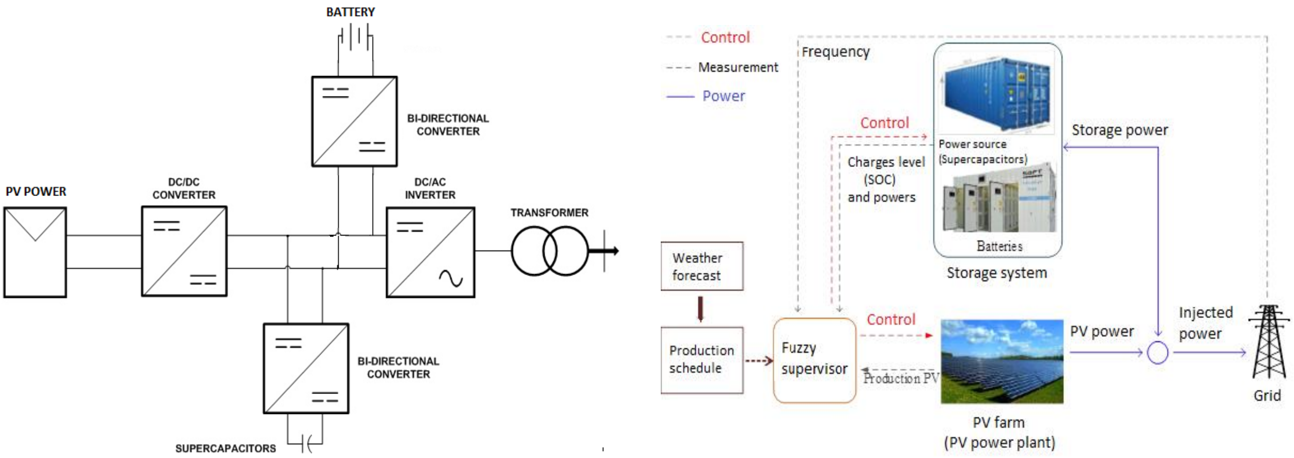
1. Studied Photovoltaic system description

Figure 1 presents a synopsis of the photovoltaic power plant studied 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 (super-capacitors) and a source of energy storage (lithium batteries with high specific energy). The main purpose of adding a source of power storage is to increase the lifetime of the energy storage one.

2. Fuzzy logic supervisor

Energy management for electrical energy storage is an important topic of research, particularly in multisource systems that combine random and difficult sources to predict such as photovoltaics renewable energy. In fact, in addition to the need for real-time management incorporating unpredictability production, management have to ensure several objectives at once (constraints and network services, storage levels and availability, lifespan and aging, etc.) [10].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.

Supervisor construction is based on a multi-step methodology with fuzzy logic as described in [11]. Fuzzy logic is suitable to manage complex hybrid energy sources with multi-objective supervision and many scenarios to test, as it is difficult to obtain and use precise models, or to predict behavior of sun, as well as load consumptions.



a) Architecture

b) Management structure

Fig.1. Block diagram of the studied system

A. Operating Specifications

Operating specifications for fuzzy logic based supervisor are summarized in Table I.

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. . The error on the production schedule : - Error margin on the production schedule : Less than 10 % in hourly energy of the power plant compared with production program. Beyond this constraint, there is a risk that	. Two power storage references: - long-term (batteries), - short-term (power source: super-capacitors). . Degradation factor of photovoltaic production.

	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.	

B. Supervisor structure and inputs outputs determination

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

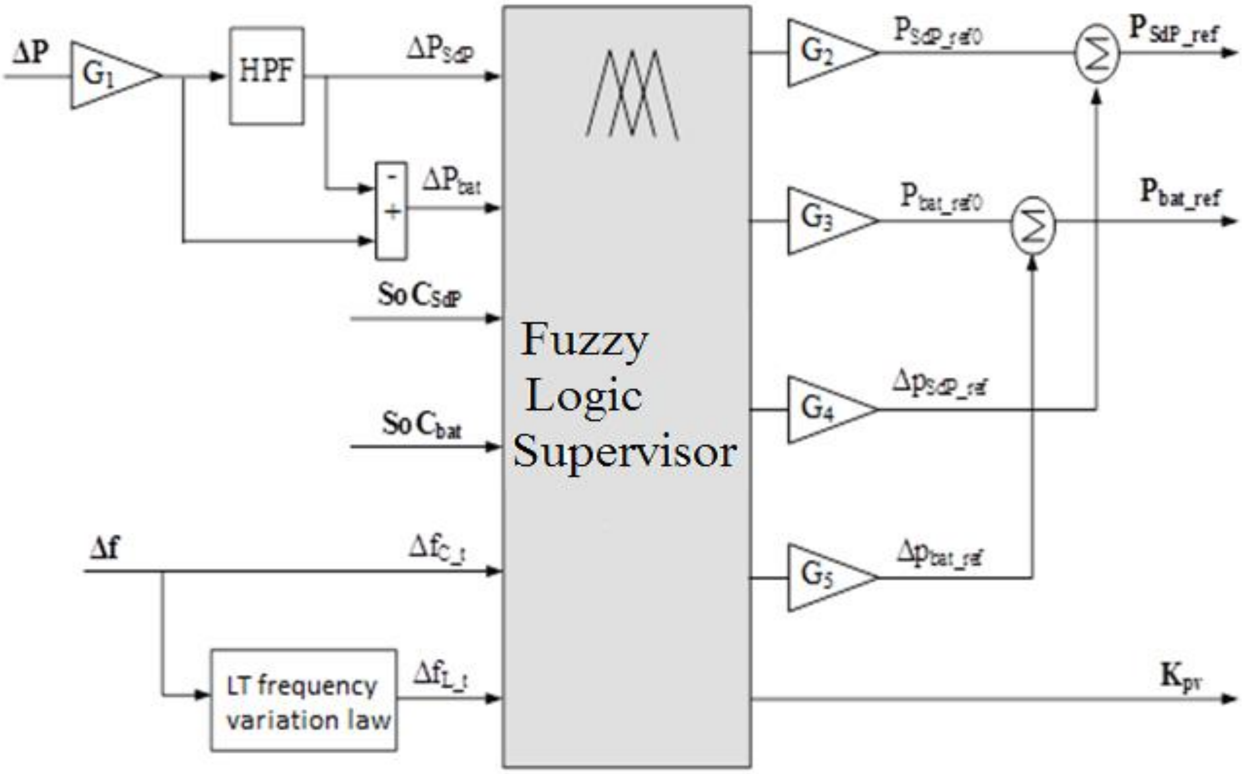


Fig.2. Block diagram of the fuzzy supervisor

$\boldsymbol{\Delta P}$: 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). $\mathbf{K_{pv}}$: PV production degradation factor.

C. Operating modes (functional graphs)

Figure 3 summarizes the functional graph of the system and the various sub-graphs detailing the principle of the three main modes of operation:
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.

D. Memberships functions

This step consists on defining the numerical values of fuzzy inputs (fuzzification) considered in figure 2 in function of objectives, constraints and system specifications (figure 4).

Linguistic fuzzy states notations:

L: Low, M: Medium, H: High, Z: Zero, P: positive (positive), N: negative.

E. Fuzzy Modes (operational graphs)

This step consists on translating and developing the functional graphs with the membership functions. Figure 5 shows all operational graphs in the three modes of operation defined above.

F. Performance indicators

Performance indicators are designed to measure developed supervisor effectiveness. Following management objectives, we propose two indicators respectively dedicated to measure planned production satisfaction and frequency support efficiency.

• Indicator of program production satisfaction: This indicator is based on the MAPE score evaluated each 30 minutes with the formula:

$$M = \frac{100}{n} \sum_{t=0}^{n} \frac{\left| E_{inj} - E_{pg} \right|}{E_{pg}} \tag{1}$$

E_{inj} : injected 30 min energy to the grid and E_{pg} planned production.

• Indicator of frequency changes: This indicator is based on calculating the average of frequency change in 15 minutes: $\frac{1}{T} \sum_{t=0}^{T} \left| \Delta f_{C\_t} \right|$.

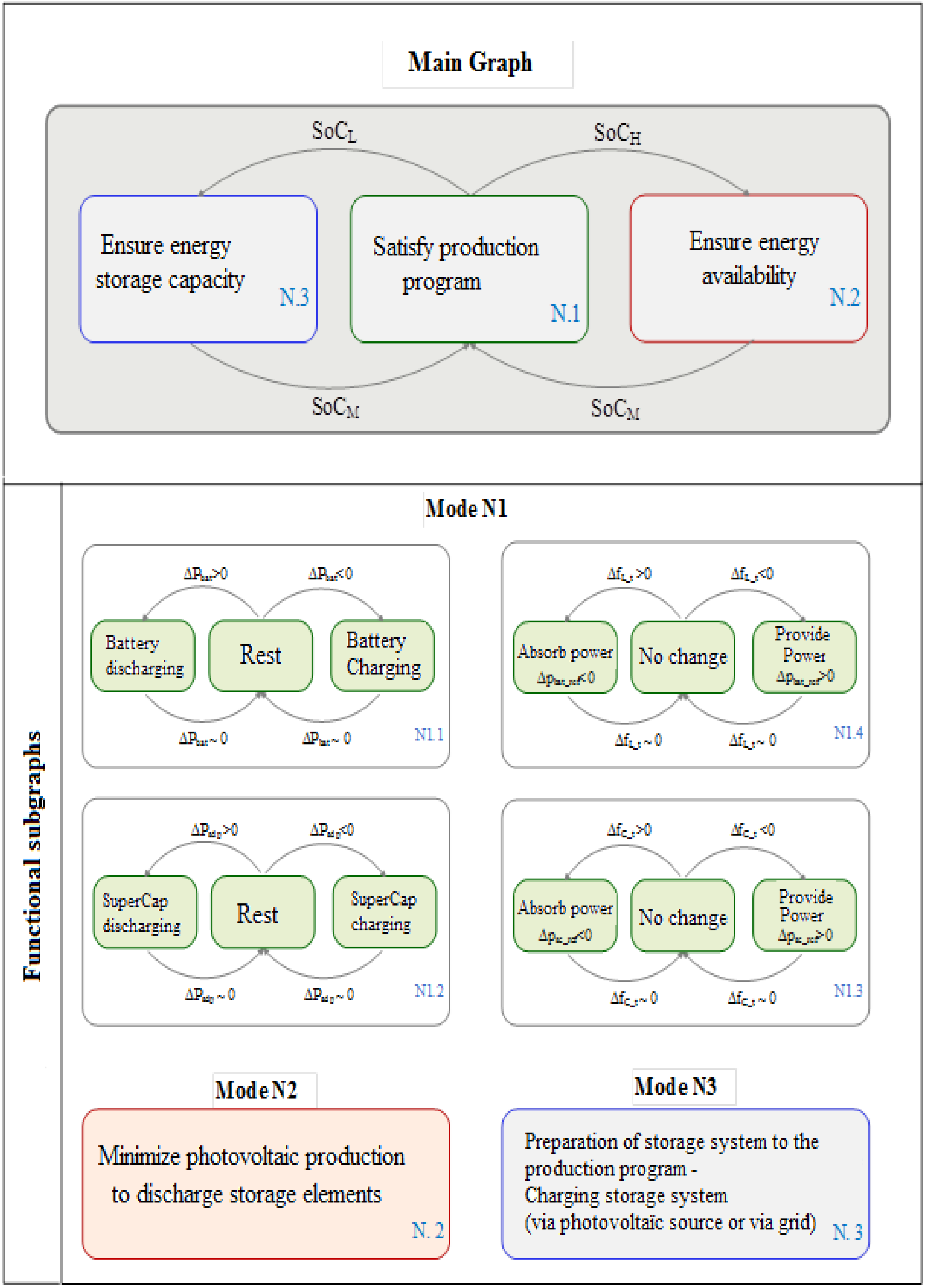


Fig.3. Block diagrams of the studied system

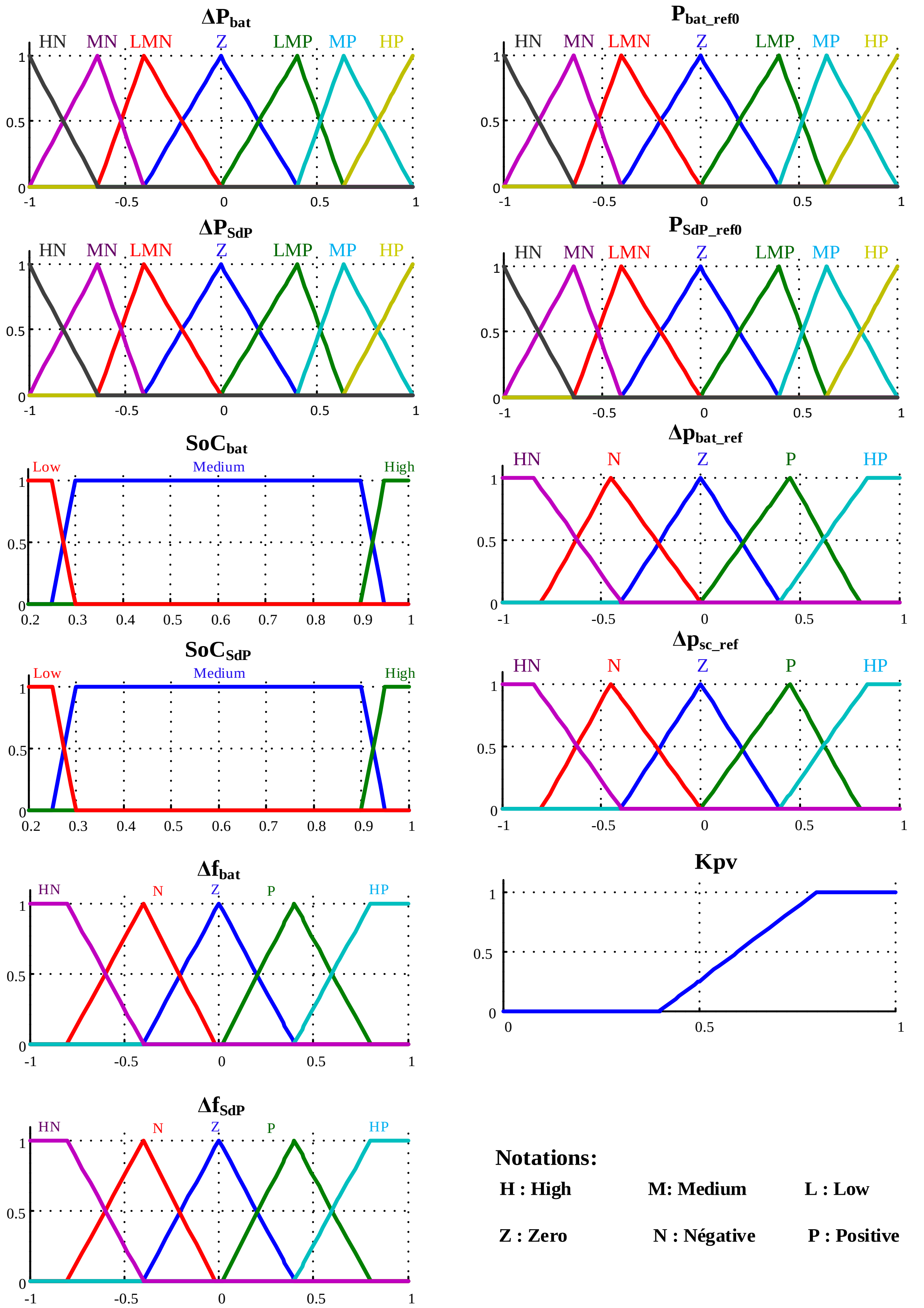


Fig.4. Membership functions associated with the direct various inputs and outputs of the supervisor

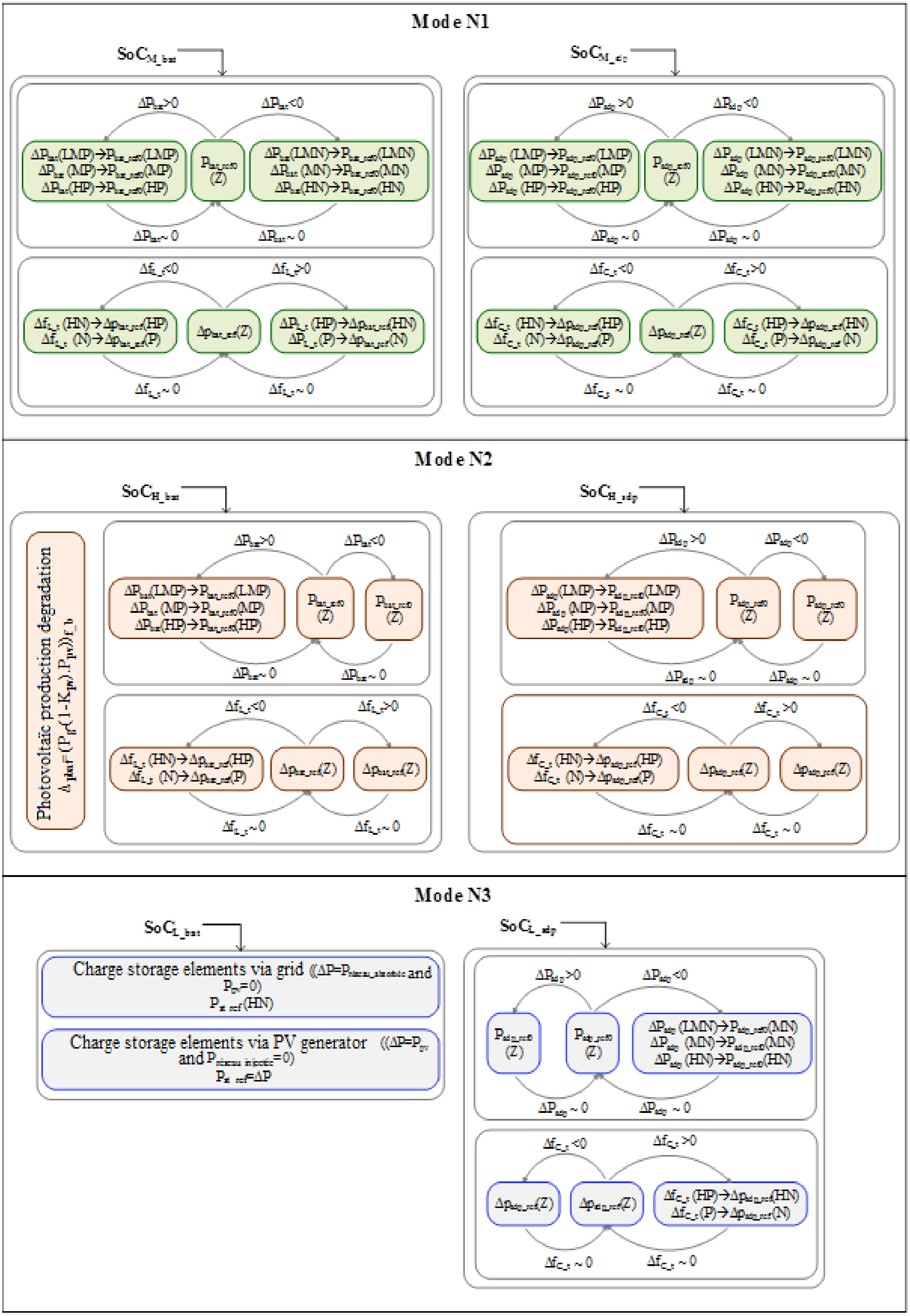


Fig.5. Operational grpahs

3. Principle of batteries deterioration calculating

To quantify the total damage produced by different storage elements charge-discharges cycles, we use the cumulative law proposed by Miner [13-14]. It is defined as follows:

$$D = \sum_{i=1}^{N} \frac{n_i}{N_i} \qquad (2)$$

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 equal to 80%. Figure 6 shows the principle of batteries cumulative degradation calculation.

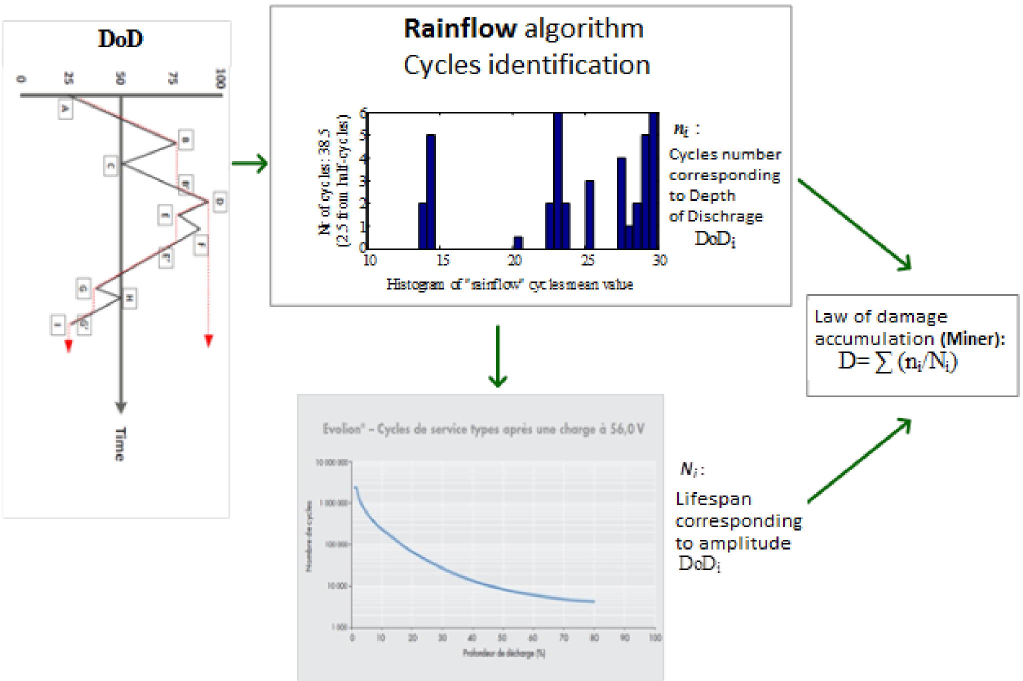


Fig. 6. Principle of batteries deterioration calculating

4. Results

This section is divided into two parts whose objectives are:
- developed supervision strategy validation by simulation;
- showing the contribution of storage hybridization on batteries durability.

Simulations are done according to these powers:

- Photovoltaic source peak power: 30 kW.
- Nominal NCA lithium batteries power (energy storage source): 6 kW.
- Nominal power for storage power source (super-capacitors): 5kW.

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. It should be noted that photovoltaic production profiles are modified to incorporate effects of sudden weather changes.

A. Supervisor validation

Figure 7 shows the evolution of storage power to meet production schedule. Figure 8 distinguishes the response of the two storage units. Figure 9 shows the percentage of error on production program satisfaction (MAPE score evaluated every 30 minutes). It remains below 0.8% for studied case. Figure 10 shows that network support function reduces frequency variations amplitude.

B. Storage elements lifespan assessment

According to results found by damage accumulation method (Table 2), it is clear that the addition of a source of power storage (super-capacitors) allows increasing the longevity of lithium batteries NCA (source of energy).

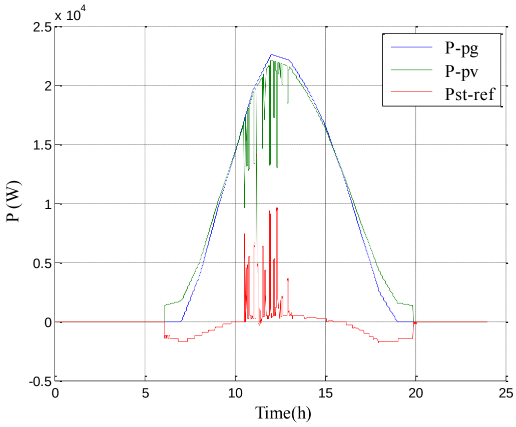


Fig. 7. Evolution of PV power plant powers on a day.

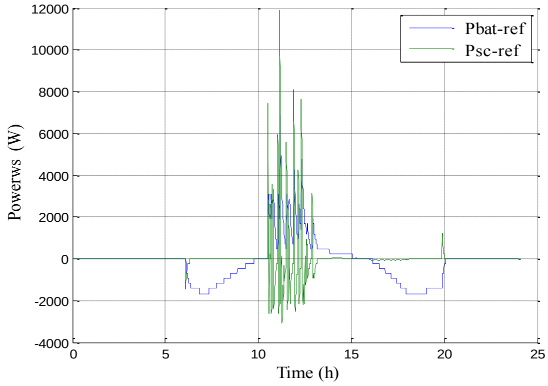


Fig. 8. Complementary operation between NCA lithium batteries and super-capacitors power storage source.

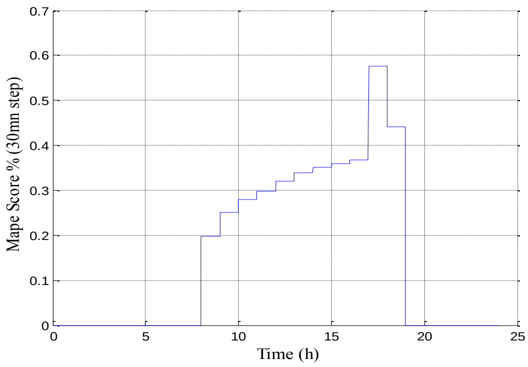


Fig. 9. Percentage of error on production program satisfaction (MAPE score evaluated every 30 minutes).

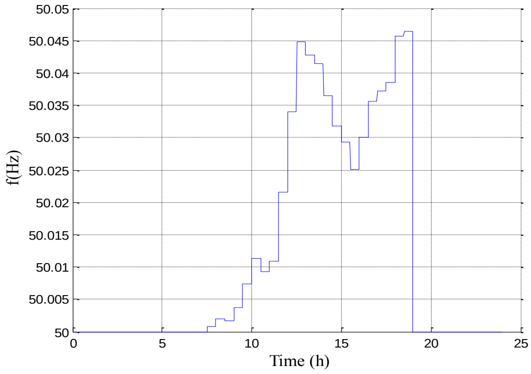


Fig. 10. Evolution of frequency every 15 minutes.

Table II: Comparison of storage elements Lifespan for different without and with super-capacitors

			Lifetime (years)	Lifetime (number of cycles)
Only energy storage source	**Batteries Lithium NCA (6 kW)**		**12.5**	**3825**
Hybrid storage (Energy and power sources)	**Energy source : Batteries Lithium NCA (6 kW)**		**25**	**6750**
	Power source : SuperCaps Maxwells (5kW)	**Batteries NCA 6 kW**	**> 25**	**>10^6 for a DoD of 80% [13]**

Conclusion

This work concerns the development of a management algorithm for a photovoltaic system that combines two storage technologies (NCA Lithium batteries and super-capacitors). Simulations show that developed algorithm achieves the desired objectives in terms of compliance with production program while respecting the various constraints of network manager. Furthermore, analysis of batteries lifespan proves that combination of batteries with super-capacitors enables to increase their longevity.

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