The
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Data-Driven Control of Power Converters

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A WORLD
TOP 100
UNIVERSITY

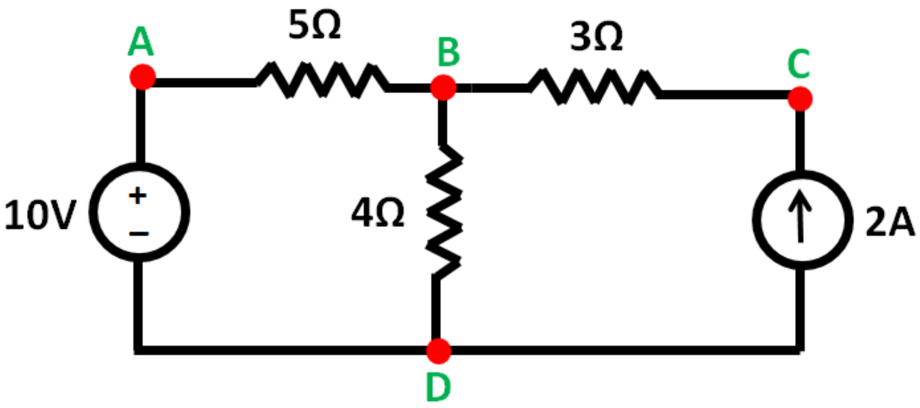
First principles: understanding nature

- The first big result in systems theory was Newton’s gravitational law in 1686.
- He linked two things which were until then considered to be objectively separate:

  - The fundamental laws of physics; and

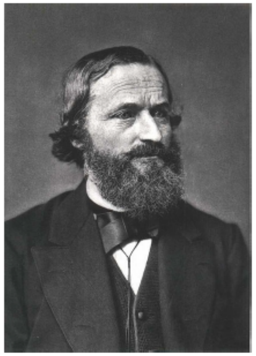
  - The world of mathematics.

First principles: understanding nature



Kirchhoff's Laws

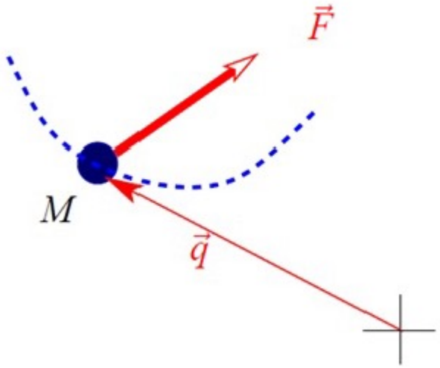
- For n voltages (loop): $\sum_{i=1}^{n} V_i = 0.$
- For m currents (node): $\sum_{j=1}^{m} I_j = 0.$



First principles: understanding nature

Newton's Second Law

- $\vec{F} = M\frac{d^2}{dt^2}\vec{q}$; where $(\vec{F}, \vec{q}) : \mathbb{R} \to \mathbb{R}^3 \times \mathbb{R}^3$.



Newton painted by William Blake

Differential equations

- In many cases, processes are described by sets of differential or difference equations:

Differential: $$R_0 w + R_1 \frac{d}{dt} w + \cdots + R_N \frac{d^N}{dt^N} w = 0 \,.$$

Difference: $$P_0 w(k) + P_1 \,(k+1) + \cdots + P_N w(k+N) = 0 \,,$$
$$k = 1, 2, 3, \ldots$$

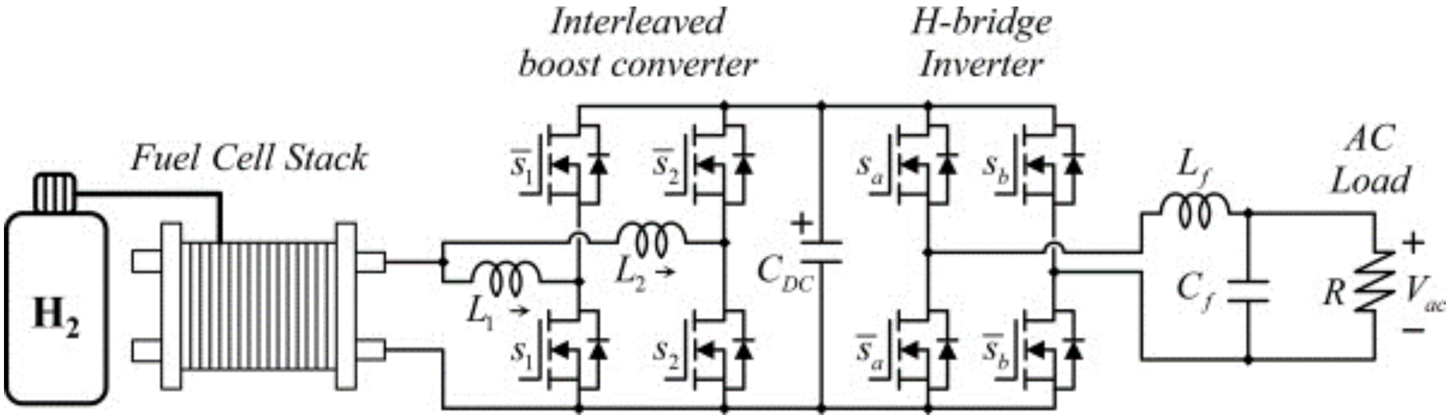
State space

- State space systems are sets of first order differential equations:

	Differential	Difference
Linear:	$\frac{\boldsymbol{d}}{\boldsymbol{dt}}\boldsymbol{x} = \boldsymbol{Ax} + \boldsymbol{Bu};$	$\boldsymbol{x}(\boldsymbol{k}+\boldsymbol{1}) = \boldsymbol{Fx}(\boldsymbol{k}) + \boldsymbol{Gu}(\boldsymbol{k}).$
Nonlinear:	$\frac{\boldsymbol{d}}{\boldsymbol{dt}}\boldsymbol{x} = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u});$	$\boldsymbol{x}(\boldsymbol{k}+\boldsymbol{1}) = \boldsymbol{g}\big(\boldsymbol{x}(\boldsymbol{k}),\boldsymbol{u}(\boldsymbol{k})\big).$

Modeling: stand-alone systems

- Modelling from first principles and model-based control is a suitable practice:



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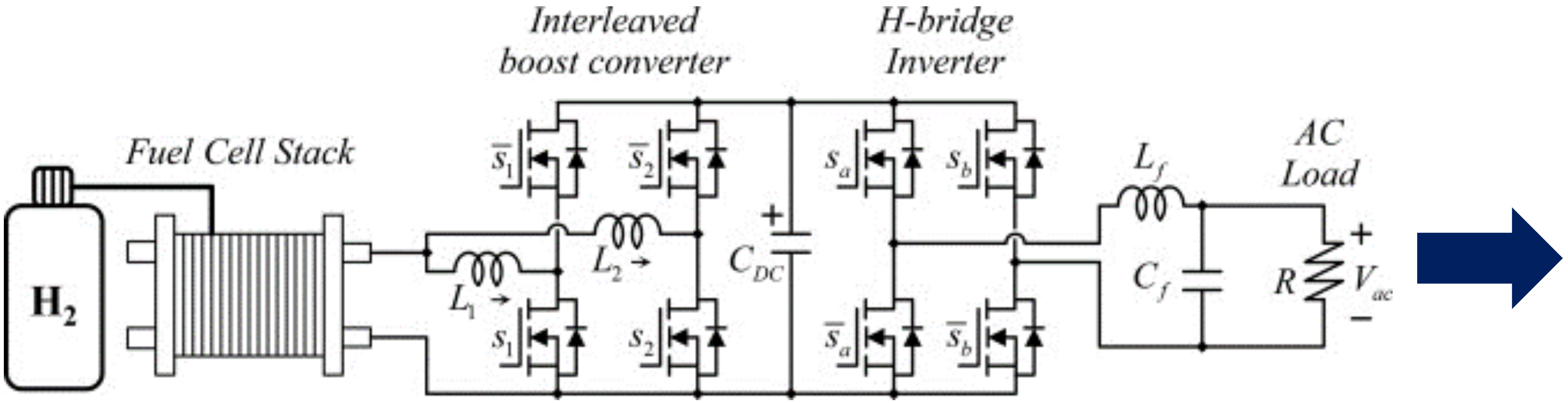

$$\begin{pmatrix} i_{L_1} \\ i_{L_2} \\ i_{L_f} \\ v_{C_f} \\ v_{C_{DC}} \end{pmatrix}$$

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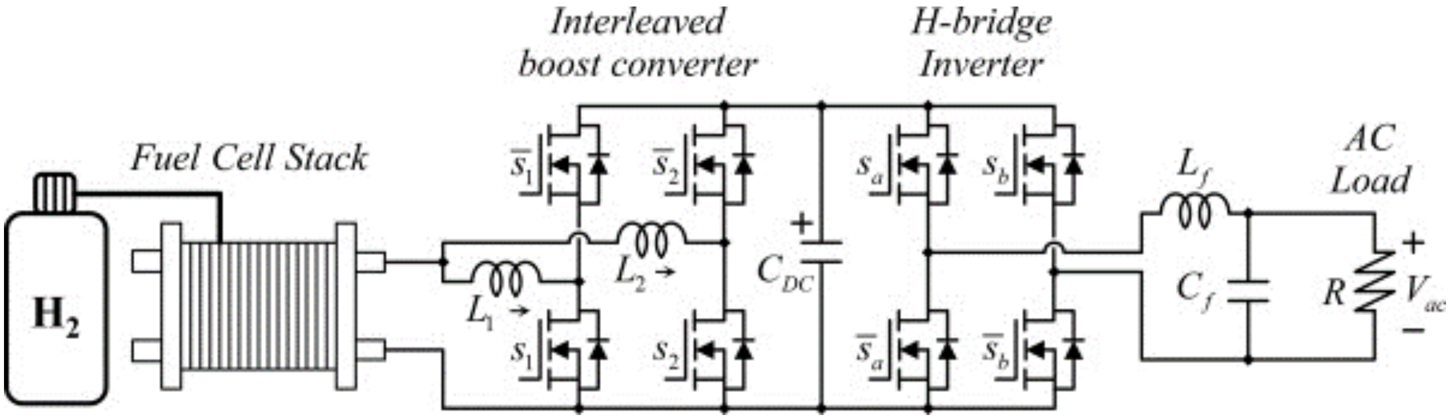
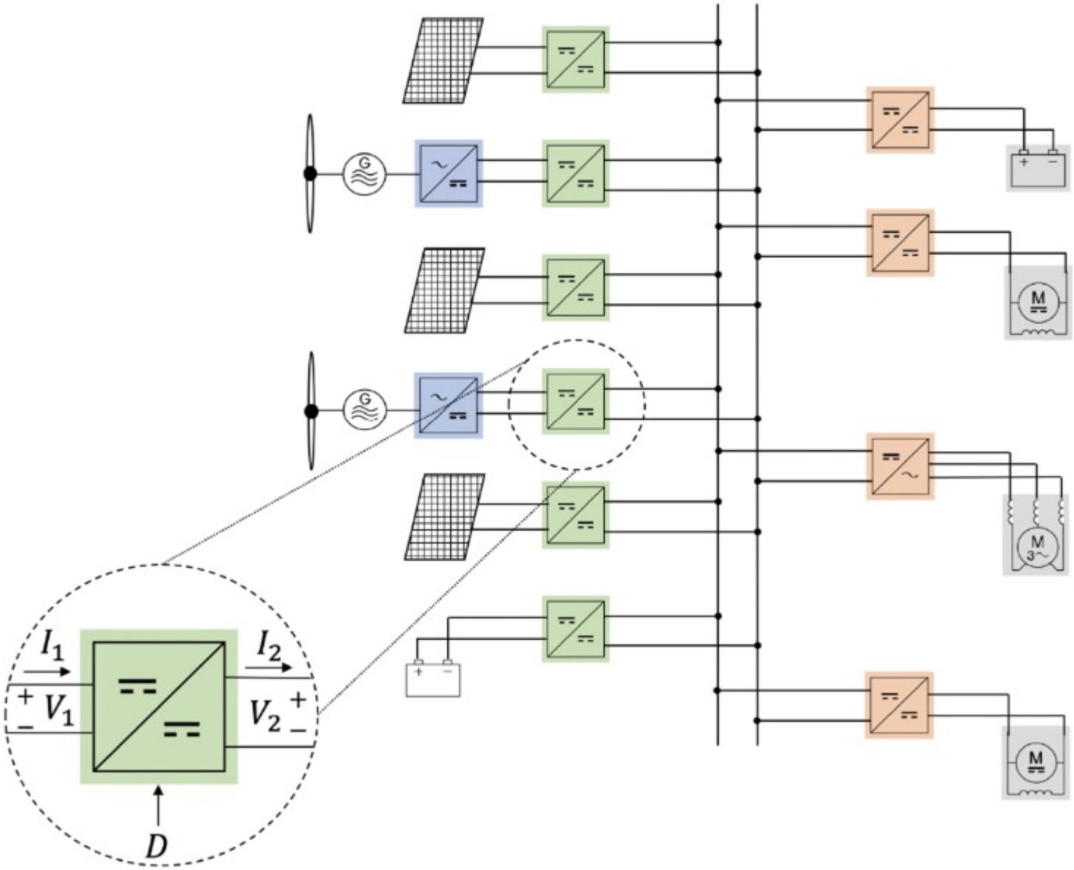


$$\begin{pmatrix} i_{L_1} \\ i_{L_2} \\ i_{L_f} \\ v_{C_f} \\ v_{C_{DC}} \end{pmatrix}$$

Dynamics are fairly predictable and the system order is manageable.

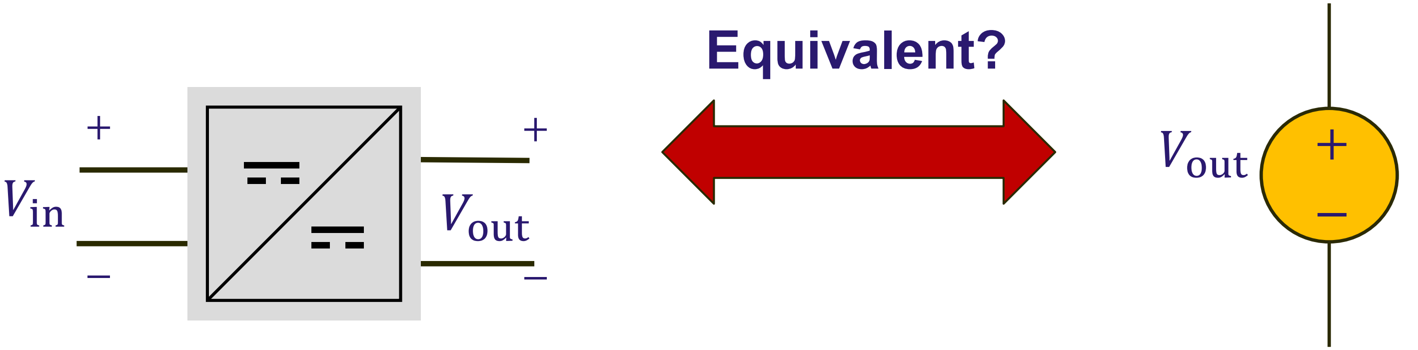
Distributed power systems

- Complex dynamical interactions
- Very high system order
- Excessive number of variables
- First principles not available: e.g. mechanical loads



Distributed power systems

Power converters are not as modular as we would like them to be…



Equivalent?

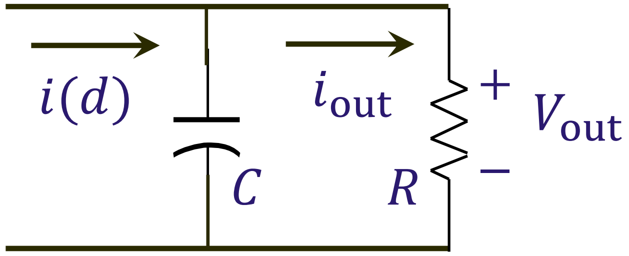
DC-DC Converter Output

Ideal voltage source

Distributed power systems

Output capacitor of DC-DC converter

Resistive load



Distributed power systems

Output capacitor of DC-DC converter

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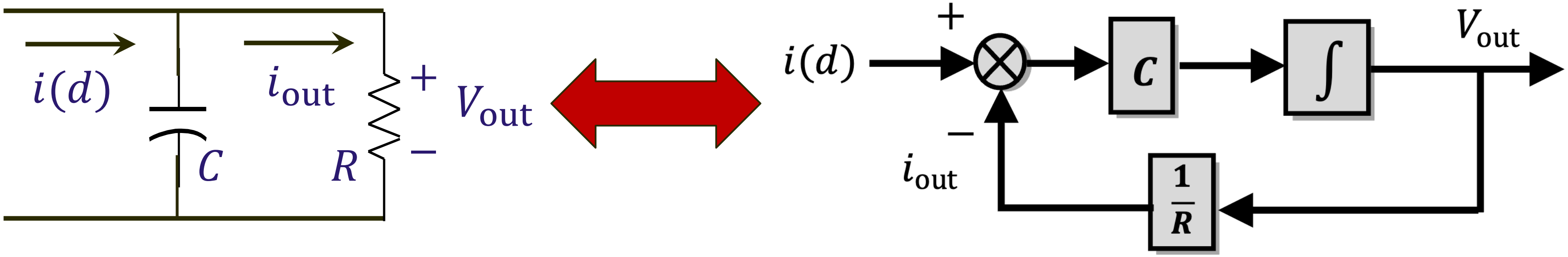
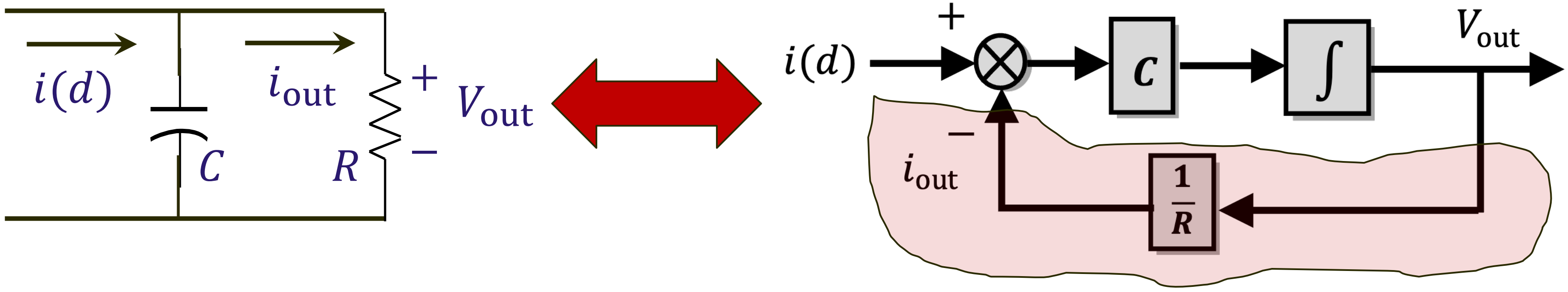


$$\frac{d}{dt}V_{\text{out}} = i(d) - \frac{1}{R}V_{\text{out}}$$

Distributed power systems

Output capacitor of DC-DC converter

Resistive load



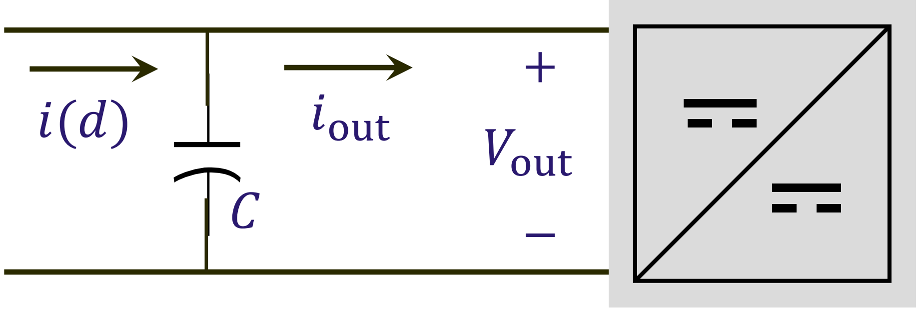
$$C\frac{d}{dt}V_{\text{out}} = i(d) - \frac{1}{R}V_{\text{out}}$$

Negative feedback: self-stabilising mechanism

Distributed power systems

Output capacitor of DC-DC converter

Controlled converter as load

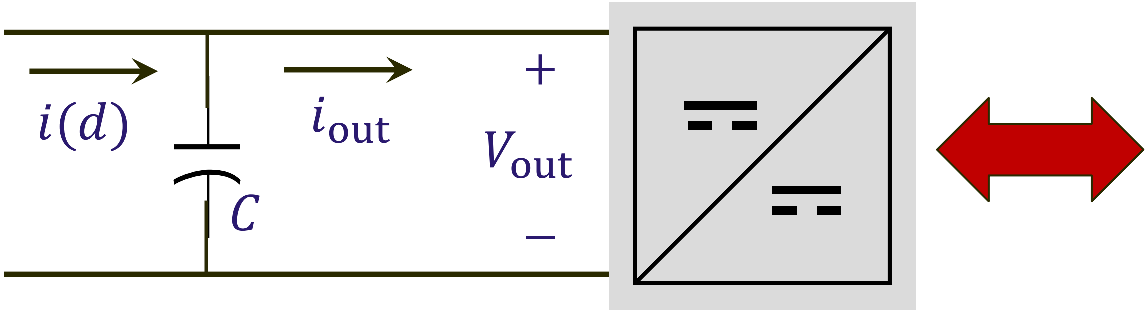


Constant Input/Output Power *"P"*

Distributed power systems

Output capacitor of DC-DC converter

Controlled converter as load



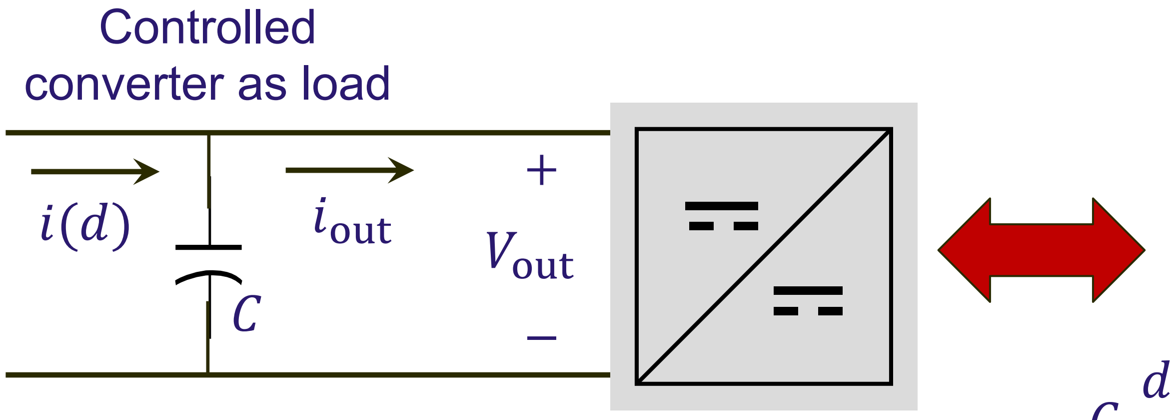
Constant Input/Output Power *"P"*

Nonlinear output current

$$C\frac{d}{dt}V_{\text{out}} = i(d) - \frac{\boldsymbol{P}}{\boldsymbol{V}_{\textbf{out}}}$$

Distributed power systems

Output capacitor of DC-DC converter



Constant Input/Output Power *"P"*

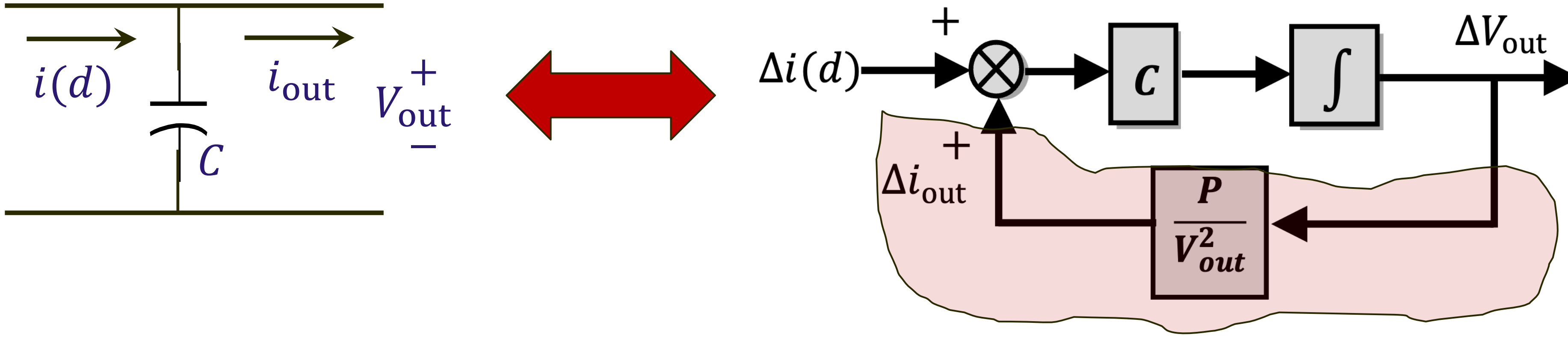
Small-signal analysis

$$C\frac{d}{dt}\Delta V_{\text{out}} = \Delta i(d) + \frac{\boldsymbol{P}}{\boldsymbol{V_{\text{out}}^2}}\Delta V_{\text{out}}$$

Distributed power systems

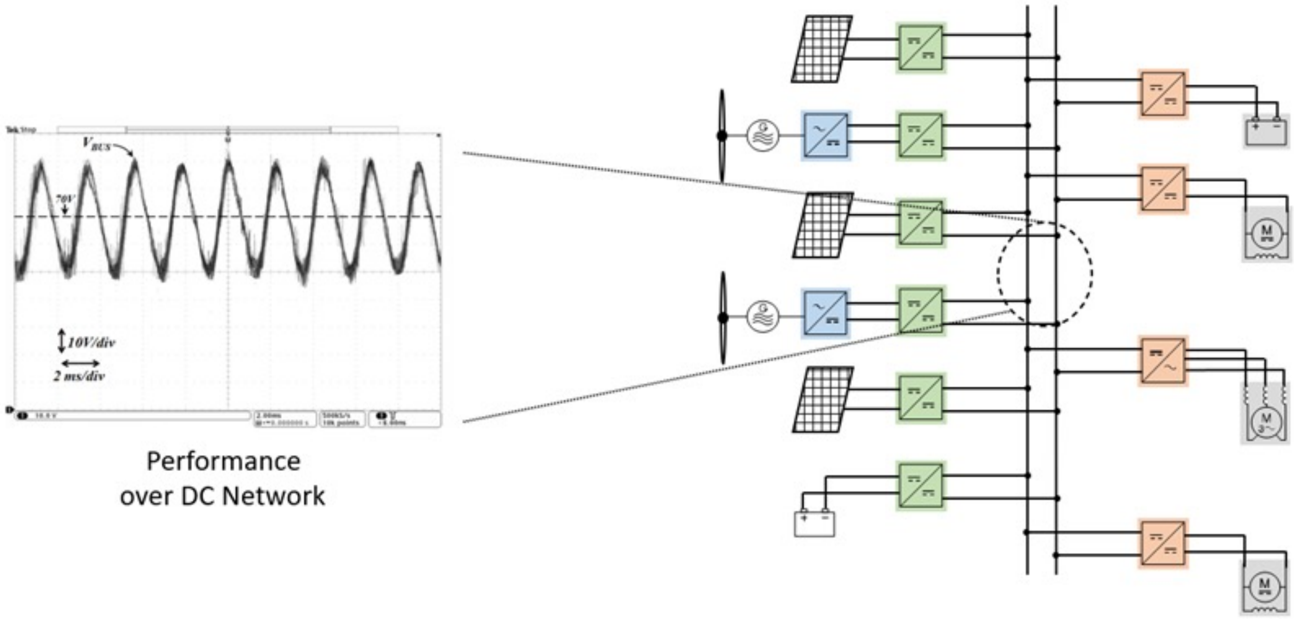
Output capacitor of DC-DC converter

Controlled converter as load



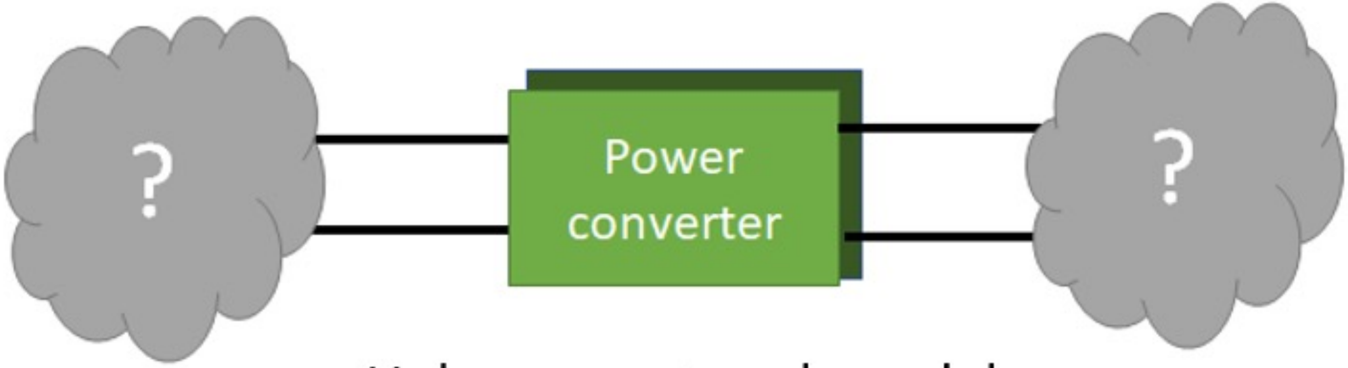
Positive feedback! → Unstable equilibrium

Distributed power systems



- Stand alone models do not predict issues due to dynamic interactions.
- “Resistive load” assumption is not advised.
- Example: Constant power load (CPL).

Distributed power systems



Unknown network model

- In real life, dynamical models of devices interconnected at the input and output are unknown!

New concept: Data-Driven Control

- **A model is** a mathematical description that provides **information** about the system dynamics.

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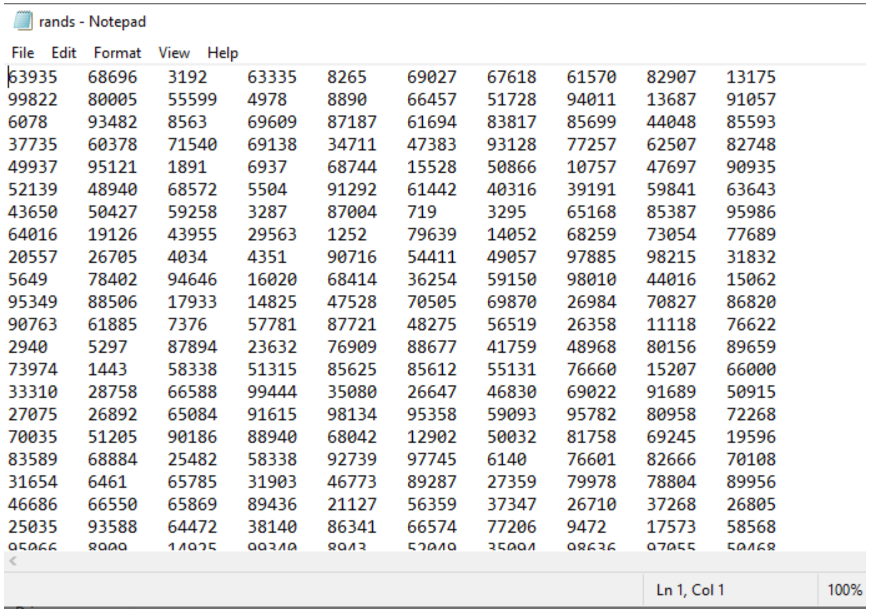

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```

$$\frac{dy}{dx} = f(x)$$

$$\frac{dy}{dx} = f(x, y)$$

$$x_1 \frac{\partial y}{\partial x_1} + x_2 \frac{\partial y}{\partial x_2} = y$$

New concept: Data-Driven Control

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- The influence of parasitic elements, leakage currents/voltages and other unmodelled components is negligible. Not true: stray capacitances, leakage to ground paths (common mode currents), electromechanical loads.
- We trust that a controller will compensate all the unknown influences and uncertainty. Not true: a controller can only guarantee stability by extending the assumptions on parameter deviations and disturbances.

New concept: Data-Driven Control

Data-driven approaches assume that:

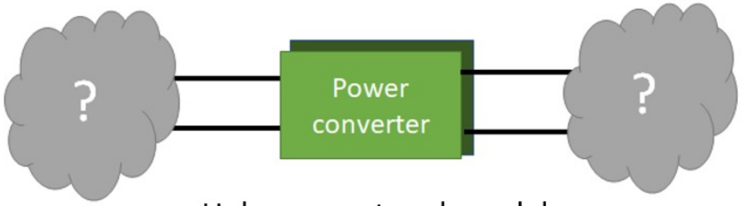
- The system is observable and controllable. (Also assumed by model-based approaches BTW)

- The data is informative. Data must capture dynamics of the system (constant voltages/currents are not useful).

New concept: Data-Driven Control

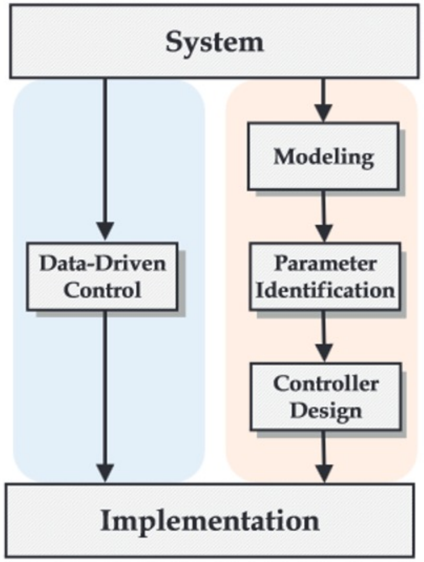
- **Data-driven control** replaces models by data.

- Power converter interconnected



Unknown network model

Replacing models by data with guaranteed stability.

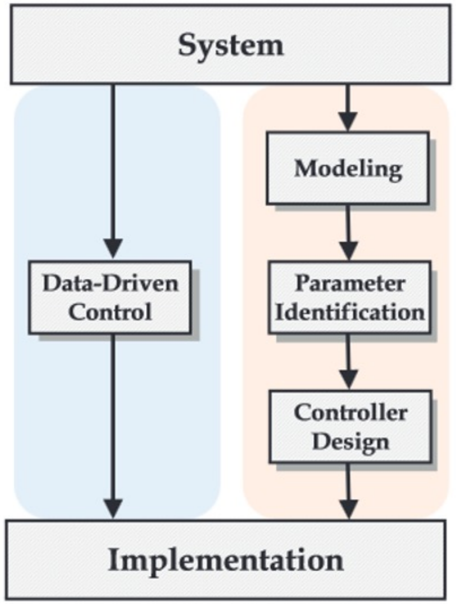


- Goal: guaranteeing performance specifications such as stability without a model in a **<u>deterministic</u>** way.

New concept: Data-Driven Control

- System identification + model-based control is a two-step procedure.
- Data driven control is a model-free approach.
- It does not require, at any point, the explicit realization of a model.
- Control synthesis is purely driven by matrices constructed from experimental data.

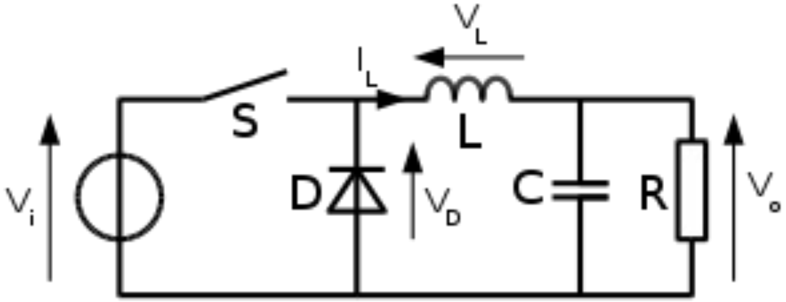
Replacing models by data with guaranteed stability.



New concept: Data-Driven Control

- Data-driven control is based on information of the real-life device, not on an ideal abstraction.

Beautiful abstraction!



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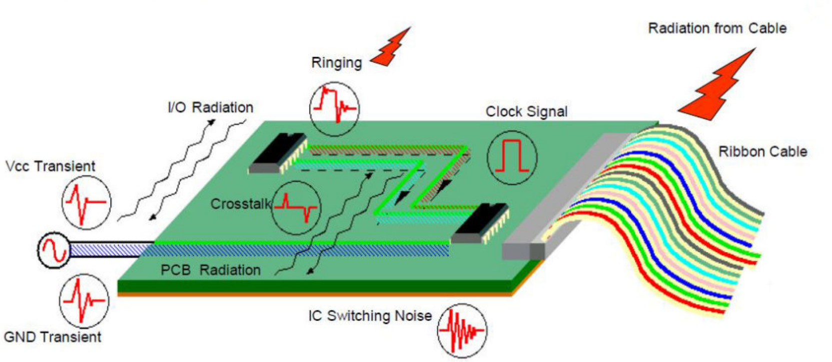
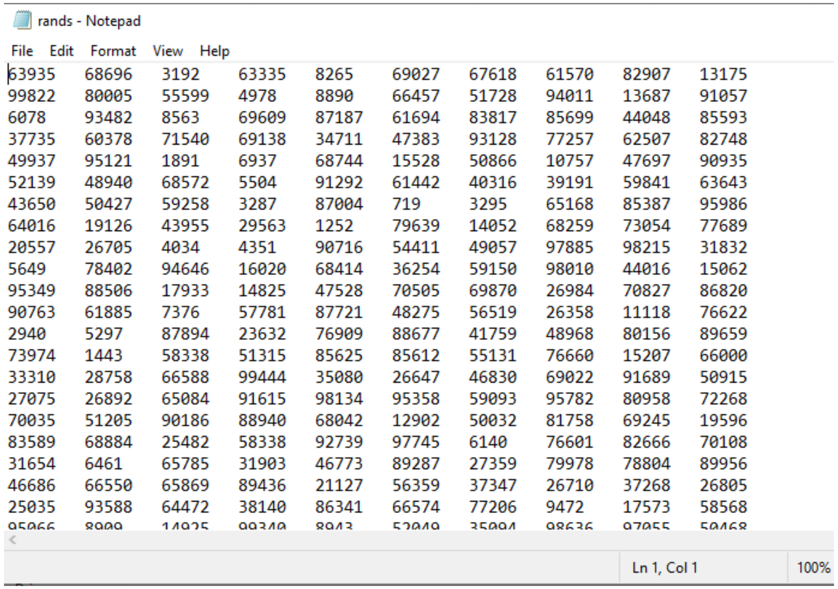
Real imperfect world!





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```

New concept: Data-Driven Control

"Truth is not what you want it to be; it is what it is. And you must bend to its power or live a lie."

— Miyamoto Musashi

Model-based control (discrete-time)

- System of difference equations (plant dynamics):

$$P_0 w(k) + P_1\, w(k+1) + \cdots + P_N w(k+N) = 0\,.$$

- Introducing a shift operator: $\sigma\, w(k) = w(k+1)$ we can simply write:

$$P_0 w + P_1 \sigma w\ + \cdots + P_N \sigma^N w = 0\,.$$

- The shift operator can be taken as an algebraic element:

$$\underbrace{(P_0 + P_1 \sigma\ + \cdots + P_N \sigma^N)}_{P(\sigma)} w = 0\,.$$

Control by interconnection

- Consider a plant modelled as a linear differential system:

$$\begin{bmatrix} P(\sigma) \\ C(\sigma) \end{bmatrix} w = 0\,.$$

- A controller $C(\cdot)$ is a restriction rule.

Willems, Jan C., and Jan W. Polderman. Introduction to mathematical systems theory: a behavioral approach. Vol. 26. Springer Science & Business Media, 1997.

Stabilisation

- The existence of a stabilising controller $C(\cdot)$ is equivalent to the existence of a Lyapunov function $Q_\Psi \geq 0$ such that

$$\sigma Q_\Psi(w) - Q_\Psi(w) < 0 \text{ for all } w \text{ generated by } \begin{bmatrix} P\left(\frac{d}{dt}\right) \\ C\left(\frac{d}{dt}\right) \end{bmatrix} w = 0 .$$

Rapisarda, Paolo, and Chiaki Kojima. "Stabilization, Lyapunov functions, and dissipation." Systems & control letters 59, no. 12 (2010): 806-811.

Stabilisation

- The same condition can be expressed as

$$\sigma Q_{\Psi}(w) - Q_{\Psi}(w) + w^{\top}[P(\sigma)^{\top} \quad C(\sigma)^{\top}]V(\sigma)w + w^{\top}V(\sigma)^{\top}\begin{bmatrix} P(\sigma) \\ C(\sigma) \end{bmatrix} w < 0\,;$$

In words, a trajectory w that satisfies $\begin{bmatrix} P(\sigma) \\ C(\sigma) \end{bmatrix} w = 0$ will zero-out the green green tail.

Rapisarda, Paolo, and Chiaki Kojima. "Stabilization, Lyapunov functions, and dissipation." Systems & control letters 59, no. 12 (2010): 806-811.

Stabilisation

- Then the condition:

$$\sigma Q_{\Psi}(w) - Q_{\Psi}(w) + w^{\top}[P(\sigma)^{\top} \quad C(\sigma)^{\top}]V(\sigma)w + w^{\top}V(\sigma)^{\top}\begin{bmatrix} P(\sigma) \\ C(\sigma) \end{bmatrix} w < 0\,;$$

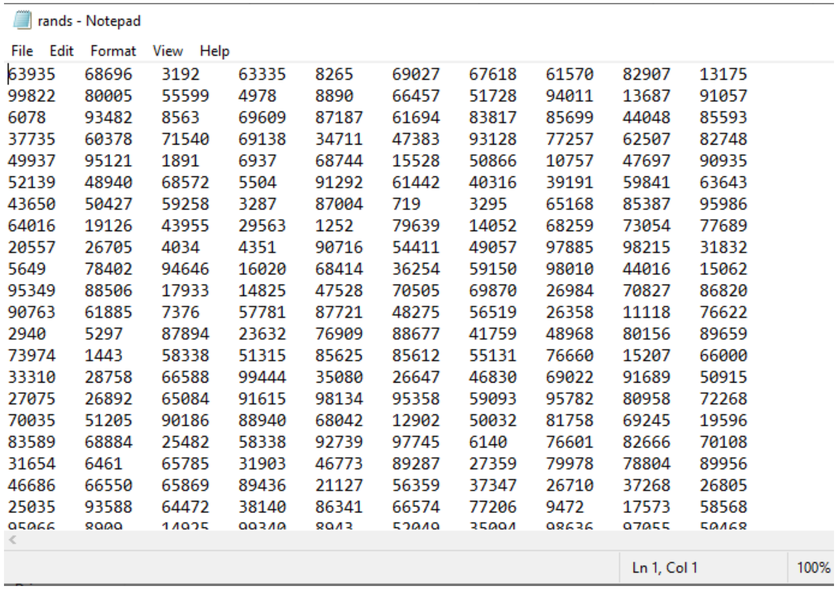
When factorising, the condition can be numerically implemented using linear matrix inequalities (LMIs):

$$\begin{bmatrix} 0_{Nq\times q} & \widetilde{\Psi} \\ 0_{q\times q} & 0_{q\times Nq} \end{bmatrix} - \begin{bmatrix} 0_{q\times Nq} & 0_{q\times q} \\ \widetilde{\Psi} & 0_{Nq\times q} \end{bmatrix} + [\tilde{P}^{\top} \quad \tilde{C}^{\top}]\tilde{V} + \tilde{V}^{\top}\begin{bmatrix} \tilde{P} \\ \tilde{C} \end{bmatrix} < 0\,.$$

- Given a matrix $\tilde{P}$ The matrices $\widetilde{\Phi}$, $\widetilde{\Psi}$, $\tilde{V}$ and $\tilde{C}$ can be computed using Yalmip.
- $\tilde{C}$ implements the stabilising controller.

Stabilisation

- The matrix $\tilde{P}$ is associated to the plant dynamics and can be obtained by factorising a matrix of data



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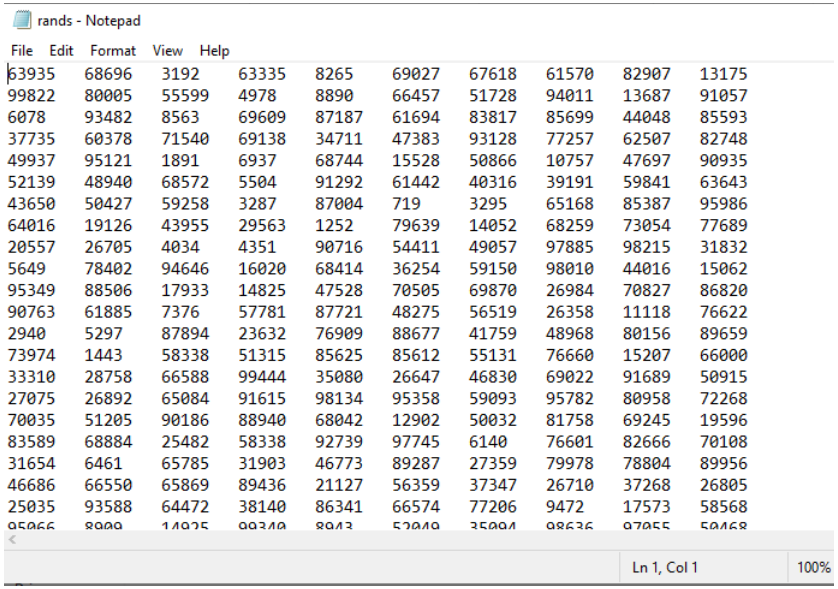
Singular Value Decomposition (SVD)

$\tilde{P}$

Data-driven control algorithm

Input-data



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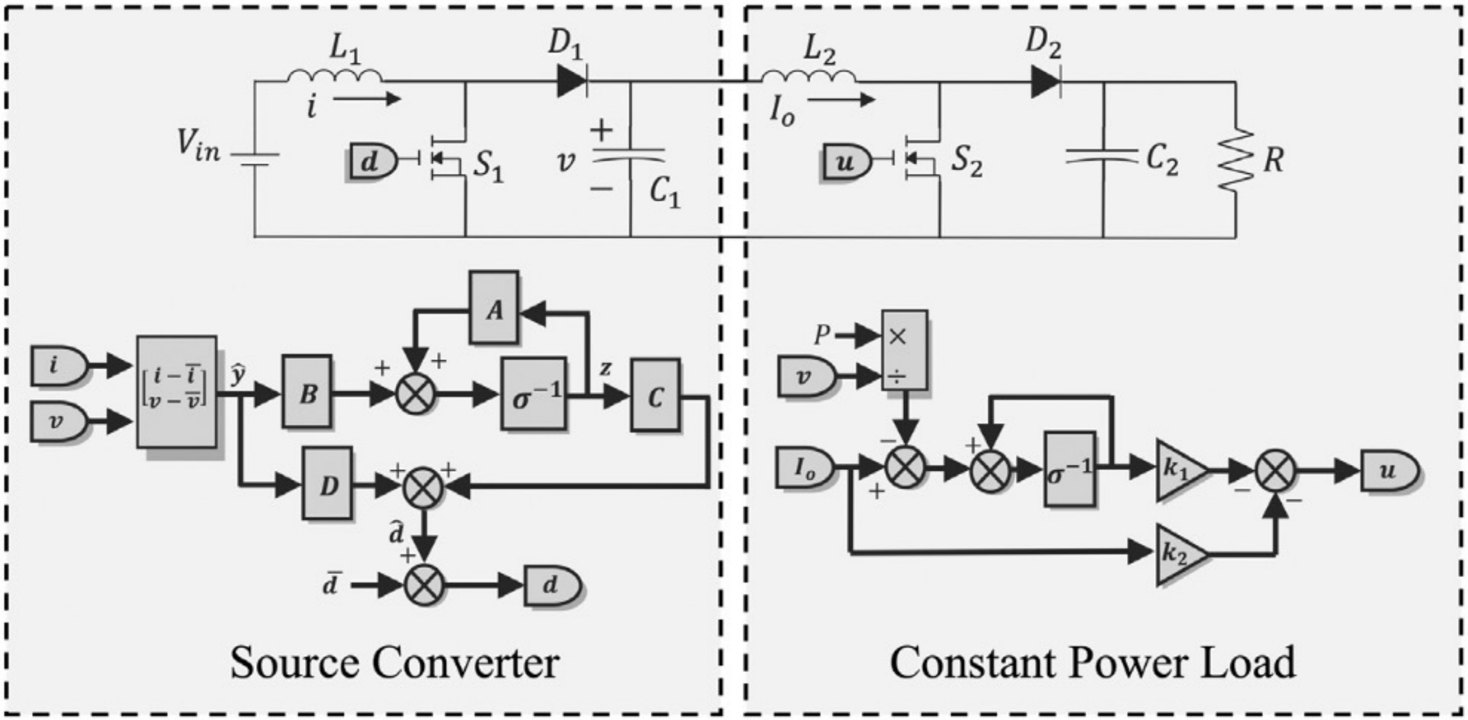
49937   95121   1891    6937    68744   15528   50866   10757   47697   90935
52139   48940   68572   5504    91292   61442   40316   39191   59841   63643
43650   50427   59258   3287    87004   719     3295    65168   85387   95986
64016   19126   43955   29563   1252    79639   14052   68259   73054   77689
20557   26705   4034    4351    90716   54411   49057   97885   98215   31832
5649    78402   94646   16020   68414   36254   59150   98010   44016   15062
95349   88506   17933   14825   47528   70505   69870   26984   70827   86820
90763   61885   7376    57781   87721   48275   56519   26358   11118   76622
2940    5297    87894   23632   76909   88677   41759   48968   80156   89659
73974   1443    58338   51315   85625   85612   55131   76660   15207   66000
33310   28758   66588   99444   35080   26647   46830   69022   91689   50915
27075   26892   65084   91615   98134   95358   59093   95782   80958   72268
70035   51205   90186   88940   68042   12902   50032   81758   69245   19596
83589   68884   25482   58338   92739   97745   6140    76601   82666   70108
31654   6461    65785   31903   46773   89287   27359   79978   78804   89956
46686   66550   65869   89436   21127   56359   37347   26710   37268   26805
25035   93588   64472   38140   86341   66574   77206   9472    17573   58568
```

Matrix Factorisation $\tilde{P}$

Lyapunov condition (LMI)

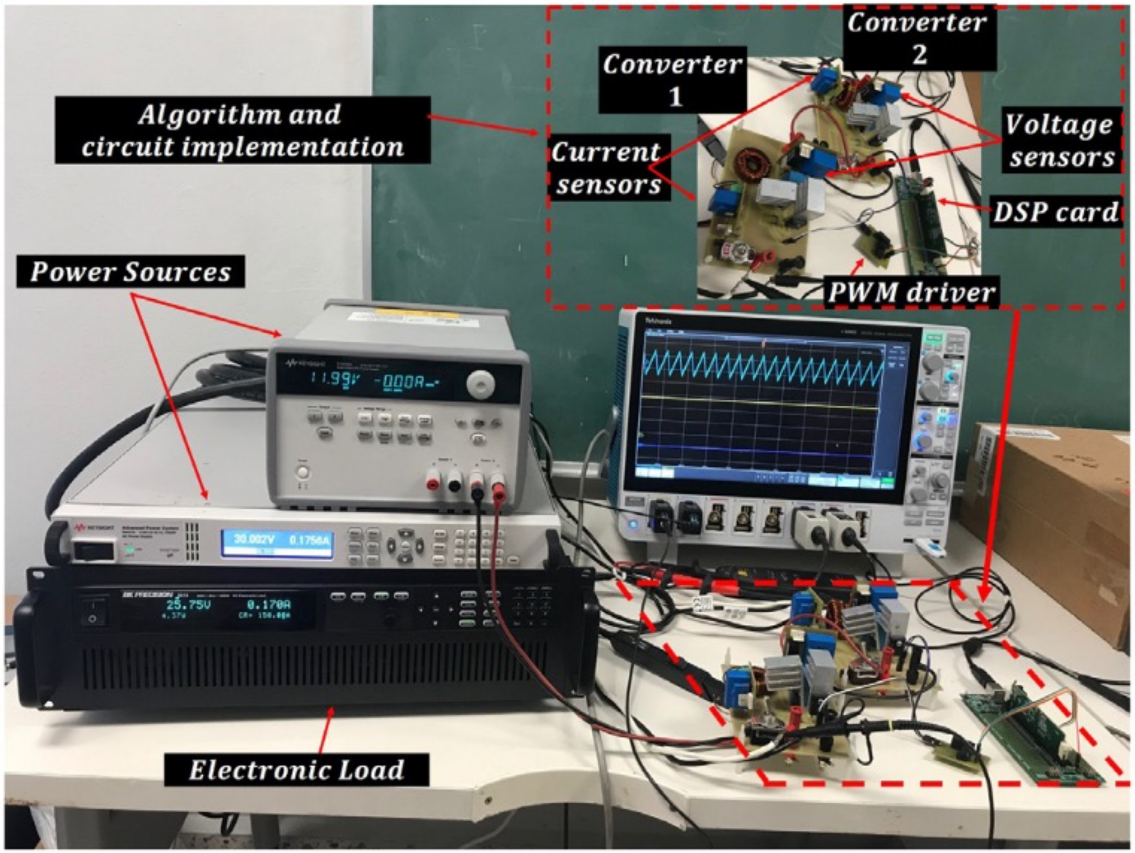
Controller

Example: Boost converter



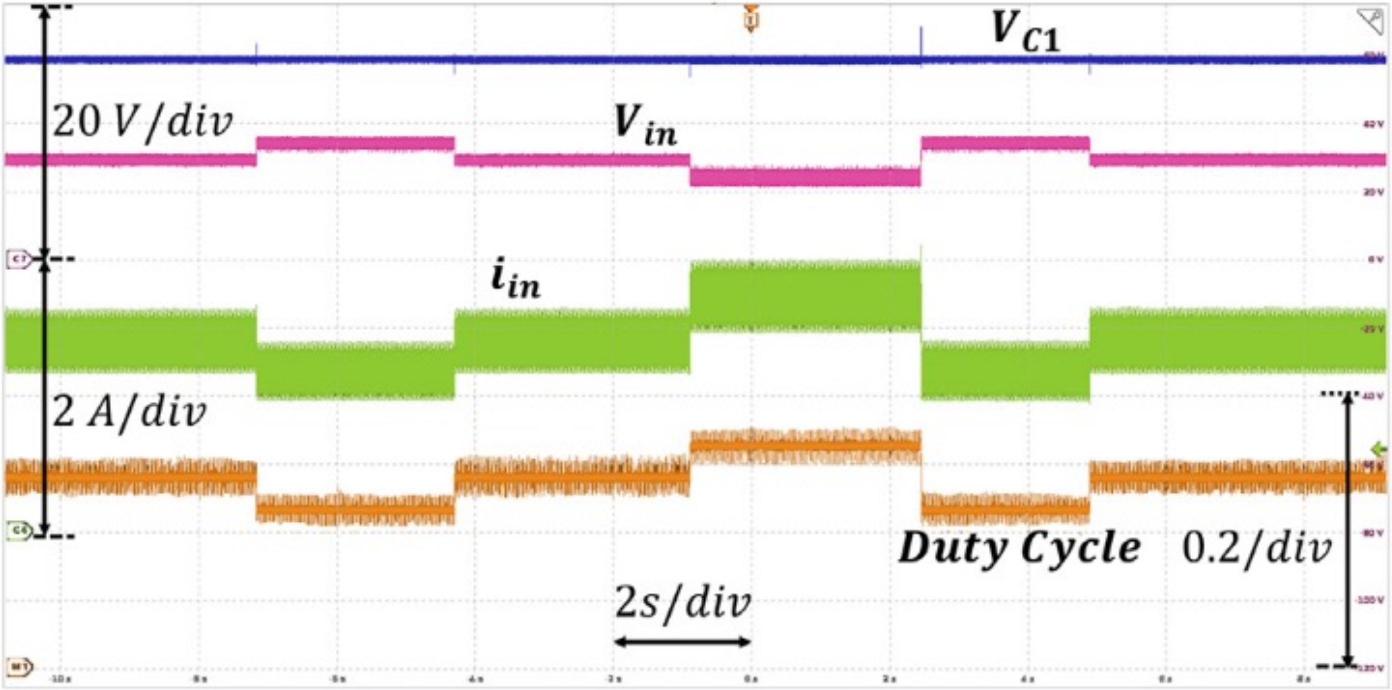
Ruiz-Martinez, O. F., Mayo-Maldonado, J. C., Escobar, G., Valdez-Resendiz, J. E., Maupong, T. M., & Rosas-Caro, J. C. (2020). Data-driven stabilizing control of DC–DC converters with unknown active loads. Control Engineering Practice, 95, 104266.

Example: Boost converter



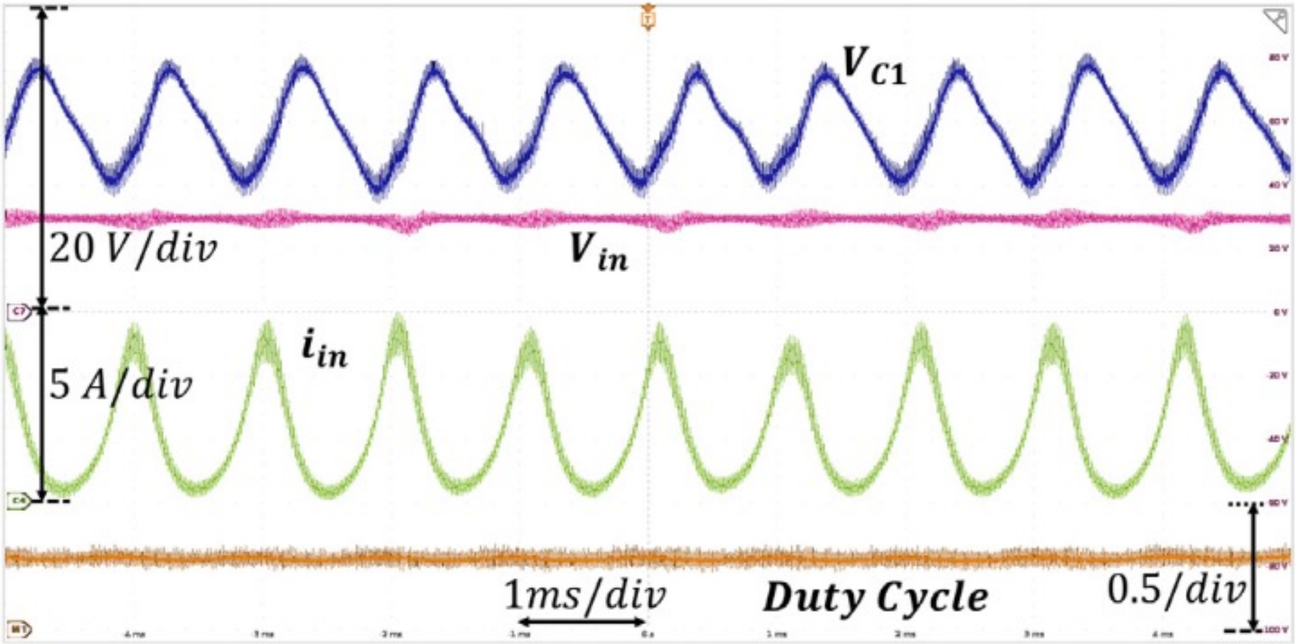
Example: Boost converter

- Model-based design with resistive load



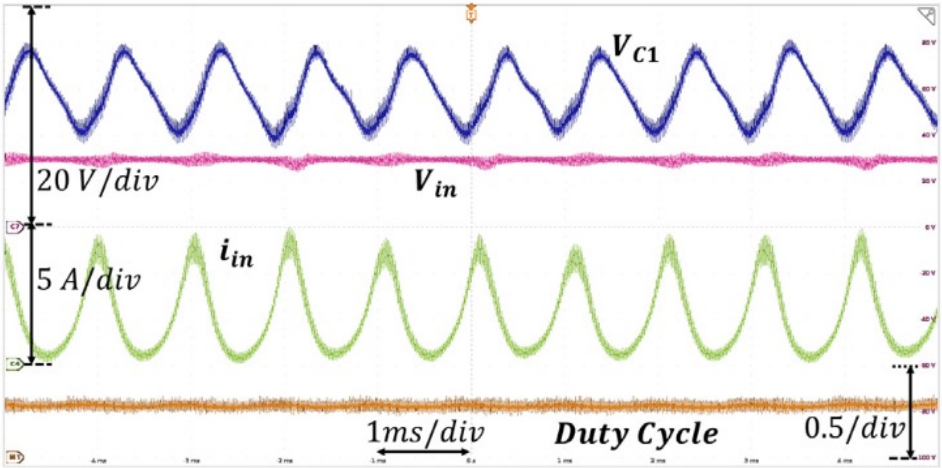
Example: Boost converter

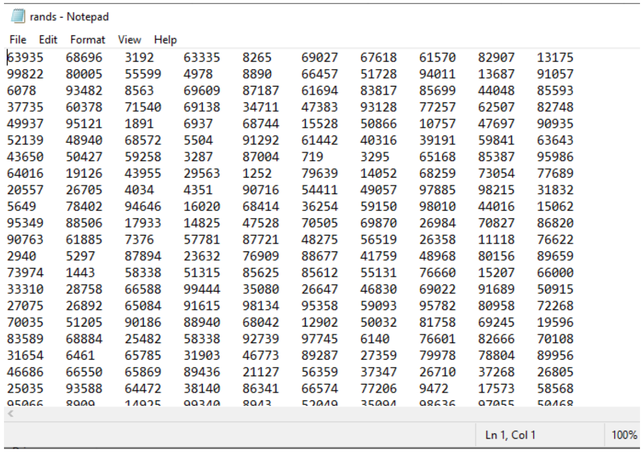
- Model-based design when swapping to a constant power load



Example: Boost converter

- Measurement data:





```
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99822   80005   55599   4978    8890    66457   51728   94011   13687   91057
6078    93482   8563    69609   87187   61694   83817   85699   44048   85593
37735   60378   71540   69138   34711   47383   93128   77257   62507   82748
49937   95121   1891    6937    68744   15528   50866   10757   47697   90935
52139   48940   68572   5504    91292   61442   40316   39191   59841   63643
43650   50427   59258   3287    87004   719     3295    65168   85387   95986
64016   19126   43955   29563   1252    79639   14052   68259   73054   77689
20557   26705   4034    4351    90716   54411   49057   97885   98215   31832
5649    78402   94646   16020   68414   36254   59150   98010   44016   15062
95349   88506   17933   14825   47528   70505   69870   26984   70827   86820
90763   61885   7376    57781   87721   48275   56519   26358   11118   76622
2940    5297    87894   23632   76909   88677   41759   48968   80156   89659
73974   1443    58338   51315   85625   85612   55131   76660   15207   66000
33310   28758   66588   99444   35080   26647   46830   69022   91689   50915
27075   26892   65084   91615   98134   95358   59093   95782   80958   72268
70035   51205   90186   88940   68042   12902   50032   81758   69245   19596
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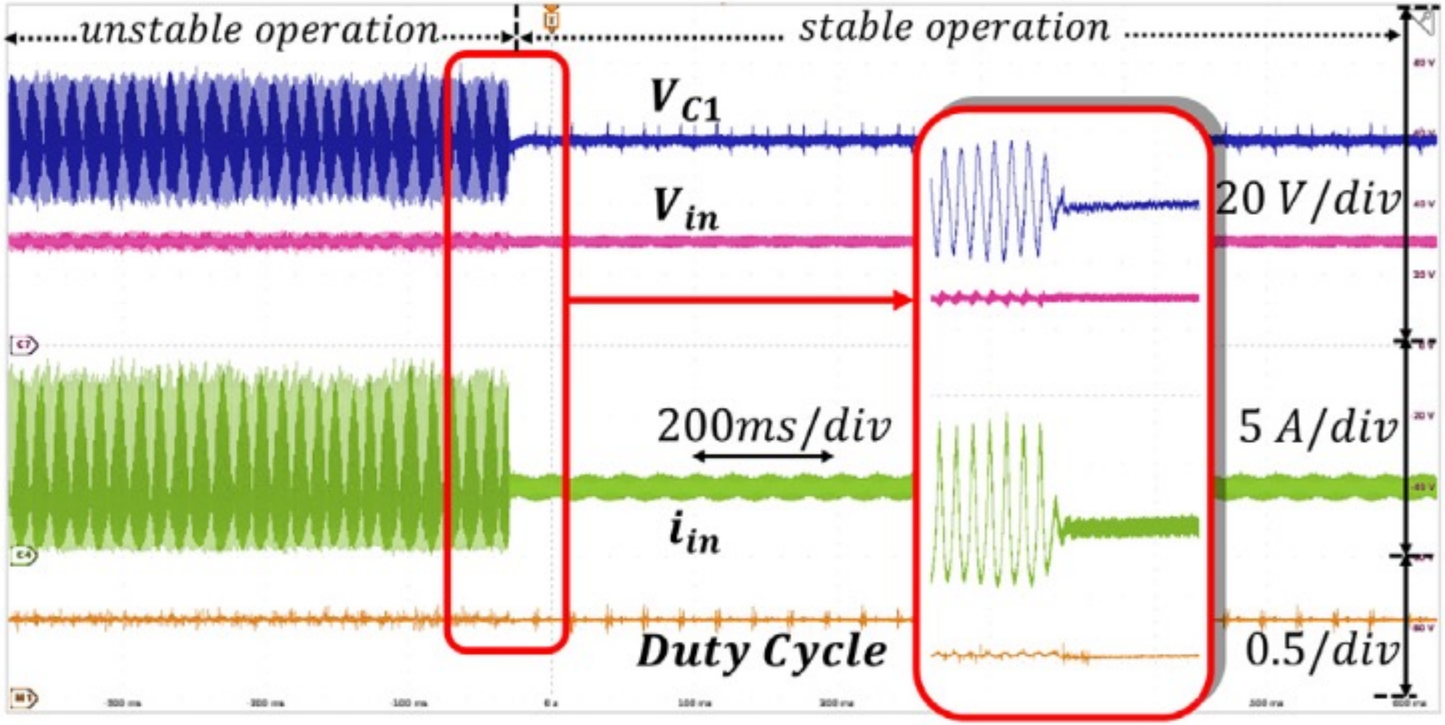
31654   6461    65785   31903   46773   89287   27359   79978   78804   89956
46686   66550   65869   89436   21127   56359   37347   26710   37268   26805
25035   93588   64472   38140   86341   66574   77206   9472    17573   58568
```

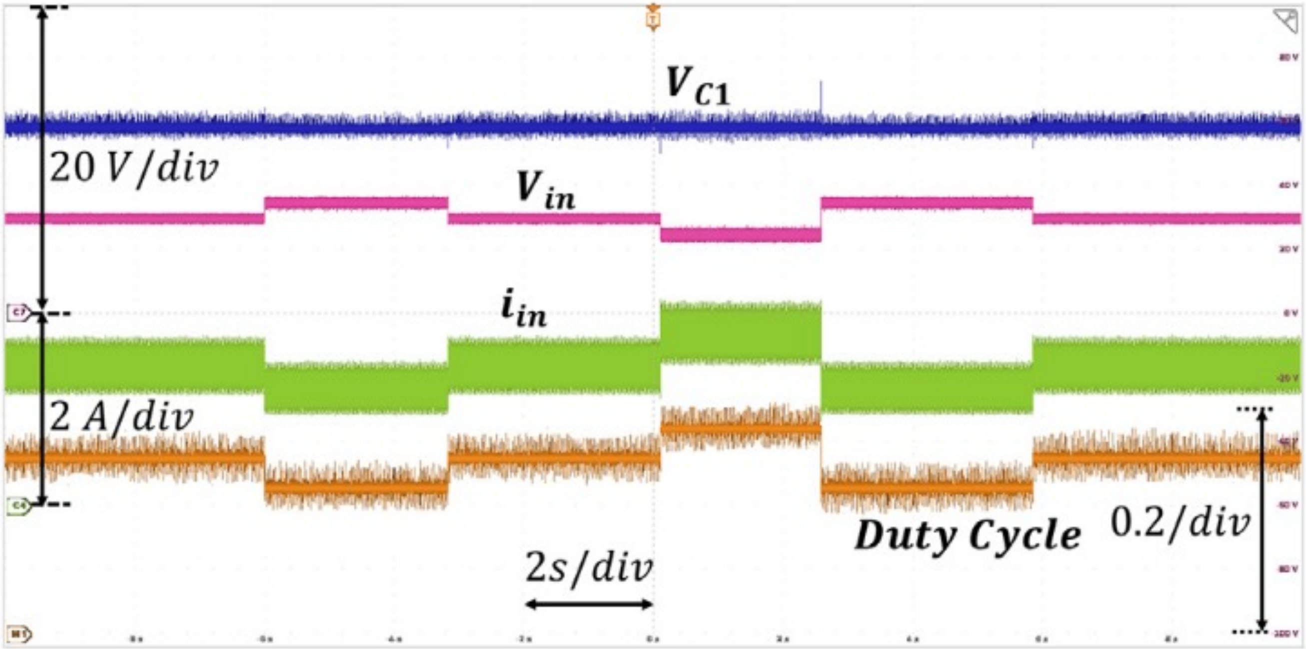
Example: Boost converter

- Data-driven controller activation

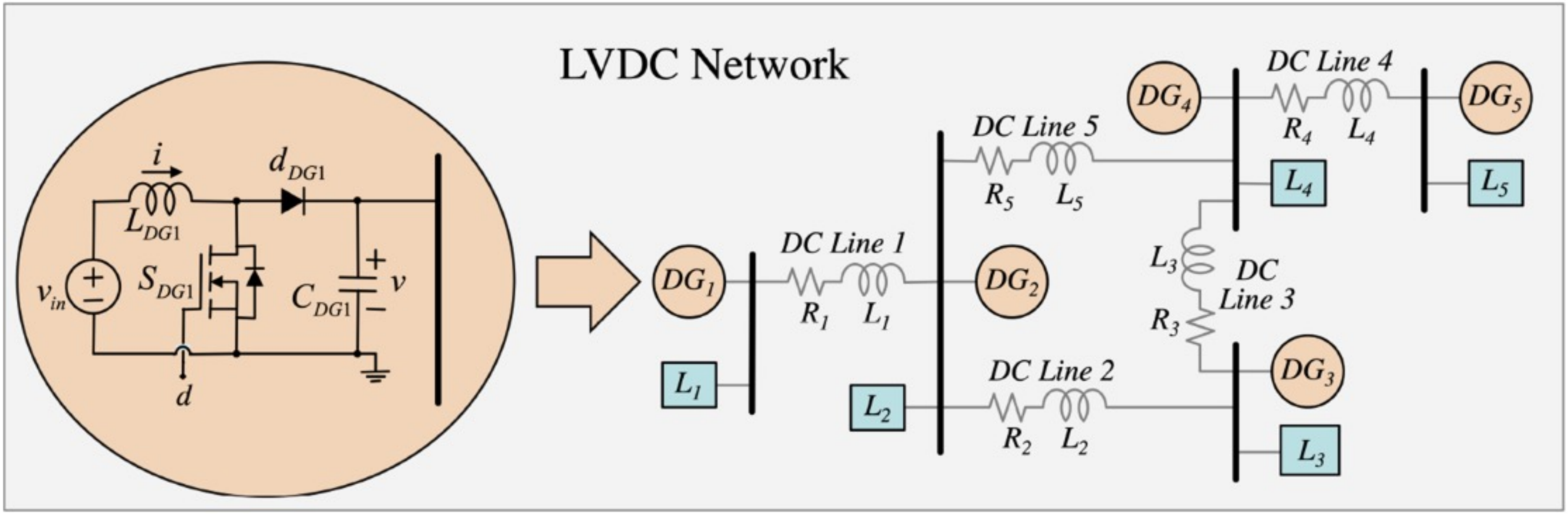


Example: Boost converter

- Data-driven controller performance



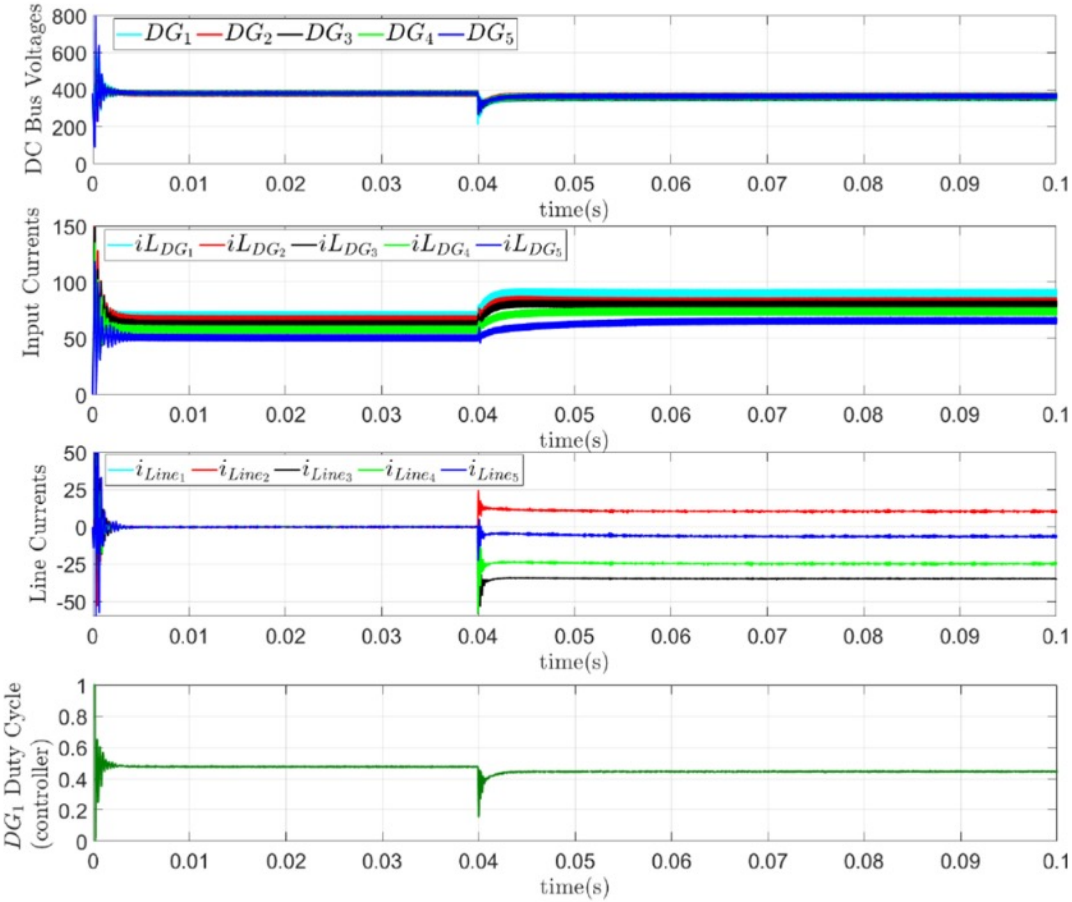
Example: LVDC Network



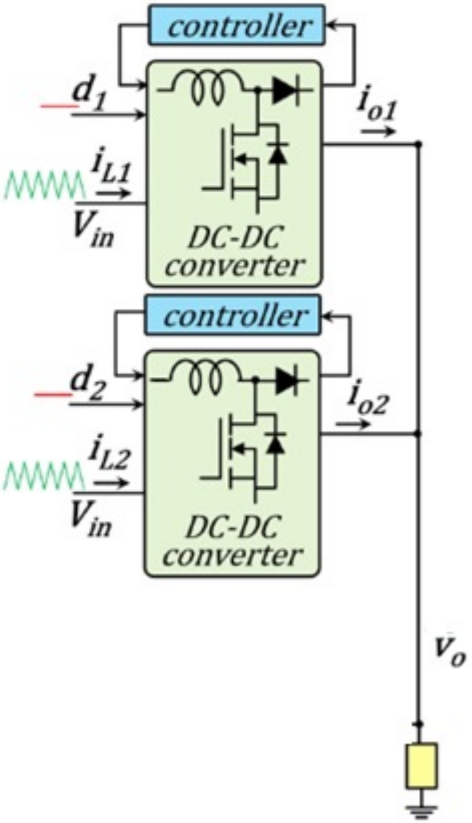
Ruiz-Martinez, O. F., Mayo-Maldonado, J. C., Escobar, G., Frias-Araya, B. A., Valdez-Resendiz, J. E., Rosas-Caro, J. C., & Rapisarda, P. (2019). Data-driven control of LVDC network converters: Active load stabilization. *IEEE Transactions on Smart Grid*, 11(3), 2182-2194.

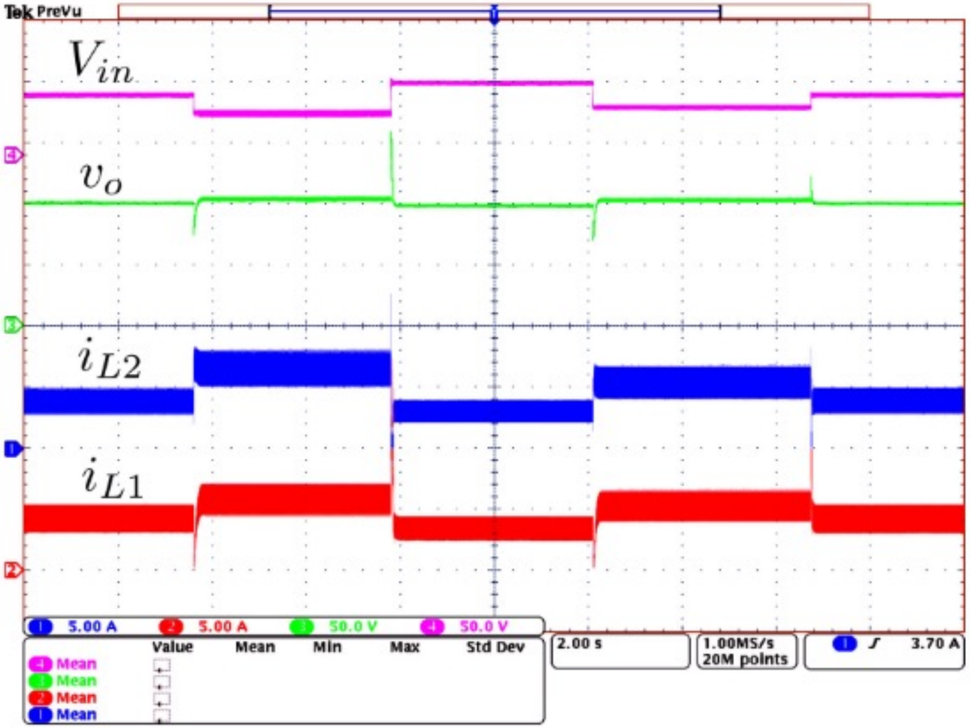
Example: LVDC Network

- Renewable energy intermittency
- Load variation
- CPL stabilisation
- Power sharing



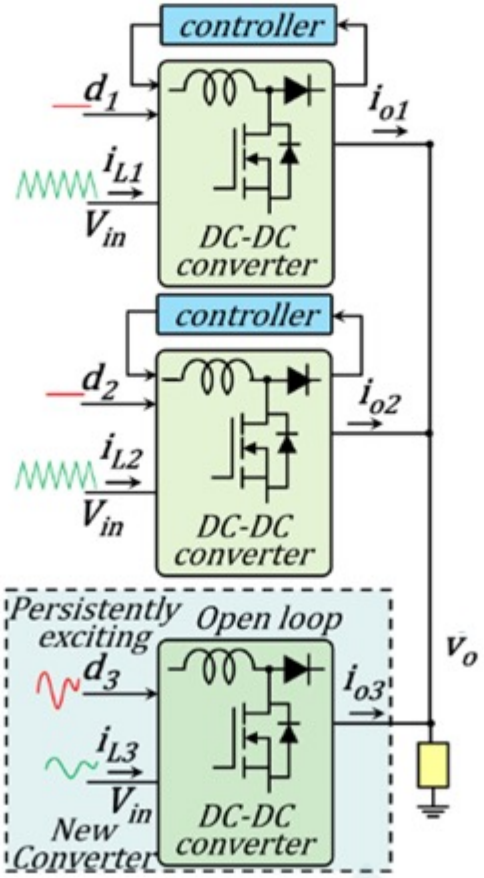
Example: Modular DC Microgrid

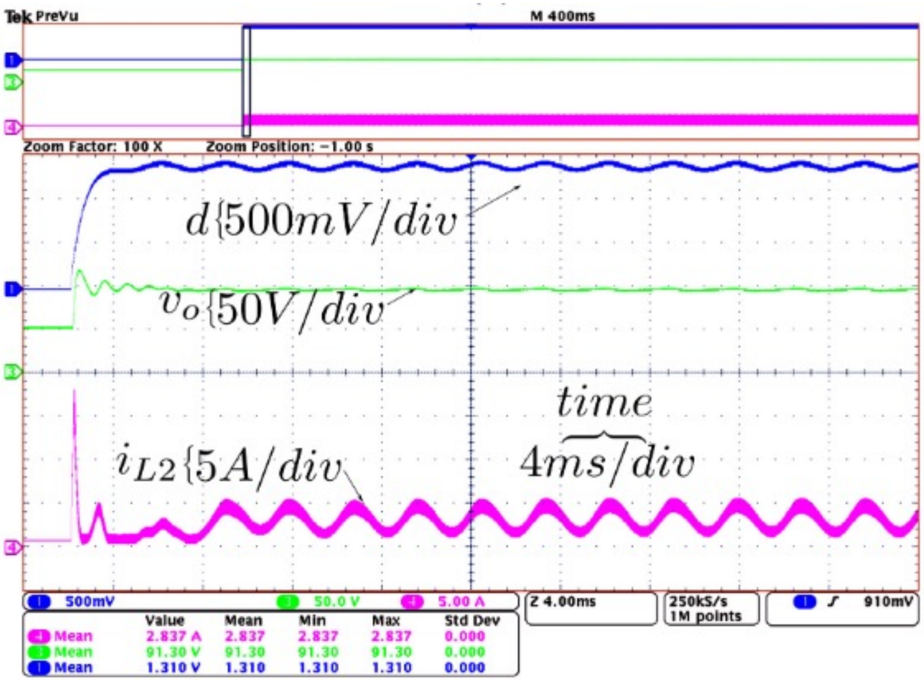




J. Loranca-Coutiño, J. C. Mayo-Maldonado, G. Escobar, T. M. Maupong, J. E. Valdez-Resendiz and J. C. Rosas-Caro, "Data-Driven Passivity-Based Control Design for Modular DC Microgrids," in IEEE Transactions on Industrial Electronics, vol. 69, no. 3, pp. 2545-2556, March 2022.

Example: Modular DC Microgrid

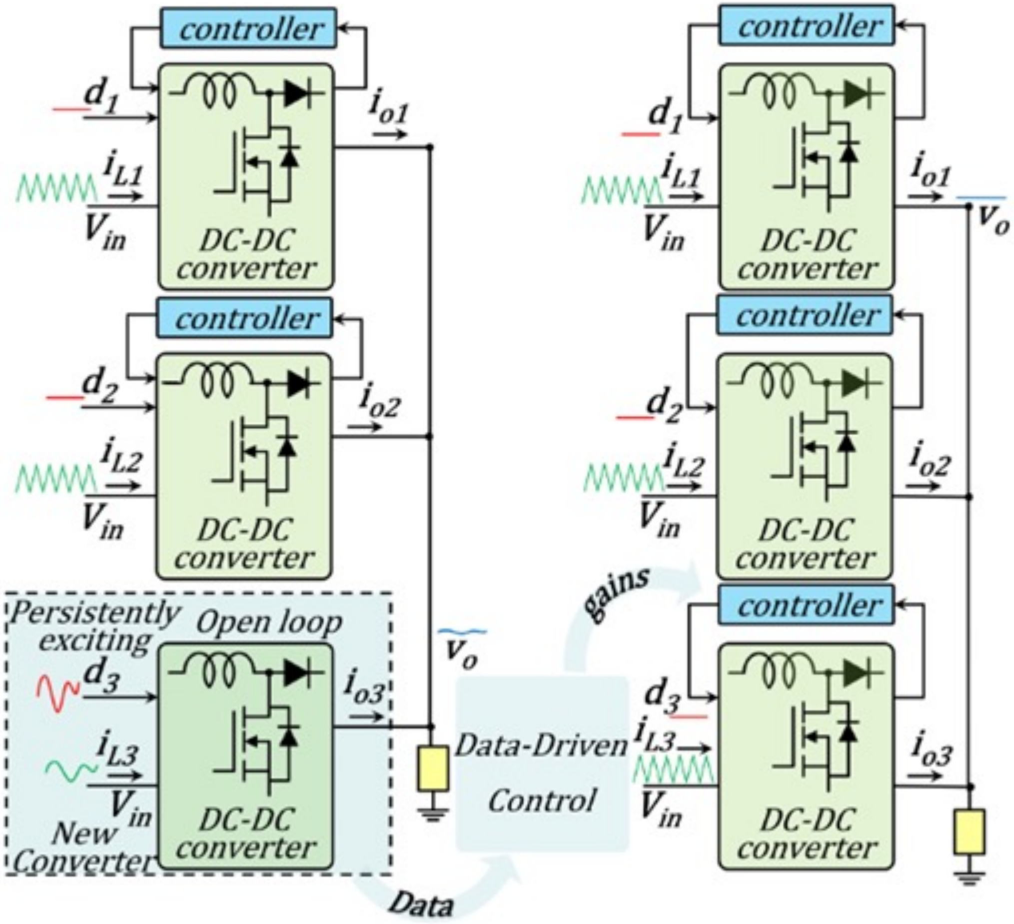




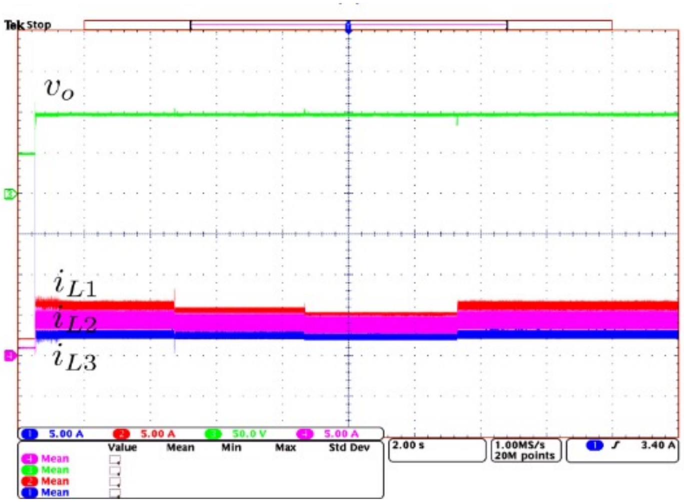
	Value	Mean	Min	Max	Std Dev
4 Mean	2.837 A	2.837	2.837	2.837	0.000
3 Mean	91.30 V	91.30	91.30	91.30	0.000
1 Mean	1.310 V	1.310	1.310	1.310	0.000

Data from new converter

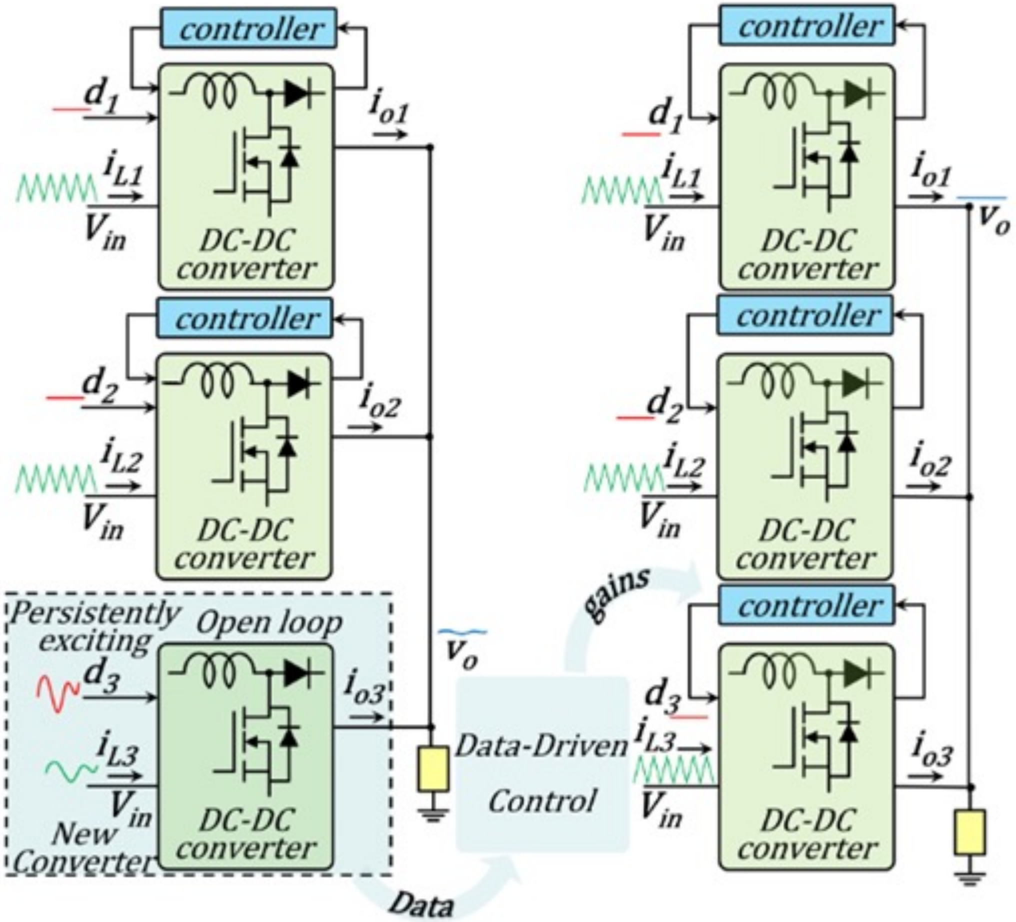
Example: Modular DC Microgrid



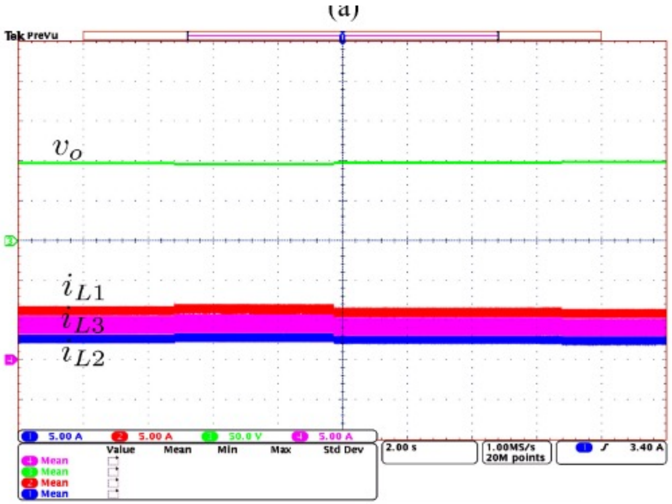
Voltage variations



Example: Modular DC Microgrid

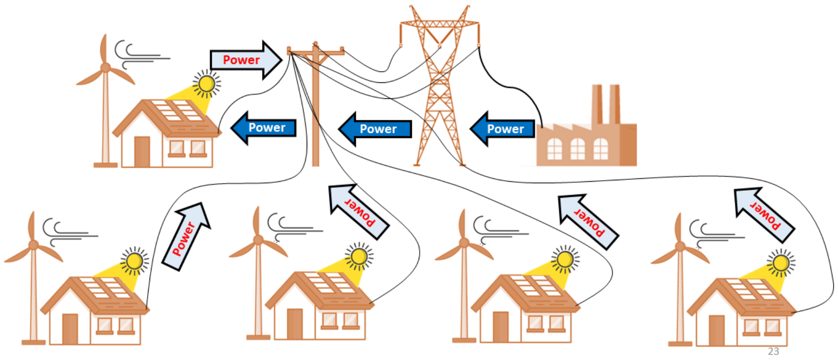


Load variations

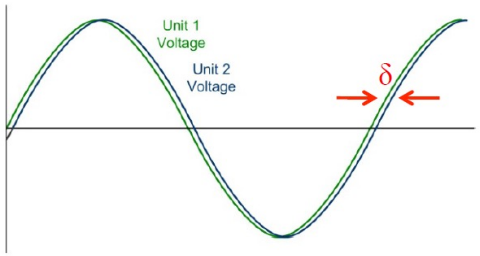


Distribution AC Systems

- High penetration of renewables:



- ➢ Bidirectional power flow (false fault tripping)
- ➢ Short distances (smaller X/R ratio)
- ➢ Low inertia (high inttermitency)
- ➢ Harmonic distortion (inverter influence)
- ➢ Congestion (peak-hour/load-demand mismatch)
- ➢ Faults (open circuit, short circuit, etc.)

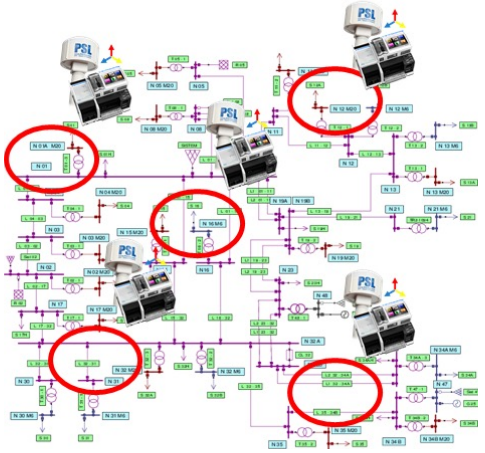


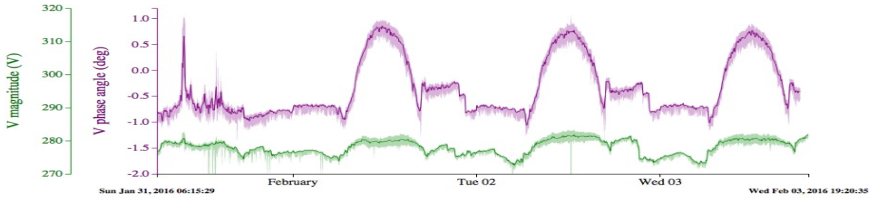
Small phase angle δ between different locations on the grid, drives AC power flow.

Micro PMU: 0.001° Resolution for Phase angles, voltages and currents

Phasor Measurement Units

- Micro PMU deployment





✓ Monitoring (network observability)

✓ Fault detection algorithms (resilience)

✓ Hosting capacity (planning)

✓ Dynamic phasor estimation (harmonics)

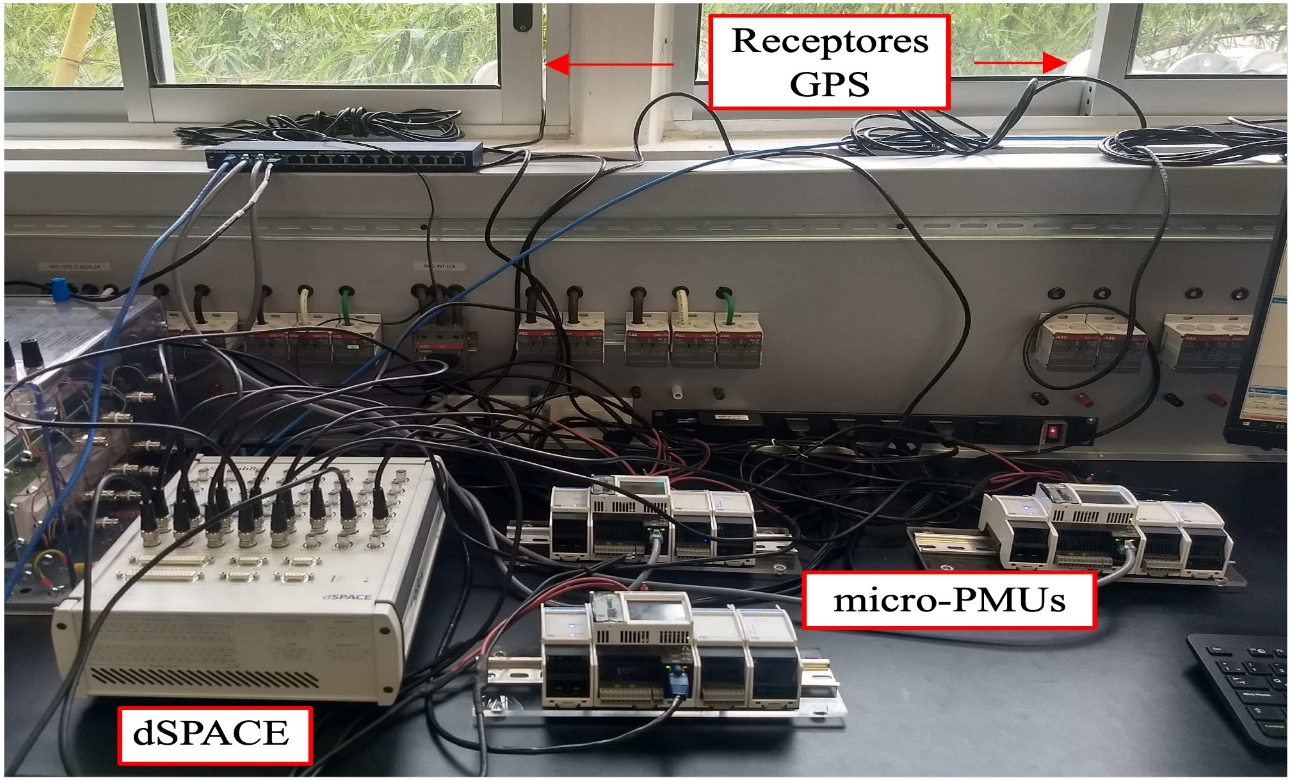
✓ Control of distributed generation (microgrid concept)

✓ uPMU algotithm validation (laboratory)

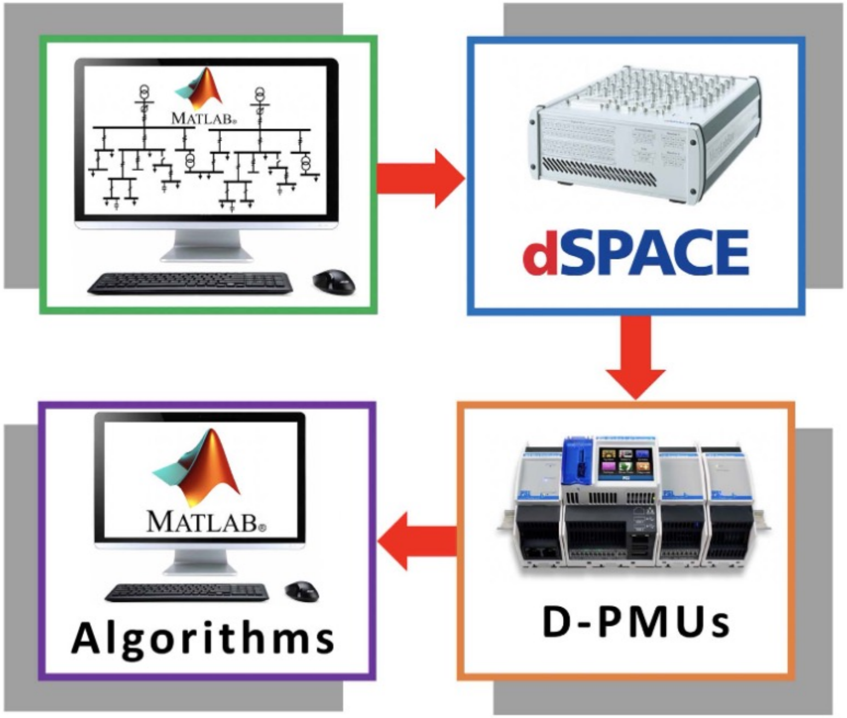
✓ uPMU placement algorithms (artificial intelligence)

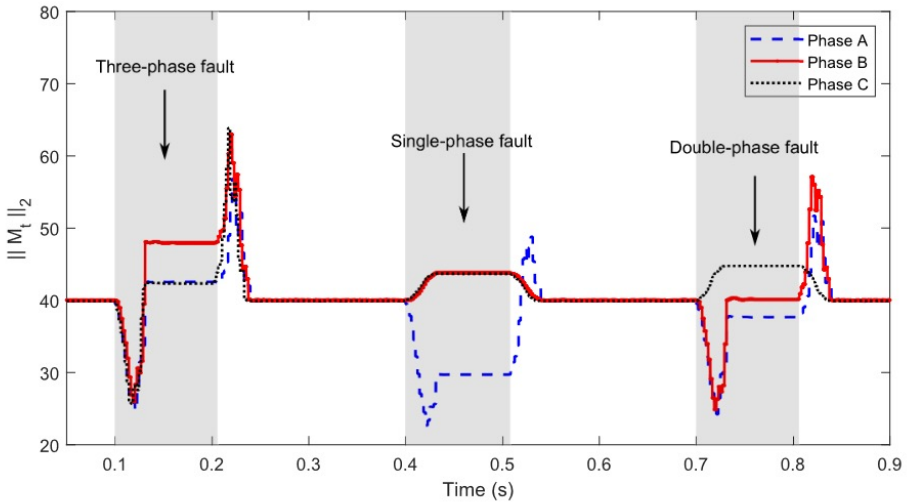
✓ uPMU installed on the real grid.

Phasor Measurement Units



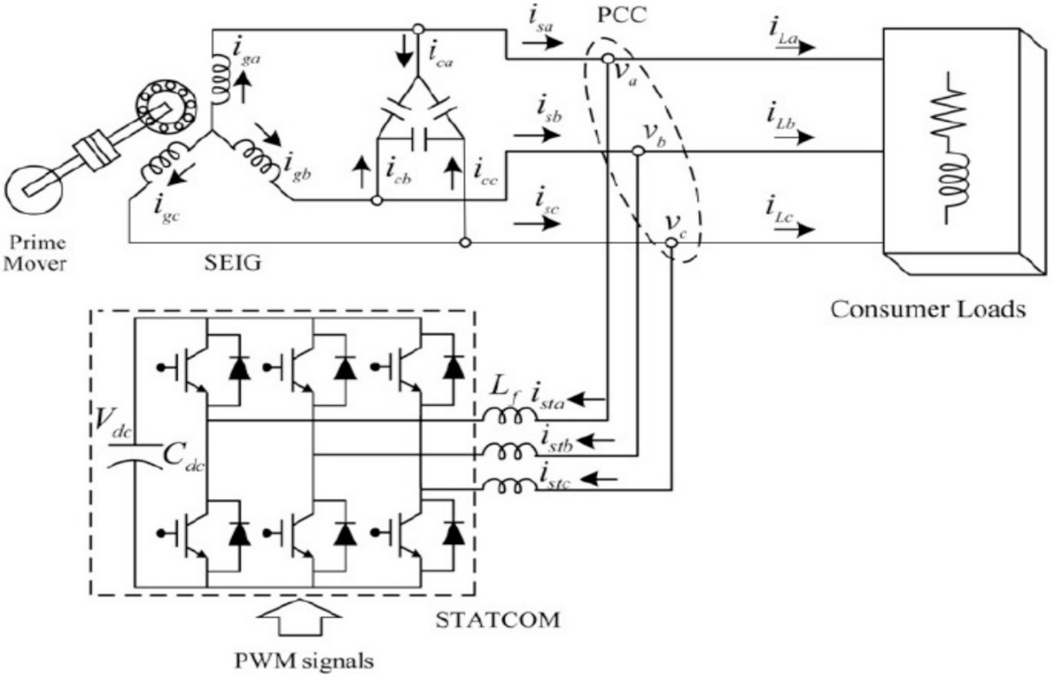
Example: Fault Detection in AC Distribution Network



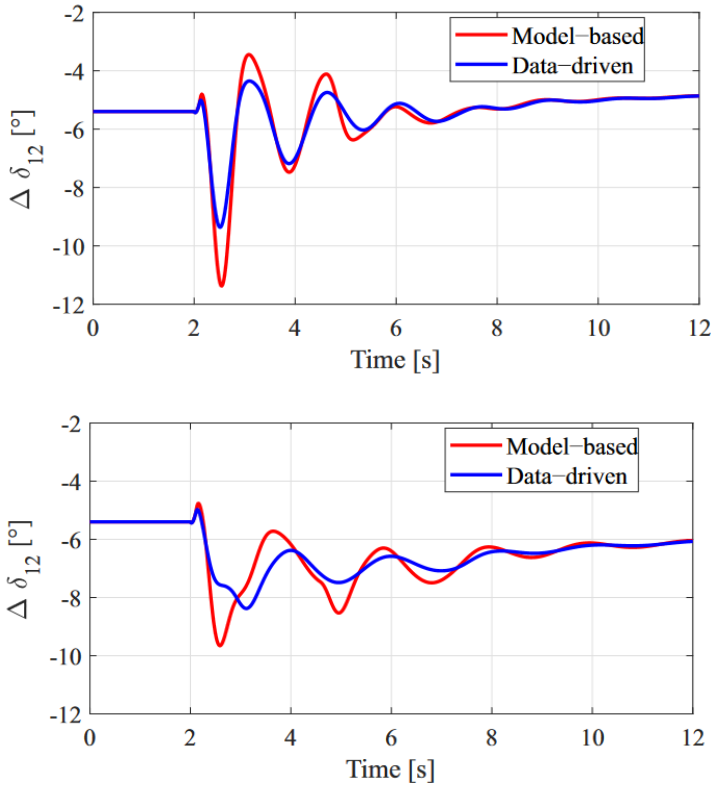


The laws of the system change depending on the fault.

Example: Data-driven control of STATCOM



Rotor angle during faults



Conclusions

- Data-driven control permits to generate controllers purely from measurement data.

- It is advisable for those cases where a full model specification is not available.

- Stability can be deterministically guaranteed.

- Smart grid technologies such as Micro Phasor Measurement Units permit data driven control implementation in large scale AC systems.

The University Of Sheffield.

Thank you!

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