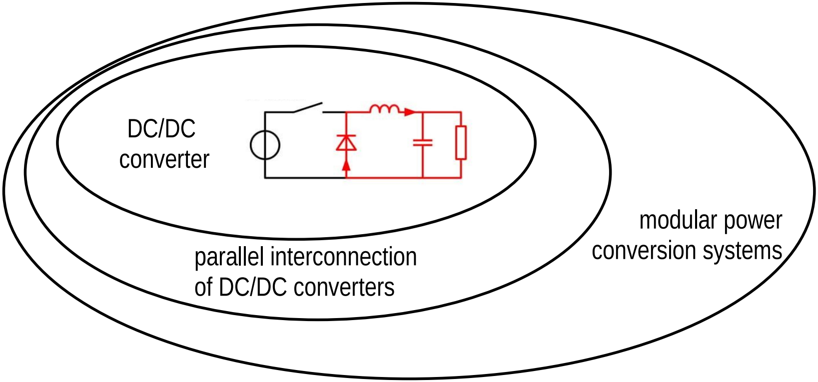
Control of Modular Power Conversion Systems

First assessment of six years of research

Jean-François TRÉGOUËT

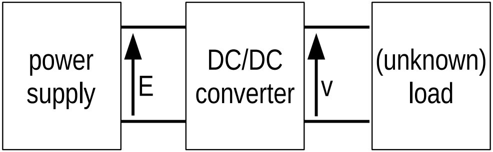
March 31st 2022

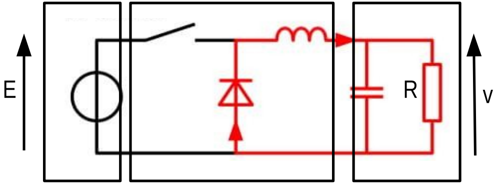
Topic of the talk



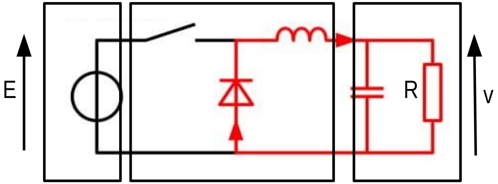
A few basics

Basics about buck converter





- $R > 0$ is unknown



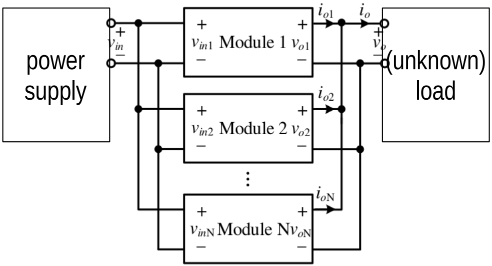
How to regulate v ?

- PWM and average model : 2-dimensional linear system with continuous input d
- open loop control $d(t) = v_r/E$ ensures $v(t) \to v_r$ for all $R > 0$, via natural feedback ! But:
  - too slow
  - parasitic elements induce steady-state error $v(+\infty) \neq v_r$
- closed-loop control : $(i, v) \mapsto d$

A robust output regulation problem

Problem statement

Modular DC/DC power conversion systems



Multiple paths for the power:

- distribution of stresses of components
- ease of maintenance and repair
- improved thermal management

increased reliability... if properly controlled !

and also

- *reduced output ripple by interleaving phase of PWM*

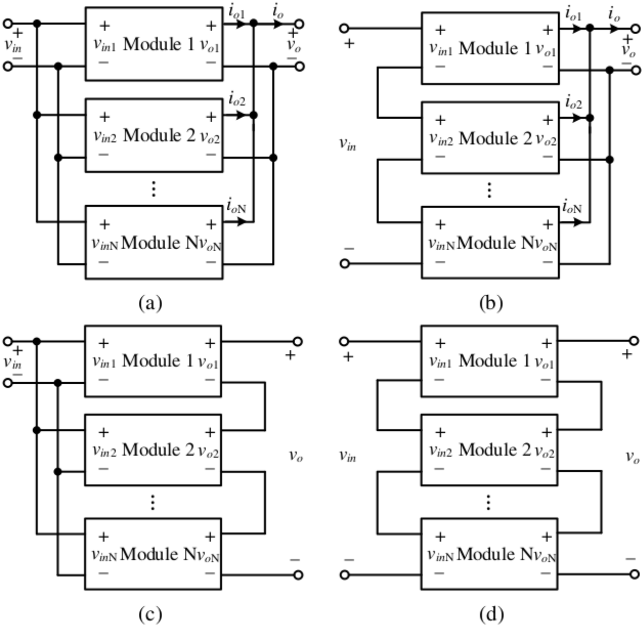
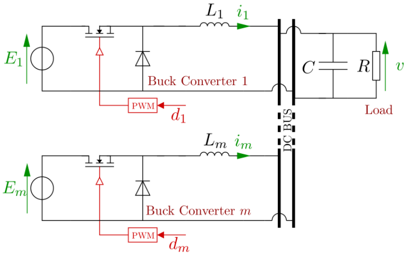
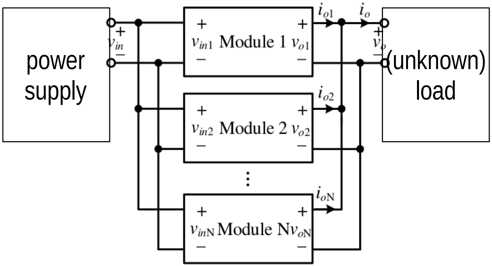


Fig. 1. Four series-parallel connection structures. (a) IPOP. (b) ISOP. (c) IPOS. (d) ISOS.

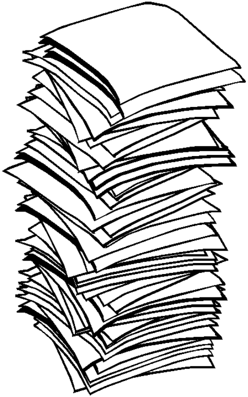
Focus on parallel buck interconnection





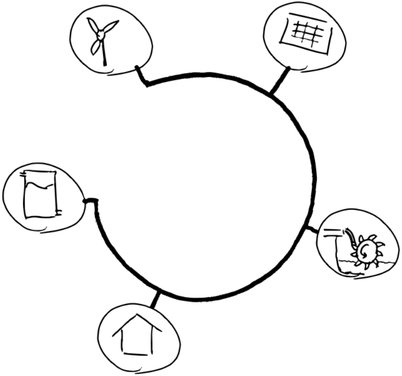
Why ?

1. to get **papers** published



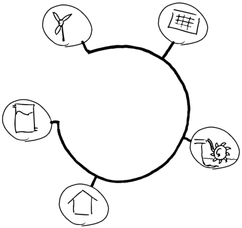
Why ?

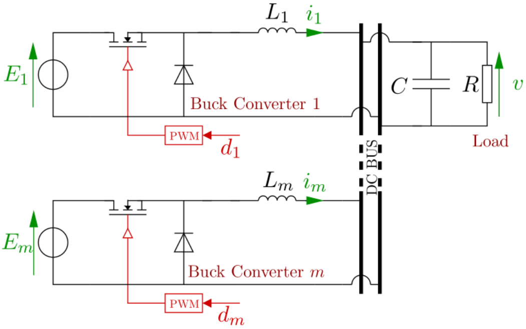
1. to get **papers** published
2. as first step toward **DC μ-grid**



Why ?

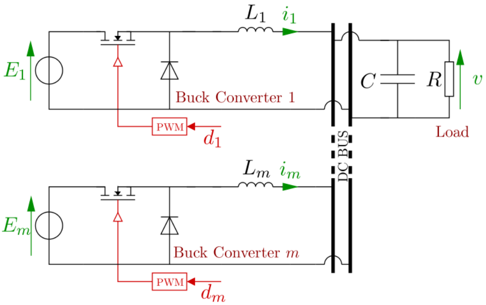
1. to get **papers** published
2. as first step toward **DC µ-grid**





$$L_1 \neq \ldots \neq L_m$$

Basics about parallel buck interconnection



- m inputs : $d_1, \dots, d_m$ (in $[0, 1]$)
- $m + 1$ states (with **coupled** dynamics) : $(i_1, \dots, i_m, v)$
- 1 unknown parameter : $R \in [\underline{R}, \bar{R}]$

Control objectives

1. $v(t) \to v_r$
2. $i(t) \to i_{\text{opt}}(R)$

Conflicting but ordered list

Same things rephrased in control terms

$$\dot{x}(t) = A(\theta)x(t) + Bu(t) \tag{1}$$
$$e(t) = Cx(t) + e_0 \tag{2}$$

Find[1] $x \mapsto u \in [0,1]^m$, such that

$$x(t) \to \arg\min_x J(x) \quad \text{s.t.} \quad \dot{x} = 0,\ e = 0,\ x \in \mathbb{X} \tag{3}$$

for all $x(0)$ and for all $\theta \in \Theta$.[2]

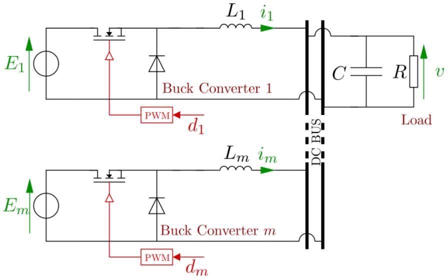
Under-determined robust output regulation problem

[1] Dynamic feedback is possible, and even desirable !

[2] Θ is known. Unlike θ !

Achievements

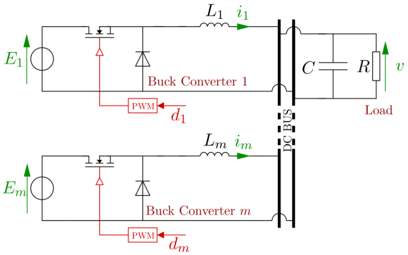
What was the state-of-the-art (in 2015) ?



- homogeneous set of bucks ($L_1 = \ldots = L_m$)
  - balanced current-sharing is optimal
- no formal stability proofs[3]
- no garanties against :
  - input saturation ($d_k(t) \in [0, 1]$)
  - excursion from nominal load R_0

[3] Frequency separation used informally as the fundamental tool for achieving closed-loop.

What has been achieved (in 2019) ?



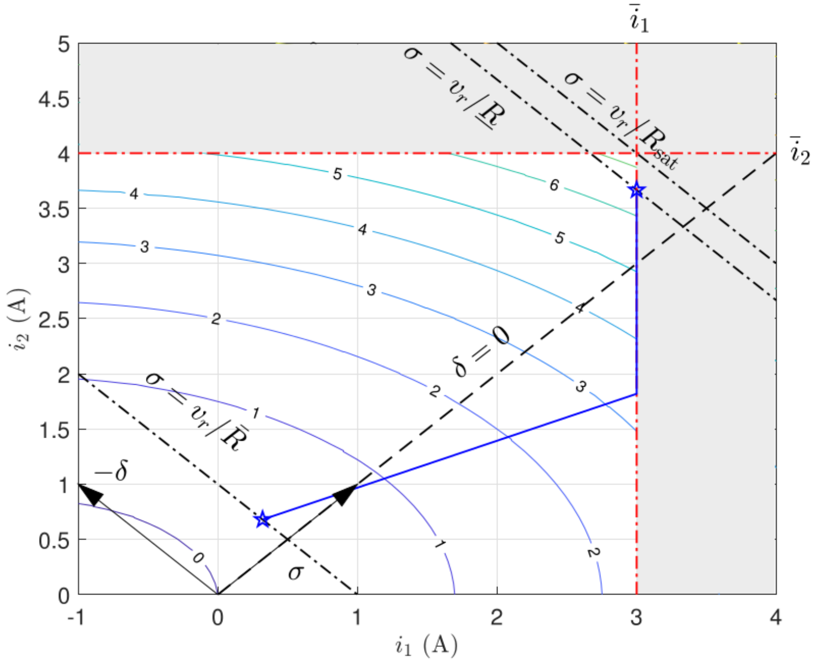
New control law

- voltage regulation
- optimal current sharing (minimizing overall losses) under current constaints

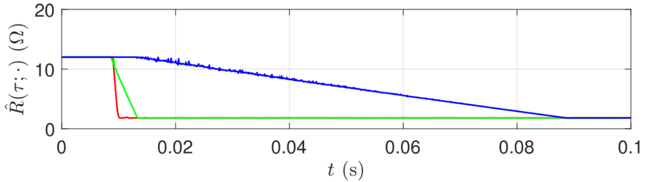
is achieved (asymptotically) for all load and for any heterogeneous set of converters.

Assessment

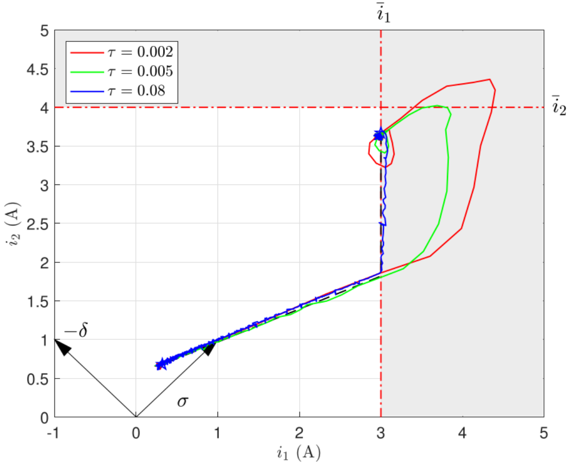
- formal proof (with input saturation) ;
- experimental validation.



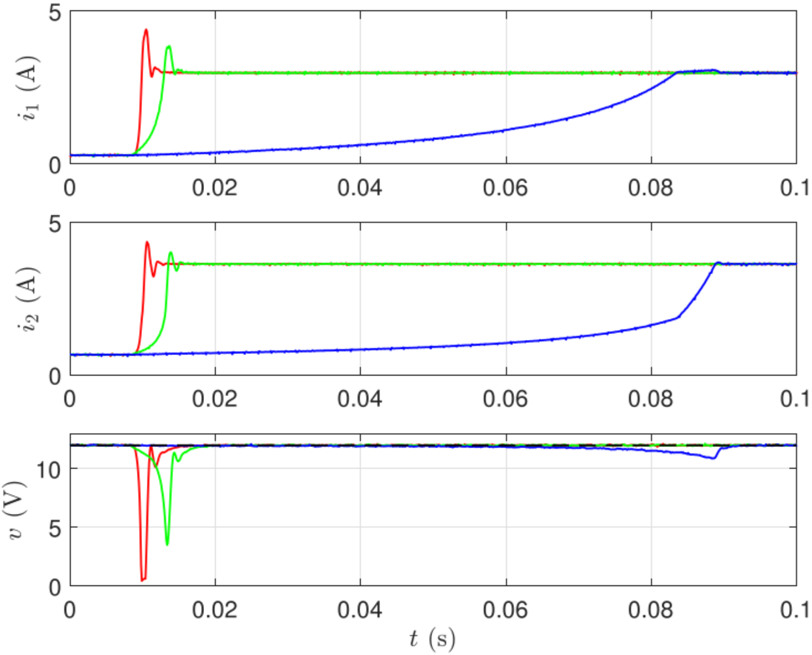
$\bar{i}_1$
$\bar{i}_2$
$\sigma = v_r/\underline{R}$
$\sigma = v_r/R_{sat}$
$\sigma = v_r/\bar{R}$
$\delta = 0$
$-\delta$
σ
i_1 (A)
i_2 (A)



$\hat{R}(\tau;\cdot)$ (Ω)
20
10
0
0
0.02
0.04
0.06
0.08
0.1
t (s)

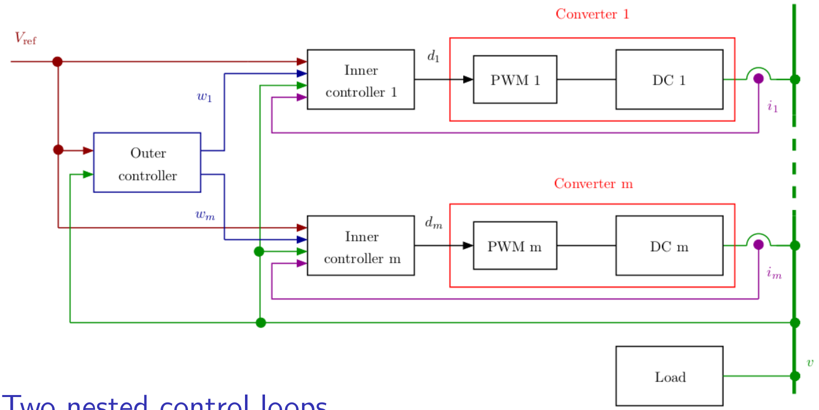


$\bar{i}_1$
$\bar{i}_2$
$\tau = 0.002$
$\tau = 0.005$
$\tau = 0.08$
$-\delta$
σ
i_2 (A)
i_1 (A)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-1
0
1
2
3
4
5


5
0
i_1 (A)
0
0.02
0.04
0.06
0.08
0.1
5
0
i_2 (A)
0
0.02
0.04
0.06
0.08
0.1
10
5
0
v (V)
0
0.02
0.04
0.06
0.08
0.1
t (s)

An (historical) glimpse on the intellectual journey

Two nested control loops and frequency separation



Two nested control loops

- inner robustely stabilizing loop (somewhere)
- outer external loop achieving asymptotic optimality via partial inversion (of the quasi-steady state)

Bad interraction prevented via frequency separation

The quasi-steady state (external loop design)

$$v = \frac{\mathbf{1}^\intercal G w + \mathbf{1}^\intercal i_0}{1/R + \mathbf{1}^\intercal N} \quad \text{with} \quad \mathbf{1} = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \in \mathbb{R}^m \tag{4}$$

- $v = v_r$: 1 equation and m unknowns $w_1, \ldots, w_m$

many solutions

Using the change of variable $Gw = \mathbf{1} z_v + \Gamma z_i$, (4) becomes:[4]

$$v = \frac{m z_v + \mathbf{1}^\intercal i_0}{1/R + \mathbf{1}^\intercal N} \tag{5}$$

- $v = v_r$: 1 equation and 1 unknown $z_v \in \mathbb{R}$

unique solution and $z_i \in \mathbb{R}^{m-1}$ is free !

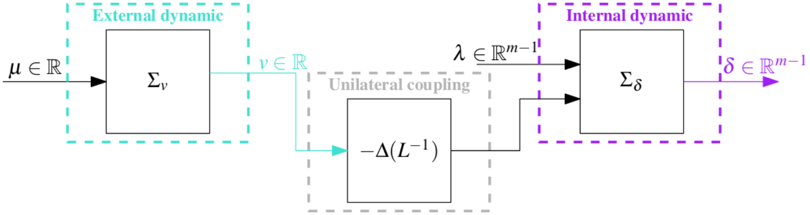
[4] $\mathrm{Ker}\,\{\mathbf{1}^\intercal\} = \mathrm{span}\,\{\Gamma\}$.

A powerfull change of variable

Performing the following change of variables **from the outset** (no inner loop)

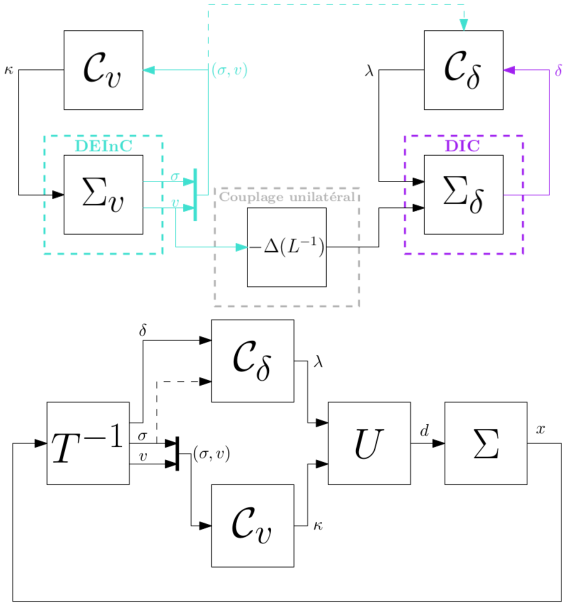
$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ v \end{bmatrix} \mapsto \begin{bmatrix} i_1 - i_2 \\ i_2 - i_3 \\ i_1 + i_2 + i_3 \\ v \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \sigma \\ v \end{bmatrix}, \qquad \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \mapsto \approx \begin{bmatrix} d_1 - d_2 \\ d_2 - d_3 \\ d_1 + d_2 + d_3 \end{bmatrix} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \mu \end{bmatrix}$$

decouples the voltage dynamics from current distribution dynamics !



Geometric (not frequency) separation !

How about control ?



Faster convergence can be achieved !

A physical interpretation

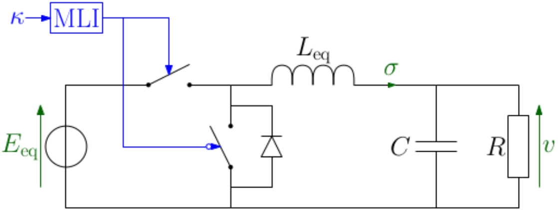
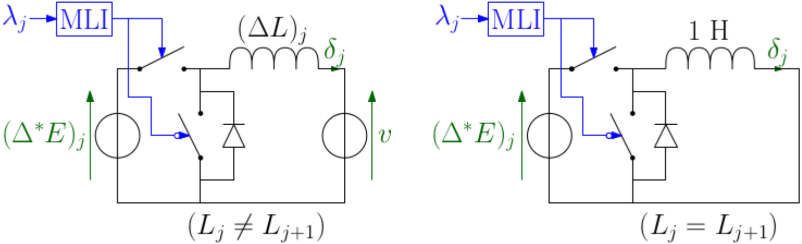


FIGURE 4.22 – Interprétation physique de Σ_v



Ultimate version of the cdv (v3)

By changing :

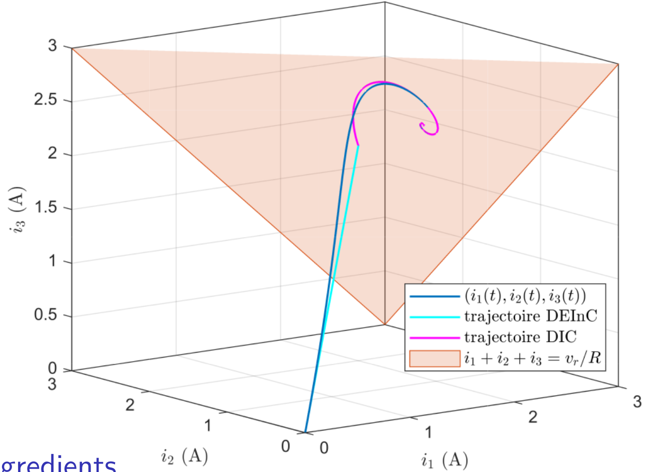
- input vector,
- state vector,
- time scale

one gets:

$$\frac{\mathrm{d}x_a(\tau)}{\mathrm{d}\tau} = \begin{bmatrix} \mathbf{0}_{m\times m} & \mathbf{0}_m \\ \mathbf{0}_m^\intercal & \begin{bmatrix} 0 & -1 \\ 1 & -\frac{\theta}{Q_c} \end{bmatrix} \end{bmatrix} x_a(\tau) + \begin{bmatrix} \mathbf{I}_m \\ \mathbf{0}_m^\intercal \end{bmatrix} u_a(\tau)$$

extremely sparsed (and well conditionned) matrices!

Unveiling the deep geometric structure of the system



Key ingredients

- $(i_1 - i_2, i_2 - i_3)$ are the coordinates of x in $\mathcal{R}^\star =$ the controllable weakly unobservable subspace
- $\mathcal{R}^\star$ does not depend on R
- $\mathcal{R}^\star$ is A-invariant

What else ?

Next time, we could talk about...

Already published stuff

- a **port Hamiltonian** point of view
- how to deal with current constraints during **transient**
- **direct control** $d(t) \in \{0,1\}^m$
  - cf Aboubacar Ndoye: **Phd since Dec. 7th, 2022**

Stuff on the right track

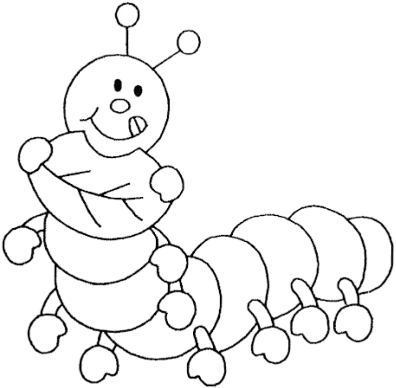
- a **new step-down converter** (from control to power electronics)
- multicell converters with **flying-capacitor** voltages (yet another modular power converters)

Stuff to be done (one day)

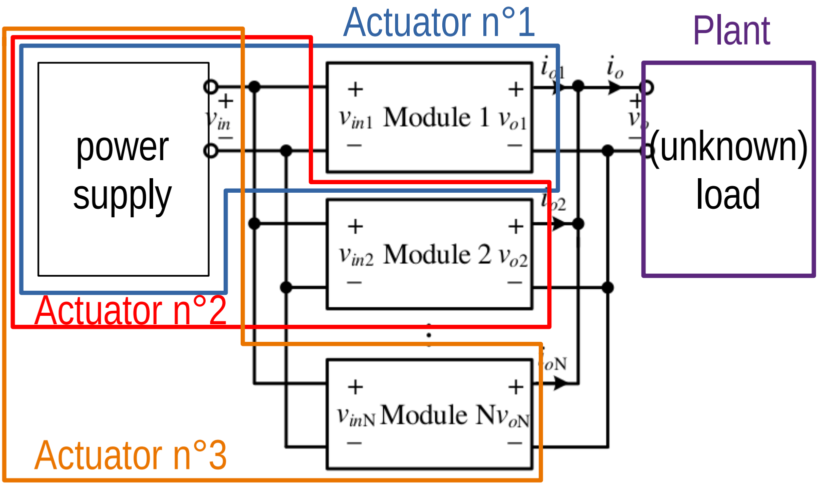
- **universal** methodology to control modular power converters
- achieve optimality even in **transient**

and also...

My favorite topic



Over-actuated systems


Actuator n°1
Plant
power
supply
v_{in}
i_{o1}
i_o
v_{in1} Module 1 v_{o1}
v_o
(unknown)
load
i_{o2}
v_{in2} Module 2 v_{o2}
Actuator n°2
i_{oN}
v_{inN} Module N v_{oN}
Actuator n°3

One more (last) thing

Acknowledgements

Students

- Cyril Lacombe: master students in 2015 (now with RTE)
- Jérémie Kreiss: Phd student from 2016-2019 (now with CRAN)
- Aboubacar Ndoye: Phd student from 2018-2021

Colleagues with Ampère

- Romain Delpoux
- Damien Ébérard
- Jean-Yves Gauthier
- Xuefang Lin-Shi

Overseas colleagues

- Marc Bodson (with Univ. of Utah, USA)
- Madieh Sadabadi (with Univ. of Sheffield, UK)

Bibliography

- Delpoux, Romain, Jean-François Trégouët, Jean-Yves Gauthier, and Cyril Lacombe. 2019. "New Framework for Optimal Current Sharing of Nonidentical Parallel Buck Converters." Control Systems Technology, IEEE Transactions on 27 (3): 1237–43.
- Kreiss, Jérémie, Marc Bodson, Romain Delpoux, Jean-Yves Gauthier, Jean-François Trégouët, and Xuefang Lin-Shi. 2021. "Optimal Control Allocation for the Parallel Interconnection of Buck Converters." Control Engineering Practice 109: 104727.
- Kreiss, Jérémie, Jean-François Trégouët, Romain Delpoux, Jean-Yves Gauthier, and Xuefang Lin-Shi. 2018a. "A Geometric Point of View on Parallel Interconnection of Buck Converters." In 17th European Control Conference, 70–75.
- Trégouët, Jean-François, and Romain Delpoux. 2019. "New Framework for Parallel Interconnection of Buck Converters: Application to Optimal Current–Sharing with Constraints and Unknown Load." Control Engineering Practice 87: 59–75.
- Kreiss, Jérémie, Jean-François Trégouët, Romain Delpoux, Jean-Yves Gauthier, and Xuefang Lin-Shi. 2019. "A New Framework for Dealing with Input Constraints on Parallel Interconnection of Buck Converters." In 18th European Control Conference, 429–34.
- Kreiss, Jérémie, Jean-François Trégouët, Damien Ébérard, Romain Delpoux, Jean-Yves Gauthier, and Xuefang Lin-Shi. 2020. "Hamiltonian Point of View on Parallel Interconnection of Buck Converters." Control Systems Technology, IEEE Transactions on 29 (1): 43–52.
- Sadabadi, Mahdieh S., Nenad Mijatovic, Jean-François Trégouët, and Tomislav Dragicevic. 2021. "Distributed Control of Parallel Dc-Dc Converters Under Fdi Attacks on Actuators." IEEE Transactions on Industrial Electronics In press: 1–1.
- Trégouët, Jean-François, and Romain Delpoux. 2017. "Parallel Interconnection of Buck Converters Revisited." In IFAC–Papersonline. 20th World Congress of the Ifac, 50:15792–7. 1.
- Trégouët, Jean-François, Romain Delpoux, and Jean-Yves Gauthier. 2016. "Optimal Secondary Control for Dc Microgrids." In Proceedings of the 25th Ieee International Symposium on Industrial Electronics (Isie), 510–15.