

# SESSION 1

Chairman Robin ROCHE, FEMTO-ST FCLab

1. Impacts of SCs on battery lifetime in HESS on DC Microgrids in BiPV, M. Gaetani-Liseo C. Alonso, B. Jammes, LAAS-CNRS, Univ. Toulouse III
2. Battery voltage increase based on DC/DC converters in parallel association, JP. Sawicki, P. Petit, F. Maufay, M. Aillerie, LMOPS-EA 4423, Univ. de Lorraine et CentraleSupélec
3. Variable speed diesel -PV power generation for micro micro-grid applications, M.M.G. Lawan, J. Raharijaona, M.B. Camara, B. Dakyo, GREAH Univ. du Havre-Normandie
4. Impacts of demand side management strategies application on a marine energies based multi-source system, A. Roy, F. Auger, S. Bourguet, F. Dupriez-Robin, Quoc Tuan Tran, IREENA – Univ. de Nantes, CEA-Tech Pays de la Loire, INES CEA-LITEN/DTS/LSEI
5. Energy management system for a grid-connected wind farm and battery storage hybrid plant via MPC strategy, A. Aguilera-Gonzalez, R. Lopez-Rodriguez, I. Vechiu, ESTIA, Grenoble Institute of Technology
6. Energy management in a DC/DC resonant converters-based battery/supercapacitor hybrid system, M. Arazi, A. Payman, M. Camara, B. Dakyo, GREAH Université du Havre-Normandie

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# Impacts of Super-Capacitors on battery lifetime in hybrid energy storage system on LVDC MG in Building integrated PV

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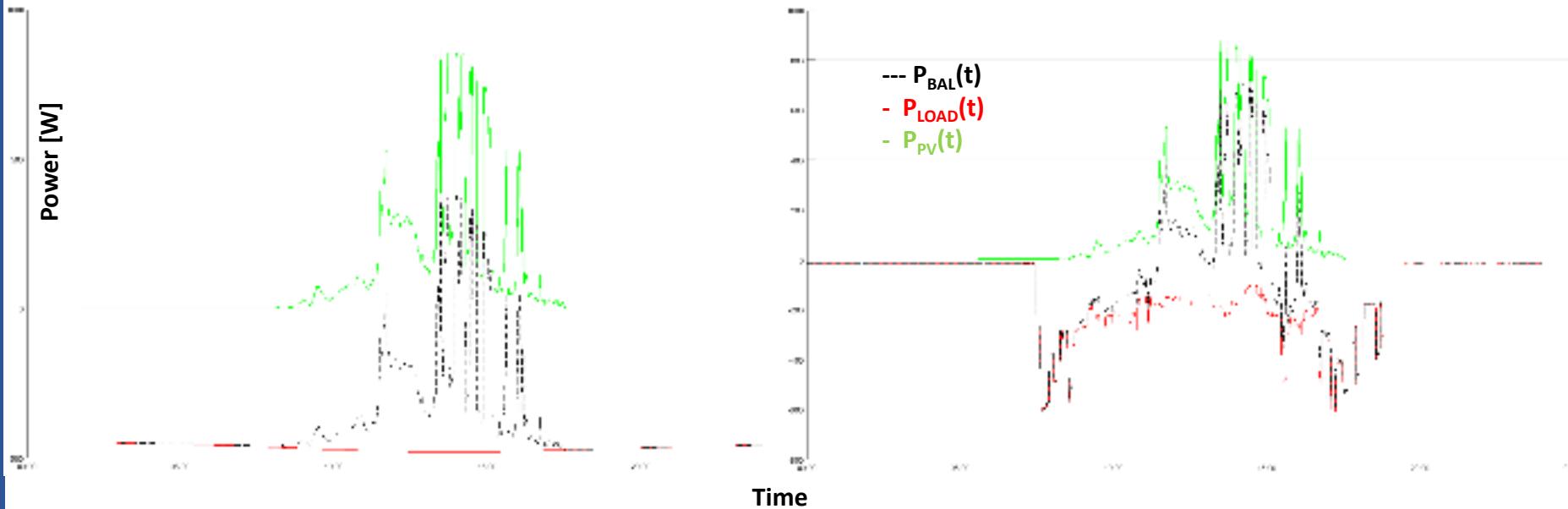


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- Context
- Methodology and Simulation
- Results and work in progress
- Conclusion

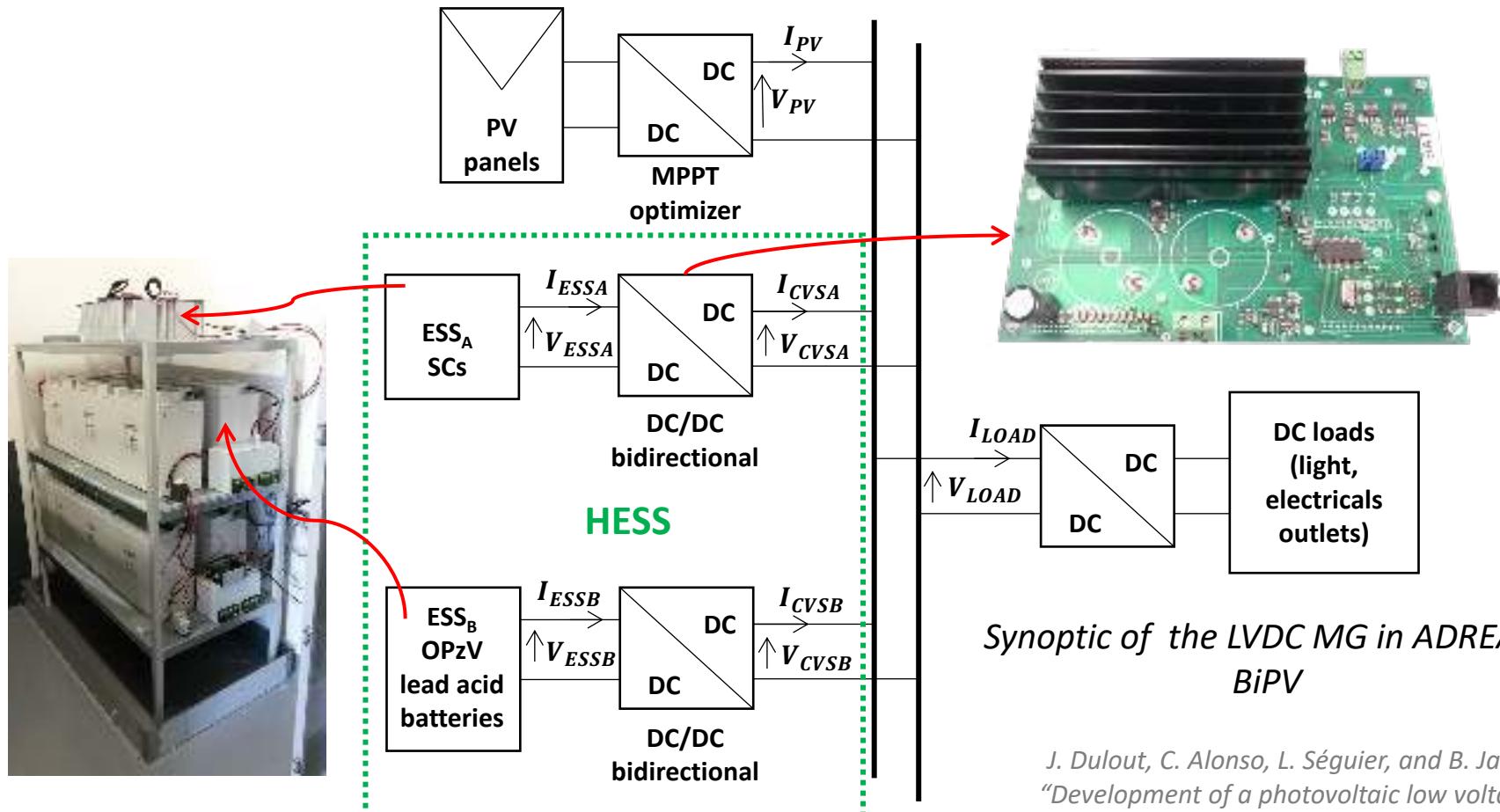
# Context (1/2)

Intermittent and unforeseeable PV sources + time shift demand => ESSs strategies  
=> sizing + energy or/and power management



# Context (2/2)

- HESS : Super Capacitors (SCs) and OPzV batteries

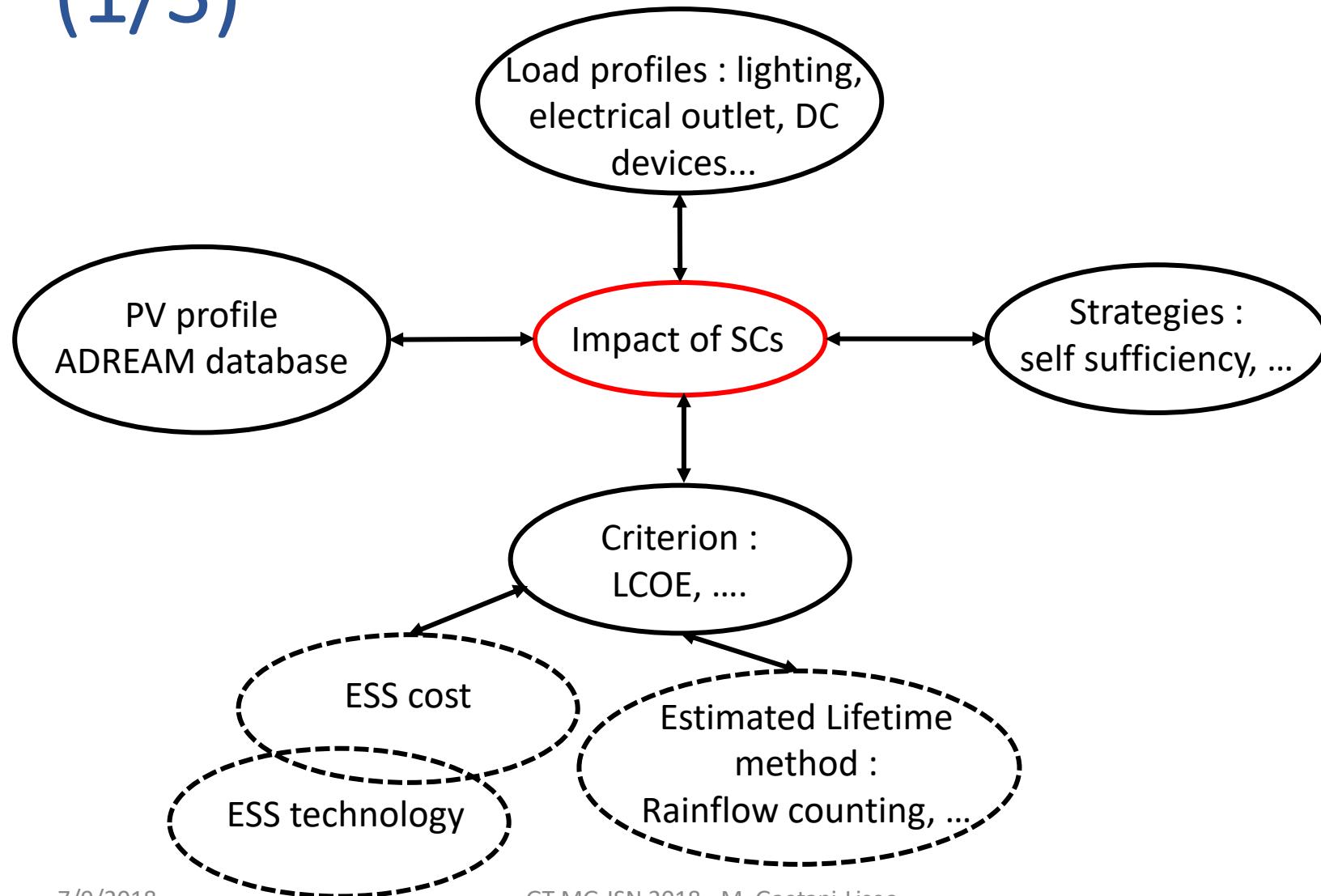


J. Dulout, C. Alonso, L. Séguier, and B. Jammes,  
“Development of a photovoltaic low voltage DC  
microgrid for buildings with energy storage systems,”  
in ELECTRIMACS 2017, 2017, vol. 2017, p. 6p.

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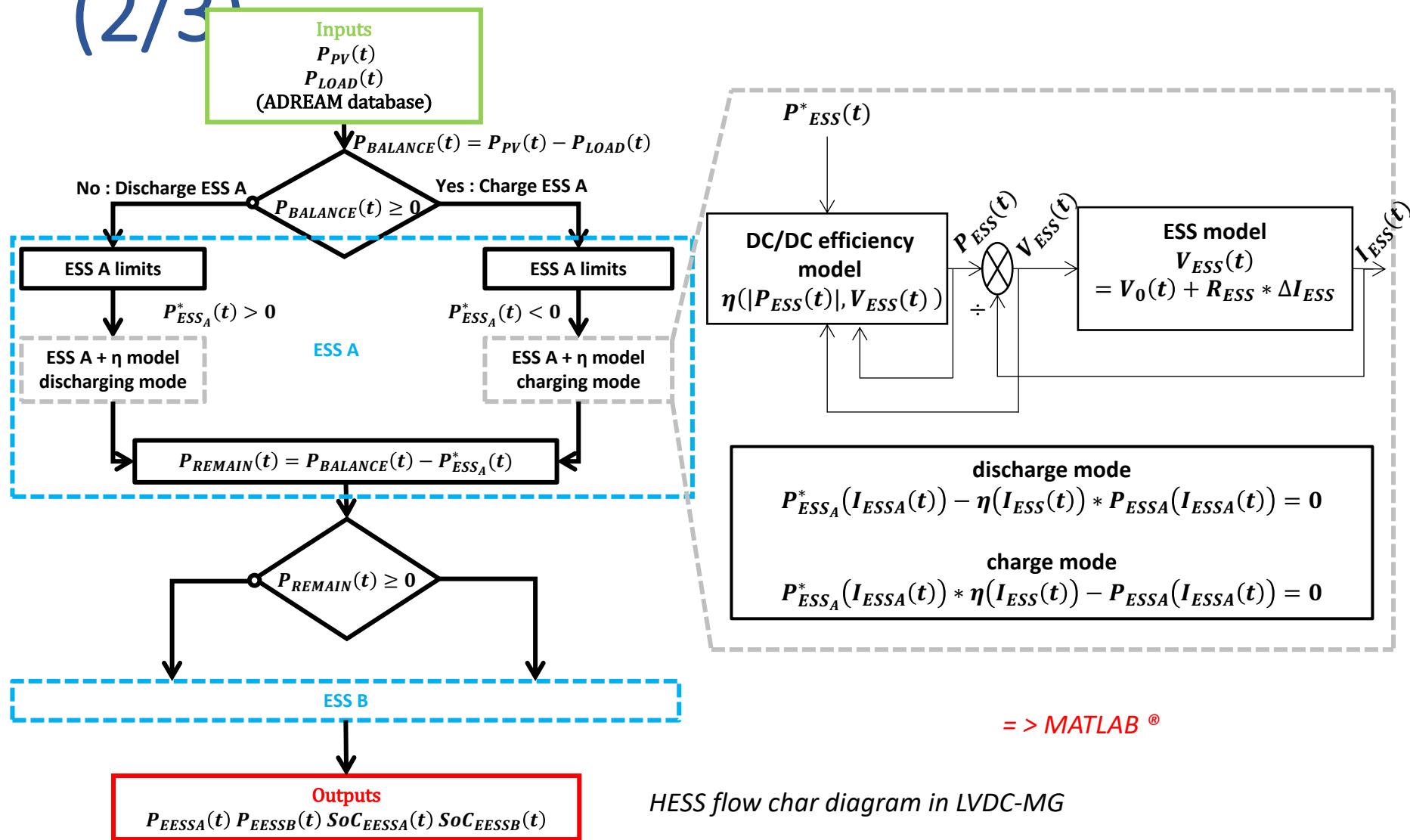
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# Methodology and Simulation (1/3)



# Methodology and Simulation

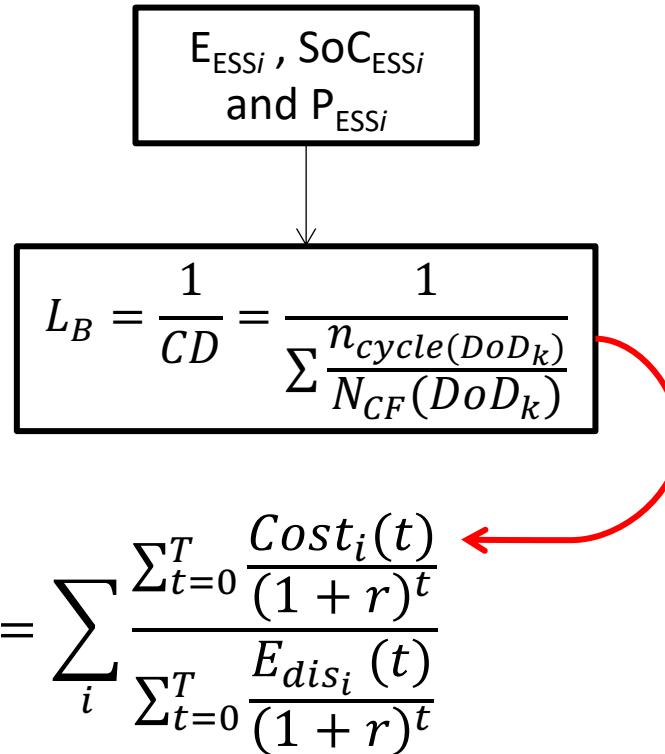
(2/3)



# Methodology and Simulation

(3/3)

- Criteria : LCOE



$$LCOE = \sum_i \frac{\sum_{t=0}^T \frac{Cost_i(t)}{(1+r)^t}}{\sum_{t=0}^T \frac{E_{disi}(t)}{(1+r)^t}}$$

T : Time horizon 20 years  
r : discount rate

B. Battke and T. S. Schmidt, "A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications" Renewable and Sustainable Energy reviews 25 pp. 240-250 2013

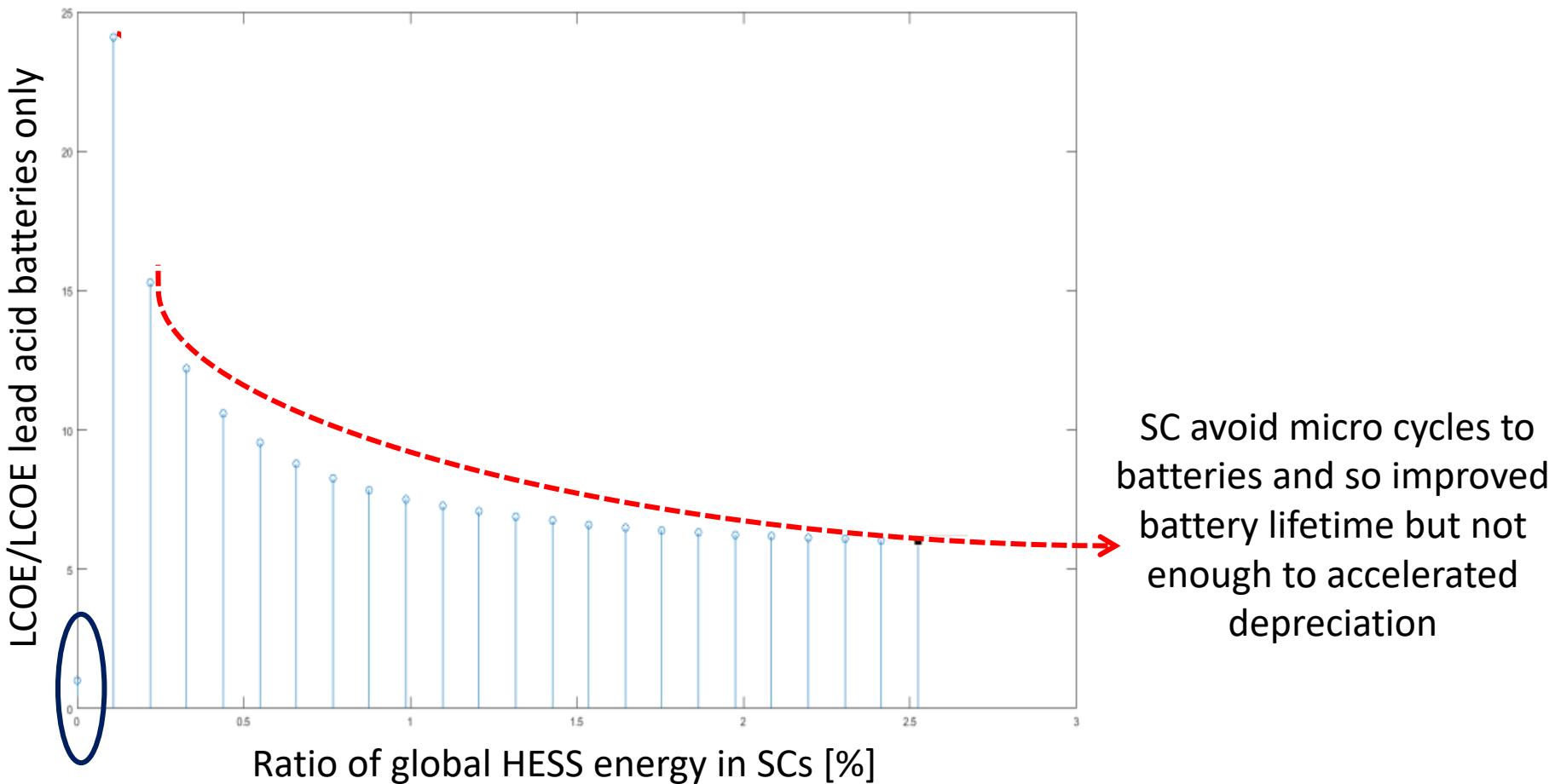
R. Dufo-López, J. M. Lujano-Rojas and J. L. Bernal-Agustín, "Comparison of different lead-acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems" Appl. Energy, vol. 155, pp. 242–253 2014

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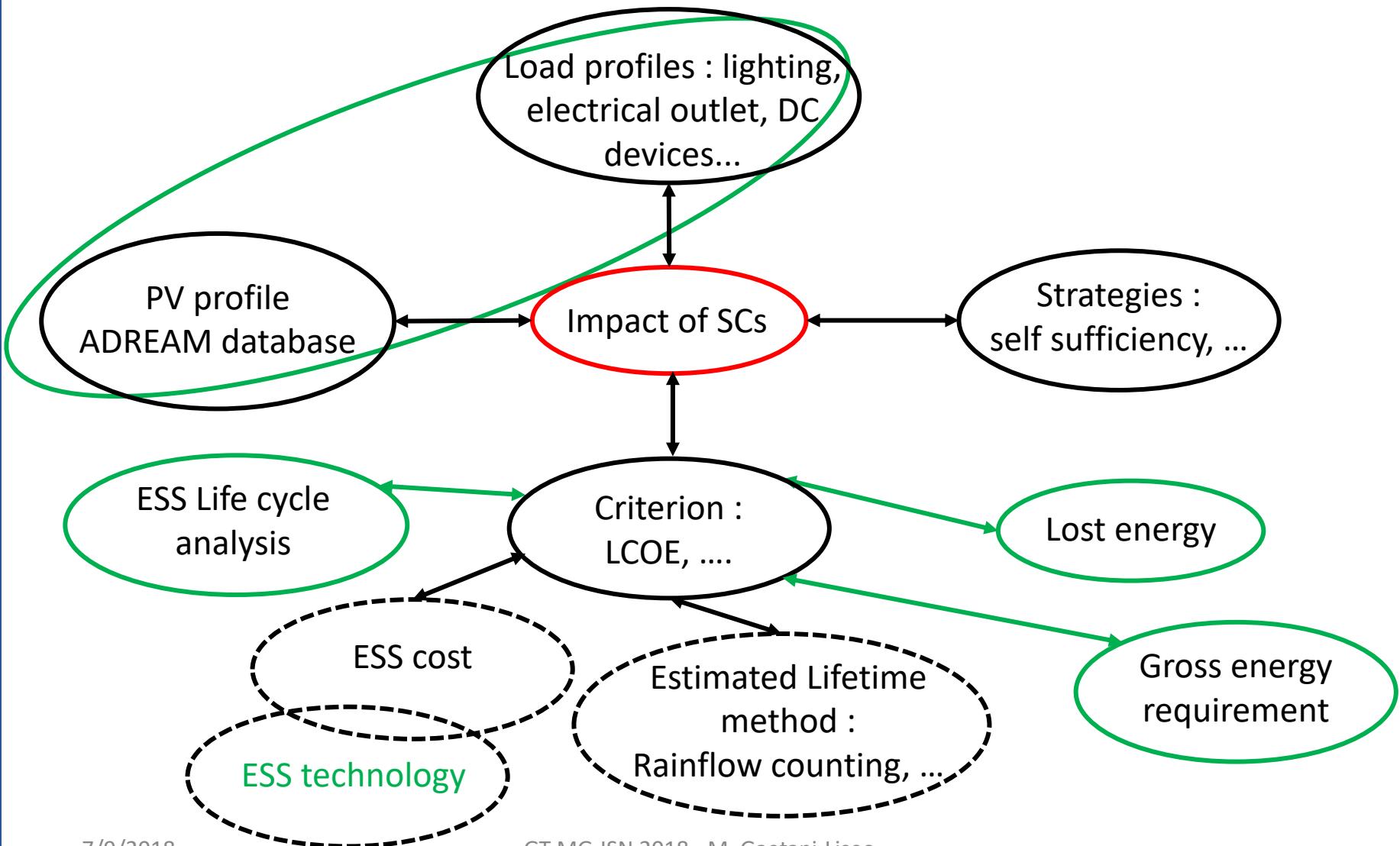
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# Results and work in progress (1/2)

- Impact of SCs on lead acid batterie lifetime



# Results and work in progress (2/2)



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- Context
- Methodology and Simulation
- Results and work in progress
- Conclusion

# Conclusion

- HESS architecture with SCs in LVDC MG in BiPV
- Simulation algorithm and methodology
- Impact on batteries lifetime and LCOE
- Work in progress : comparative studies and multi criterion analysis
- Perspectives : calculation time and models sensitivity

# Thank you for your attention

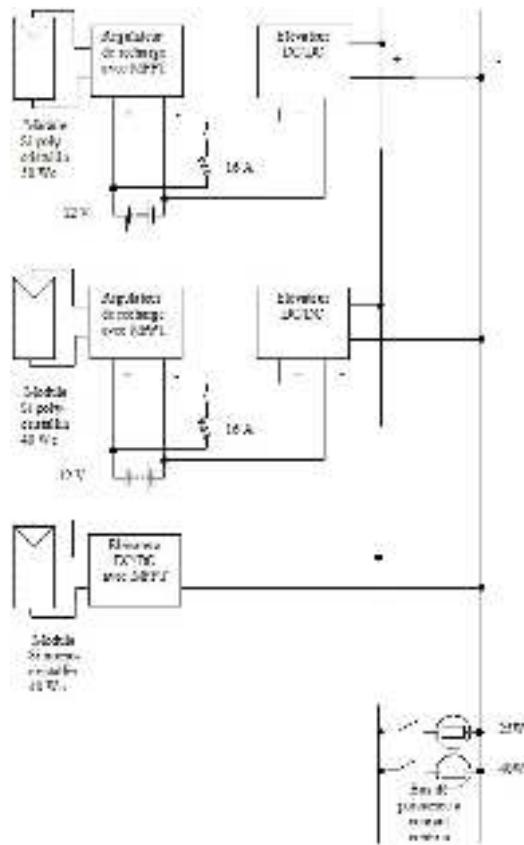


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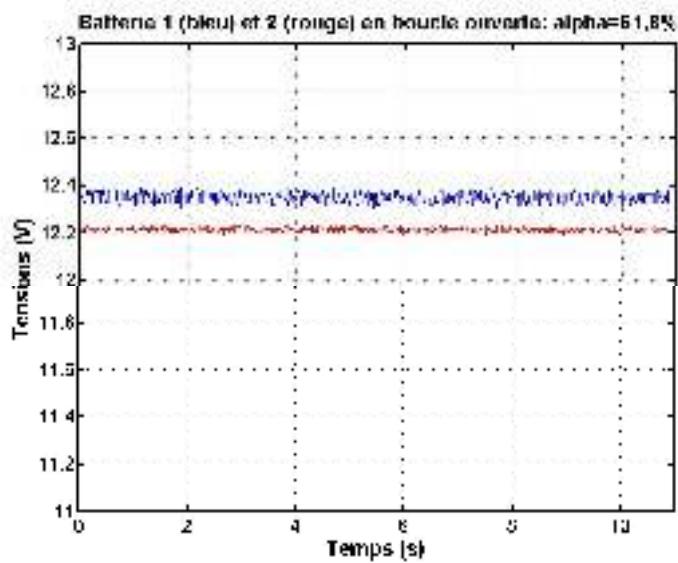
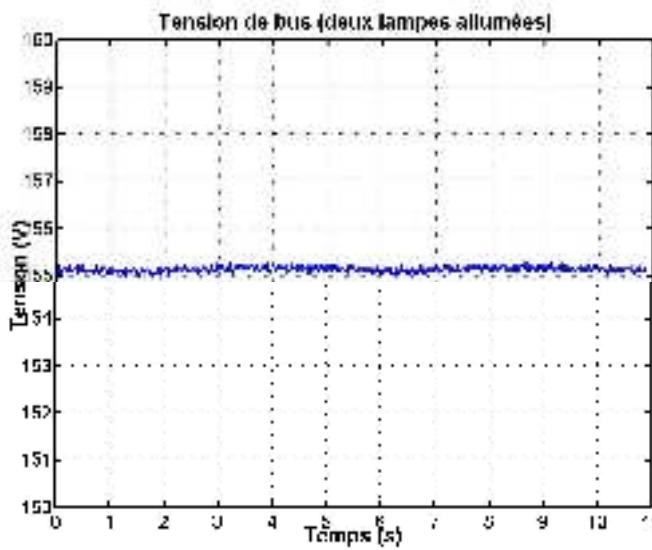
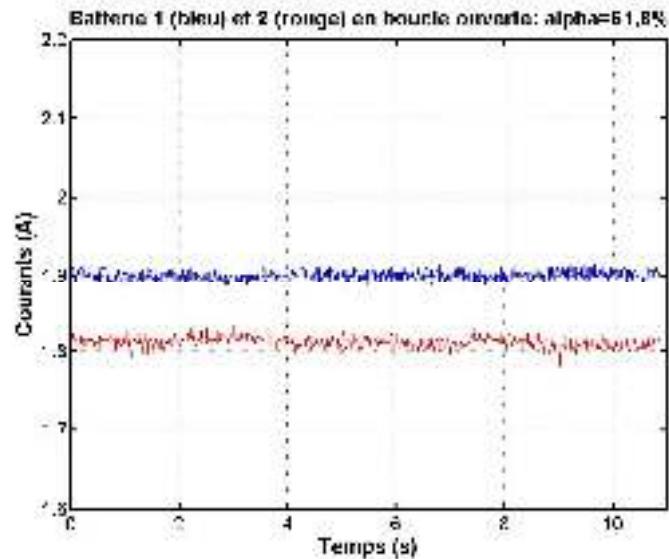
## Couplage parallèle de batteries par élévation de tension

J.P. Sawicki , P. Petit , F. Maufay , M. Aillerie

LMOPS-EA 4423, Université de Lorraine/CentraleSupélec



## Injection en boucle ouverte



$$\alpha = \frac{V_2 - 1}{V_1 + m}$$
 Formule valable en conduction continue

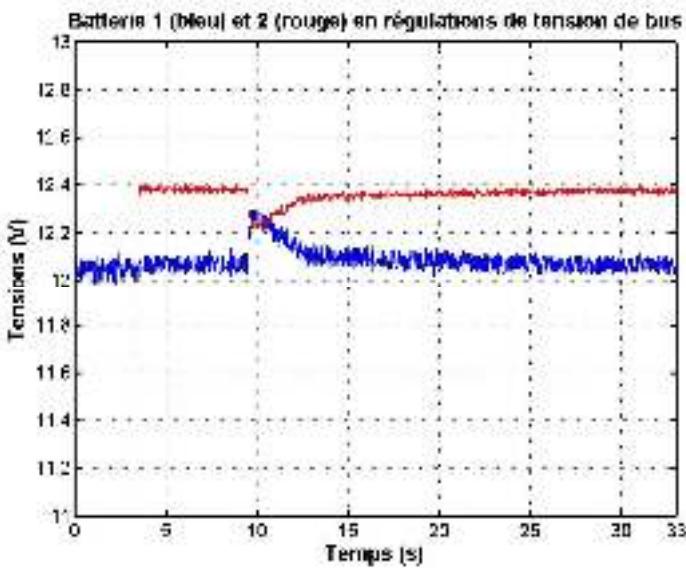
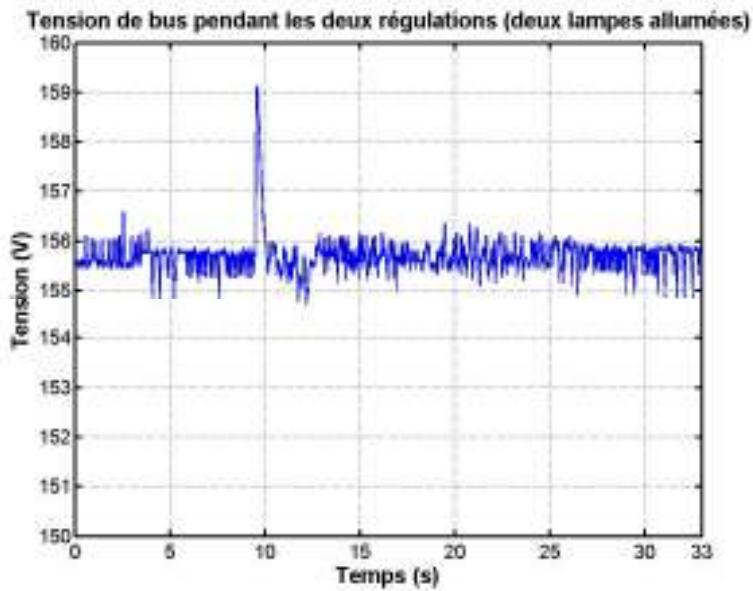
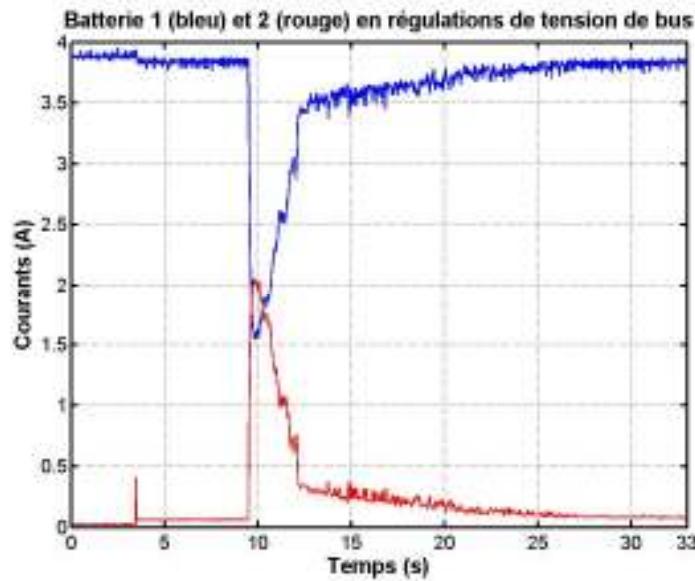
$\alpha$ : rapport cyclique  $\in [0,1]$

$V_1$ : tension de batterie

$V_2$ : tension de bus

$m$ : rapport d'élévation du transformateur

## Injection en boucle fermée: régulations de tension de bus

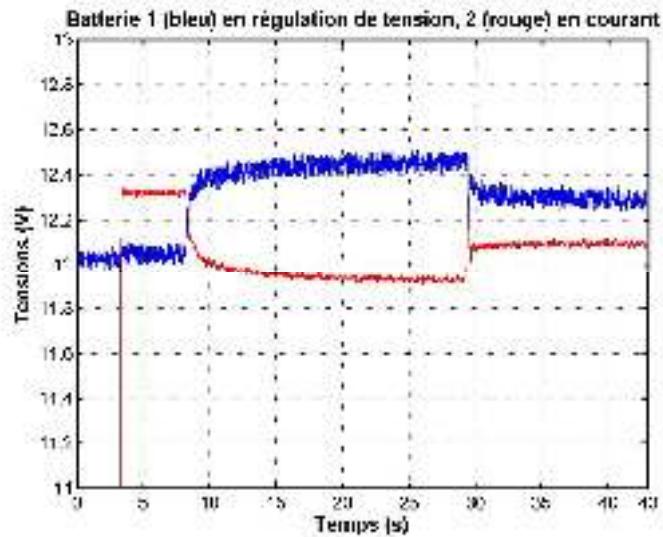
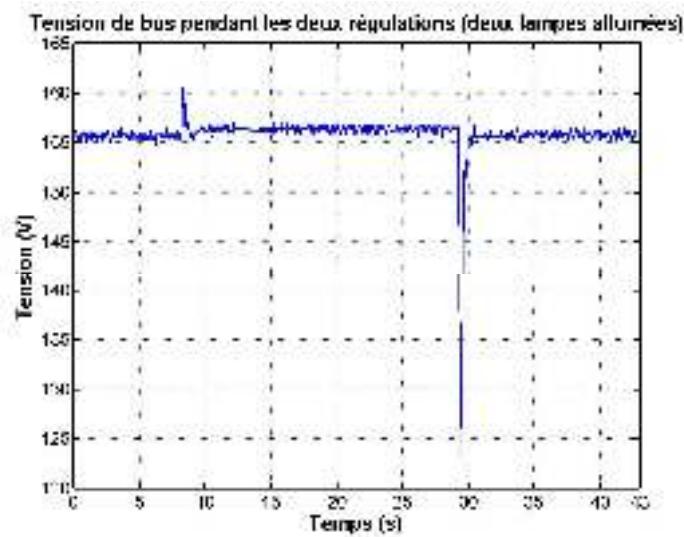
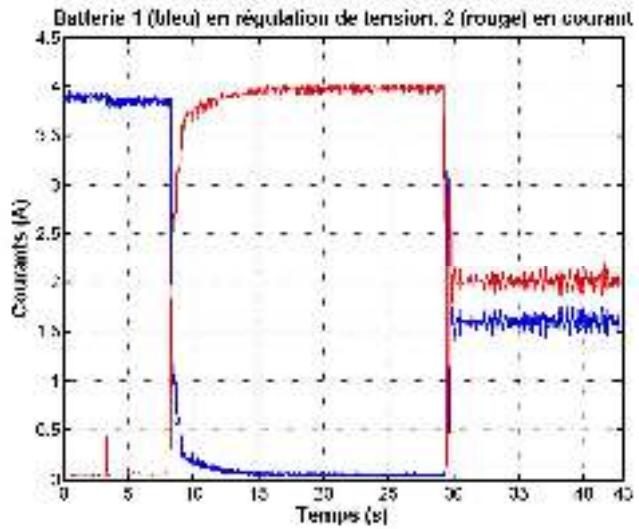


$$\alpha(n) = \frac{\frac{V_2\text{-duty}(n)}{V_1(n)} - 1}{\frac{V_2\text{-duty}(n)}{V_1(n)} + m} \quad (1)$$

$$V_2\text{-duty}(n) = V_2\text{-duty}(n-1) + \frac{T_e}{T_i} * \varepsilon_{V2}(n) \quad (2)$$

$$\varepsilon_{V2}(n) = V_2\text{ref} - V_2(n) \quad (3)$$

## Injection en boucle fermée: régulations de tension de bus et de courant de batterie



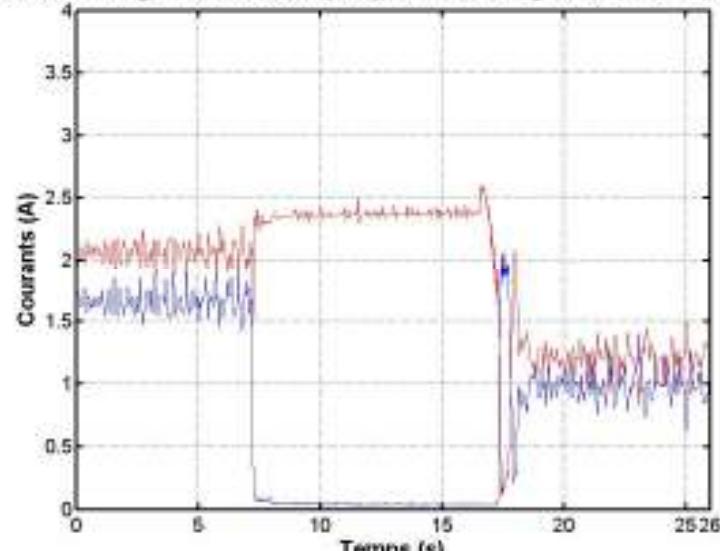
$$\alpha(n) = \frac{\frac{V_2(n)}{V_{1\_duty}(n)} - 1}{\frac{V_2(n)}{V_{1\_duty}(n)} + m} \quad (4)$$

$$V_{1\_duty}(n) = V_{1\_duty}(n-1) + \frac{T_e}{T_i} * \varepsilon_{I1}(n) \quad (5)$$

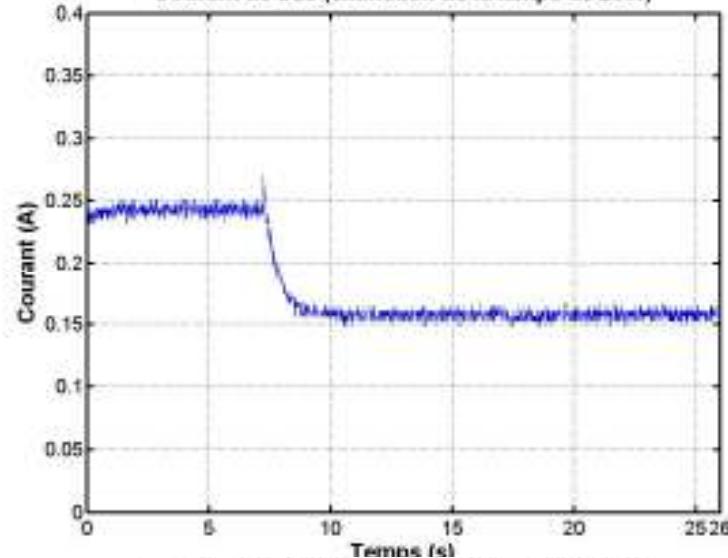
$$\varepsilon_{I1}(n) = I_{1ref} - I_1(n) \quad (6)$$

## Augmentation de l'impédance du bus

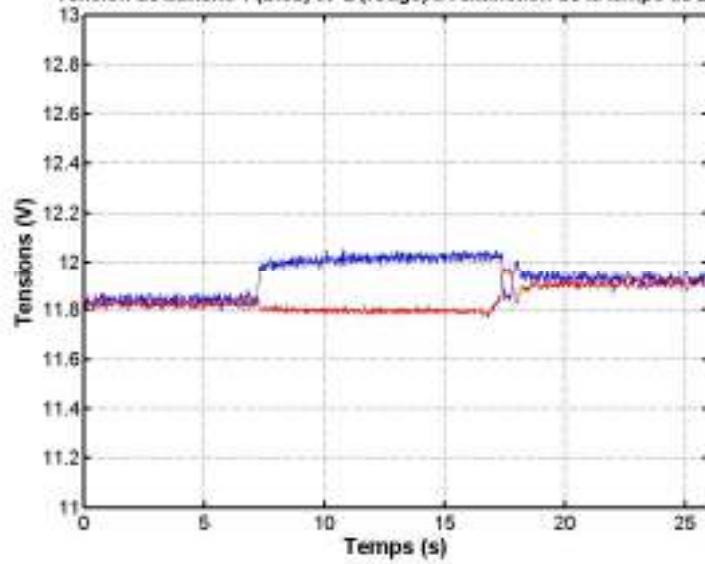
Batterie 1 en régulation de tension (bleu), batterie 2 en régulation de courant (rouge)



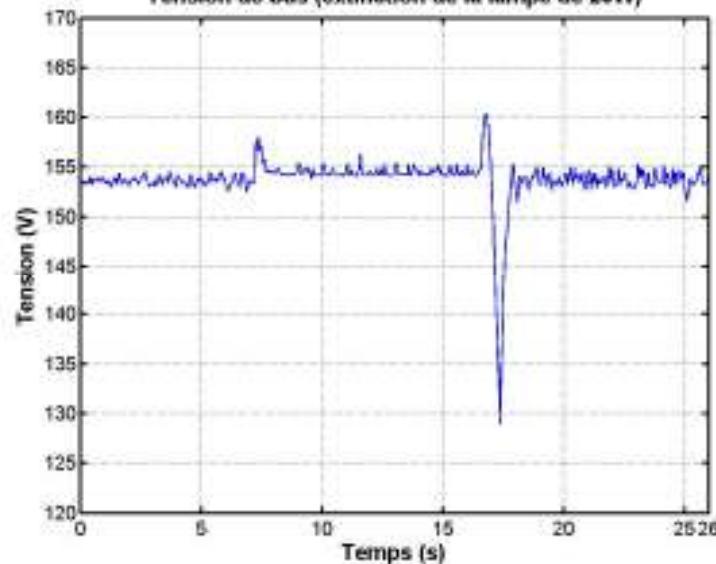
Courant de bus (extinction de la lampe de 25W)



Tension de batterie 1 (bleu) et 2 (rouge) à l'extinction de la lampe de 25W



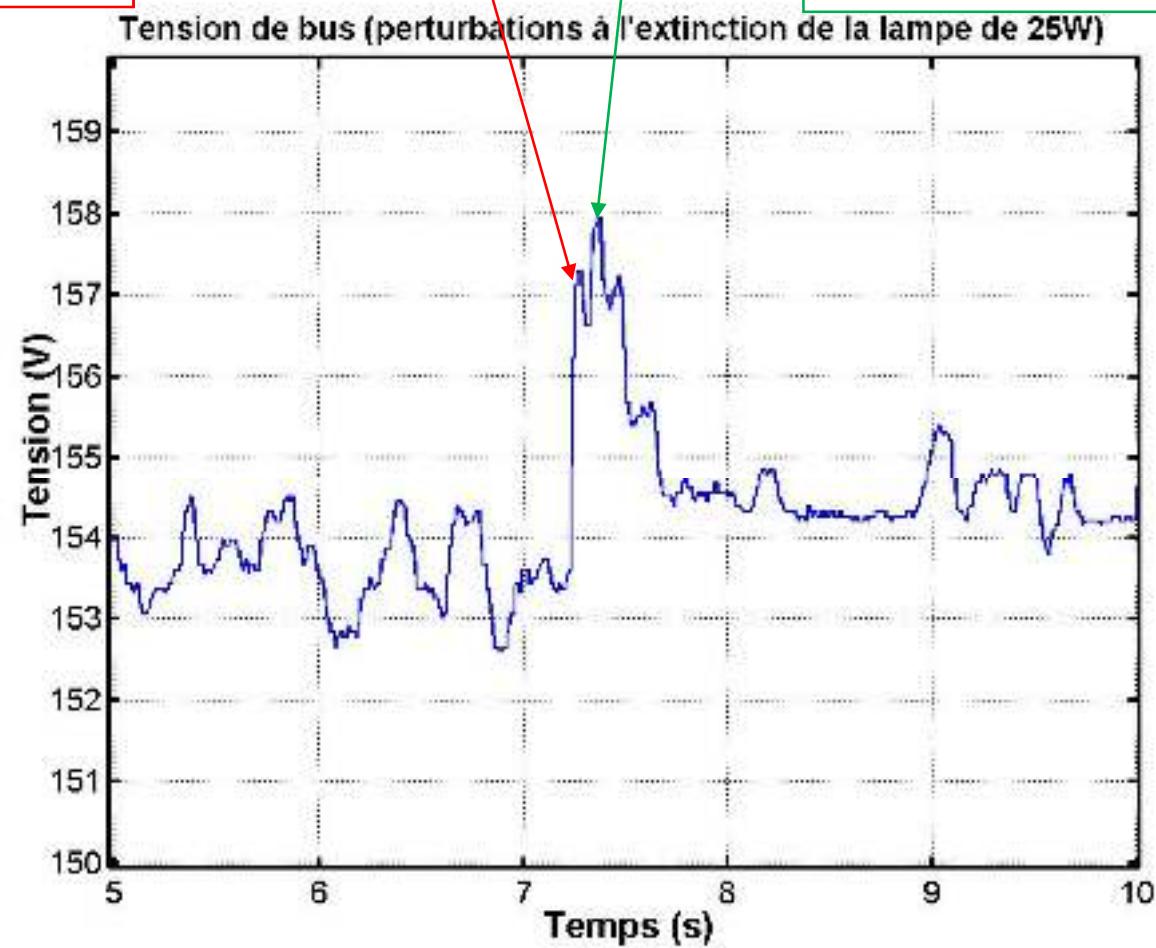
Tension de bus (extinction de la lampe de 25W)



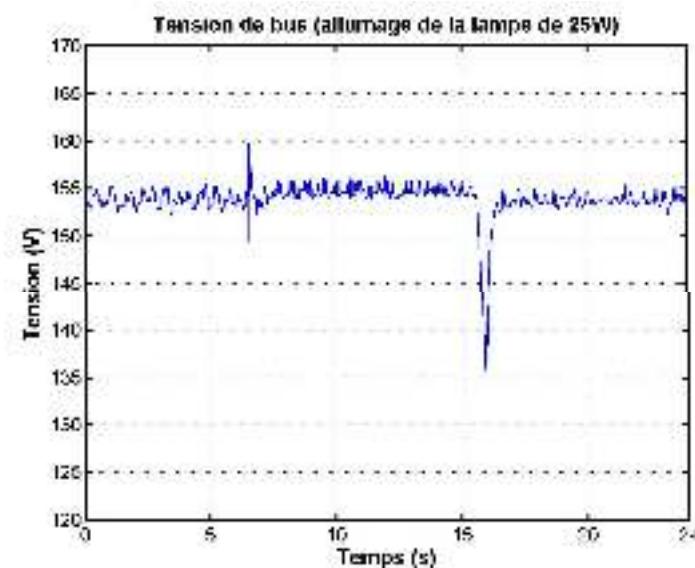
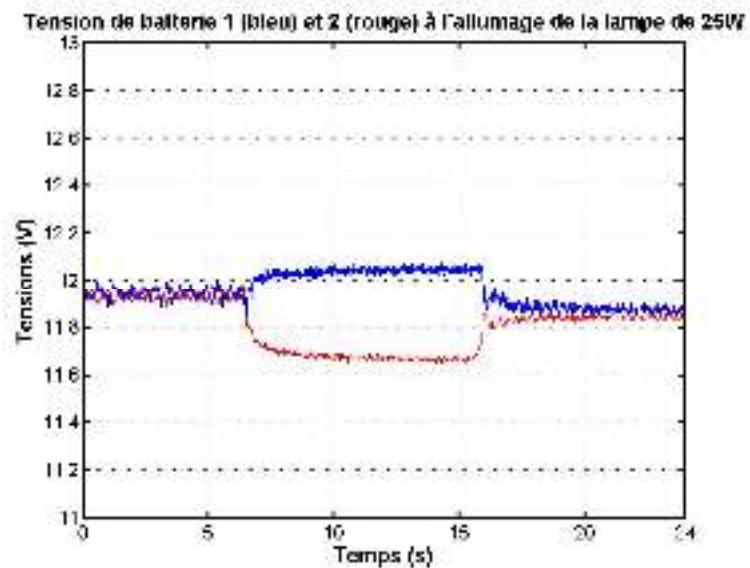
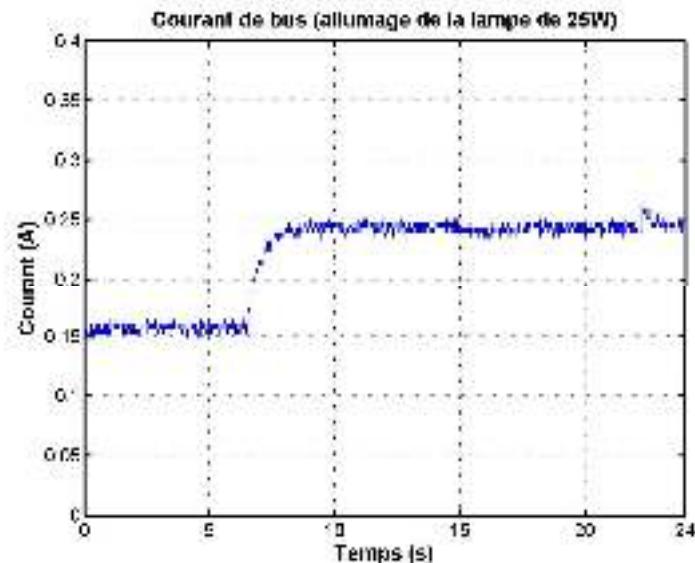
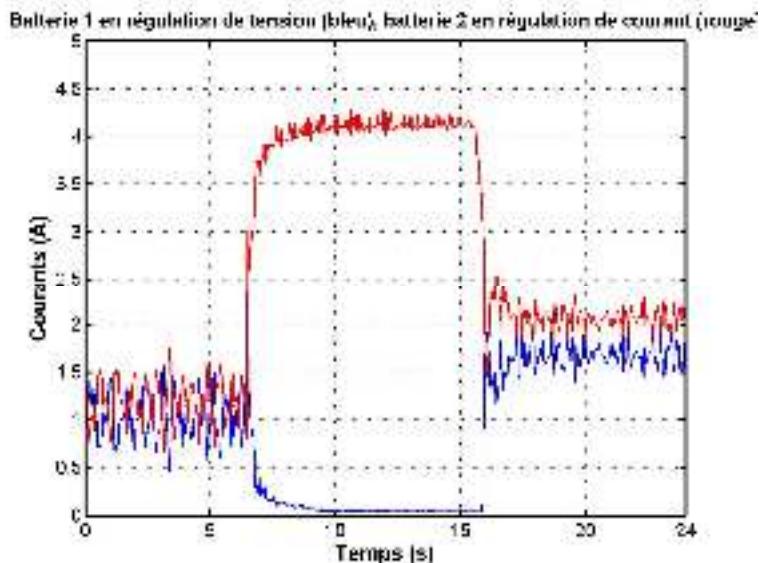
## Augmentation de l'impédance du bus: détail des pics de tension

Pic dû à l'extinction de la lampe de 25 W:  
détection par le convertisseur 2

Pic dû à l'application de la nouvelle consigne de tension de bus par le convertisseur 2



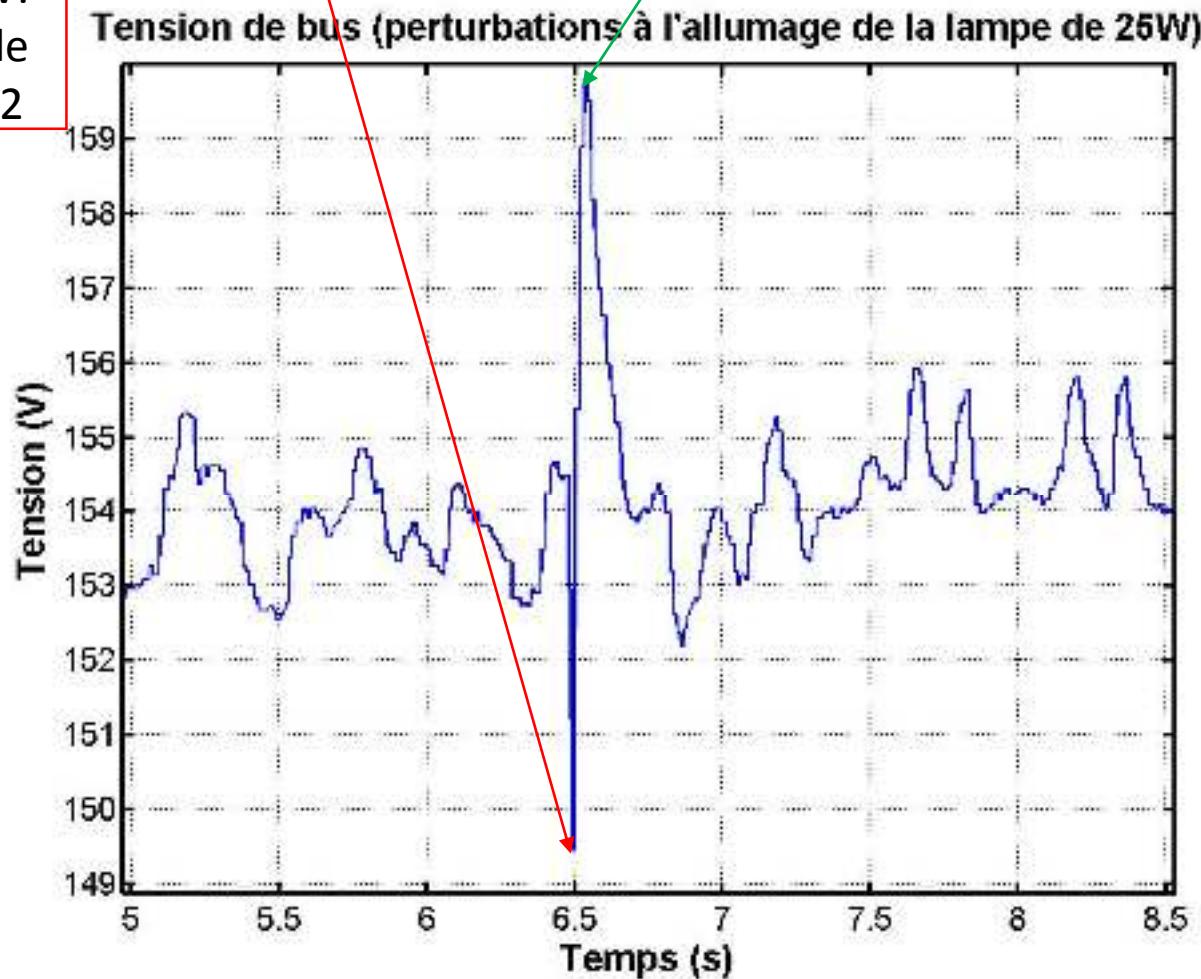
## Diminution de l'impédance du bus



## Diminution de l'impédance du bus: détail des pics et creux de tension

Creux dû à l'allumage de la lampe de 25 W: détection par le convertisseur 2

Pic dû à l'application de la nouvelle consigne de tension de bus par le convertisseur 2





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# SYSTÈME HYBRIDE BASÉ SUR UN GROUPE DIESEL À VITESSE VARIABLE ASSOCIÉ À UN GENERATEUR PV DESTINÉ À ALIMENTER UN MICRO-RESEAU

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CAMARA, Member, IEEE, Brayima DAKYO, Member IEEE

Groupe de Recherche en Electrotechnique et Automatique  
(GREAH) Université Le Havre, 75 rue Bellot, 76600 Le Havre –  
France

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## PLAN

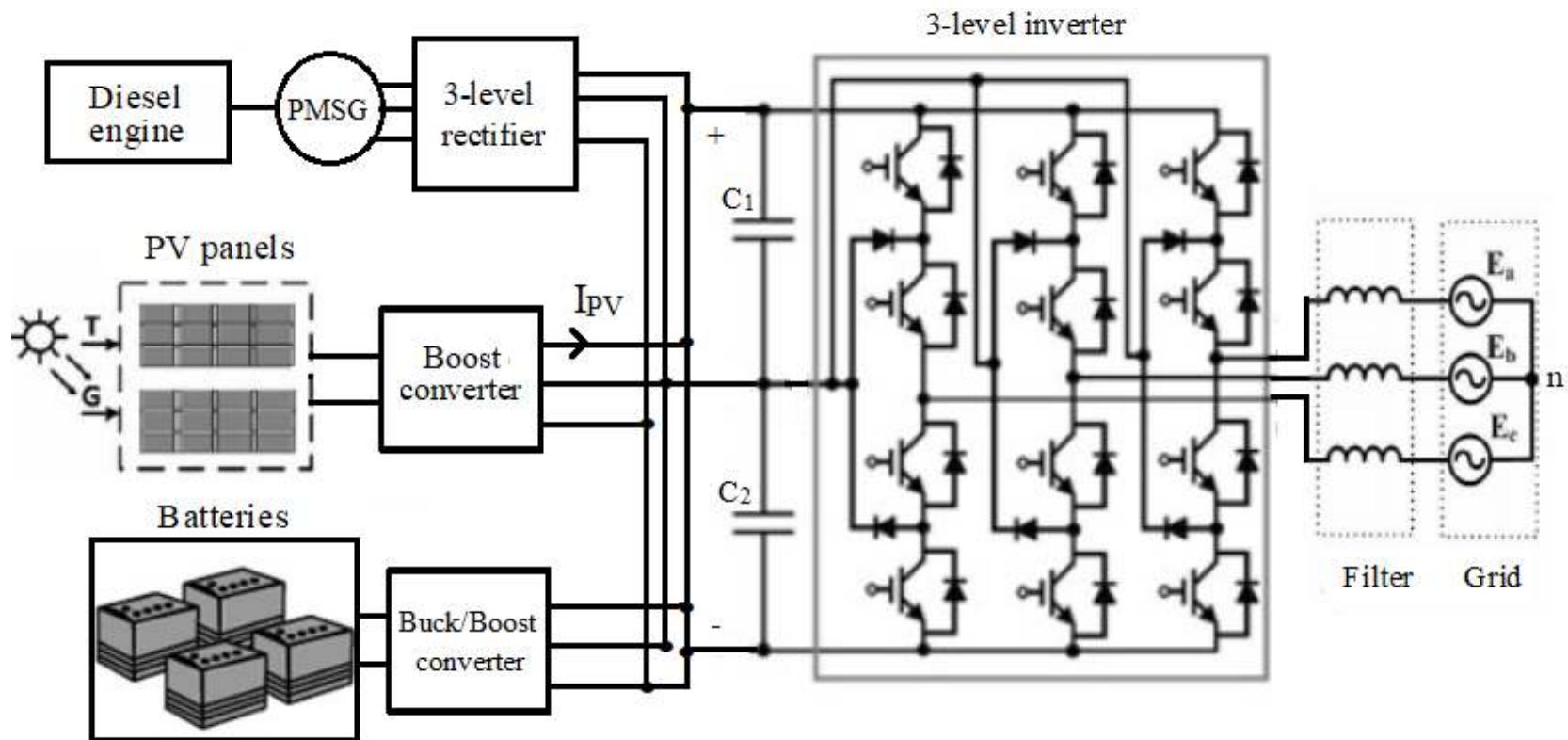
- INTRODUCTION
- METHODE DE CONTROL DU SYSTÈME MULTI-SOURCE
- RESULTATS DE SIMULATION
- CONCLUSION

# INTRODUCTION

Système hybride:

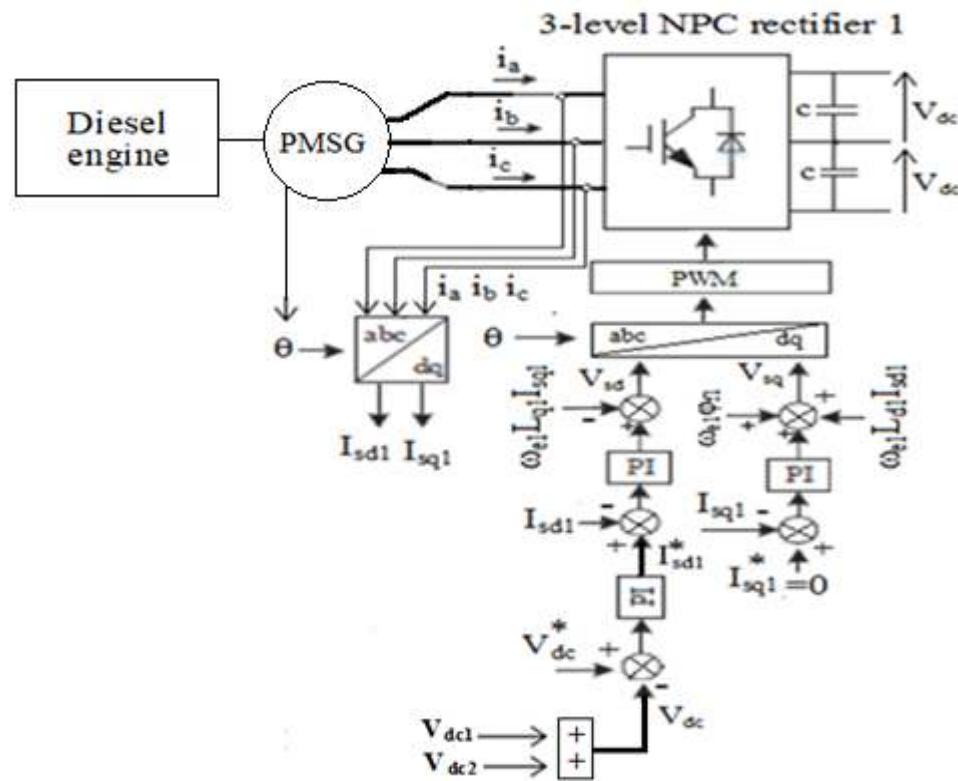
- Groupe diesel à vitesse variable de  $P_n=2.5\text{kW}$
- Générateur PV de  $3.7\text{kW}$
- Pack de batteries Li-ion de  $86\text{Ah}/158\text{V}$
- Micro-réseau de tension entre phase de  $400\text{ V}$

# INTRODUCTION (SUITE)

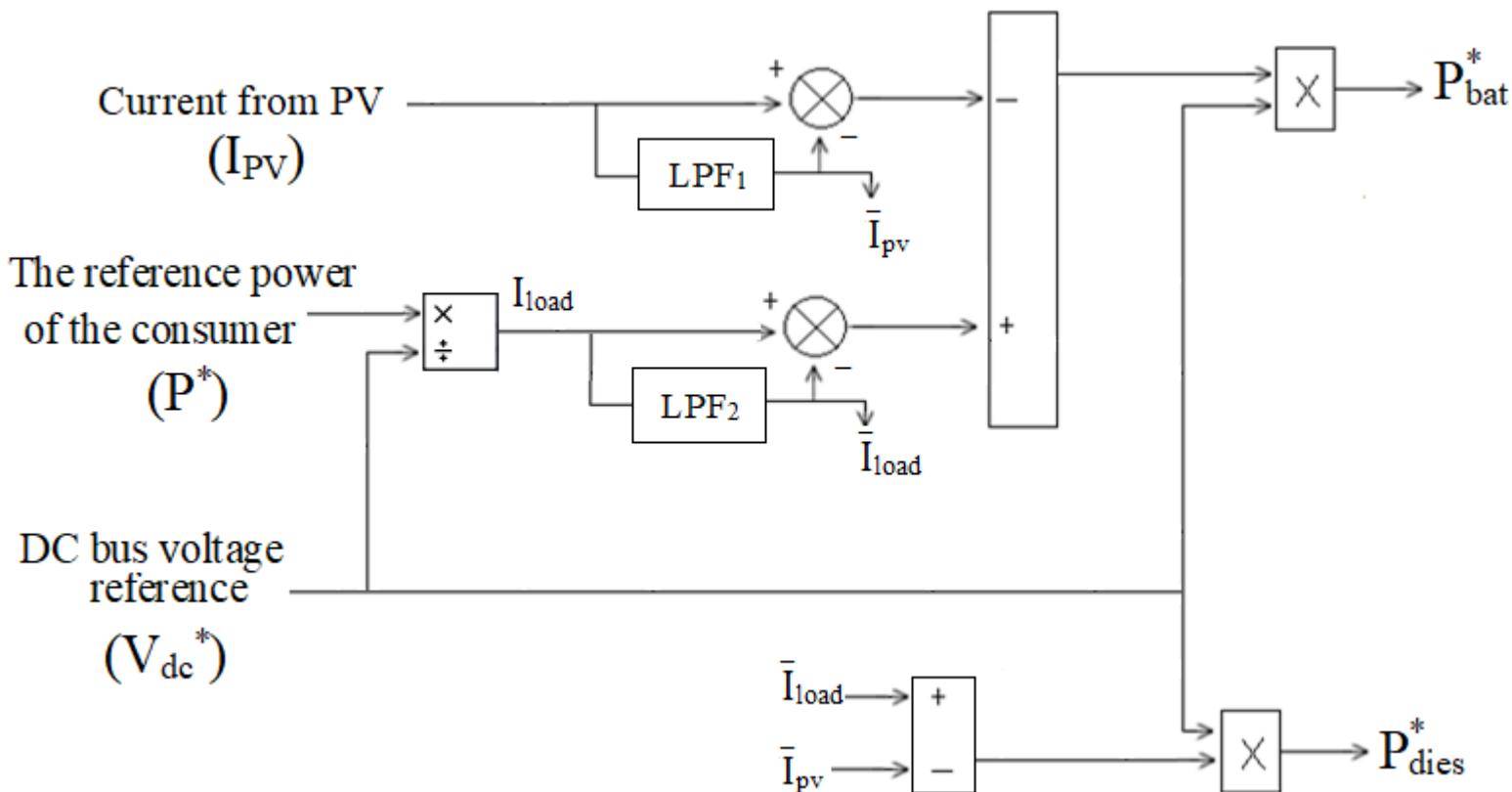


## METHODE DE CONTROL DU SYSTEME MULTI-SOURCE

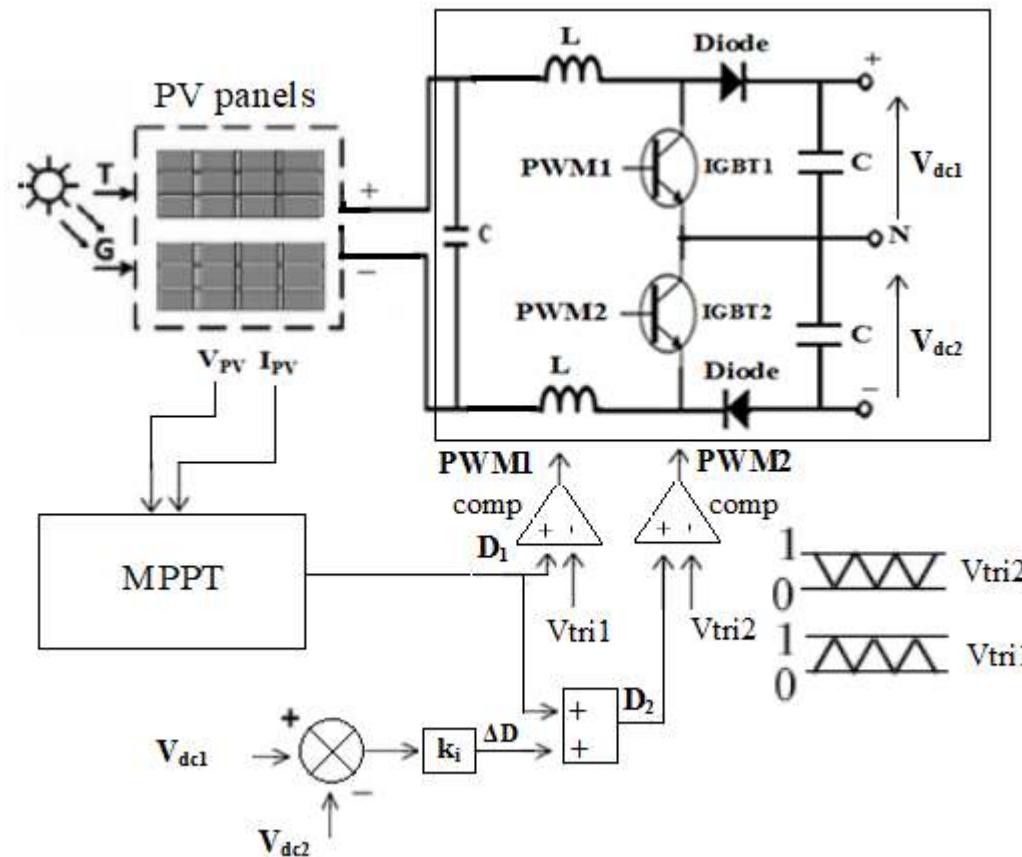
- STRATÉGIE DE CONTROL DE LA TENSION DU BUS CONTINU



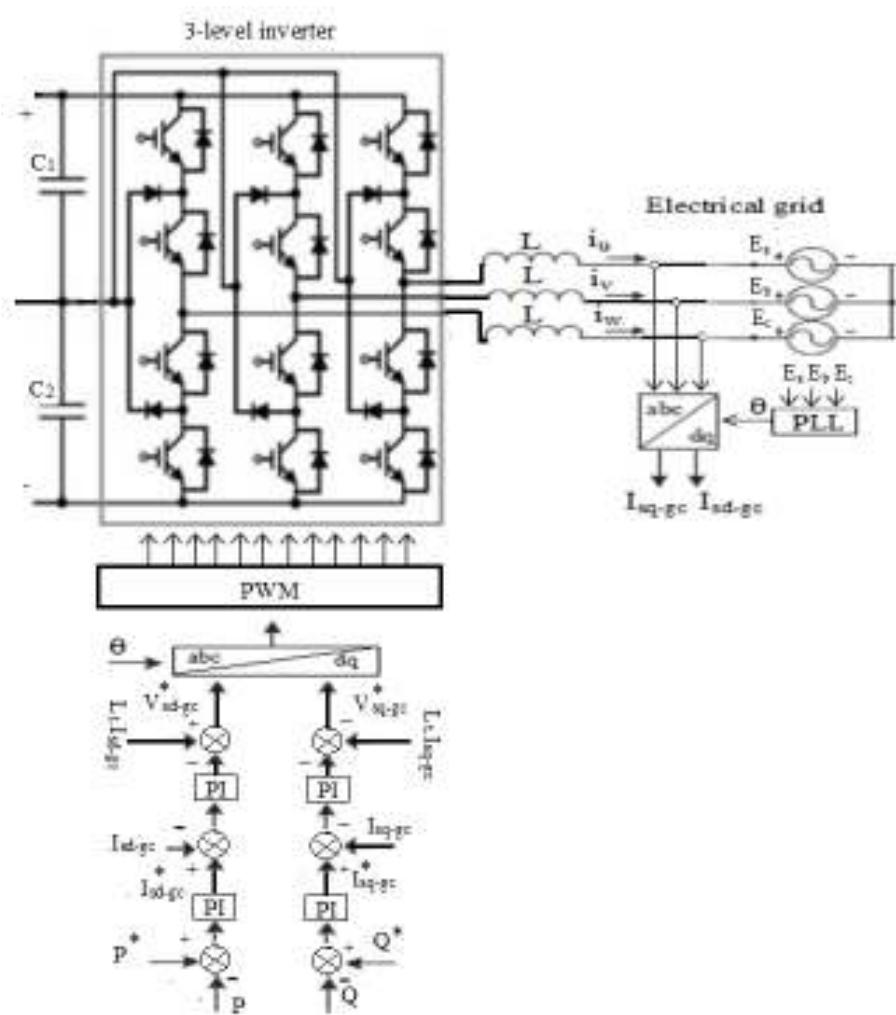
- APPROCHE FREQUENCIELLE



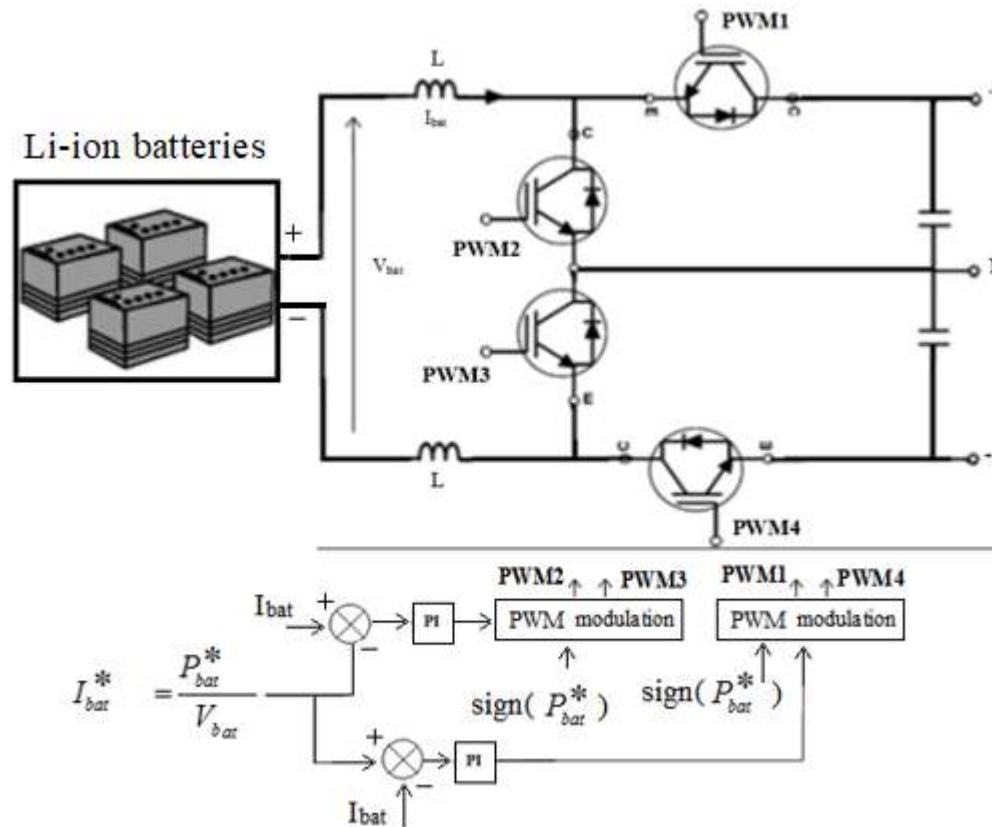
- STRATEGIE DE CONTROL DU CONVERTISSEUR DOUBLE BOOST ASSOCIE AU GENERATEUR PV



- COMMANDÉ DE L'ONDULEUR NPC CONNECTÉ AU MICRO-RESEAU



- Commande du convertisseur double buck/boost associé au pack de batteries Li-ion

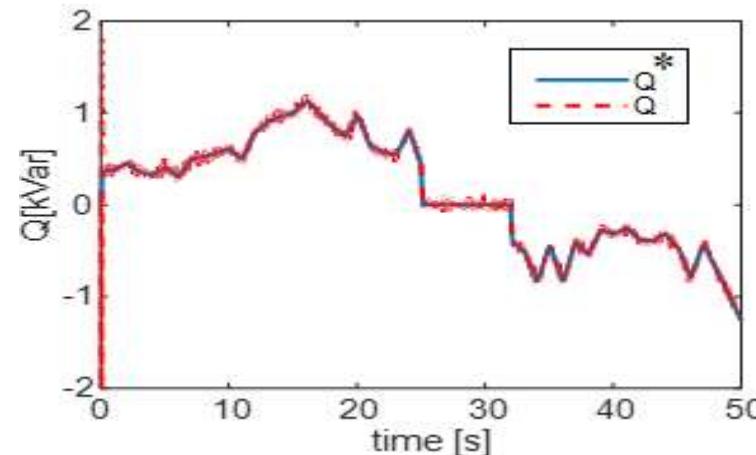
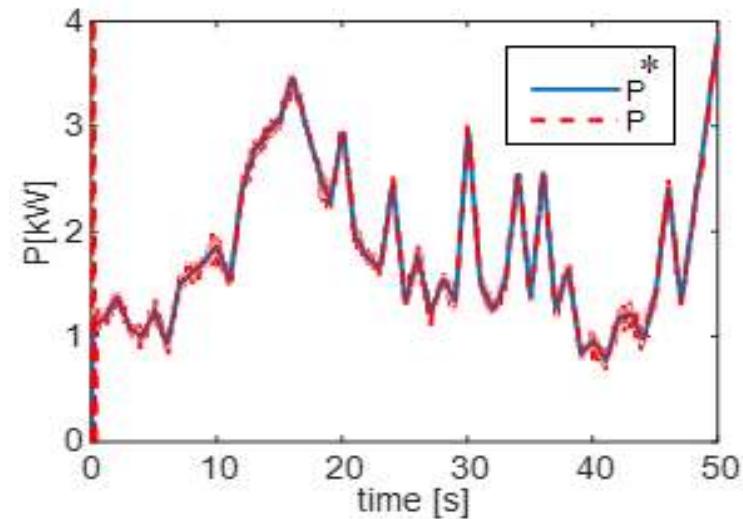
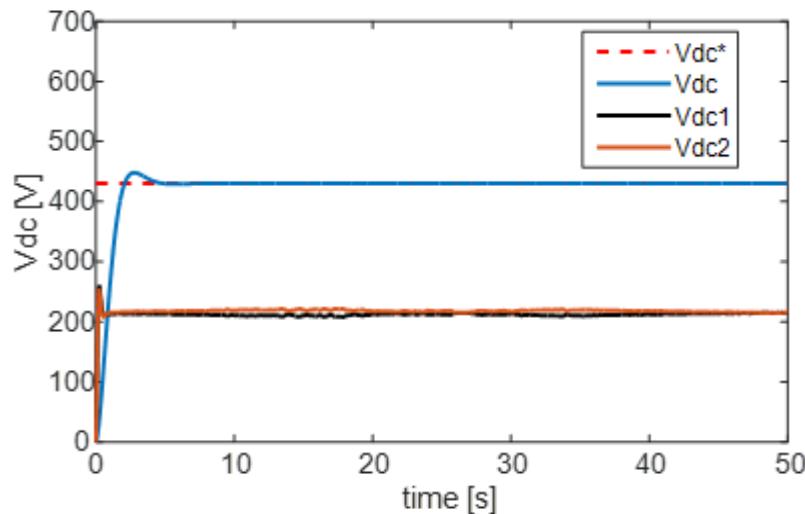


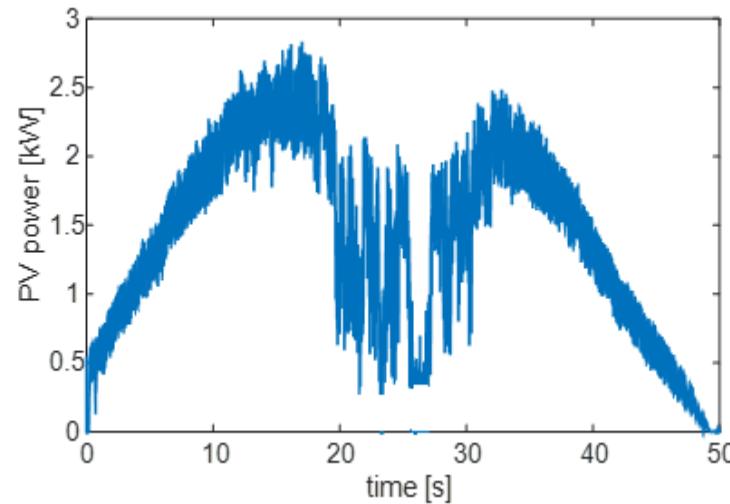
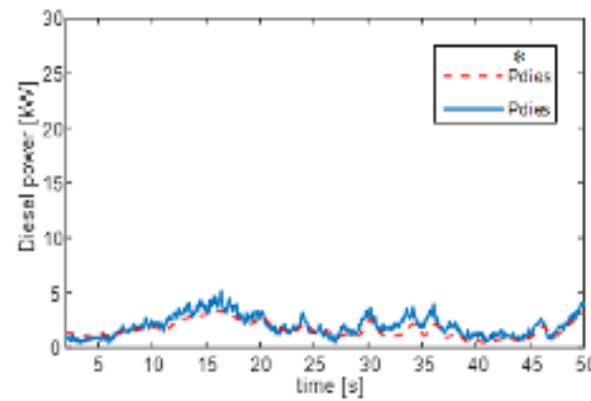
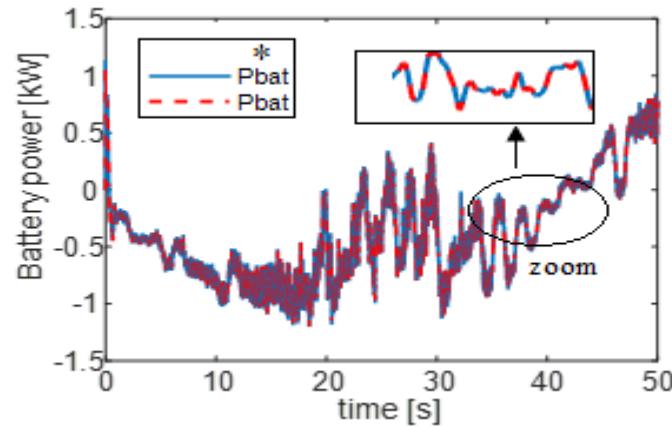
# RESULTATS DE SIMULATION

$$\begin{cases} \tan(\Psi) = \pm 0.327 \\ Q^* = P^* \cdot \tan(\Psi) \end{cases}$$

La tension du bus continu de référence  $V_{dc}^*$  est fixée à 430V

Le générateur PV est basé sur 3 modules en parallèle et 4 en série avec 96 cellules en série pour chaque module. La puissance max d'un module est 305W. L'irradiance est une demi-sinusoidale variable.





# CONCLUSION

Dans ce travail, nous avons présenté les stratégies de contrôle du système multi-sources basé sur :

- La génératrice synchrone à aimants permanents (PMSG) pour diesel à vitesse variable auquel sont jumelés
- Un générateur photovoltaïque et
- Un park de batteries Li-ion.

Les stratégies de contrôle proposées sont axées sur le contrôle de la vitesse de la PMSG , le contrôle de la tension du bus continu, le contrôle de la puissance active et réactive et la gestion de l'énergie au niveau du PV et batteries. Les résultats des simulations montrent que les stratégies de contrôle proposées sont satisfaisantes et que les variables contrôlées sont très proches des références. Il faut également noter que l'intégration des batteries assure en plus du stockage la compensation des fluctuations de la puissance produite. Enfin le control de l'équilibre des tensions des condensateurs du bus continu est réalisé afin d'éviter leur destruction.

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# Impacts of Demand Side Management strategies application on a marine energies based multi-source system

Anthony Roy<sup>1,2</sup>, François Auger<sup>1</sup>, Salvy Bourguet<sup>1</sup>, Florian Dupriez-Robin<sup>2</sup>, Quoc Tuan Tran<sup>3</sup>

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2. CEA-Tech Pays de la Loire, Technocampus Océan, 5 Rue de l'Halbrane, 44340 Bouguenais, France

3. Institut National de l'Énergie Solaire (INES), CEA-LITEN/DTS/LSEI, 50 Av. du Lac Léman, 73370 Le Bourget-du-Lac, France

# Outline

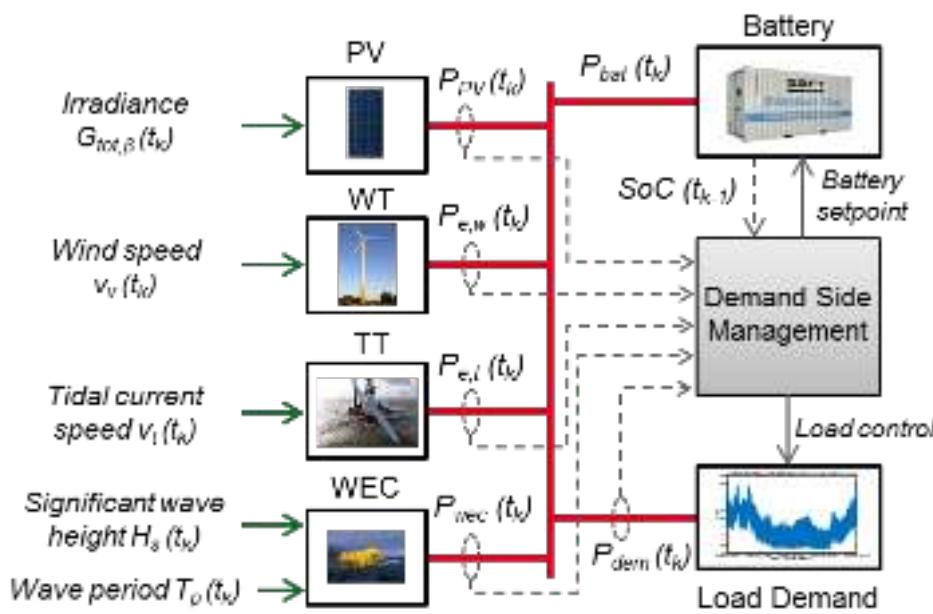
- Context
- Overview of multi-source system
- Demand Side Management strategies
- Results
- Conclusion - Perspectives

# Context

- Intermittency and variability of marine renewable energies require the use of storage solutions and gensets to ensure the island demand to be met
  - However, in some remote areas, fuel import is costly due to logistical constraints
  - Energy Management System of an off-grid multi-source system without genset needs flexibility to avoid high costs due to battery requirements
  - Demand Side Management strategies can bring some flexibility, by shifting (advance or delay) or by shedding several kinds of loads.
- By using the excess power, which benefits could bring an advance scheduling strategy applied to water heaters and electric heating ?

# Overview of multi-source system

- 4 sources considered : solar, wind, tidal and wave energies
- Lithium-ion battery storage
- Load : Ouessant Island demand
- Simulation carried out for a 5 years long period (2011-2015) at hourly time step



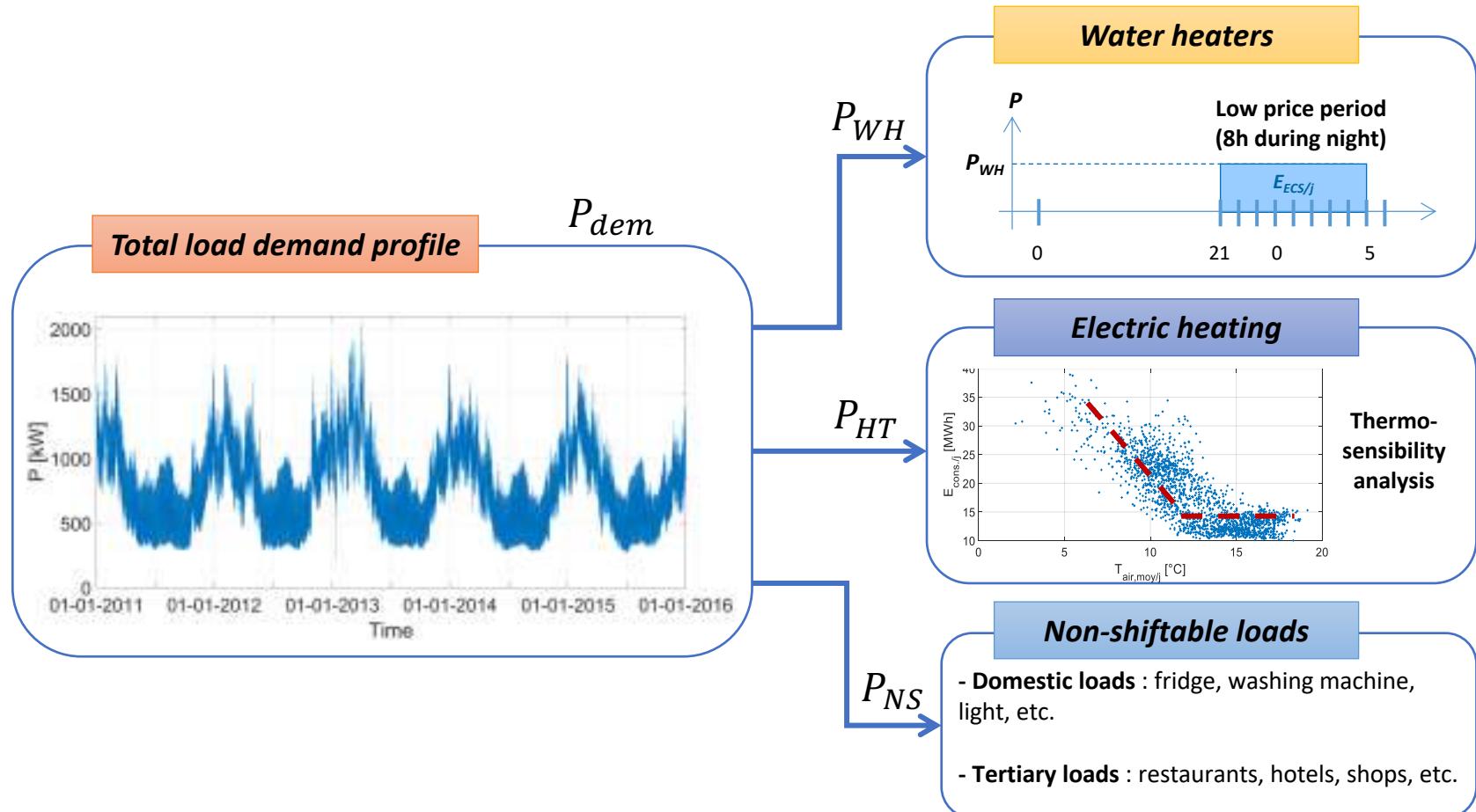
| Source | Ref.             | $P_{rated}$ | Quantity                           |
|--------|------------------|-------------|------------------------------------|
| PV     | BP Solar SX3190B | 190 W       | 1500<br>( $P_{PV\ inst} = 285$ kW) |
| Wind   | Enercon E53      | 800 kW      | 6<br>( $P_{WT\ inst} = 4,8$ MW)    |
| Tidal  | Tocardo T500     | 300 kW      | 6<br>( $P_{TT\ inst} = 1,8$ MW)    |
| Wave   | Oyster           | 290 kW      | 3<br>( $P_{WEC\ inst} = 870$ kW)   |

| Storage     | Ref.               | $E_{rated}$ | Quantity                           |
|-------------|--------------------|-------------|------------------------------------|
| Lithium-ion | Saft Intensium Max | 1,09 MWh    | 7<br>( $E_{bat\ inst} = 7,63$ MWh) |

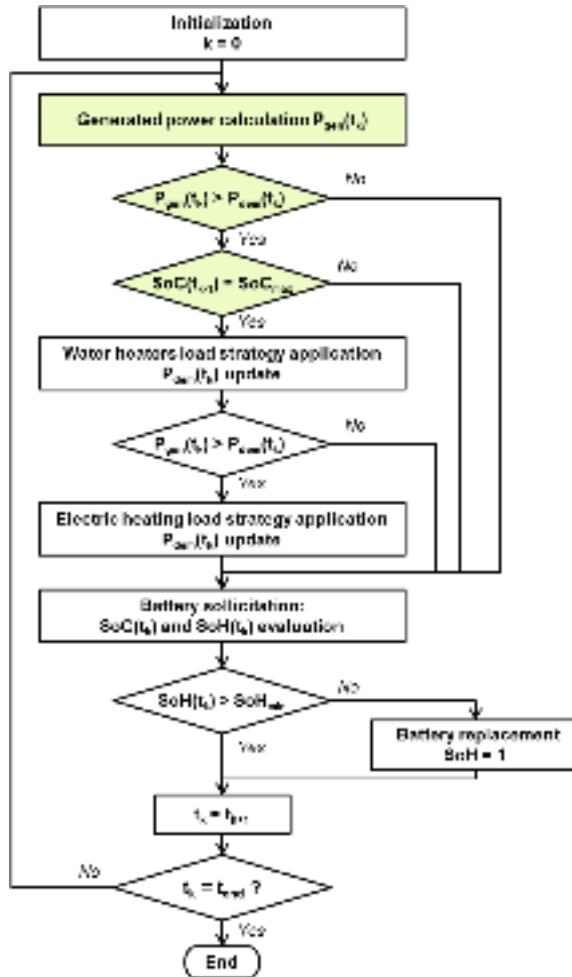
# Demand Side Management strategies

## Load profile decomposition



# Demand Side Management strategies

## MS system simulation flowchart



## Conditions to apply anticipation-based DSM strategies

- Excess of generated power

$$P_{gen}(t_k) > P_{dem}(t_k)$$

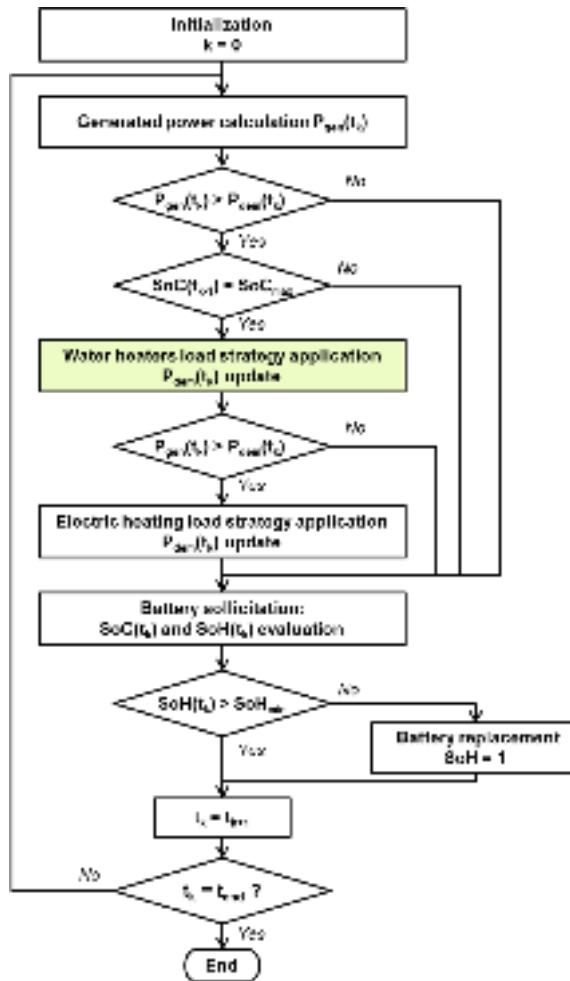
$$P_{exc}(t_k) = P_{gen}(t_k) - P_{dem}(t_k)$$

- Battery fully charged

$$SoC(t_{k-1}) = SoC_{max}$$

# Demand Side Management strategies

## MS system simulation flowchart



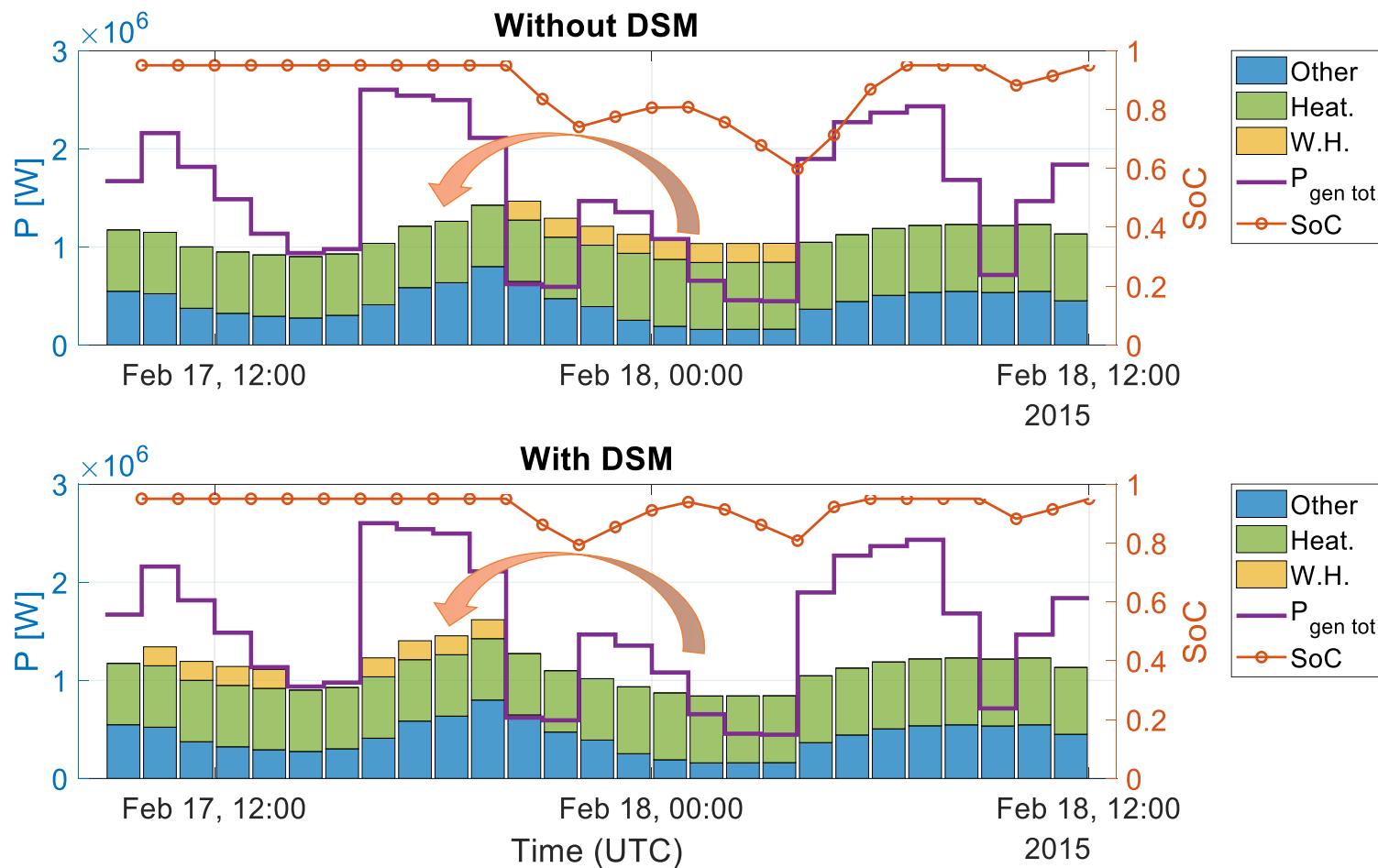
## Water heaters DSM strategy

If  $P_{exc}(t_k) > 0$ :

- Water heaters are turned on at  $t_k$ , before their initially planned working time  $t_{k+A}$ , whatever the power amount generated at  $t_{k+A}$
- Anticipation time:  $1 \leq A \leq 10$
- Constraints:  $P_{exc}(t_k)$ ,  $P_{WH}(t_k)$  and  $P_{WH}(t_{k+A})$

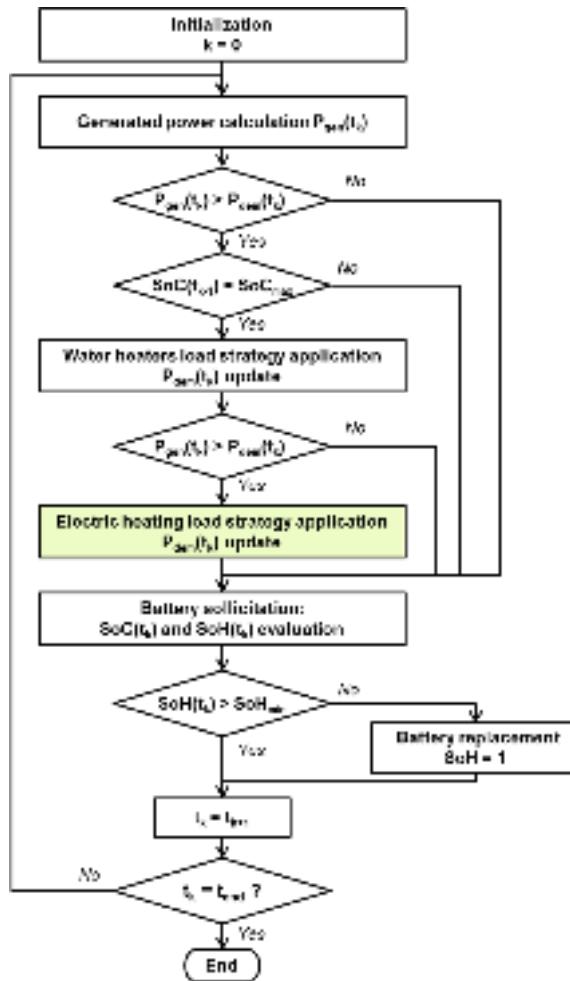
# Demand Side Management strategies

## Water heaters DSM strategy



# Demand Side Management strategies

## MS system simulation flowchart



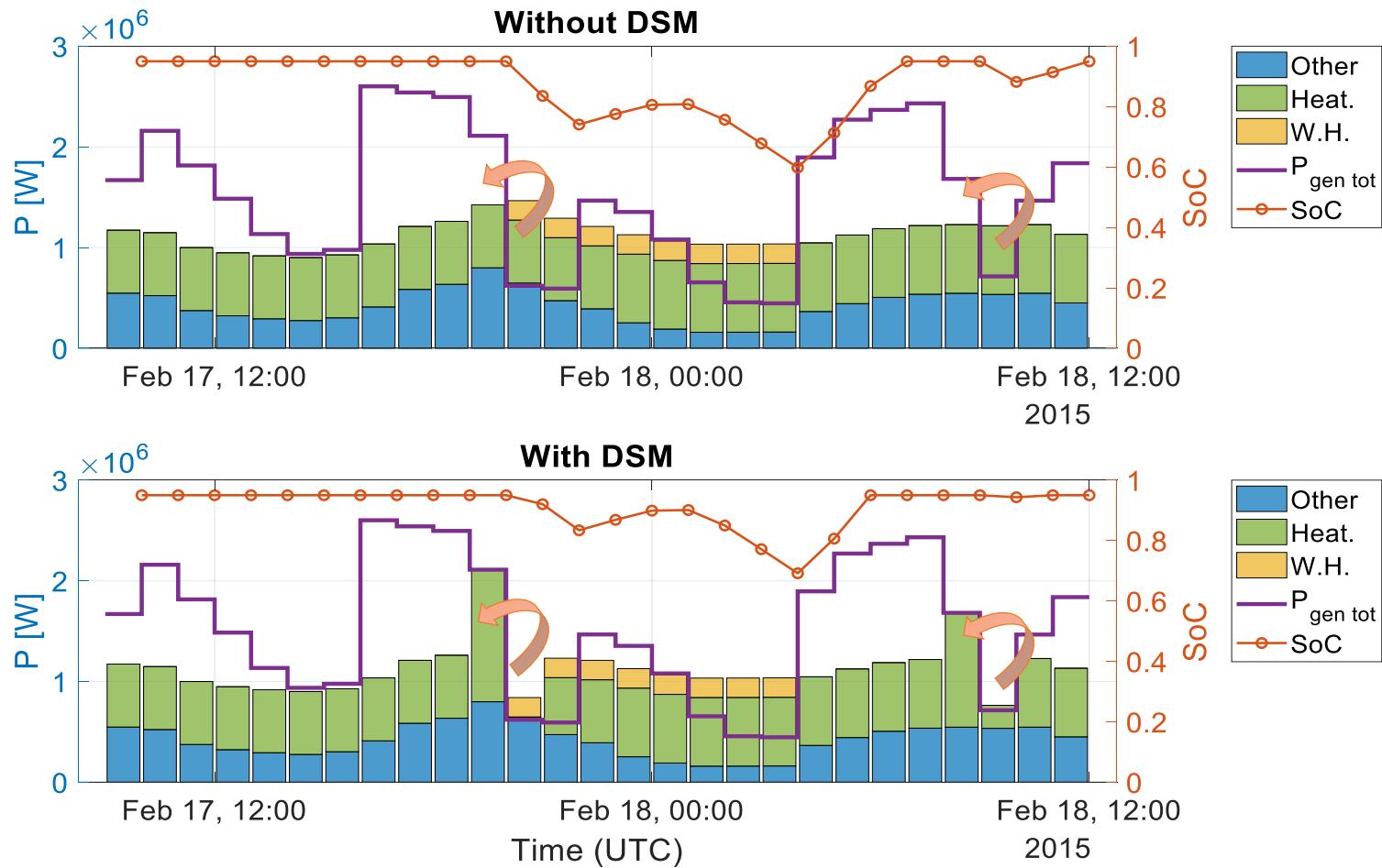
## Electric heating DSM strategy

If  $P_{exc}(t_k) > 0$  and  $P_{exc}(t_{k+B}) < 0$ :

- Electric heating is turned on at  $t_k$ , before the initially planned working time  $t_{k+B}$
- Time window:  $B = \{1 ; 2\}$
- Constraints:  $P_{exc}(t_k)$ ,  $P_{exc}(t_{k+B})$ ,  $P_{HT}(t_k)$  and  $P_{HT}(t_{k+B})$

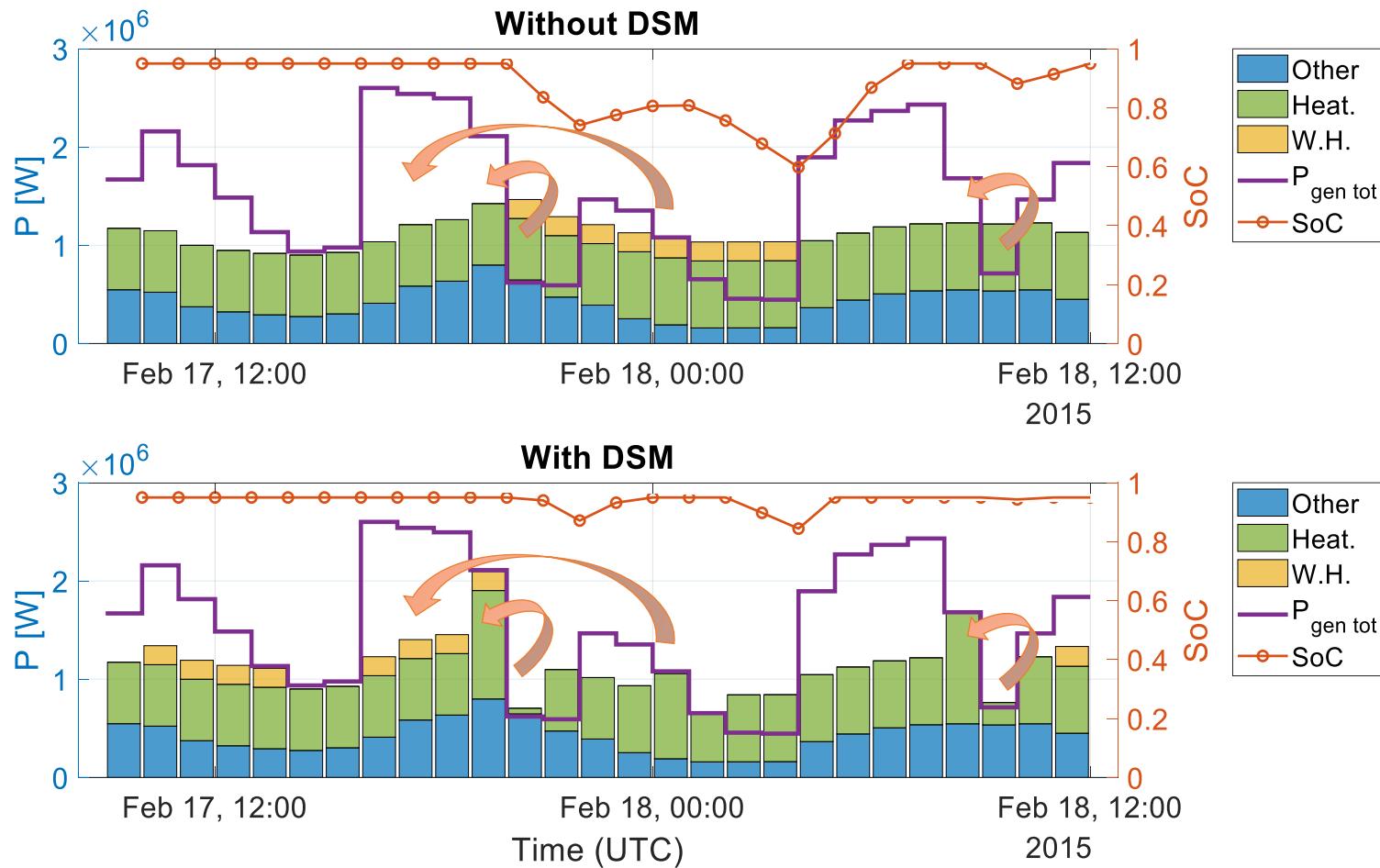
# Demand Side Management strategies

## Electric heating DSM strategy



# Demand Side Management strategies

## Water heater + Electric heating DSM strategies



# Results

## Observed benefits (simulation carried out for 2011-2015)

- Reliability improvement (unmet load hours and unmet load demand are reduced)
- Battery ageing is slowed down
- Number of batteries required for the demand to be fully satisfied could be reduced, allowing the costs to be reduced (LCOE)

| Criteria                                                   | Applied DSM strategy | Without DSM | Water heater DSM | Electric Heating DSM | Water heater + Electric Heating DSM |
|------------------------------------------------------------|----------------------|-------------|------------------|----------------------|-------------------------------------|
| Unmet load demand energy [%]                               |                      | 0,277       | 0,252 (- 8,8 %)  | 0,269 (- 2,9 %)      | 0,245 (- 11,5 %)                    |
| Unmet load hours [h]                                       |                      | 161         | 144 (- 10,6 %)   | 155 (- 3,7 %)        | 138 (- 14,3 %)                      |
| Energy supplied by the battery [GWh]                       |                      | 1,12        | 1,02 (-8,5 %)    | 1,01 (- 9,4 %)       | 0,94 (-16,5 %)                      |
| SoH                                                        |                      | 0,95        | 0,954 (+ 0,42%)  | 0,955 (+ 0,53%)      | 0,958 (+ 0,84%)                     |
| Number of batteries required $N_{bat\ req}$ (for LPSP = 0) |                      | 34          | 33               | 33                   | 33                                  |
| LCOE according to $N_{bat\ req}$ [€/kWh]                   |                      | 0,466       | 0,458 (- 1,6 %)  | 0,458 (- 1,6 %)      | 0,458 (- 1,6 %)                     |

# Results

## Global behavior of the developed DSM strategies, according to the load factor (*LF*) evaluation

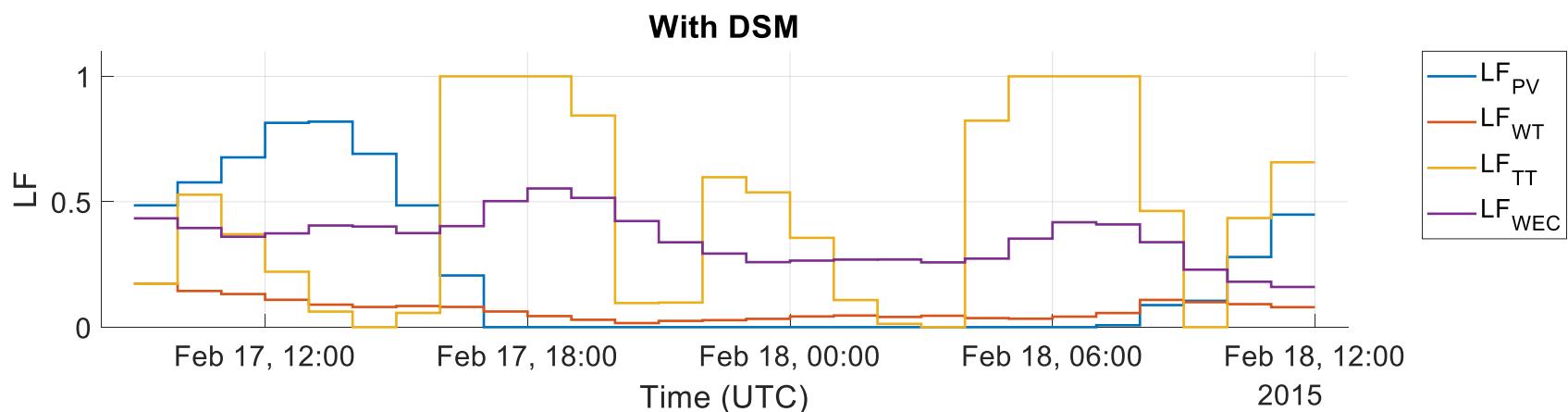
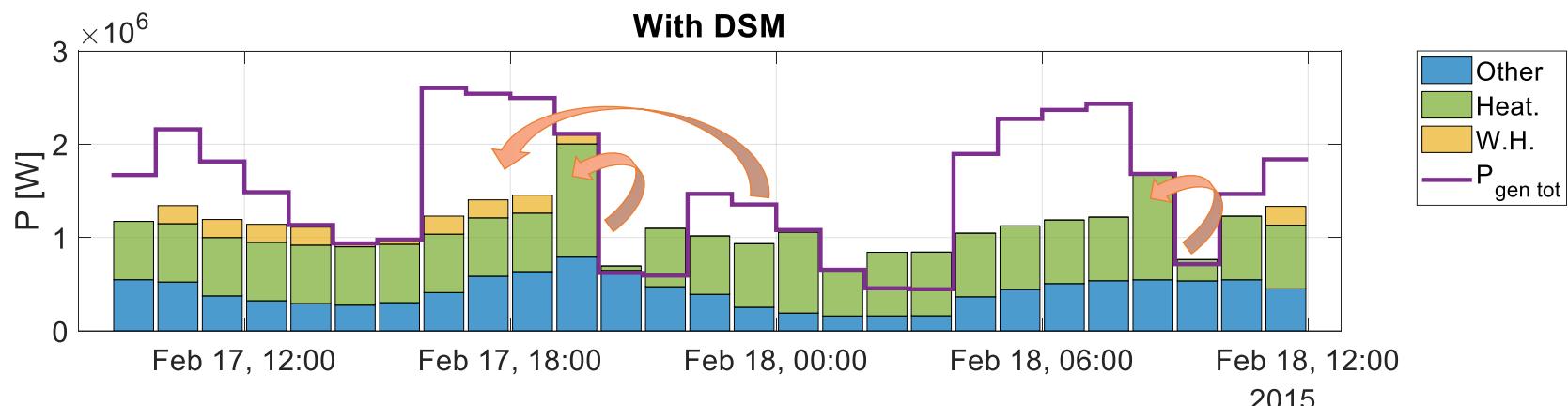
- Water heater demand is shifted at high PV energy load factor occurrences (during the day)
- Electric heating is shifted from a period with low tidal energy load factor to a period for which tidal energy load factor is high (high variability of tidal currents)

$$LF = \frac{E_{generated,real}}{E_{generated,max}}$$

| Considered occurrences for average <i>LF</i> evaluation | $LF_{PV,avg}$ | $LF_{WT,avg}$ | $LF_{TT,avg}$ | $LF_{WEC,avg}$ |
|---------------------------------------------------------|---------------|---------------|---------------|----------------|
| $P_{WH}$ increased values                               | 0             | 0,574         | 0,364         | 0,273          |
| $P_{WH}$ reduced values                                 | 0,356         | 0,589         | 0,359         | 0,275          |
| $P_{HT}$ increased values                               | 0,118         | 0,047         | 0,059         | 0,130          |
| $P_{HT}$ reduced values                                 | 0,129         | 0,072         | 0,339         | 0,159          |

# Results

**Global behavior of the developed DSM strategies, according to the load factor (*LF*) evaluation**



# Conclusion - Perspectives

## Advance scheduling strategies

- Benefits: reliability, battery ageing, system sizing and costs;
- Infra-day cycles of solar and tidal energies can be considered for the water heater demand scheduling;
- The high infra-day variability of tidal kinetic energy (but predictable) could be considered for the electric heating demand management during the most critical periods (low wind velocity for example)

## Perspectives

- Consider other DSM strategies
  - Load shifting (advance and delay)
  - Load shedding
- Take the decision to apply one of all DSM strategies according to the criticity
- Day-ahead scheduling: Solving the scheduling problem with a meta-heuristic approach for example, with a bi-objective optimization (minimize the unmet load demand and maximize the respect of the initial demand)

# Thank you for your attention

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9 Juillet 2018 – Université de Technologie de Compiègne, France

# Energy management system for a grid-connected wind farm and battery storage hybrid plant via MPC strategy

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# 1. Introduction

The main problem in the employment of wind energy generation is the intermittent nature of wind power and the occasional large fluctuations due to random behaviour of weather conditions.

A feasible technical solution is by integration of battery storage systems (BSSs) with wind farms, to avoid undesirable effects and improved power quality, and energy availability.



The grid scale energy storage project will help solve power shortages, reduce intermittencies and manage summertime peak load to improve the reliability of island electrical infrastructures.

## 2. HYBRID POWER PLANT

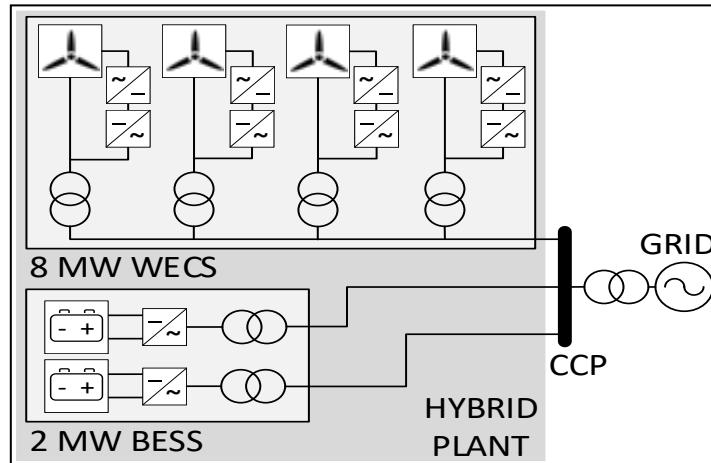


Fig. 1. Wind farm and battery storage hybrid plant

4 packs of batteries Intensium Max 20M of SAFT with a nominal power of 1 MW for a capacity of 580 kWh is considered here.

The EMS has as main objective, to dispatch power from the hybrid wind farm and battery storage plant to the electricity grid according to the variations of electricity price and peak/off-peak periods in a day.



Fig. 2. LI-ION Intensium Max 20M Battery (SAFT)

### 3. Battery Model

Combining the Shepherd's model and a state-space representation, a model is given via an equations system representing the charge and discharge cycles, as follows:

$$V_{ch} = E_0 - R i_{batt} - K_{cr} i^* \frac{Q}{i_t - 0.1Q} - K_{cv} i_t \frac{Q}{Q - i_t}$$

$$V_{dch} = E_0 - R i_{batt} - K_{dr} i^* \frac{Q}{Q - i_t} - K_{dv} i_t \frac{Q}{Q - i_t}$$

Based on this, a dynamic discrete state-space representation is proposed considering a vector of three states as follow:

$$x_1(k+1) = x_1(k) + u(k+1) \Delta$$

$$x_2(k+1) = \alpha u(k+1) + (1 - \alpha) x_2(k)$$

$$x_3(k+1) = 1 - \frac{x_1(k+1)}{Q}$$



$$x(k+1) = Ax(k) + Bu(k)$$

$$y(k) = Cx(k) + Du(k)$$

# 4. Model Validation

*Manufacturer's cell parameters*

| PARAMETER                 | SYMBOL            | VALUE   |
|---------------------------|-------------------|---------|
| Battery capacity          | $Q$               | 41 Ah   |
| Nominal capacity          | $Q_{\text{nom}}$  | 39 Ah   |
| Exponential capacity      | $Q_{\text{exp}}$  | 1 Ah    |
| Full charge voltage       | $V_{\text{full}}$ | 3.95 V  |
| Nominal voltage           | $V_{\text{nom}}$  | 3.6 V   |
| Exponential voltage       | $V_{\text{exp}}$  | 3.9 V   |
| Nominal discharge current | $I_{\text{nom}}$  | 13.67 A |

The voltage curve is presented as a function of the time for a constant discharge current of  $I_{\text{nom}}/3$  A. The minimum voltage for the battery to work is 609 V, therefore, the battery duration in these conditions is approximately 4.13 hours.

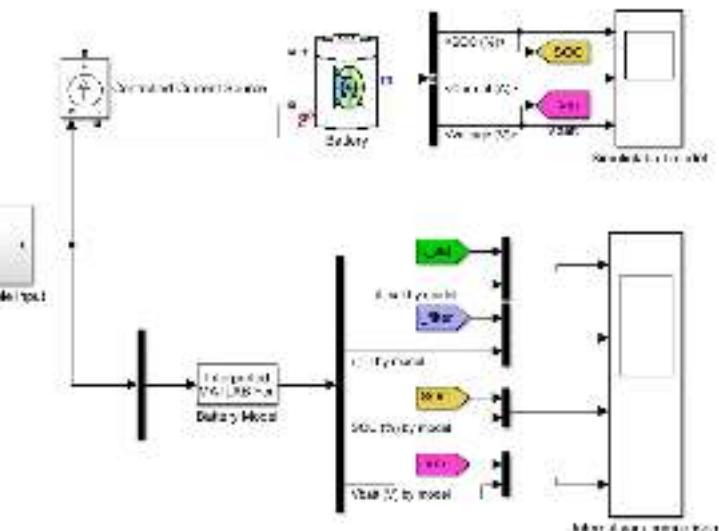


Fig. 3. Block diagram in Simulink for model validation

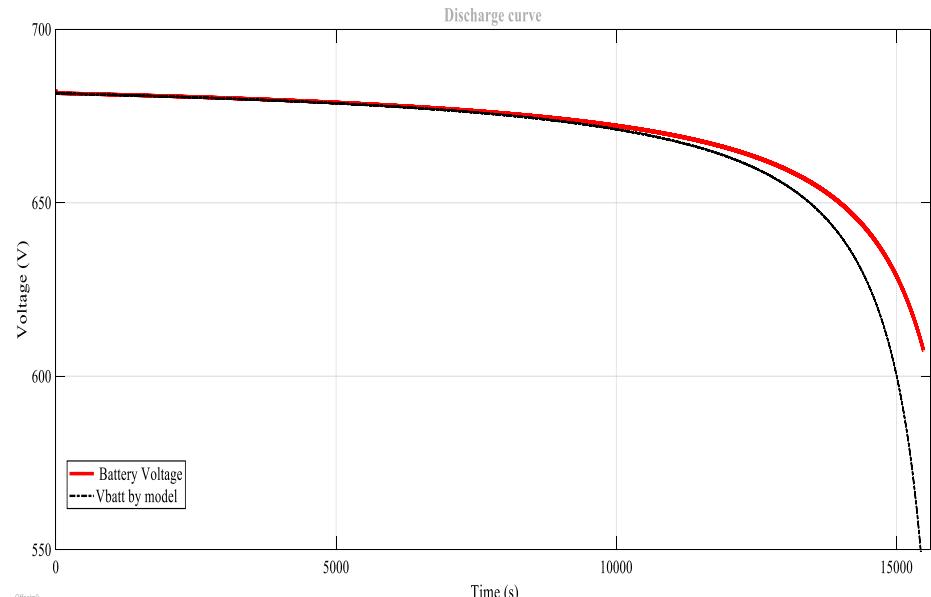
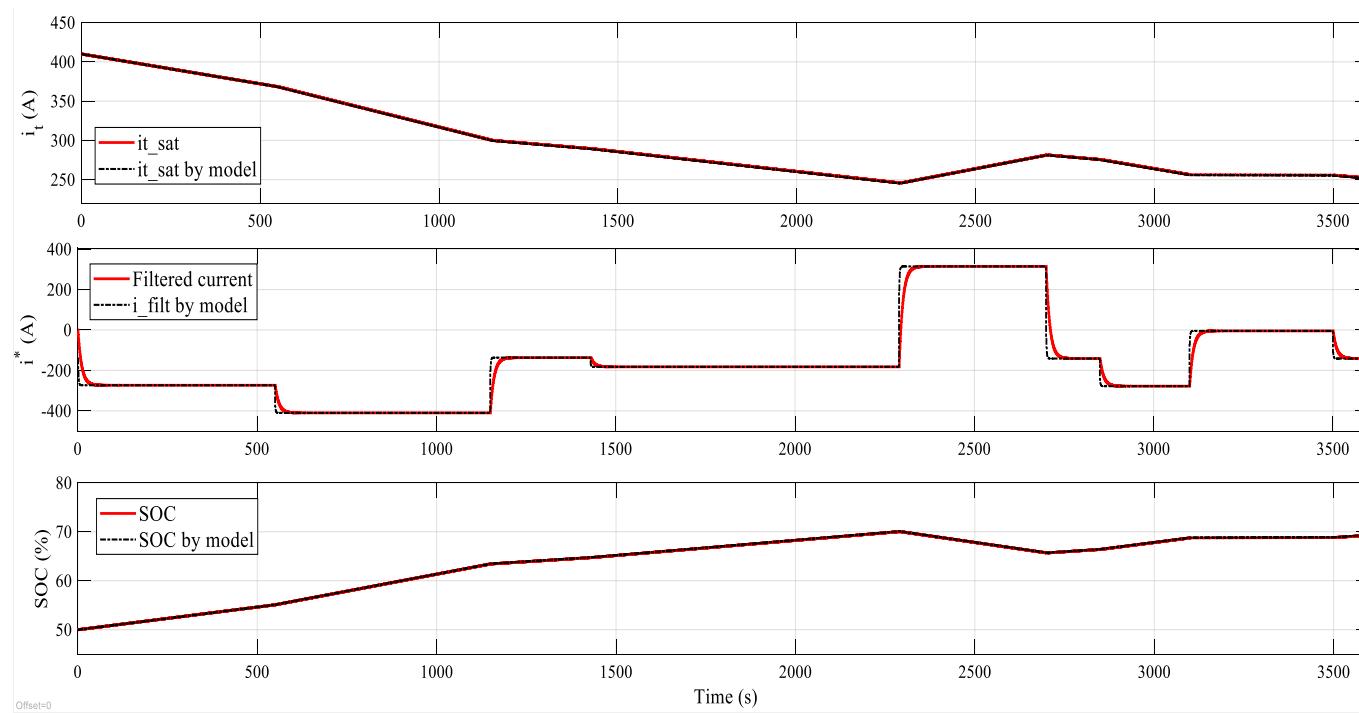


Fig. 4. Battery discharge curve obtained from the proposed model

# 4. Model Validation



*Fig. 5. Dynamic of states described by proposed model*

The upper graph shows the actual current battery charge, the middle graph represents the filtered current and the down graph shows state-of-charge. Likewise, the SOC allows appreciate the battery charge and discharge modes, in response to a variable input.

# MPC Control Strategy

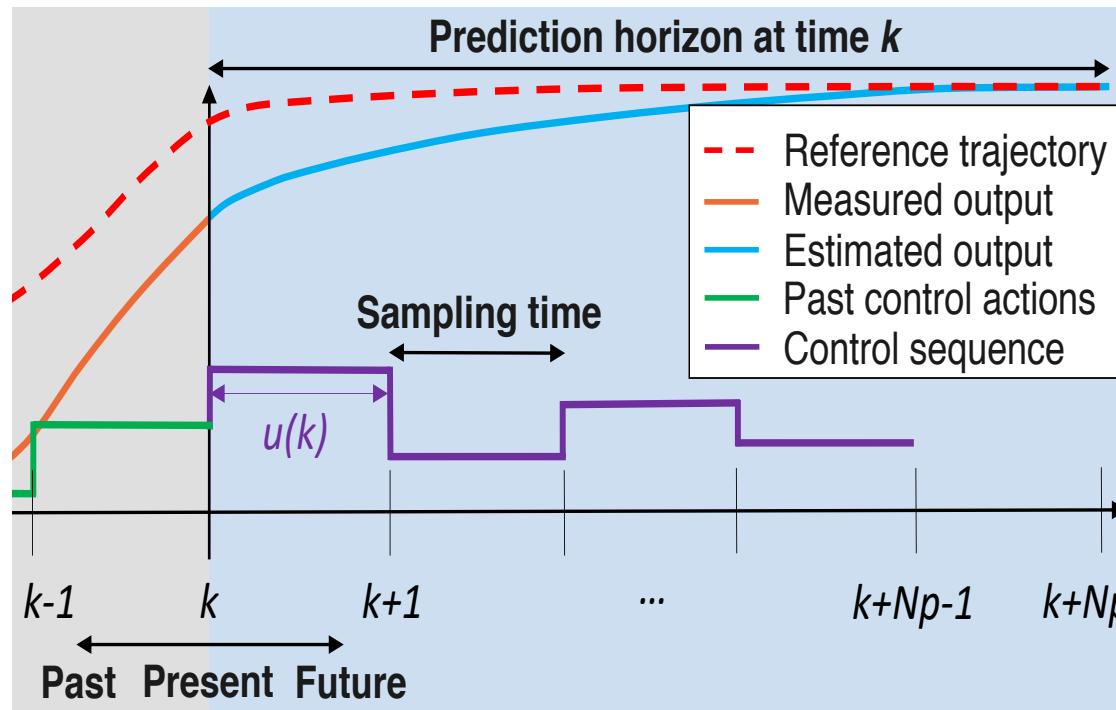


Fig.6. MPC Strategy

Model Predictive Control (MPC) strategy calculates a set of future control actions optimizing a cost criterion to keep the system as close as possible to a predefined reference trajectory.

For this, a set of [plant measurements](#) and a [trajectory of future references](#), are employed by the MPC to calculate the sequence of control moves optimizing the cost function over a horizon of time called prediction or [optimization horizon](#).

# Control trajectory estimation and Optimization

The battery discrete state-space model is rewritten in a general discrete form given

$$x(k+1) = Ax(k) + Bu(k)$$

$$x(k+2) = Ax(k+1) + Bu(k+1)$$

$$x(k+2) = A^2x(k) + ABu(k) + Bu(k+1)$$



$$x(k+i) = A^i x(k) + [A^{i-1}B, \dots, AB, B] \begin{pmatrix} u(k) \\ \vdots \\ u(k+i-2) \\ u(k+i-1) \end{pmatrix}$$

To build the prediction horizon the future state variables and the estimated outputs are given by:

$$x(k+1), x(k+2), \dots, x(k+N_s)$$

$$y(k+1), y(k+2), \dots, y(k+N_s)$$

The future control sequence is given by:

$$u(k), u(k+1), \dots, u(k+N_s - 1)$$

To minimize the control effort and considering the estimated outputs and control actions, the quadratic cost function is:

$$\Gamma_{obj}(k) = \sum_{k=1}^{N_s} \left\{ \|y(k+1|k) - y_{ref}\|^2 + \Phi u(k+1|k)^2 \right\}$$

# Applied to hybrid plant

$$\begin{aligned}\Gamma_{obj}(k) &= \alpha \|P_{inj} - P_{eng}\|^2 + \beta \|SOC_{BESS} - SOC_{ref}\|^2 \\ \Gamma_{obj}(k) &= \alpha \left( \|P_{inj} - (P_{eng} - tol)\| * \|P_{inj} - (P_{eng} + tol)\| \right) \\ &\quad + \beta \|SOC_{BESS} - SOC_{ref}\|^2\end{aligned}\xrightarrow{\text{Subject to}} \begin{array}{l} SOC^{\min} \leq SOC \leq SOC^{\max} \\ i_{charge} \leq i_{batt} \leq i_{discharge} \end{array}$$

To solve this optimization problem the following minimization function is used:

$$\min_x \frac{1}{2} x^T H x + f^T x \quad \text{Such that} \quad A \cdot x \leq b$$

where  $x$  is the states vector that minimizes  $\left( \frac{1}{2} x^T H x + f^T x \right)$

The main objective is to maintain a supply power continuously ( $P_{inj}$ ) in accordance with a predefined injection band:

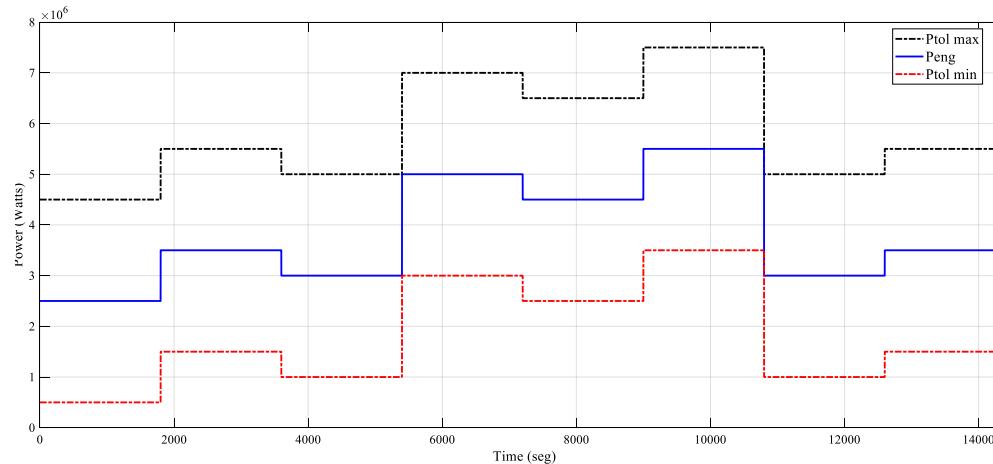
$$P_{inj} = P_{wind} + P_{batt}$$

The calculated reference trajectory required by battery power is:

$$P_{battref} = P_{wind} - P_{eng}$$

# Results

A tolerance level is defined as the 25% of the installed plant generation capacity (8MW), which is:



$$P_{eng} - tol \leq P_{inj} \leq P_{eng} + tol$$

Fig. 7. Engagement power and tolerance limits

$$P_{battref} = P_{wind} - P_{eng}$$

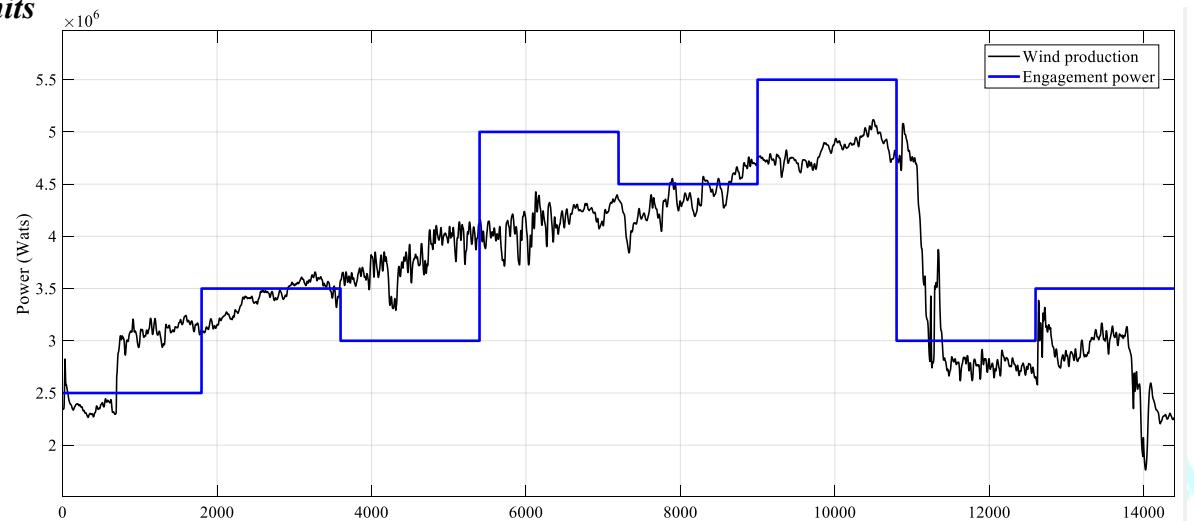


Fig. 8. Wind production power and engagement power profile

# Results

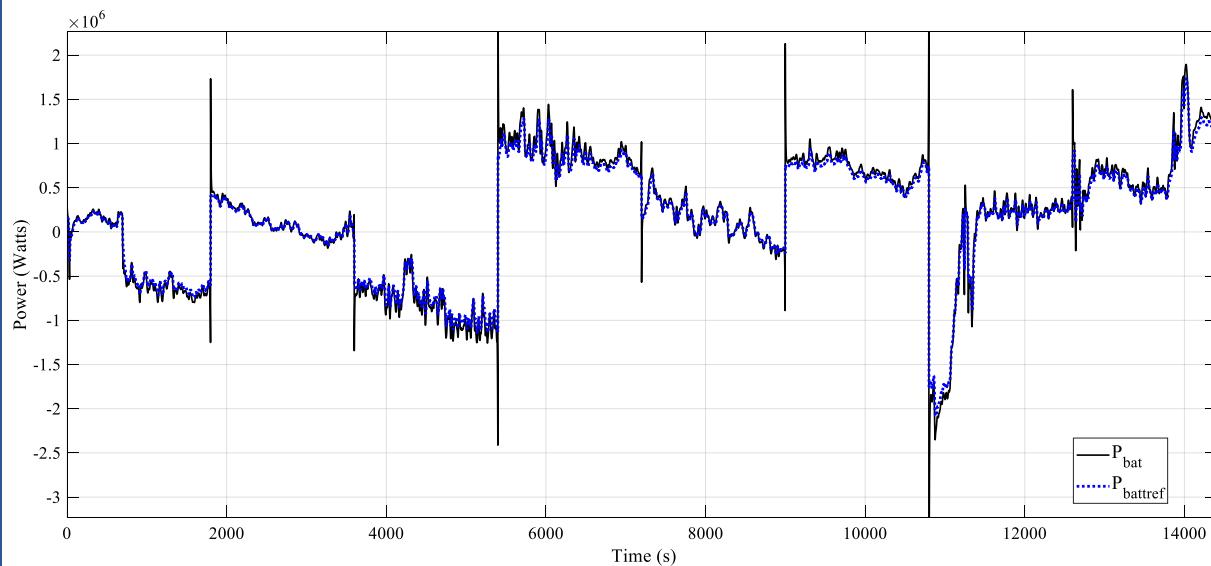


Fig. 9. Reference and measured battery power

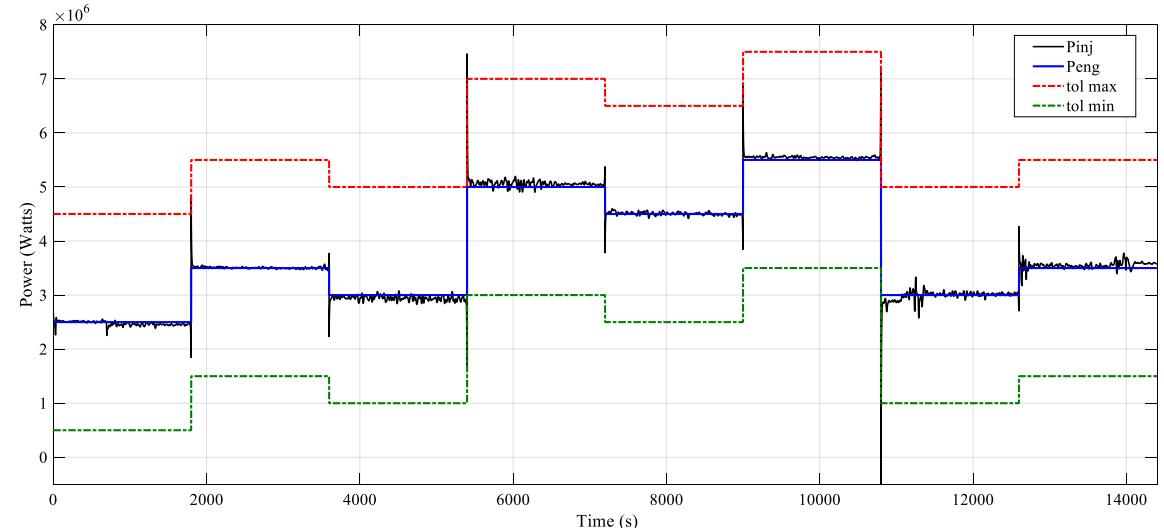


Fig. 10. Engagement power profile and injected power

# Results

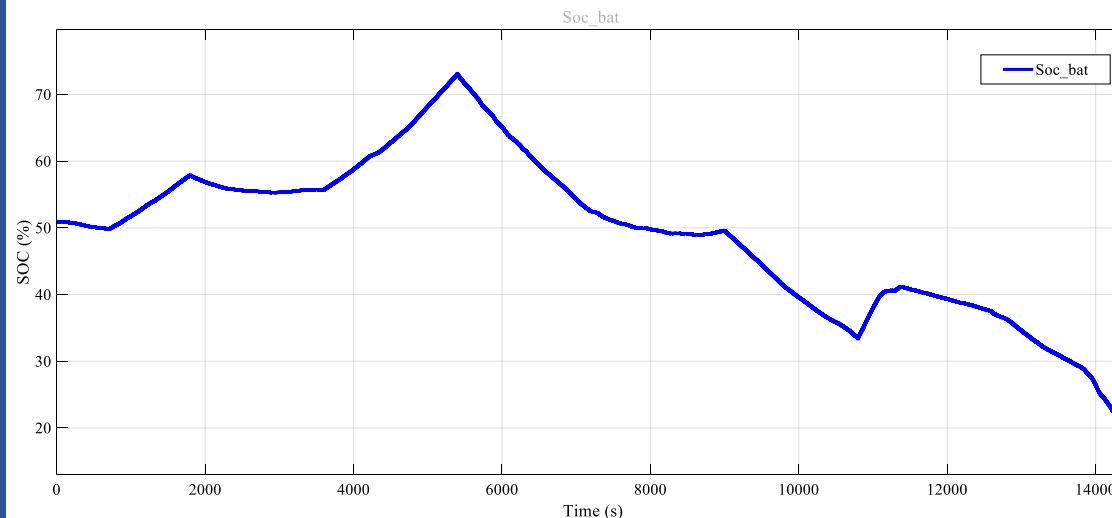


Fig. 11. SOC battery

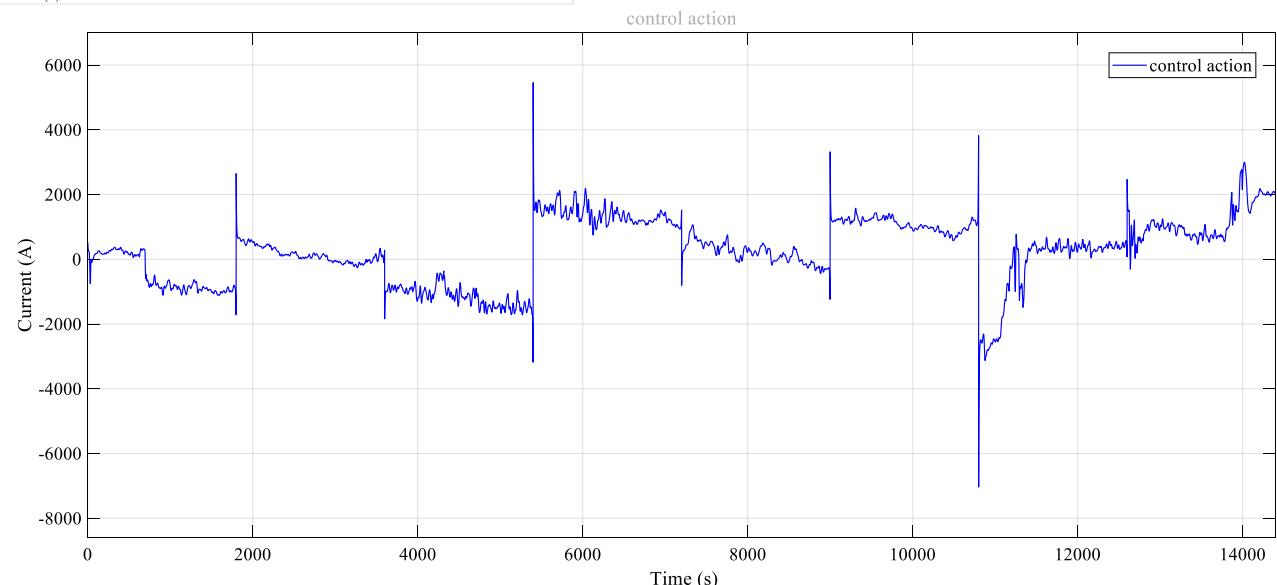


Fig. 12. Control action

# Conclusions

- A model predictive control was designed to manage the power production/injection of an island grid-connected hybrid plant.
- The system combines both, wind energy production with a storage system composed of Li-ION batteries.
- The MPC was developed based on a validated discrete model representing a Li-ION battery system, which was used to predict the future output of the BESS.
- It was proved that the EMS handles suitably the battery's charge / discharge cycles to inject the power into the grid continuously fulfilling the commitment band previously fixed.
- The MPC strategy proposed was tested via ®Matlab by using real wind data.

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# ENERGY MANAGEMENT IN A DC/DC RESONANT CONVERTERS-BASED BATTERY/SUPERCAPACITOR HYBRID SYSTEM

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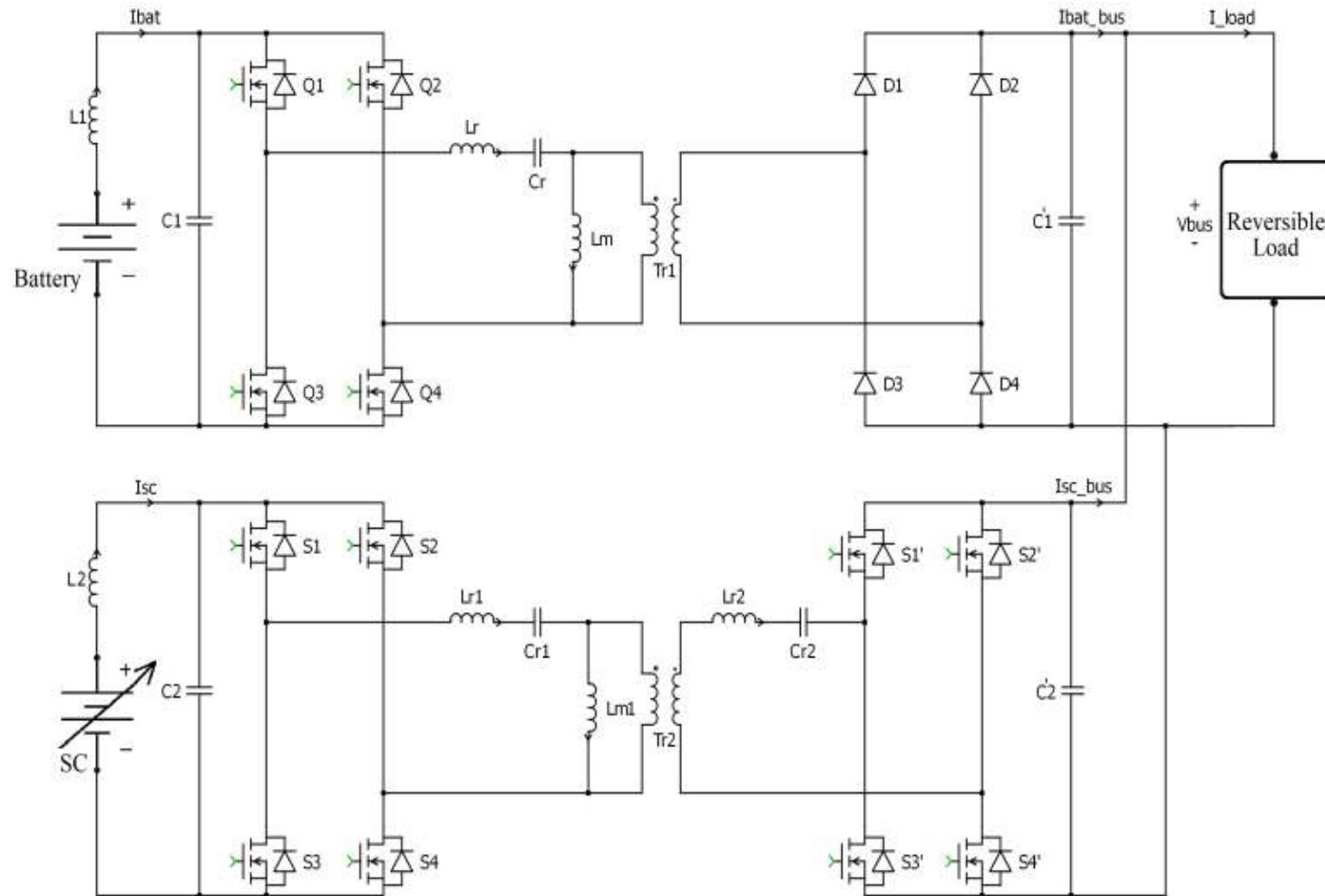
# Plan

- Introduction
- Topologies des convertisseurs DC/DC
- Contrôle et stratégie de gestion d'énergie
- Simulations
- Conclusions et perspectives

## Introduction

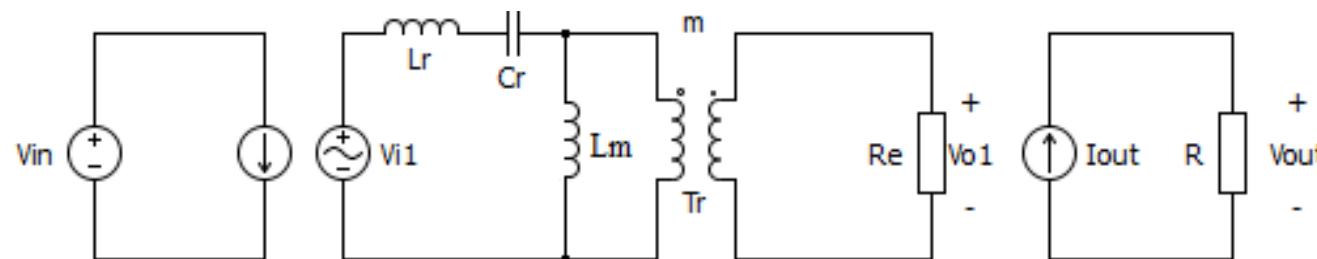
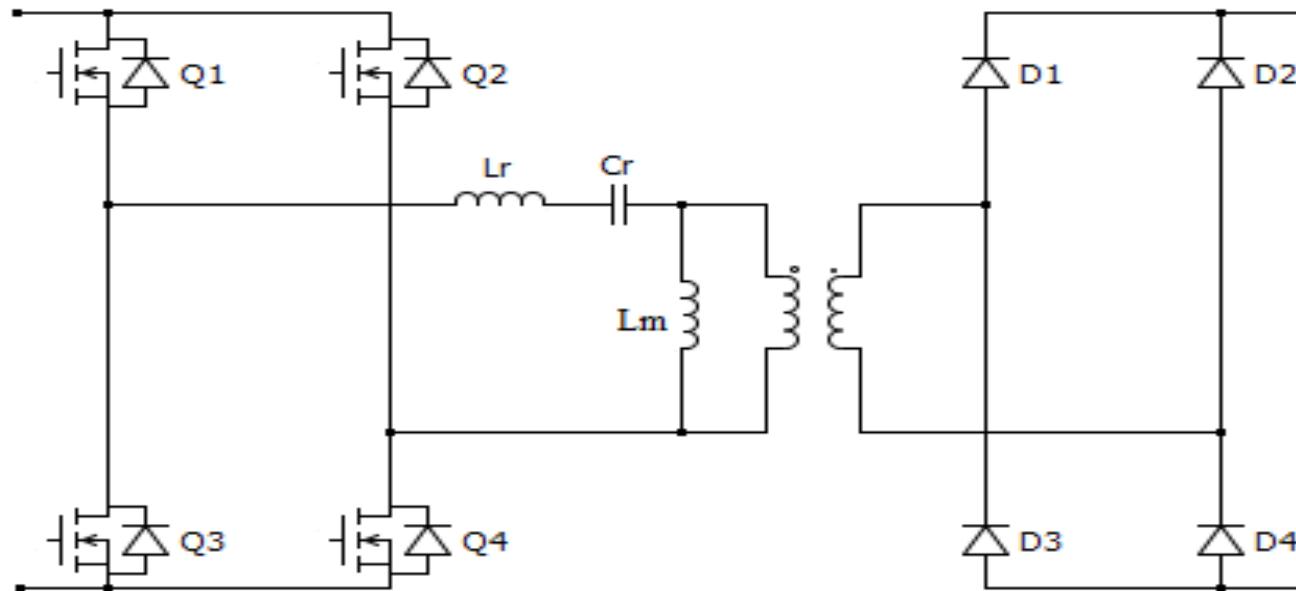
- Systèmes hybrides :
  - Compensation de la dynamique lente de la source d'énergie principale.
  - Absorption de l'énergie récupérée.
  - Minimisation du volume, du poids et du coût du système.
    - ➡ Stratégie de gestion d'énergie.
- Convertisseur DC/DC à résonance:
  - Isolation galvanique.
  - Commutation douce.
  - Forte densité de puissance et rendement élevé.

## Introduction



## Topologies des convertisseurs DC/DC

- Convertisseur à résonance LLC

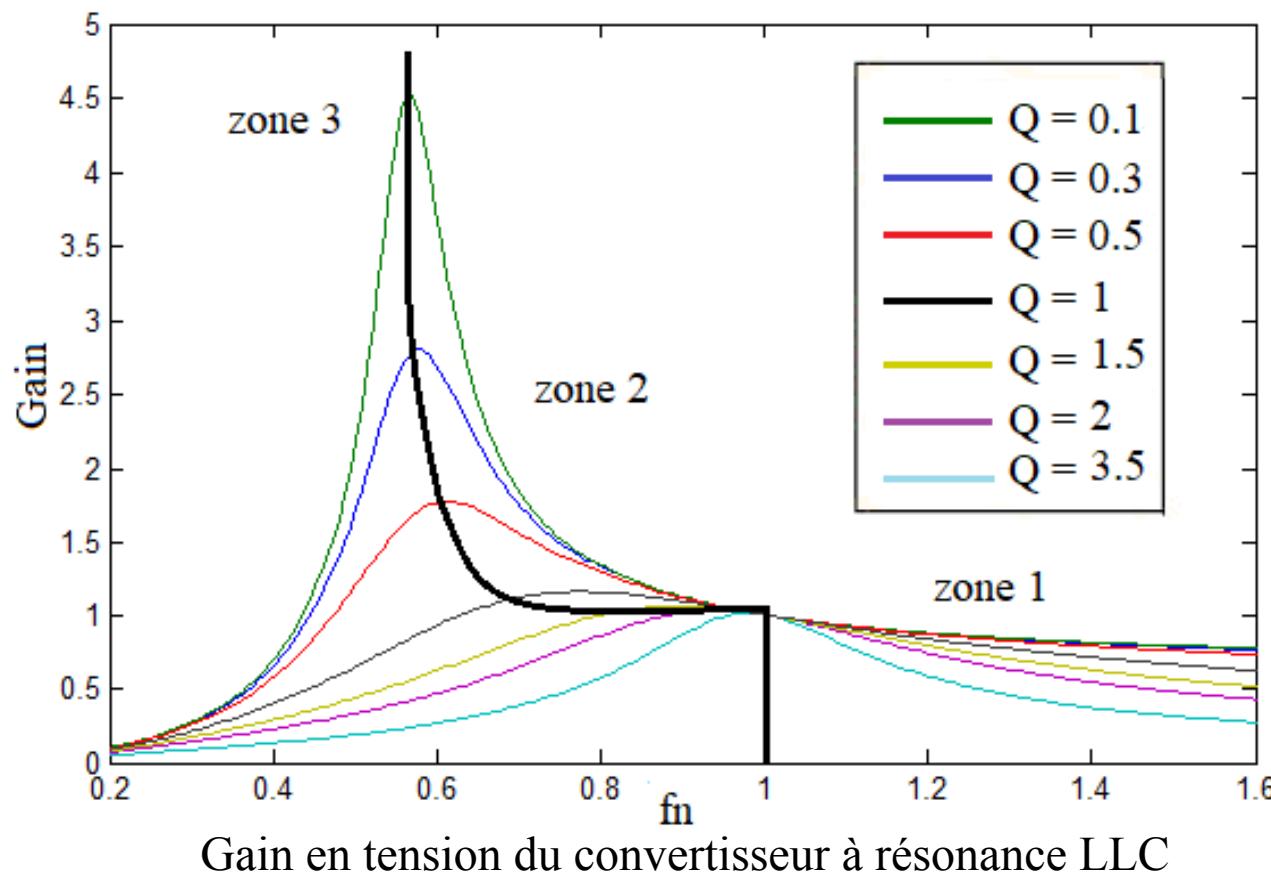


circuit équivalent en utilisant l'approximation de la première harmonique (FHA)

## Topologies des convertisseurs DC/DC

$$\text{Gain en tension : } H = \frac{mV_o}{V_i} = \frac{1}{\left[1 + \gamma - \frac{1}{f_n^2} - \frac{\gamma}{f_n^2}\right] + j\left[Q \cdot \left(\frac{\gamma \cdot f_n}{\gamma + 1} - \frac{1}{f_n}\right)\right]}$$

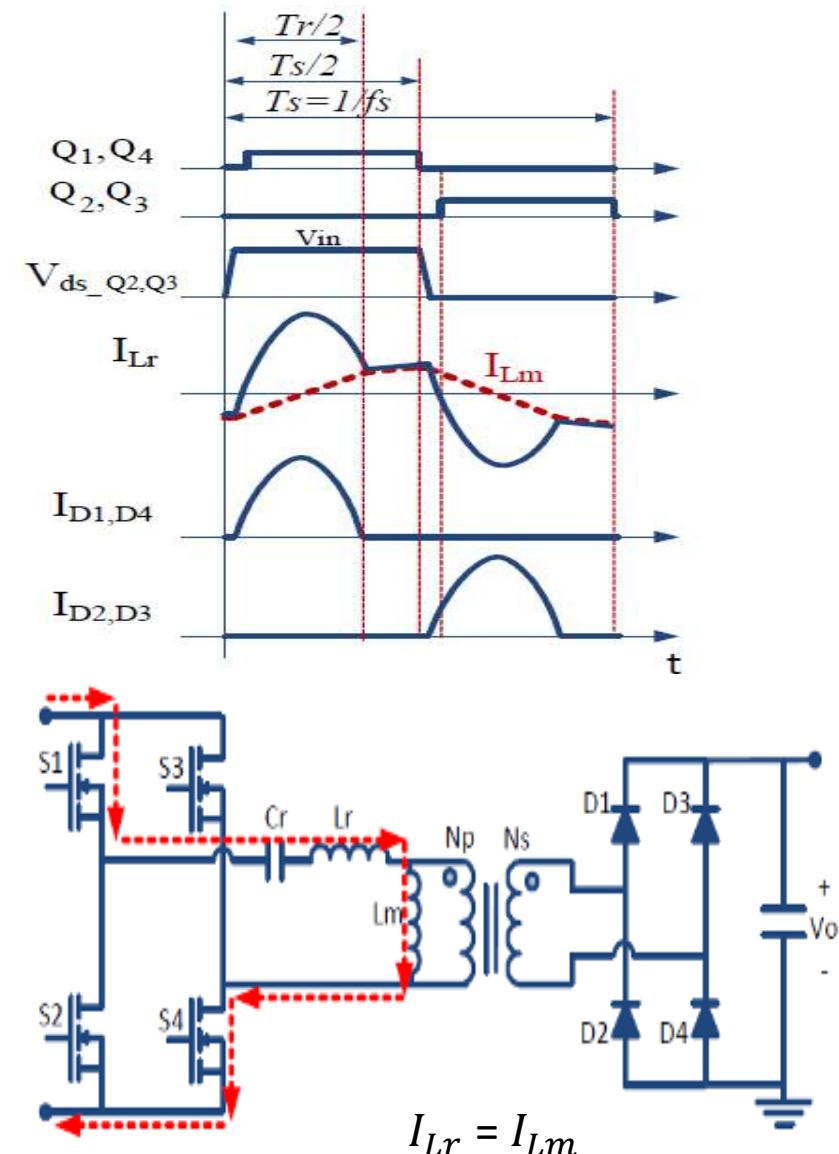
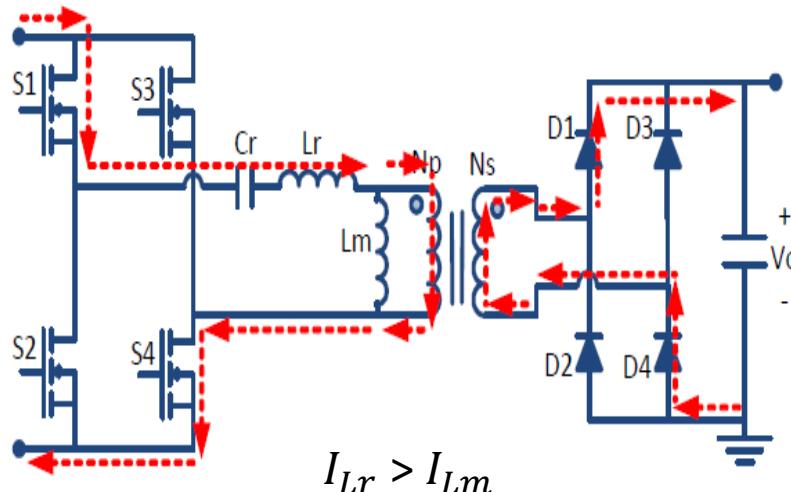
$$\text{Avec : } \gamma = \frac{L_r}{L_p} ; \quad Q = \frac{1}{R_e} \sqrt{\frac{L_e}{C_r}} ; \quad L_e = L_r + L_p ; \quad f_n = \frac{f_s}{f_r} ; \quad f_r = \frac{1}{2\pi\sqrt{L_e C_r}}$$



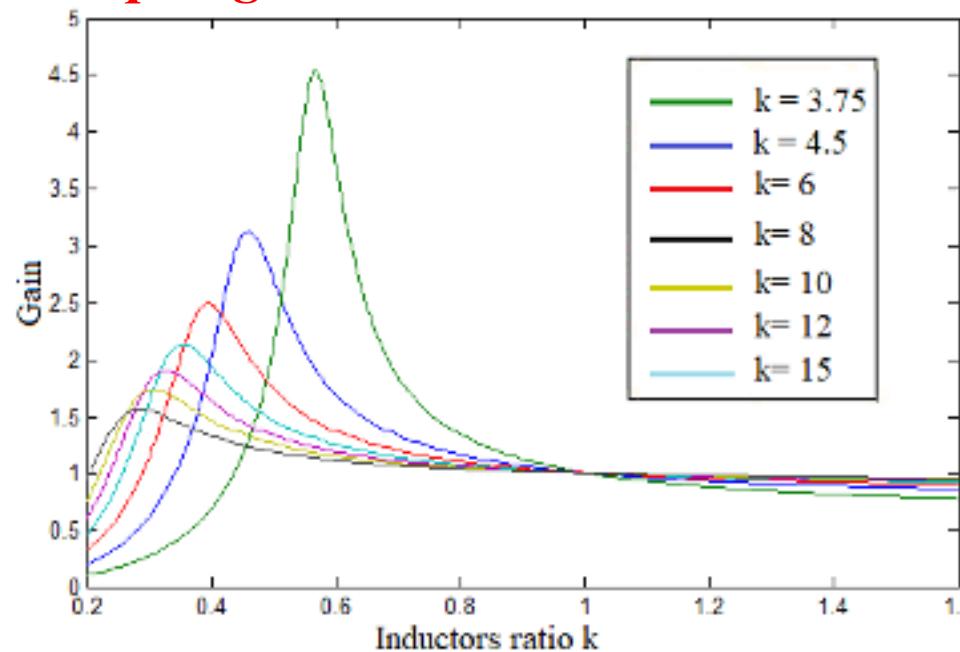
## Topologies des convertisseurs DC/DC

Fonctionnement en dessous de la fréquence de résonance  $F_s < F_r$  :

- ✓ Commutation douce ZVS des MOSFETS et des diodes du secondaire.
- ✓ Fonctionnement BOOST.
- X courants crêtes plus élevés.



## Topologies des convertisseurs DC/DC



Gain en tension du convertisseur à résonance LLC

Paramètres du convertisseur LLC

$$L_r = \frac{Q_{max} \cdot R_{min}}{2\pi \cdot f_{r1}}$$

$$L_m = k \cdot L_r \quad \text{et} \quad L_m \leq \frac{t_{dt}}{16C_{oss}f_{r1}}$$

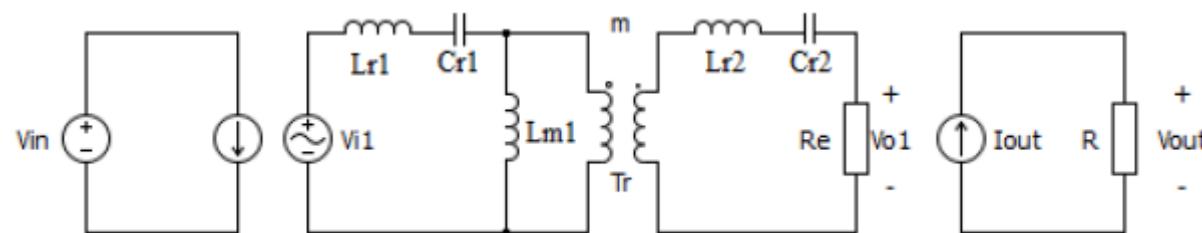
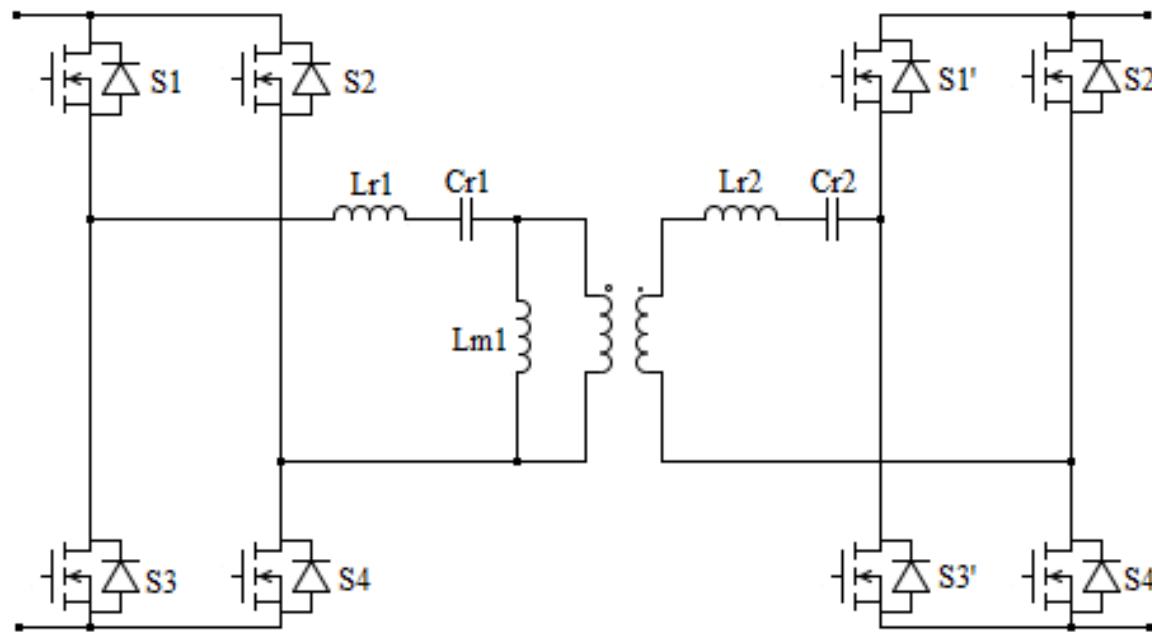
$$C_r = \frac{1}{L_r \cdot (2\pi \cdot f_{r1})^2}$$

Avec :  $Q_{max} = 0,1$ ;  $k = 3,75$ ;  
 $f_{r1} = 83\text{kHz}$

| NAMES                        | PARAMETERS   | VALUES         |
|------------------------------|--------------|----------------|
| Batteries bank voltage range | $V_{bat}$    | 60-100 V       |
| DC-bus voltage               | $V_{bus}$    | 270 V          |
| Transformer turn ratio       | $\eta_{LLC}$ | 4              |
| Magnetizing inductance       | $L_m$        | $15\mu H$      |
| Series resonant inductance   | $L_r$        | $4 \mu H$      |
| Series resonant capacitor    | $C_r$        | $0.9 \mu F$    |
| Series resonant frequency    | $F_{rl}$     | $83\text{kHz}$ |

## Topologies des convertisseurs DC/DC

- Convertisseur bidirectionnel à résonance CLLC

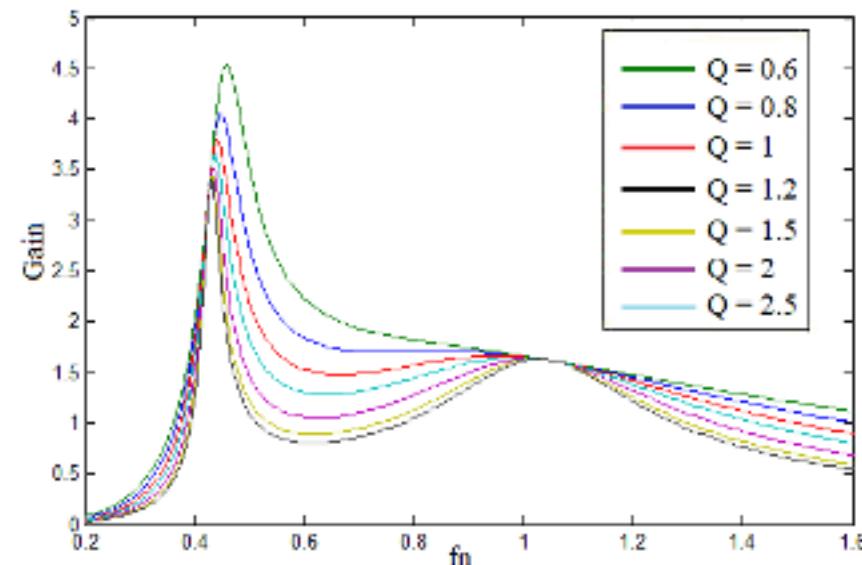


circuit équivalent en utilisant l'approximation (FHA)

## Topologies des convertisseur DC/DC

Gain en tension :  $H = \frac{f_n^3}{(f_n^3 \cdot a) + j(Q^2 \cdot b^2)}$

Avec :  $a = f_n^2(1 + \gamma) + \gamma$   
 $b = f_n^4 - f_n^2(2 + \gamma) + \gamma$



Gain en tension du convertisseur à résonance CLLC en sens direct.

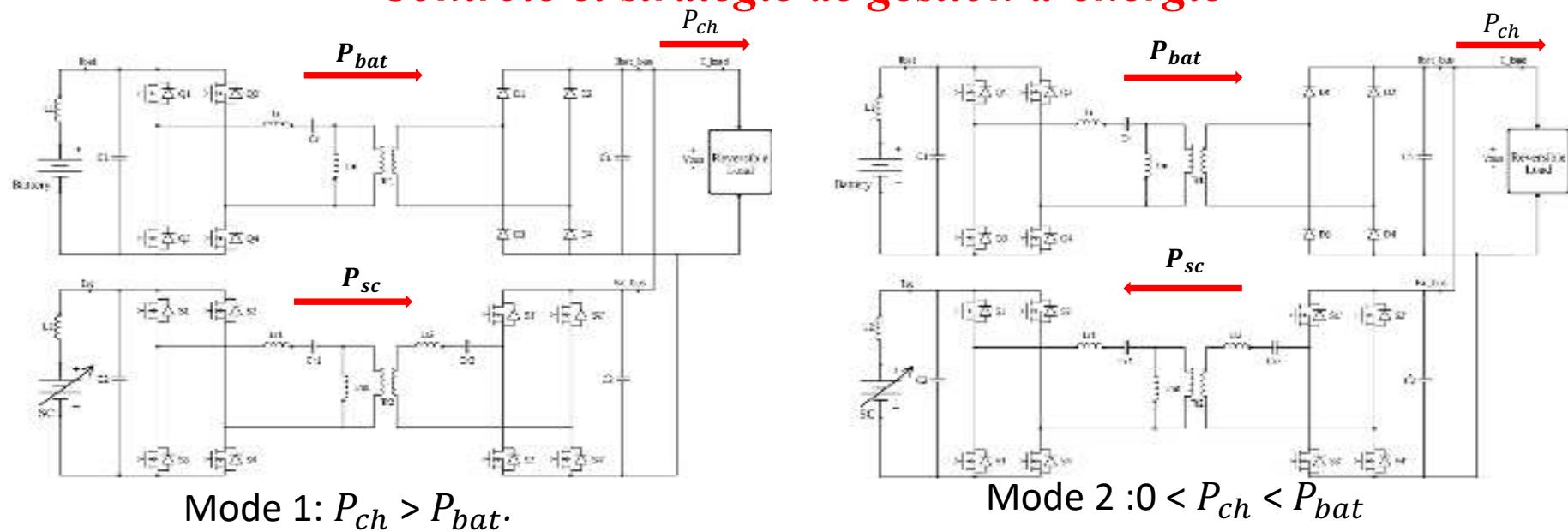
### Paramètres du convertisseur CLLC

| NAMES                                | PARAMETERS    | VALUES       |
|--------------------------------------|---------------|--------------|
| Supercapacitors bank voltage range   | $V_{st}$      | 50-100 V     |
| DC-bus voltage                       | $V_{bus}$     | 270 V        |
| Transformer turn ratio               | $\eta_{CLLC}$ | 4            |
| Magnetizing inductance               | $L_{m1}$      | 15 $\mu H$   |
| Primary series resonant inductance   | $L_{r1}$      | 4 $\mu H$    |
| Primary series resonant capacitor    | $C_{r1}$      | 0.9 $\mu F$  |
| Series resonant frequency            | $F_{rf}$      | 8.3 kHz      |
| Secondary series resonant inductance | $L_{r2}$      | 65 $\mu H$   |
| Secondary series resonant capacitor  | $C_{r2}$      | 0.09 $\mu F$ |
| Secondary resonant frequency         | $F_{r2}$      | 65 kHz       |

## *Contrôle et stratégie de gestion d'énergie*

- L'approche proposée pour la gestion d'énergie s'appuie sur les caractéristiques dynamiques des différentes sources.
- La batterie assure la puissance moyenne de la charge et la variation de la puissance est assurée par les supercondensateurs suite à la rapidité de leur réponse dynamique.
- La bidirectionnalité du convertisseur à résonance CLLC permet d'assurer la charge et la décharge des supercondensateurs selon les modes de fonctionnement suivants :

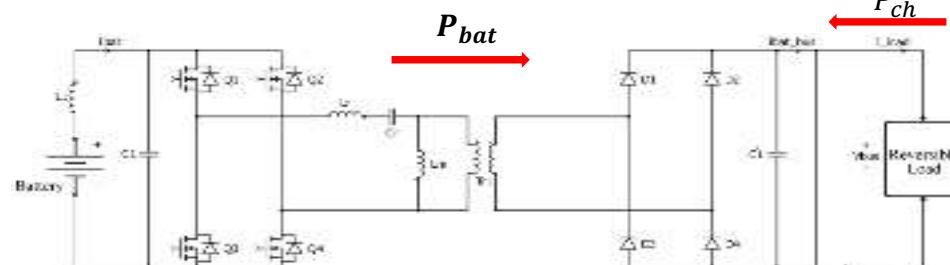
## Contrôle et stratégie de gestion d'énergie



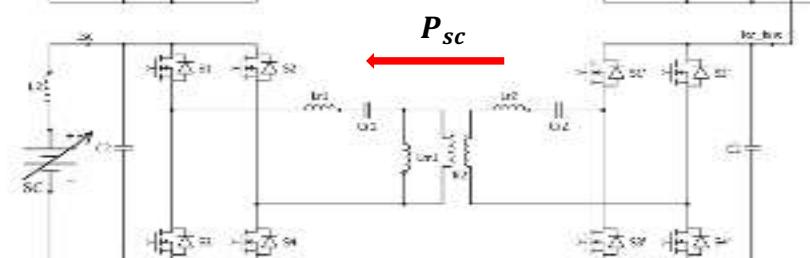
Mode 1:  $P_{ch} > P_{bat}$ .

Mode 2 :  $0 < P_{ch} < P_{bat}$

$P_{ch}$



$P_{sc}$

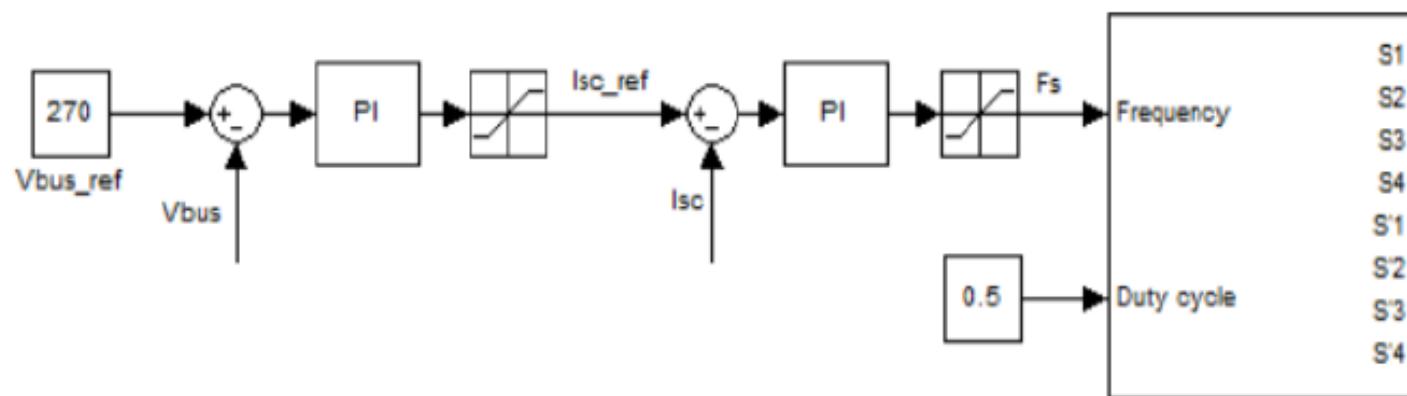


Mode 3:  $P_{ch} < 0$

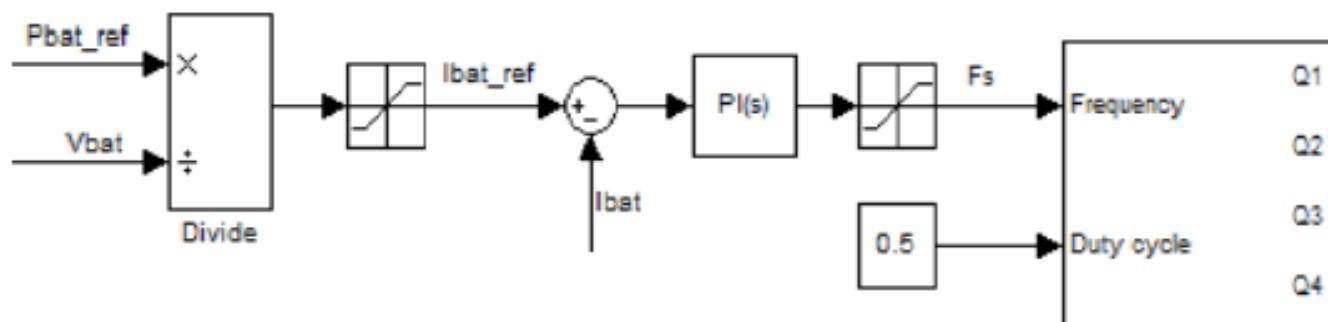
## Contrôle et stratégie de gestion d'énergie

- contrôle de la tension du bus CC

Le schéma de commande est composé de deux boucles en cascade, où la boucle externe contrôle la tension du bus et la boucle interne contrôle le courant des supercondensateurs selon la variation de la charge .

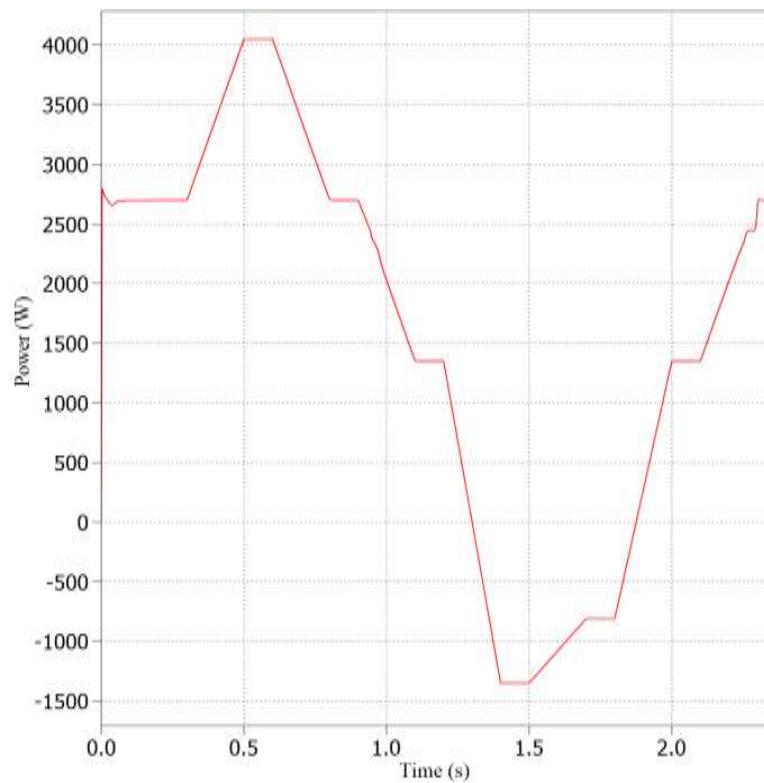


- Contrôle de la puissance de la batterie :



## Simulations

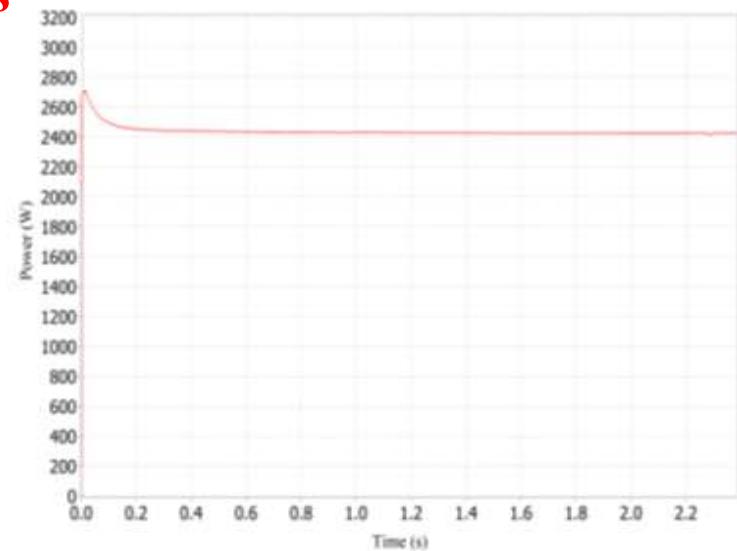
- Afin de valider la configuration et la stratégie de gestion d'énergie proposée pour le système hybride étudié, un profil aléatoire de puissance de charge est appliqué :



Profil de puissance de la charge

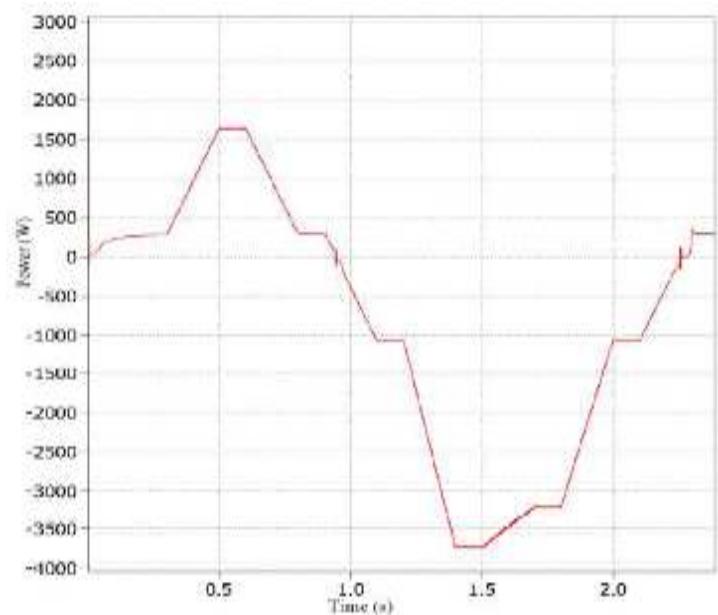
## Simulations

- la puissance fournie par la batterie est constante et elle n'est pas affectée par la variation de la puissance de charge. De cette manière, la durée de vie de la batterie peut être prolongée en évitant la décharge rapide.



Puissance fournie par la batterie

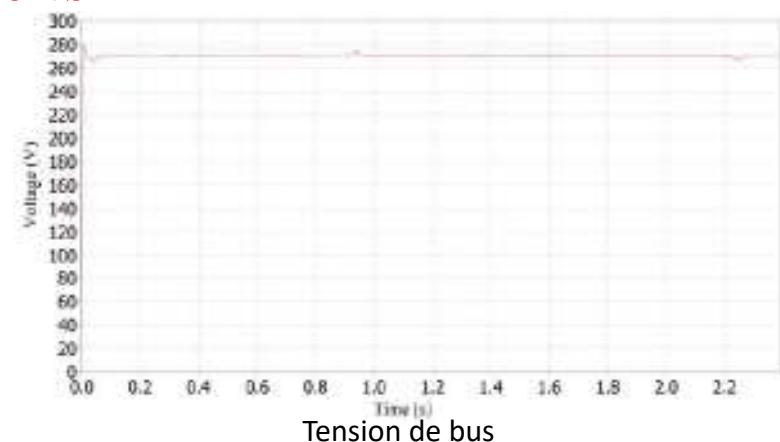
- Les variations de la puissance de charge sont assurées par les supercondensateurs qui sont caractérisés par la rapidité de la réponse dynamique.
- La puissance renvoyée par la charge est absorbée par les supercondensateurs ( $P_{sc} < 0$ )



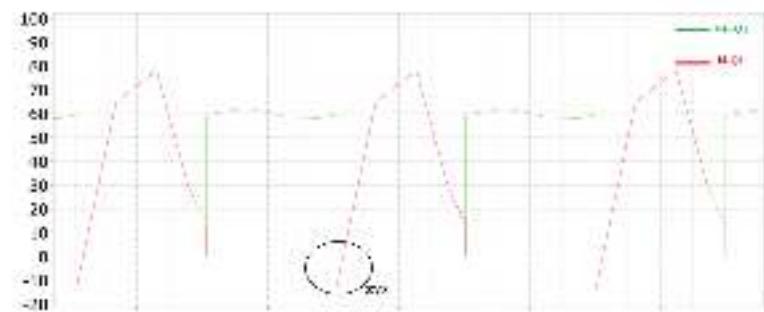
Puissance fournie par les supercondensateurs

## Simulations

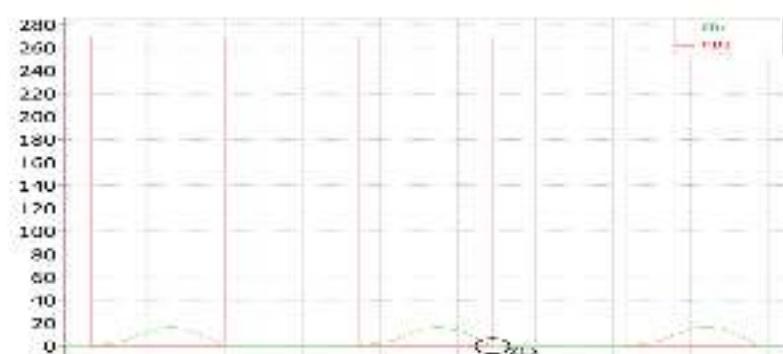
- La tension de bus suit exactement la référence fixée à 270V.



- les MOSFET primaires du convertisseur LLC peuvent atteindre ZVS, et les diodes de redressement fonctionnent en ZCS pour toutes valeurs de charge.



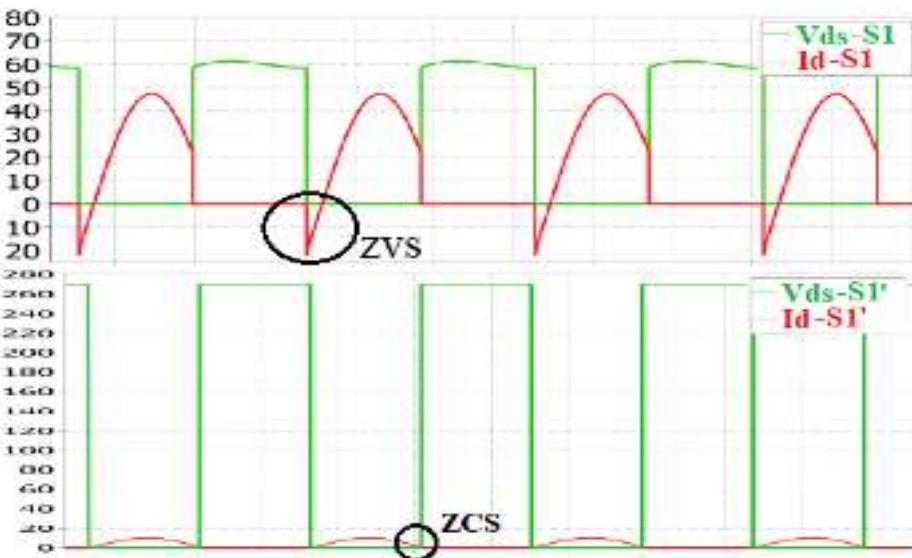
Tension  $V_{ds}$  et courant  $I_d$  du MOSFET Q1 du convertisseur LLC



Tension  $V_D$  et courant  $I_D$  des diodes du convertisseur LLC

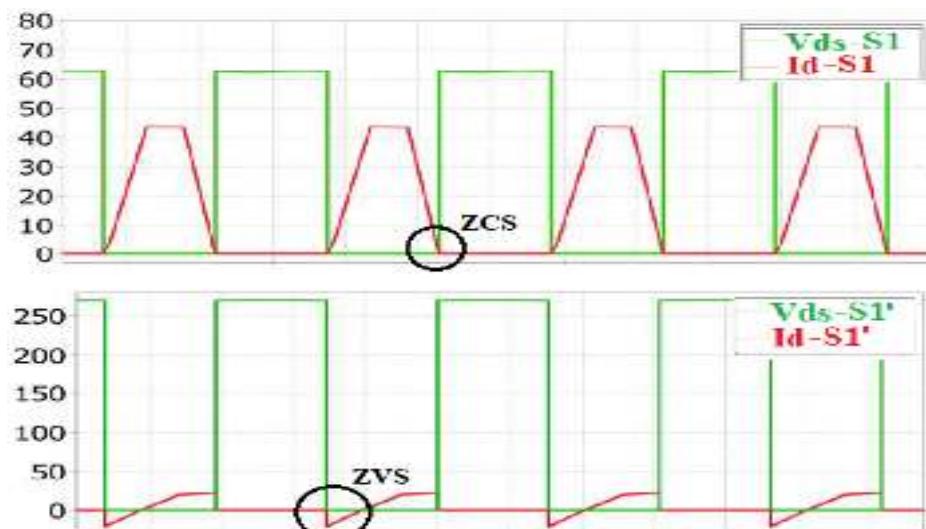
## Simulations

- Durant le mode 1, le convertisseur CLLC fonctionne en sens direct, Les MOSFET primaires s'amorcent en ZVS et les diodes de secondaire fonctionnent en ZCS.



Tension  $V_{ds}$  et courant  $I_d$  des MOSFET primaires et secondaires du convertisseur CLLC en sens direct de fonctionnement.

- Durant le mode 2 et 3 , le convertisseur CLLC fonctionne en sens inverse, Les diodes des MOSFET primaires se bloquent en ZCS et les MOSFET du secondaire fonctionnent en ZVS.



Tension  $V_{ds}$  et courant  $I_d$  des MOSFET primaires et secondaires du convertisseur CLLC en sens inverse de fonctionnement.

## *Conclusions et perspectives*

- Cet article propose l'utilisation des convertisseurs DC/DC isolés à résonance pour l'association des batteries et supercondensateurs dans un système hybride, et présente une stratégie de gestion d'énergie simple et efficace basée sur les caractéristiques dynamiques des sources.
- Les convertisseurs DC/DC à résonance, permettent d'avoir une structure à très haut rendement et forte densité de puissance.
- Les simulations réalisées valident le fonctionnement de la structure et la stratégie de gestion d'énergie proposée. La batterie fournit la valeur moyenne de la puissance et les supercondensateurs assurent la demande de la charge et la récupération de l'énergie renvoyée.
- Le futur travail sera consacré à l'application d'autre stratégie de gestion d'énergie améliorée.

**Merci pour votre attention**