CENTUM ADETEL
Transportation Solution

Modeling and simulation of an autonomous railway electrical traction system

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Benoît PERON
Antonio PRATA

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Summary

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2. Centum Adetel Transportation Solution products
3. Project description: autonomous railway electrical traction system
4. Aim & work to do
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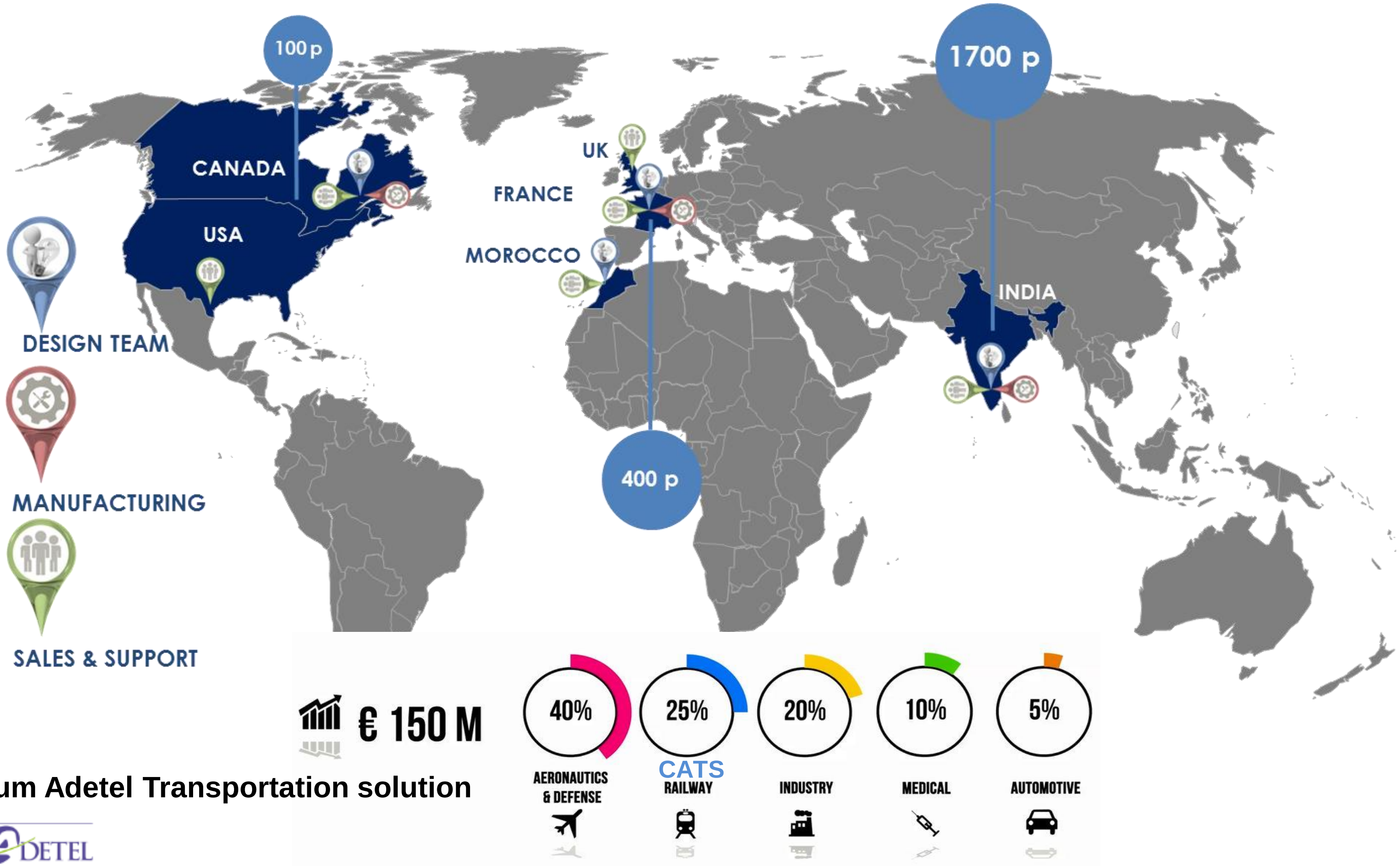
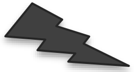
   b) Robustness of the close loops control
   c) ‘Voltage Balancing algorithm’ of the Energy Storage Elements
   d) ‘Current balancing algorithm’ between each boxes
6. Conclusion

Centum Adetel overview



CATS: Centum Adetel Transportation solution

Energy Management Solutions



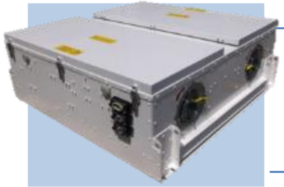
Energy Storage Module

ESM: **E**nergy **S**torage **M**odule with battery, supercap or Lithium Capacitor cells for embedded energy storage applications

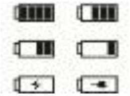
Energy storage pack

ESP: **E**mbedded **E**nergy **S**torage for catenary less or free applications

Auxiliary conversion system



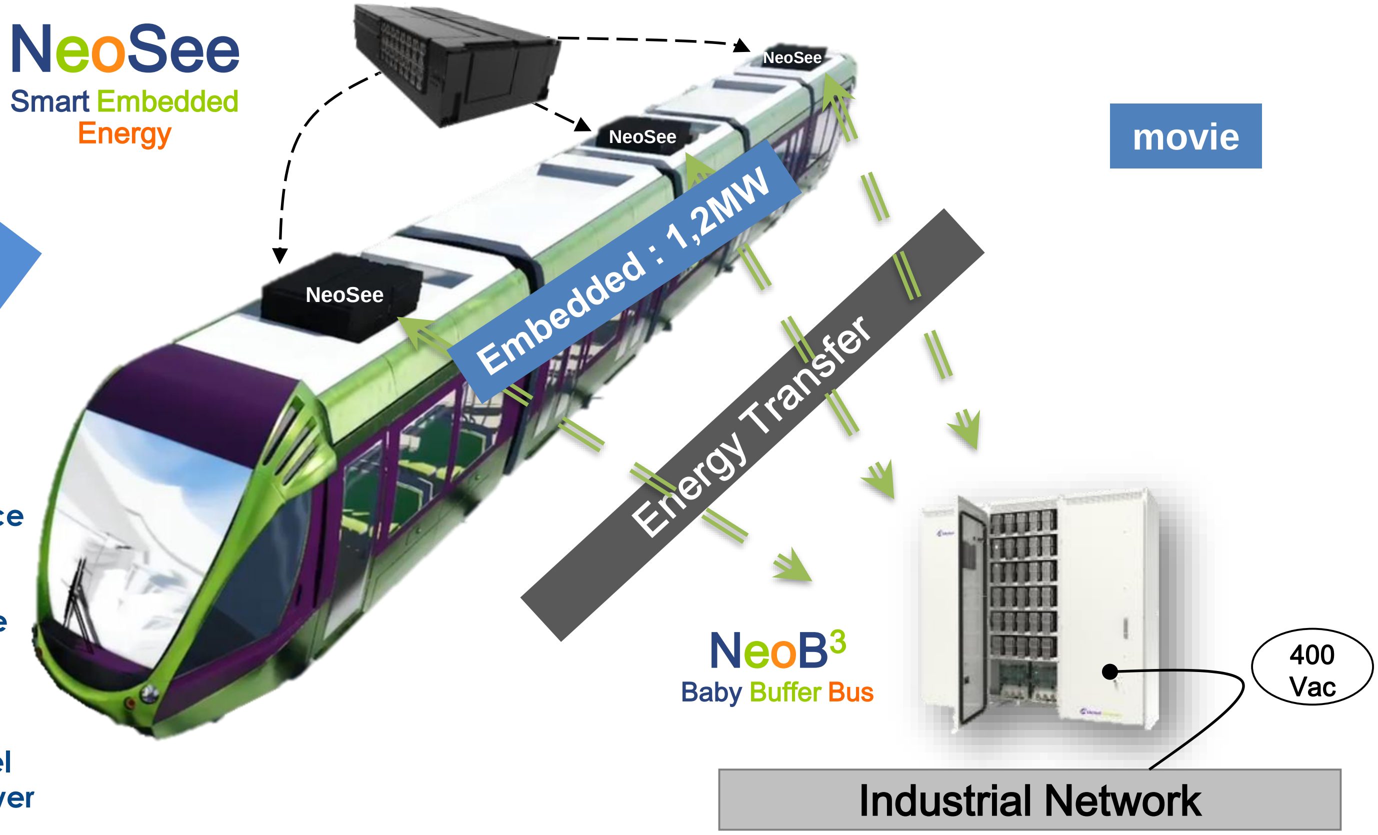
Roof or floor cabinet for auxiliary powering from catenary of TGV, sub urban train, locomotive, metro, tramway, trolley busses.



Energy storage system

Ground Energy Storage cabinet for breaking energy recovery on Substation, voltage stabilisation applications on trackside shelter.
Ultrafast Charging Station for catenary free operations

Autonomous railway electrical traction system

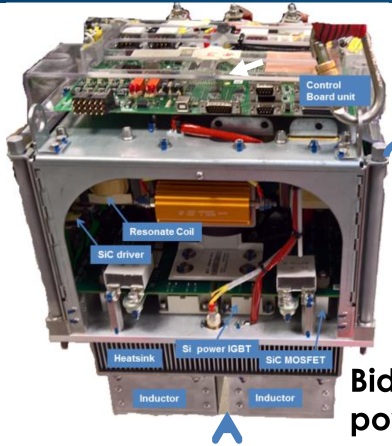


movie

Connection between charging station & vehicle is customer's responsibility

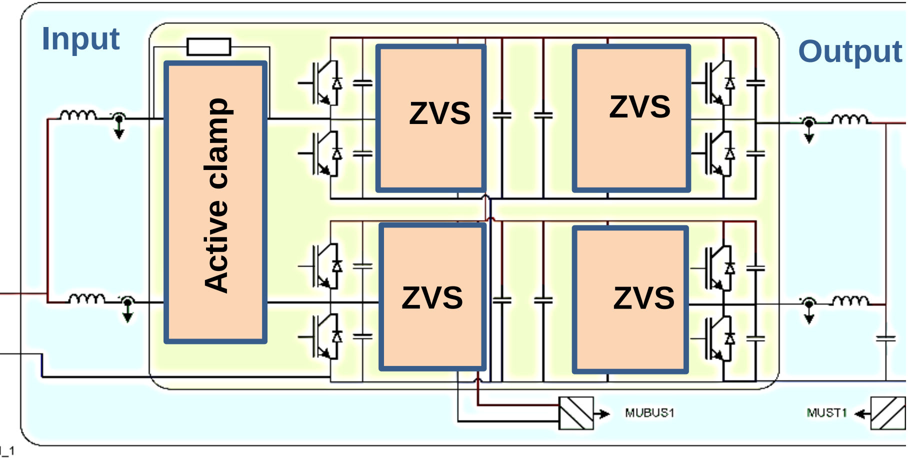
- Nowadays, autonomous railway electrical traction systems are possible thank to the performance of the Lithium Ion Capacitor
- High efficiency system due to the recovered of the kinetic energy
- Using of the Advanced Power Management system from Adetel to balance, in real time, the power between each boxes.

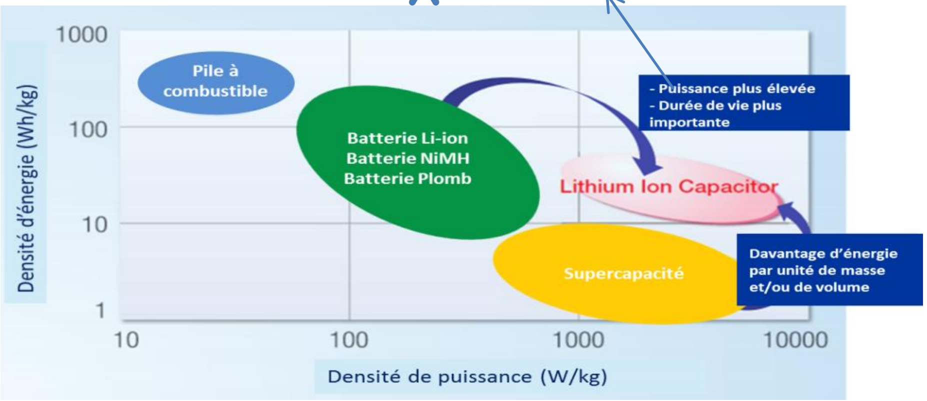
NeoSee description



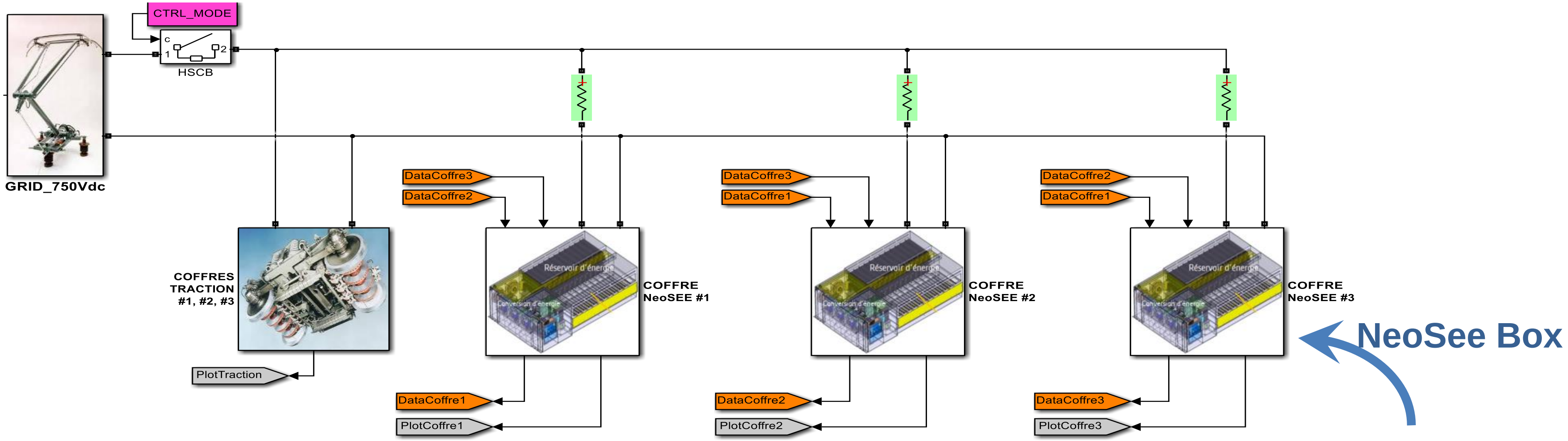
Bidirectional power converter

Lithium capacitor Power module

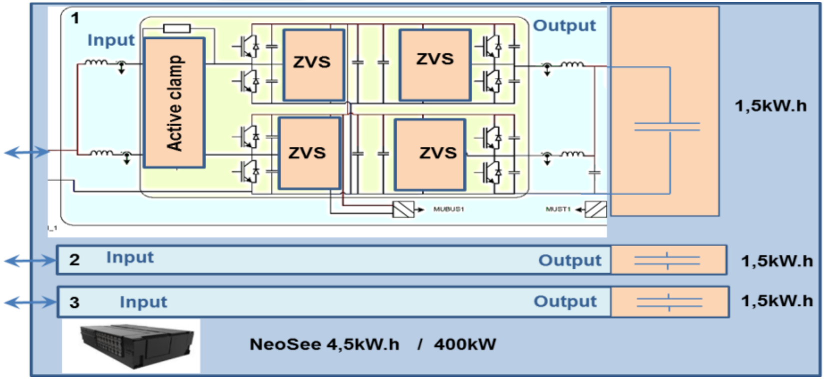




Application description



- Unlike electric vehicle, energy storage in the tramway is spread on the roof, at different position
- It is mandatory to balance the current & voltage in each boxes in Real time
- The balancing control should work in real time to avoid power oscillations: During the recovery the Kinetic energy and when the motor is supplied



Aim

1. Modeling and simulating the electric power system of an "Autonomous" Tramway, supplied either:
   a) by the **E**nergy **S**torage **M**odule
   b) or by the catenary

2. NeoSee boxes should manage the internal voltage of tramway whatever:
   a) the wiring serial resistors
   b) and the physical position of the traction & the auxiliary power supplies

3. The voltage of supercapacitors should be balanced, In each NeoSee boxes, in real time, versus the initial conditions and theirs intrinsic values

4. A numerical control algorithms should be developed and must be compliant with the final target control unit used in the real application

Work to do

1) Development of the Simulink model of the power converter and its digital control

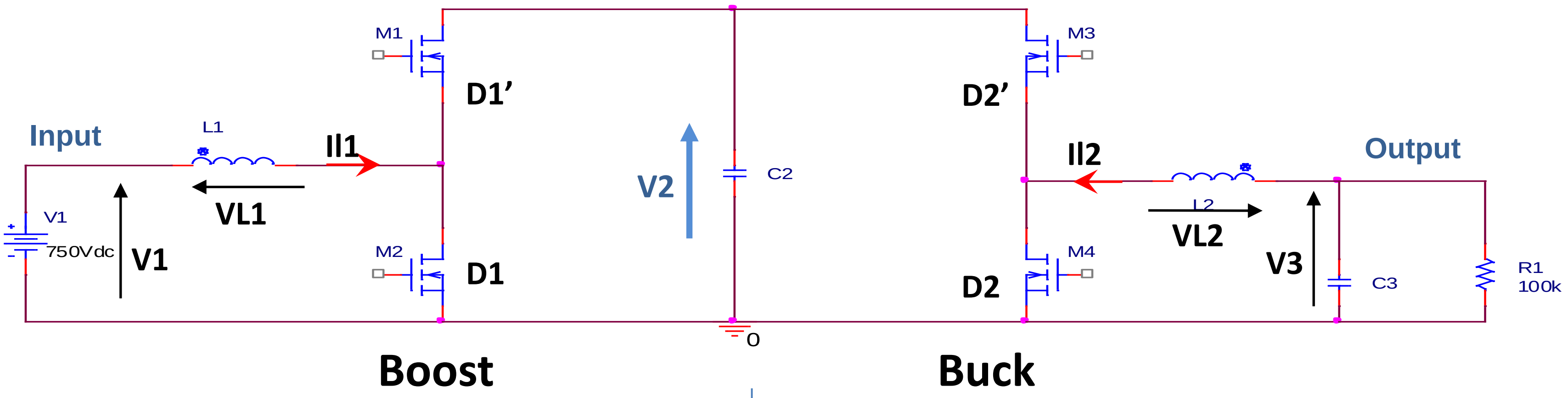
2) Development of the robust closed-loop of the power converter using a theoretical analysis

3) Find an algorithm to balance in real time the voltage across each supercapacitor whatever their initial conditions or actual values : State of charge and voltage

4) Find an algorithm to balance in real time the current between each NeoSee boxes and be able to manage the failures of the supercapacitor String and/or the failures of the NeoSee boxes

Modeling of the power converter

Average model



$$L1.\frac{d.<IL1>}{dt} = <V1> - <V2>.(1-D1)$$

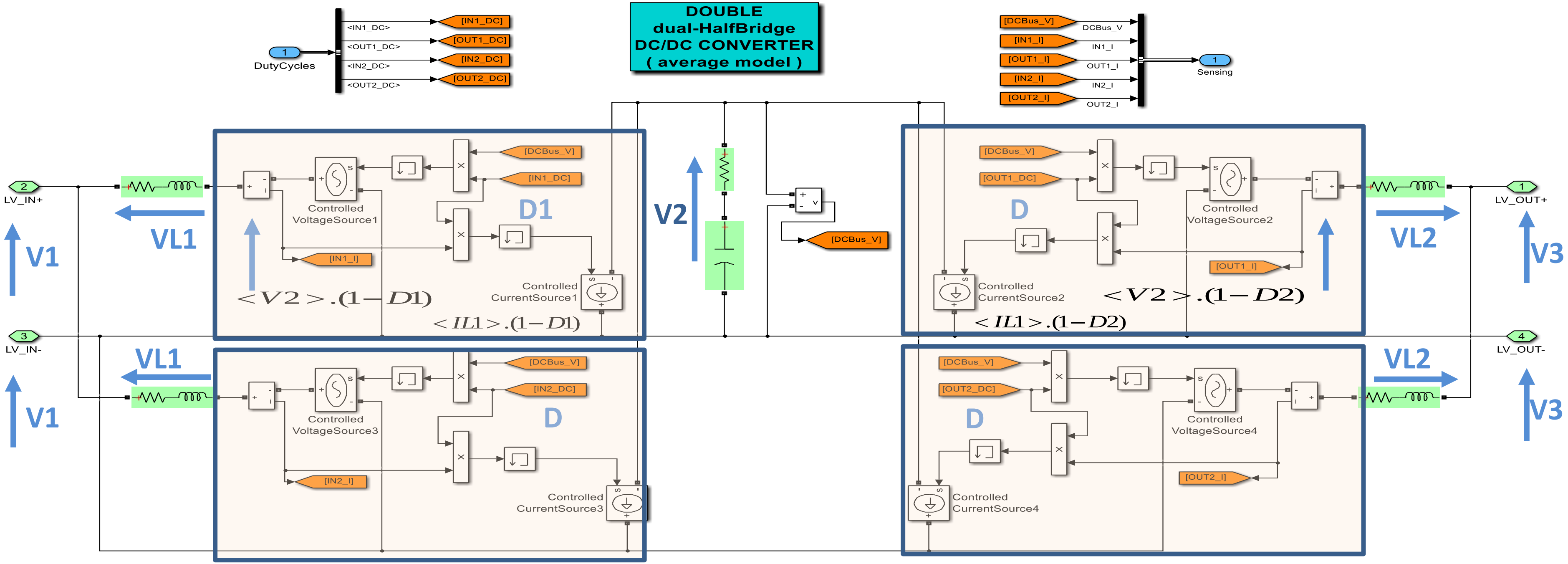
$$L2.\frac{d.<IL2>}{dt} = <V3> - <V2>.(1-D2)$$

$$C2.\frac{d<VC2>}{dt} = <IL1>.(1-D1) + <IL2>.(1-D2)$$

$$C3.\frac{d<V3>}{dt} = \frac{-<V3>}{R} - <Il2>$$

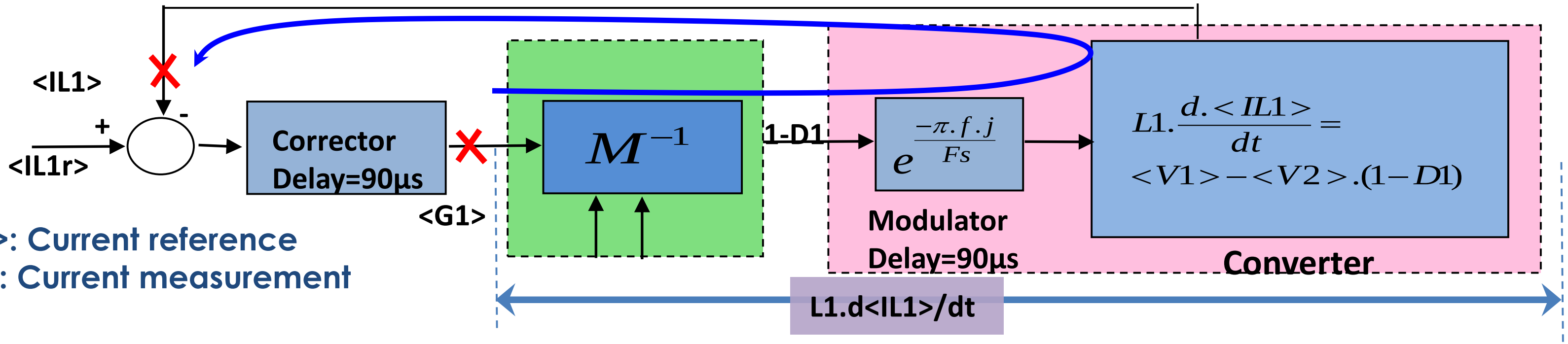
Modeling of the power converter with Simulink

Average model



- Simulink can be used to built an equivalent average model of the power converter
- This method allows to implement easily external passives components with theirs ESR & ESL

Robustness of the control loops



<IL1r>: Current reference
<IL1>: Current measurement

How does the robustness of the closed-loops increase? By the '**Direct Control Method**' using the real time calculation available in the DSP device and in Simulink, too.

Example: The closed-loop current can be simplified as L1.d<IL1>/dt whatever the externals variables variation with M-1

Average model

$$L1.\frac{d.<IL1>}{dt} = <G1> = <V1> - <V2>.(1-D1)$$

$$1-D1 = \frac{-G1 + <V1>}{<V2>} \Rightarrow M^{-1} = \frac{-G1 + <V1>}{<V2>}$$

Injection of the external variables through the open Loop

Small signal

$$\Rightarrow g1 = \frac{\partial(G1)}{\partial V1}.v1 + \frac{\partial(G1)}{\partial V2}.v2 + \frac{\partial(G1)}{\partial D1}.d1$$

$$g1 = v1 - (1-D1).v2 + V2.d1$$

By injection in the small power converter model

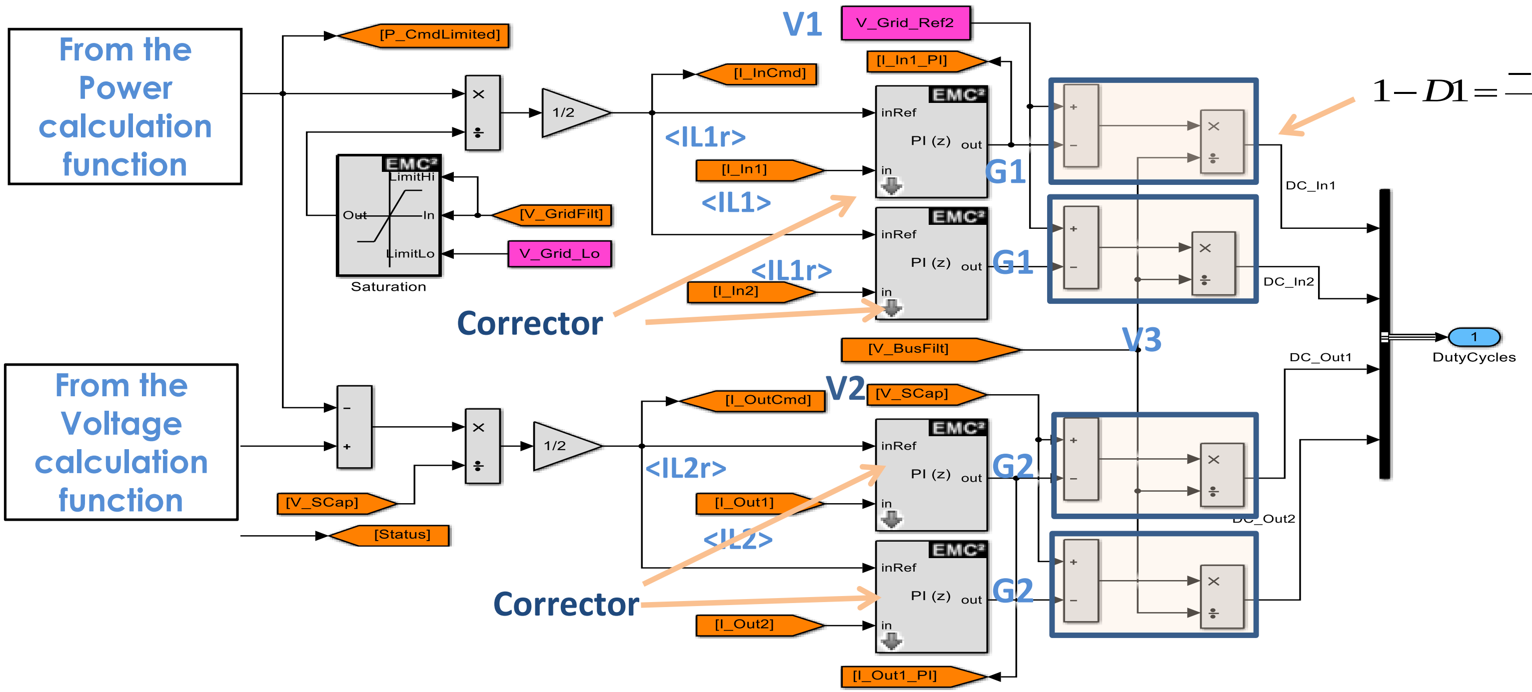
$$L1.il1.p = v1 + V2.d1 - (1-D1).v2$$

$$L1.il1.p = v1 + V2.d1 + [g1 - v1 - V2.d1]$$

$$\frac{il1}{g1} = \frac{1}{L1.p}$$

Equivalent small model of the power converter with the direct control method

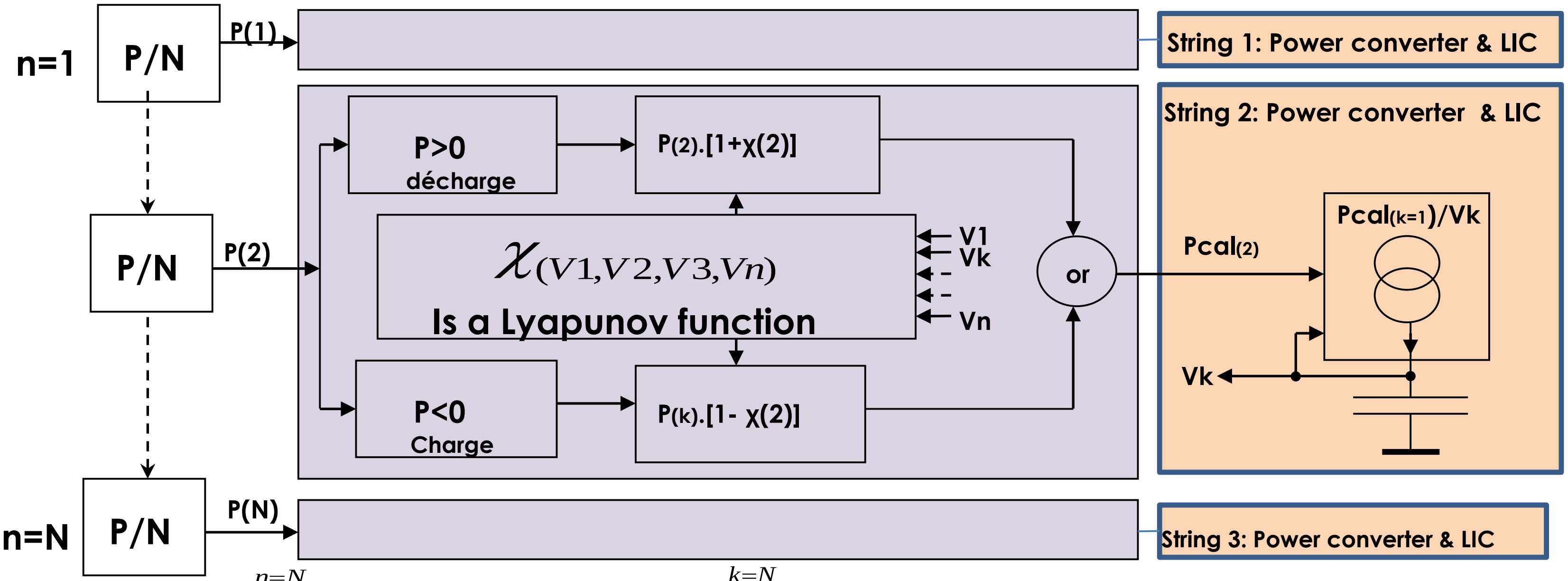
Modeling of the Direct Control with Simulink



$$1-D1=\frac{-G1+<V1>}{<V2>}$$

Conclusion: The behavior of the power converter & its regulation have been designed with Simulink

Balancing algorithm of the Energy Storage Elements



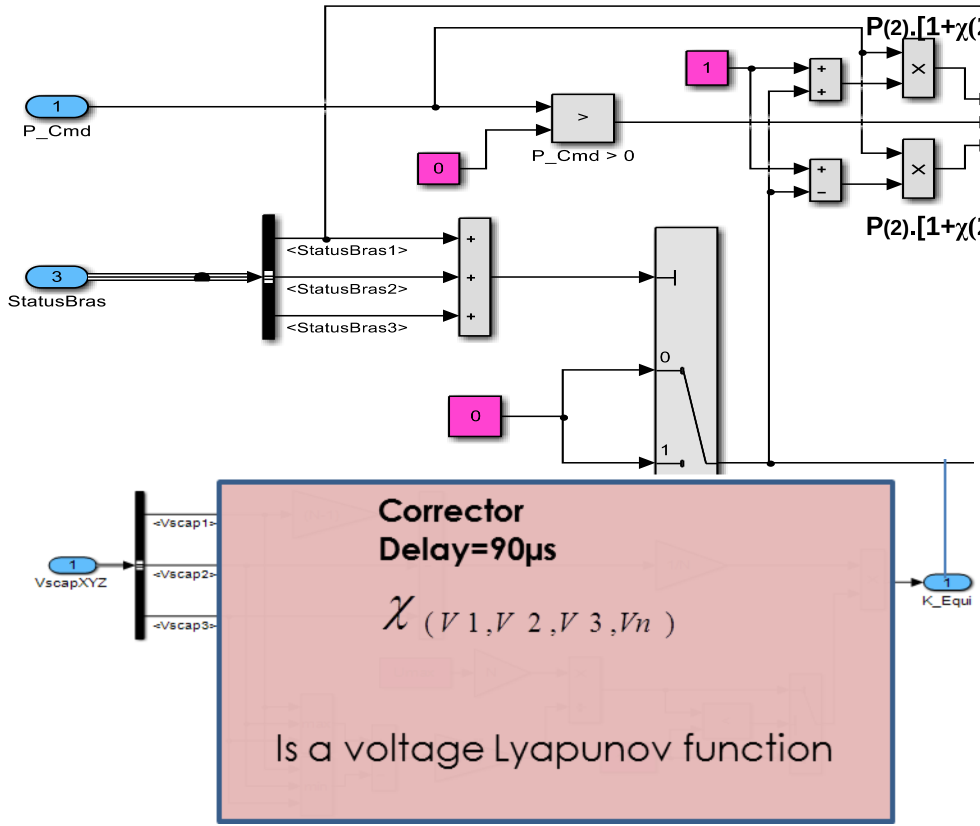
With $\sum_{1}^{n=N} \chi_{(V1,V2,V3,Vn)} = 0$ **and** $\sum_{1}^{k=N} Pcal_{(N,k)} = P$ **Whereas Pcal** $_{(N,1)}$ **#Pcal** $_{(N=k)}$ **#Pcal** $_{(N)}$

With the Lyapunov function

$\chi_{(V1,V2,V3,Vn)}$ **=0 at the equilibrium point &** $\dfrac{d[\chi_{(V1,V2,V3,Vn)}]}{dt}$ **having an opposite sign of** $\chi_{(V1,V2,V3,Vn)}$ **corresponding to the basin of attraction.**

Conclusion: The voltage Lyapunov function balances the voltage of the N strings connected in parallel

Modeling of Lyapunov balancing algorithm with Simulink



Conclusion: The Lyapunov function allows to achieve the equilibrium point for the N string connected in parallel

The Equilibrium is made after several charge and discharge sequences to provide the maximum power to the NeoSee product

Conditions:

Supercap imbalance:

SCAP_V1 = 780 V;
SCAP_V2 = 880 V;
SCAP_V3 = 580 V;

Grid voltage sensor offset:
GRID_V_Offset = -15 V;

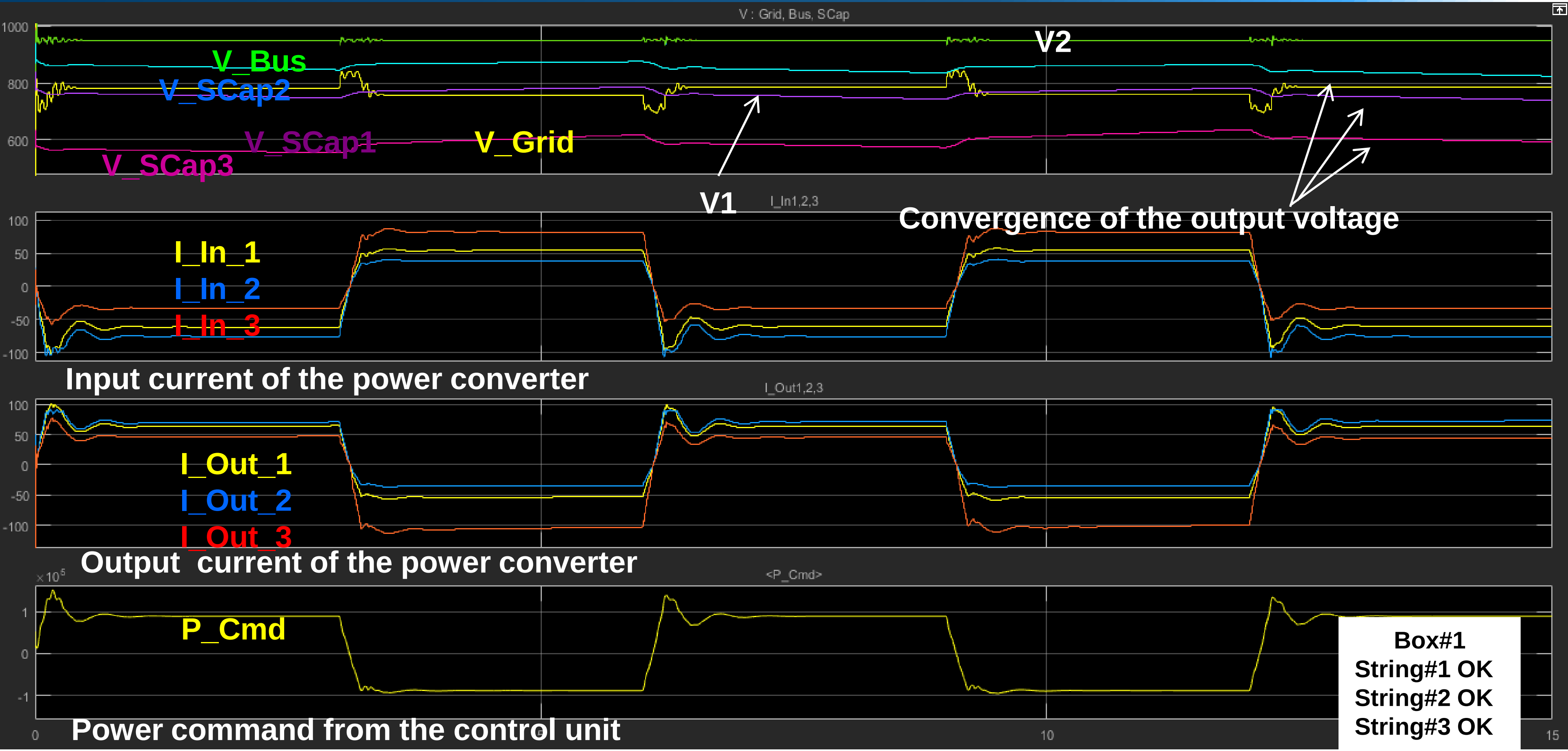
Resistance of the NeoSee-Box supply cables:

R_Cable_Coffre1 = 100 mΩ;
R_Cable_Coffre2 = 800 mΩ;
R_Cable_Coffre3 = 500 mΩ;

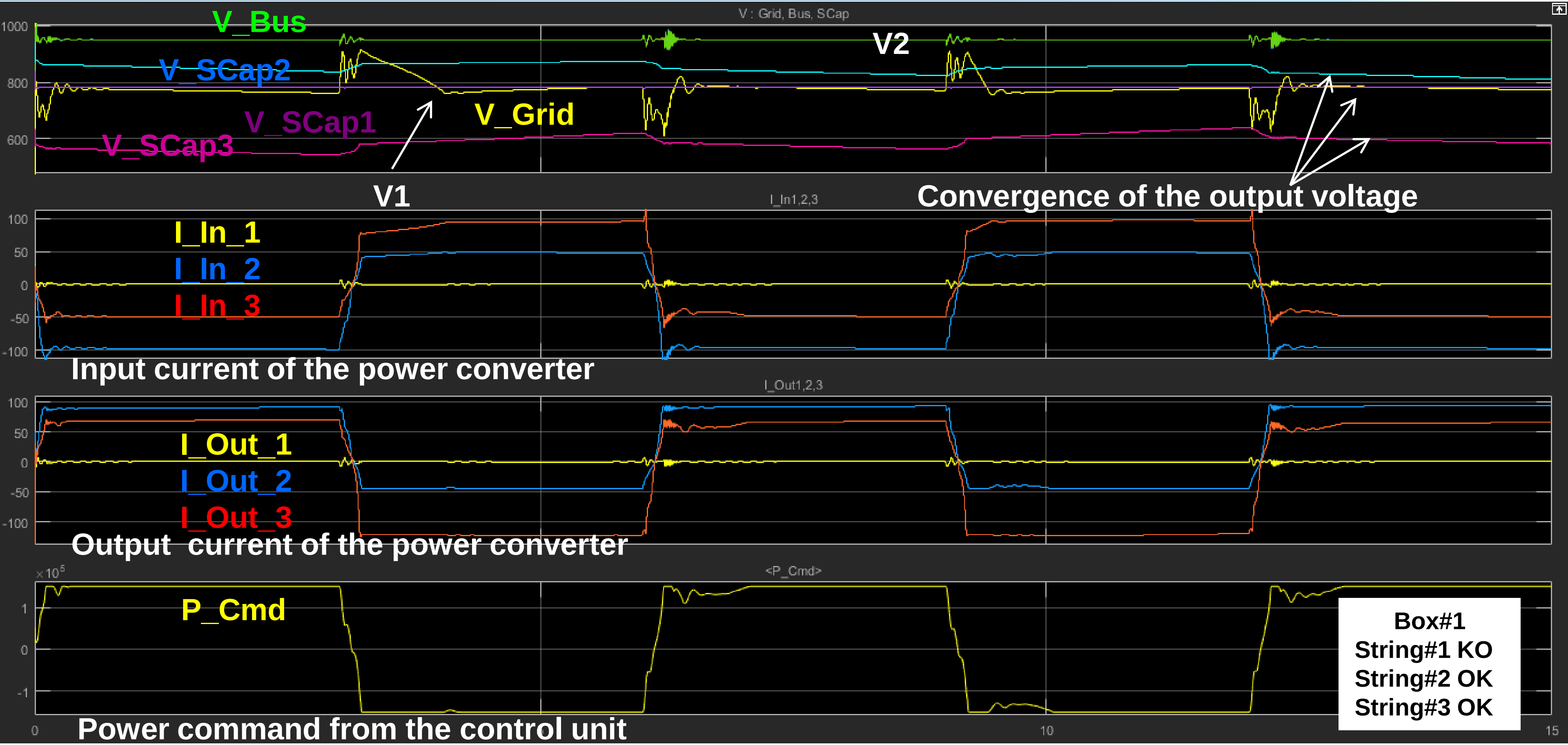
Simulation conditions have been majored to evaluate the Lyapunov functions

Delay time due to control sample, and MATLAB solver = 90 µs;
Communication time delay between strings = 400 µs;
Communication time delay between each NeoSee boxes = 80 ms;

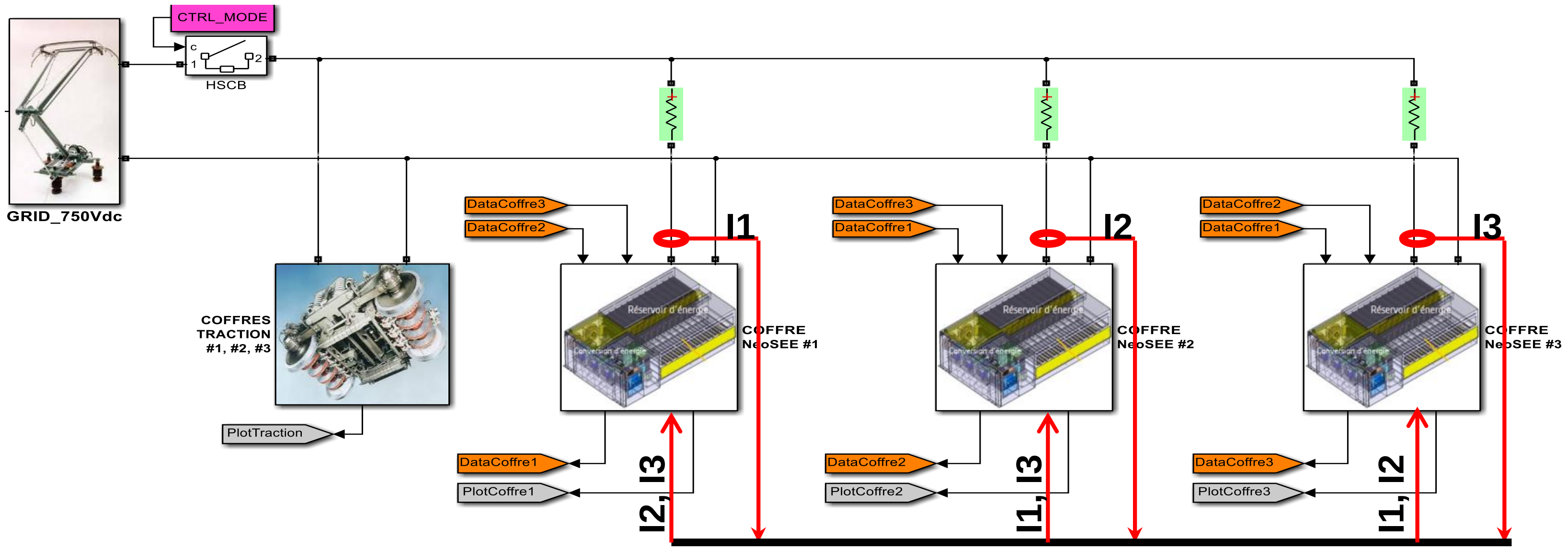
Voltage balancing - Simulation results



Voltage balancing, Failure of string #1 Simulation results



Current balancing between each NeoSee boxes

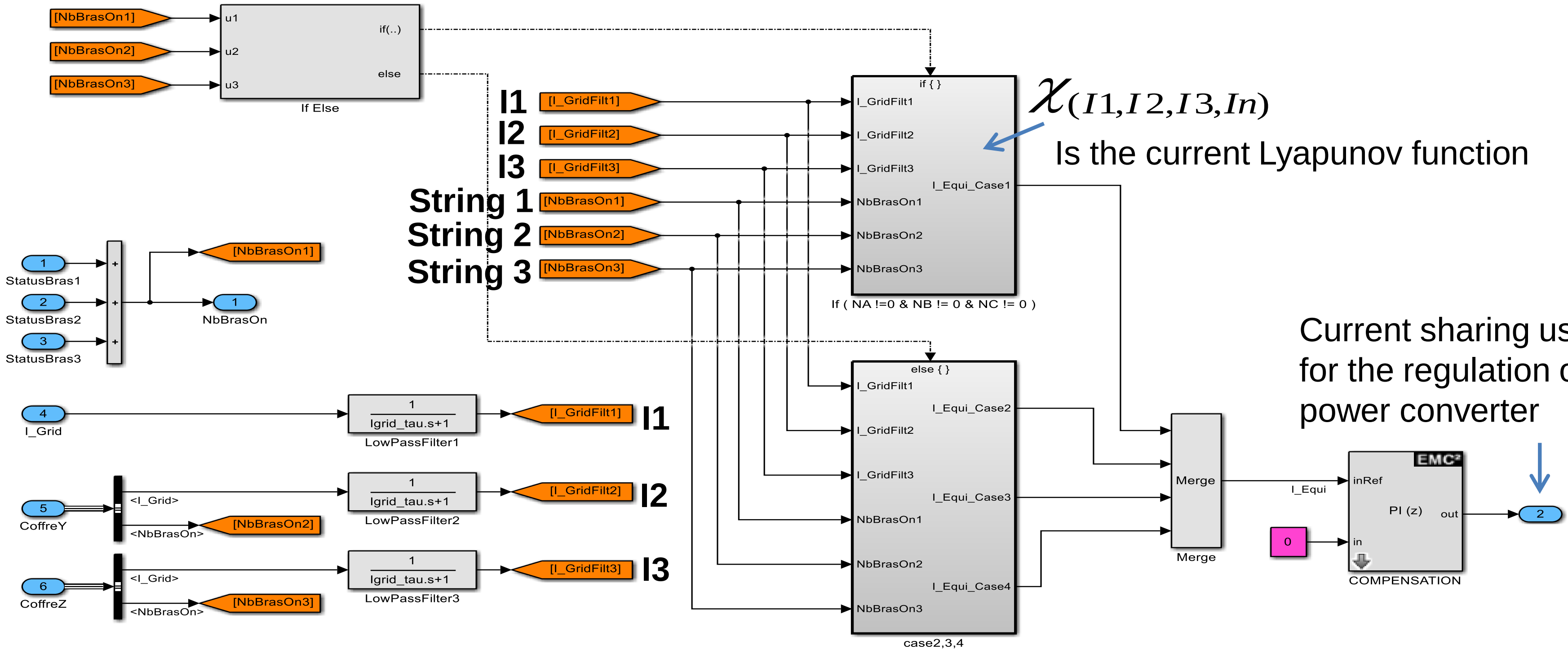


The current values between each NeoSee is shared at a low time frame (~80ms), so, an another Lyapunov function is needed, in each NeoSee control box, to balance the current and to assure the stability

This Lyapunov function allows to take into account the faults operations occurring across the capacitor

Conclusion: The Lyapunov function allows to achieve the current balancing between each NeoSee box

Current balancing between each NeoSee boxes Controller in MATLAB Simulink



$\chi(I1, I2, I3, In)$

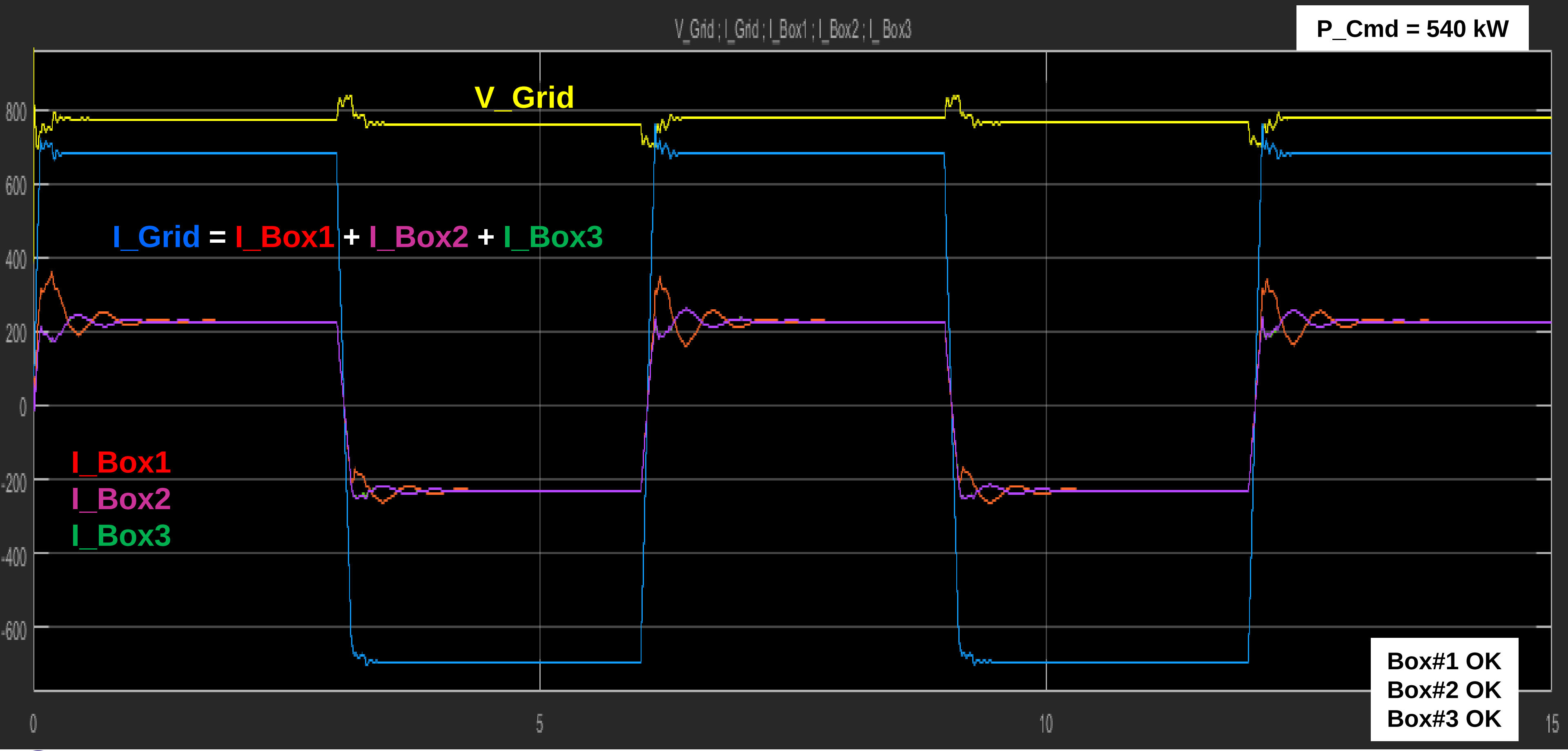
Is the current Lyapunov function

Current sharing used for the regulation of the power converter

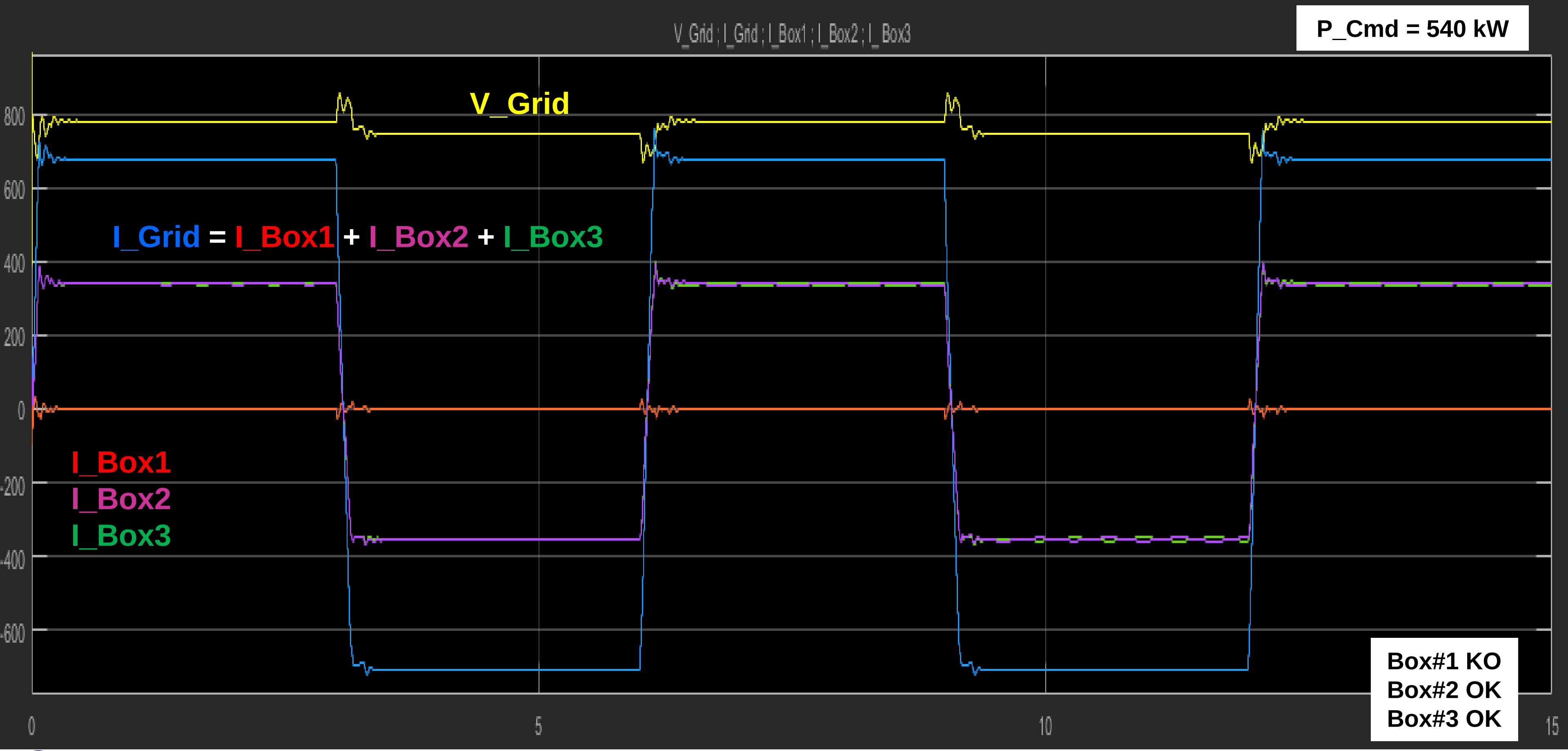
The current values between each NeoSee is shared at a low time frame (~80ms), so, an another Lyapunov function is needed, in each NeoSee control box, to balance the current and to assure the stability

This Lyapunov function allows to take into account the faults operations occurring across the capacitor

Current balancing - Simulation results



Current balancing, Failure of NeoSee Box#1 - Simulation results



Conclusion

MATLAB/Simulink/Simscape can be used to simulate complex systems taking into account the delay time from the discretization due to the numerical acquisition

The NeoSee example shows several topics that can be developed under Simulink, specifically:

1) The switching average model of the power semiconductor
2) The Direct Control algorithm has been modeled and simulated taking into account the calculation time and the discretization of the final target processor (DSP)
3) Modeling and simulating the Balancing algorithms using the Lyapunov theory

Benoît PERON: bperon@centumadetel.com
Antonio PRATA: aprata@free.fr