

4^a Escuela de SUPERCONDUCTIVIDAD

Desde la Ciudad de México

Superconducting Power Filter for DC Electrical Grids

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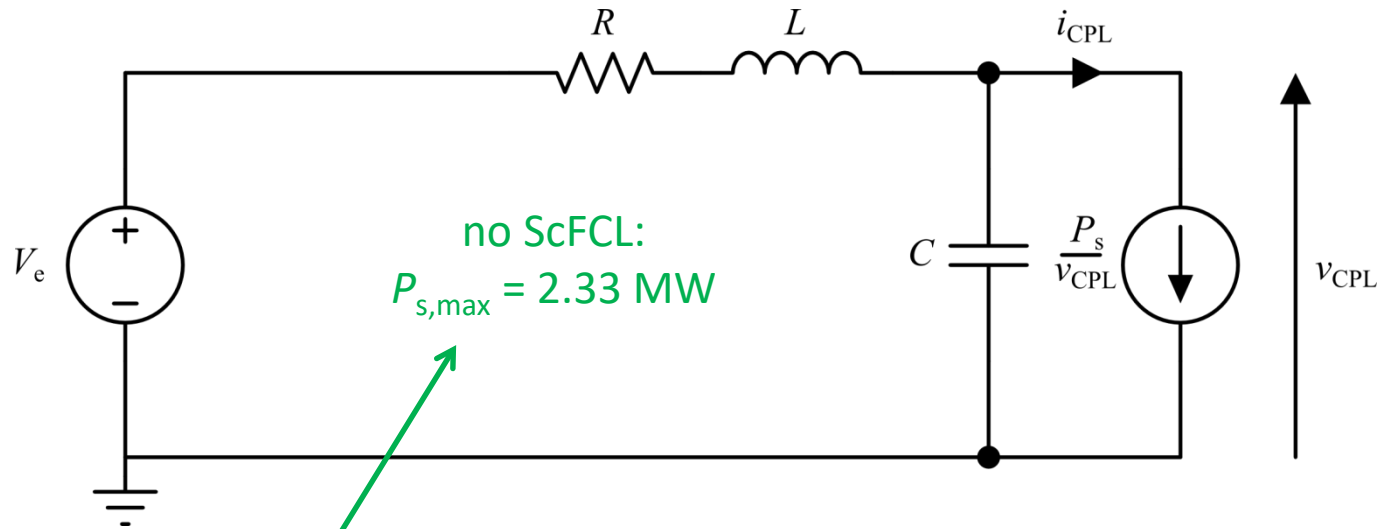


Content

- I. Stability of a DC grid with a constant power load
- II. Stability of a DC grid with a constant power load and a superconducting power filter
- III. Towards an experimental proof of concept
- IV. Conclusion

I. Stability of a DC grid with a constant power load

Analytical stability limit



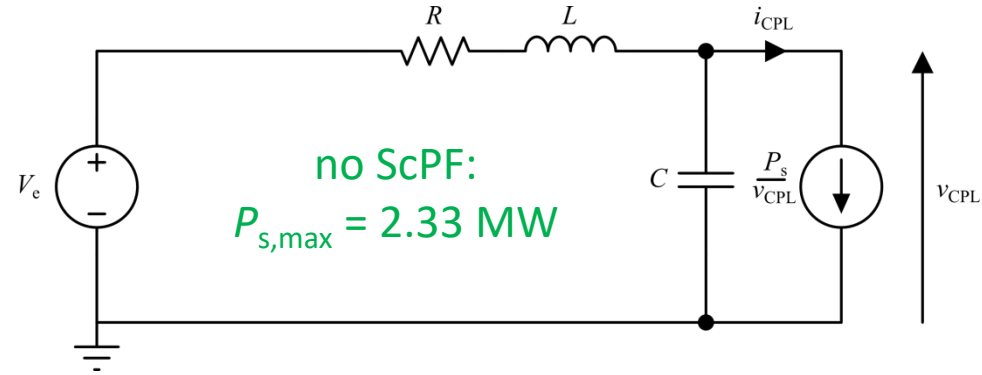
$$P_s \leq \frac{RC}{L} V_e^2$$

Table 1: DC grid parameters

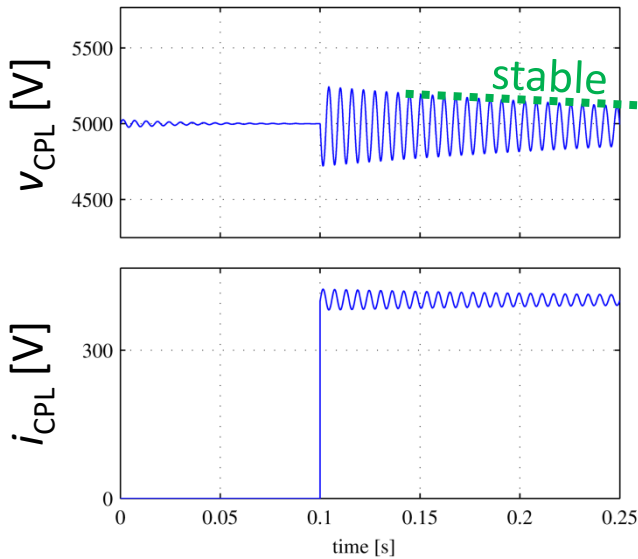
Symbol	Parameter	Value
V_e	source voltage	5 kV
R	resistance	40 m Ω
L	inductance	0.6 mH
C	capacitance	1.4 mF

[1] M. Cupelli, F. Ponci, G. Sulligoi, A. Vicenzutti, CS. Edrington, T. El-Mezyani, A. Monti, "Power flow control and network stability in an all-electric ship," *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2355-2380, Dec. 2015.

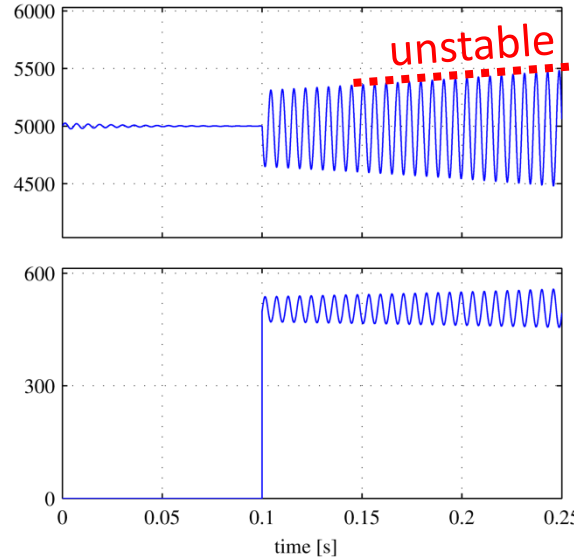
Numerical stability



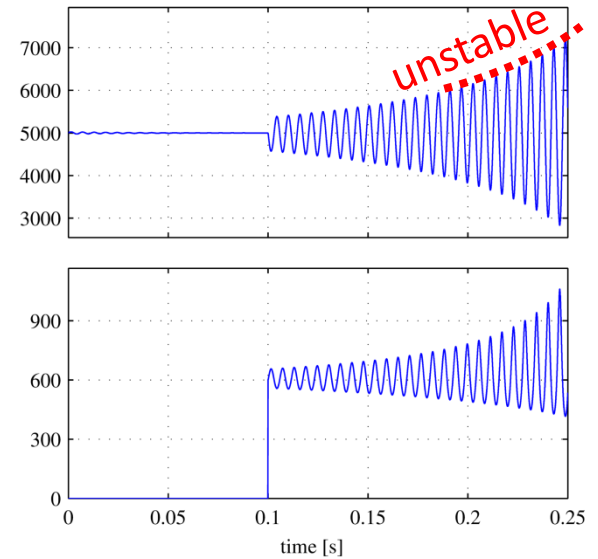
How to evaluate the stability ?
 -> envelope of v_{CPL}



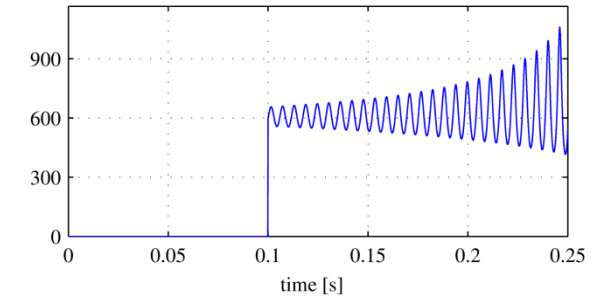
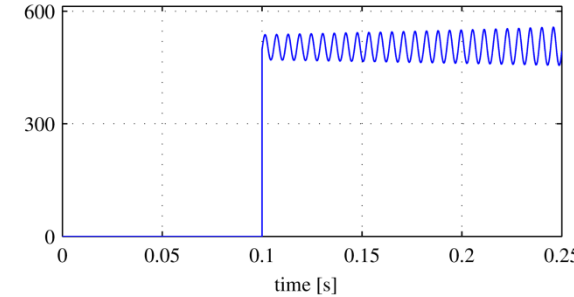
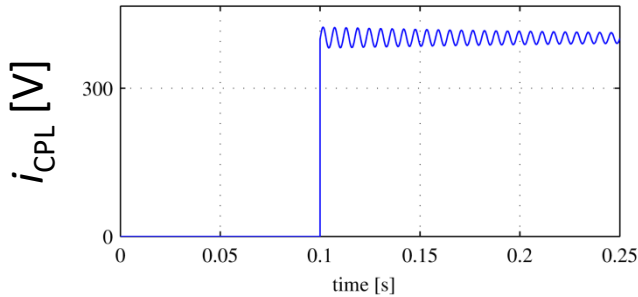
$P_s = 2.0 \text{ MW}$: stable



$P_s = 2.5 \text{ MW}$: unstable

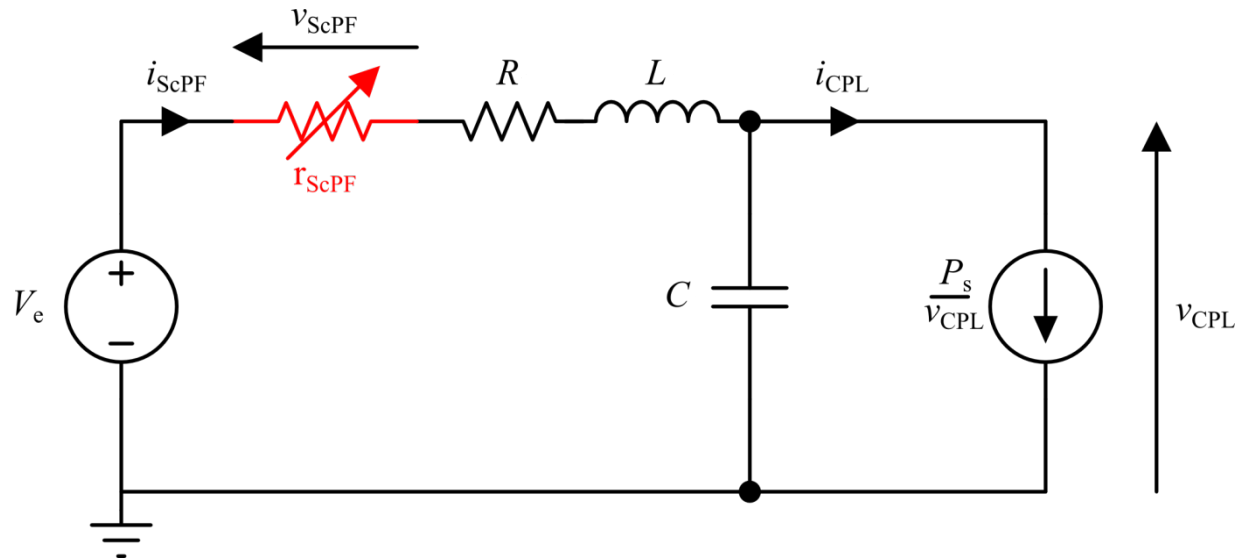


$P_s = 3.0 \text{ MW}$: unstable



II. Stability of a DC grid with a constant power load and a superconducting power filter

DC grid with a constant power load (CPL) and a superconducting power filter (ScPF)



- **Superconducting Power Filter (ScPF)** = non-inductive SC coil + RLC
- It behaves as a current dependent resistance:

$$P_s \leq \frac{[R + r_{ScPF}(i_{ScPF})] C}{L} V_e^2$$

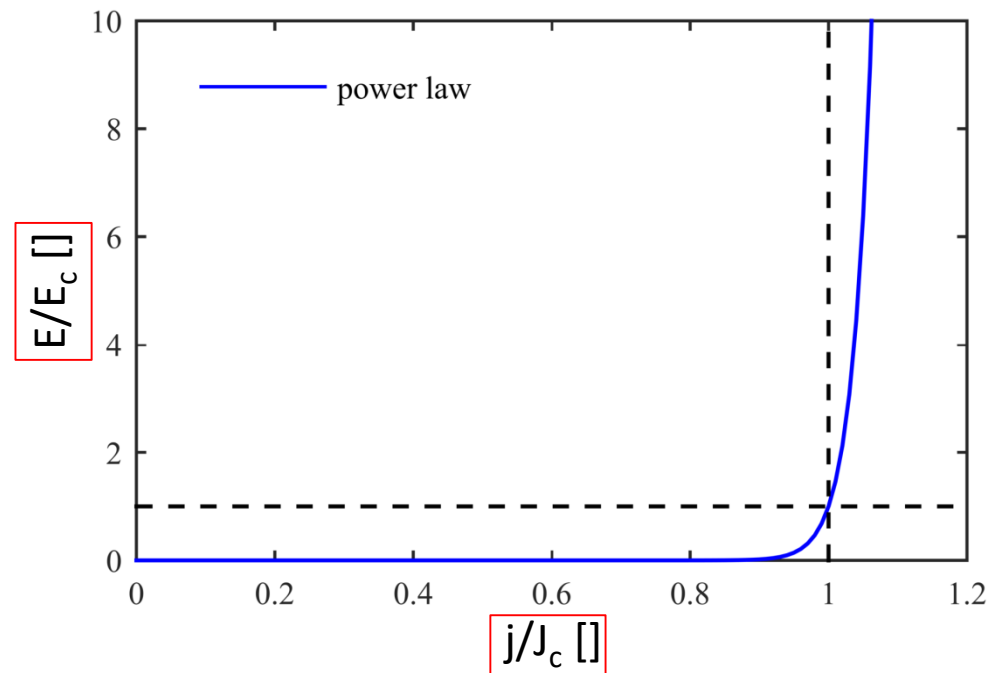
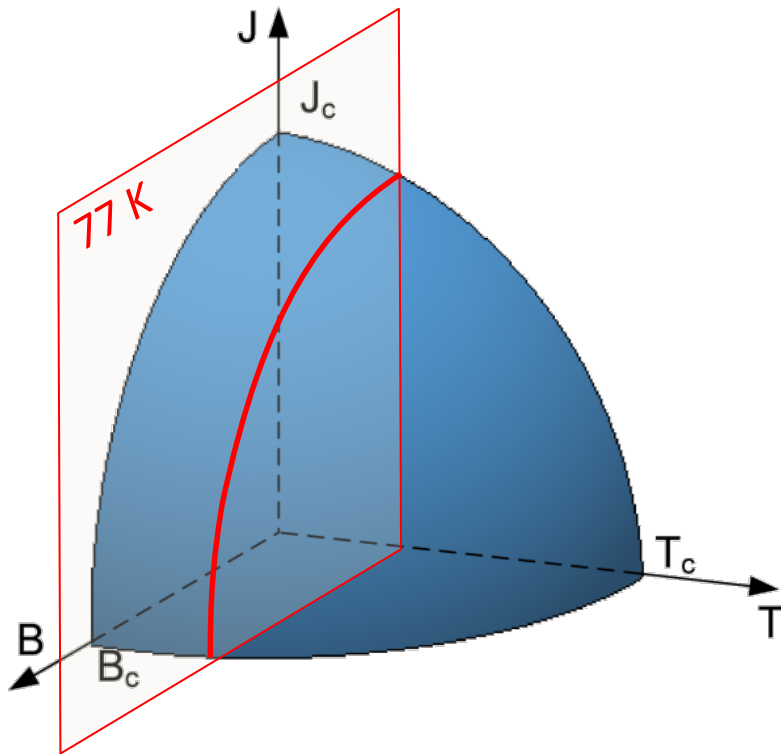
II. Stability of a DC grid with a CPL & a ScPF

1. ScPF lumped parameter thermo-electric model

Electric model

Hypothesis
thermal effect
neglected

$$E(j) = \frac{E_c}{J_c} \left| \frac{j}{J_c} \right|^{n-1} j$$



[1] B.B. Jensen, A.B. Abrahamsen, M.P. Sørensen, J.B. Hansen, "A course on applied superconductivity shared by four departments," US-China Education Review A, vol. 3, no. 3, 141-152, 2013.

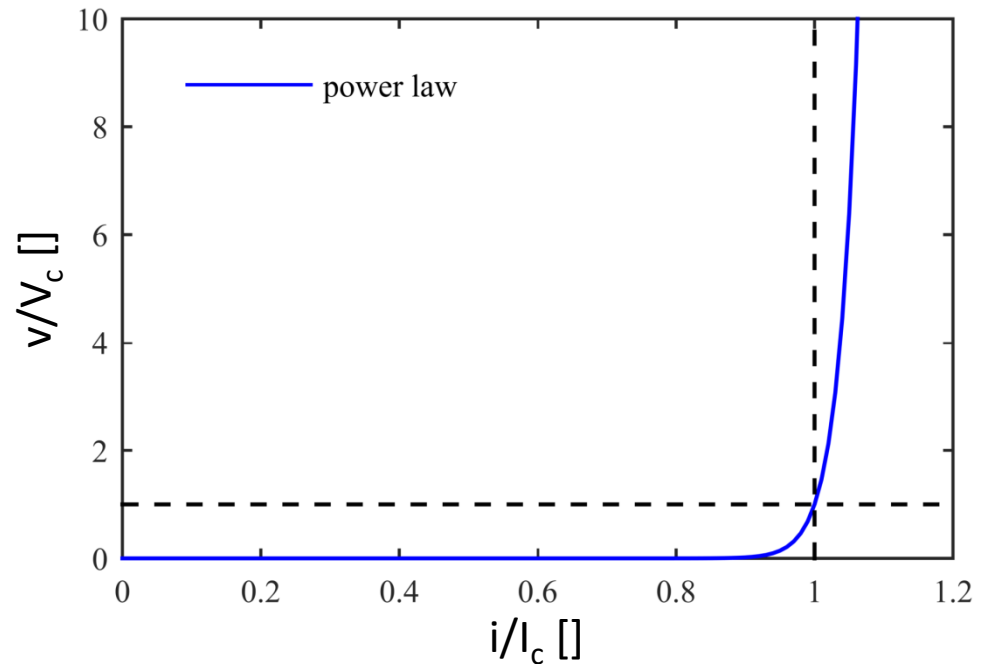
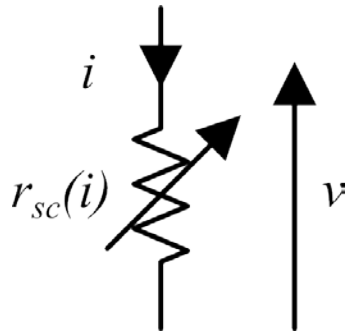
Electric model

$$\begin{aligned} v &= EL_{sc} \\ i &= jA_{sc} \\ I_c &= J_c A_{sc} \end{aligned}$$



$$\begin{aligned} E(j) &= \frac{E_c}{J_c} \left| \frac{j}{J_c} \right|^{n-1} j \\ v(i) &= \underbrace{\frac{E_c L_{sc}}{I_c} \left| \frac{i}{I_c} \right|^{n-1}}_{r_{sc}(i)} i \end{aligned}$$

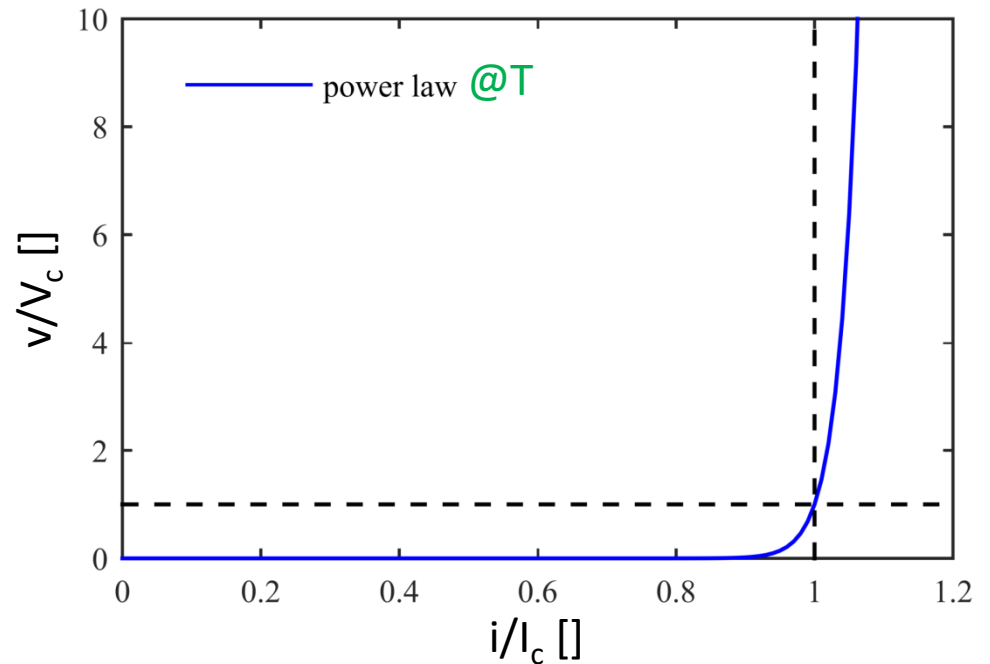
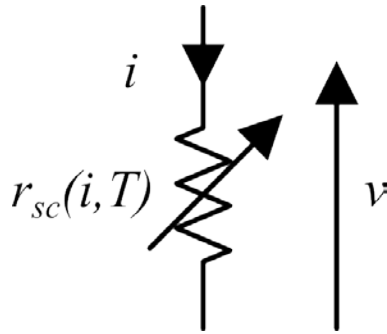
Hypothesis
thermal effect
neglected



Electric model

$$\begin{aligned}
 v &= EL_{sc} \\
 i &= jA_{sc} \\
 I_c(T) &= J_c(T)A_{sc}
 \end{aligned}
 \quad \curvearrowright \quad
 \begin{aligned}
 E(j) &= \frac{E_c}{J_c(T)} \left| \frac{j}{J_c(T)} \right|^{n(T)-1} j \\
 v(i) &= \underbrace{\frac{E_c L_{sc}}{I_c(T)} \left| \frac{i}{I_c(T)} \right|^{n(T)-1}}_{r_{sc}(i, T)} i
 \end{aligned}$$

Hypothesis
 thermal effect
 included



$$\begin{aligned}
 I_c(T) &= I_{c0} \left(\frac{92 \text{ K} - T}{92 \text{ K} - 77 \text{ K}} \right) \\
 n(T) &= n_0 \frac{77 \text{ K}}{T}
 \end{aligned}$$

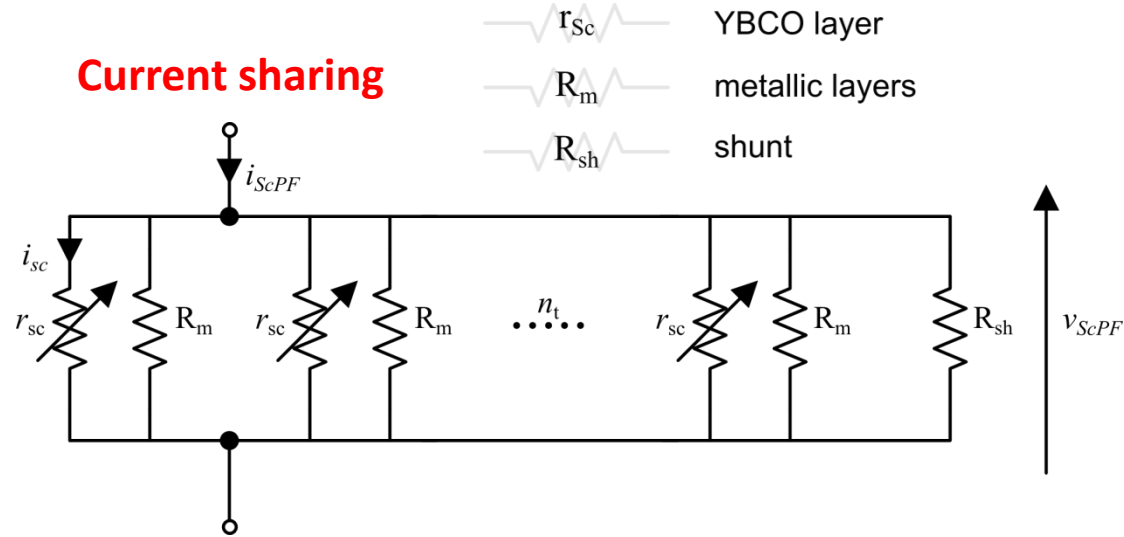
Electric model

$$v(i) = \frac{E_c L_{sc}}{I_c(T)} \left| \frac{i}{I_c(T)} \right|^{n(T)-1} i$$

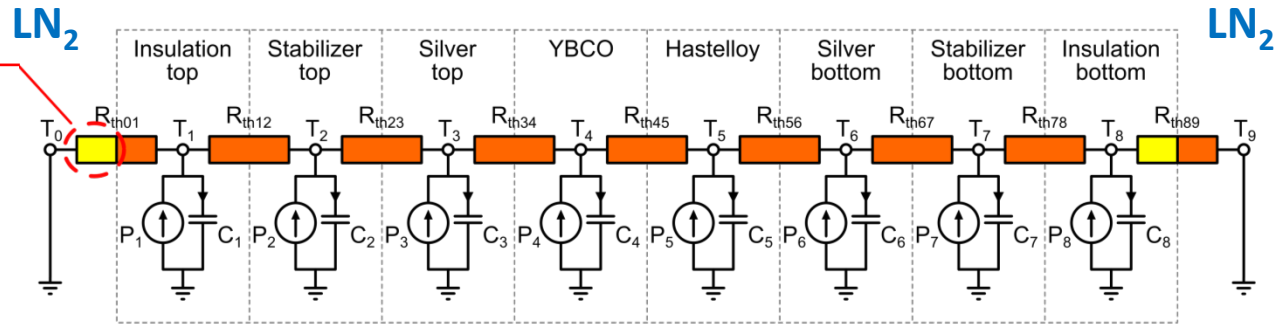
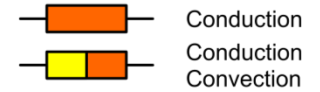
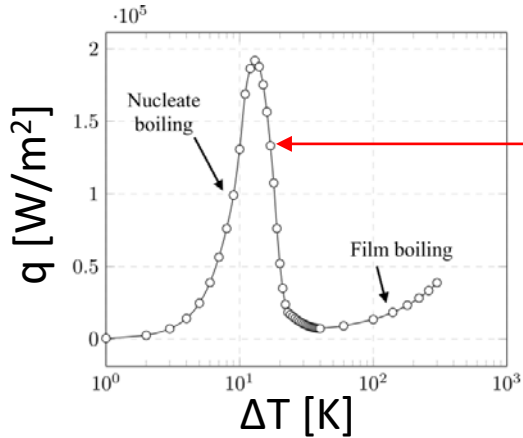
$$I_c(T) = I_{c0} \left(\frac{92 \text{ K} - T}{92 \text{ K} - 77 \text{ K}} \right)^{\frac{77 \text{ K}}{T}}$$

$$n(T) = n_0 \frac{77 \text{ K}}{T}$$

Current sharing



Thermal model



[1] J.J. Pérez-Chavez, F. Trillaud, L.M. Castro, L. Quéval, A. Polasek, R. de Andrade Jr, "Generic model of Three-phase (Re)BCO Resistive Superconducting Fault Current Limiters for Transient Analysis of Power Systems," *IEEE Trans. on Applied Superconductivity*, vol. 29, no. 6, 2019.

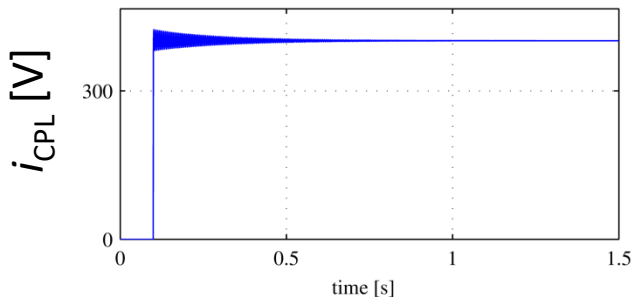
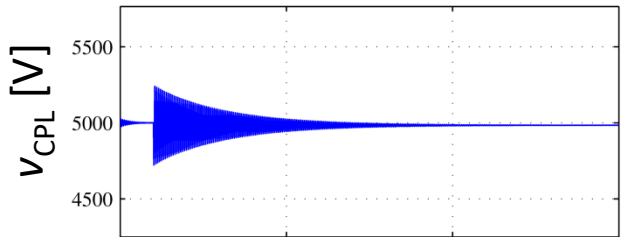
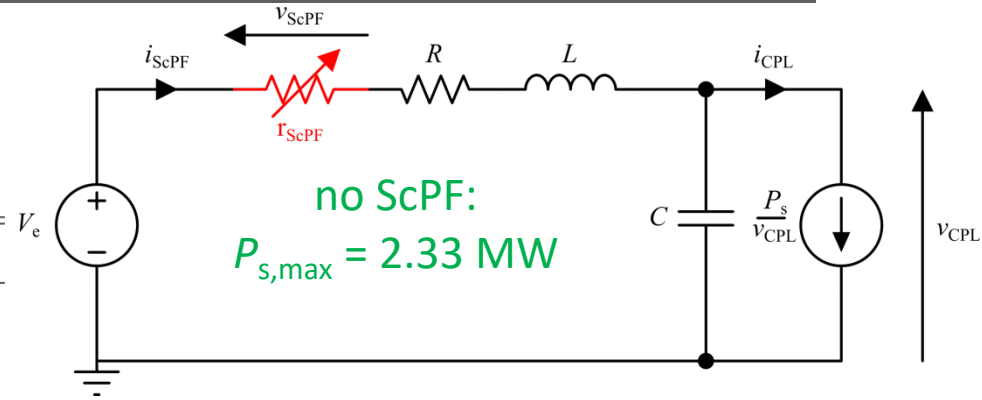
II. Stability of a DC grid with a CPL & a ScPF

2. Simulation results

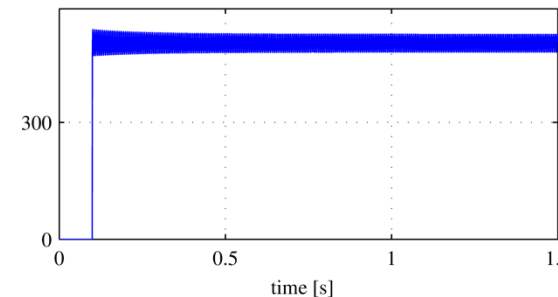
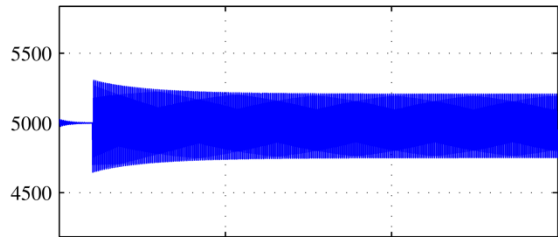
Numerical stability

Table 2: ScPF parameters

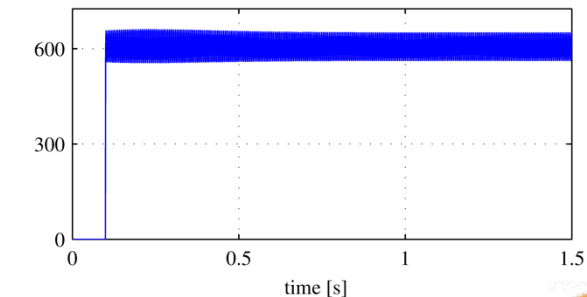
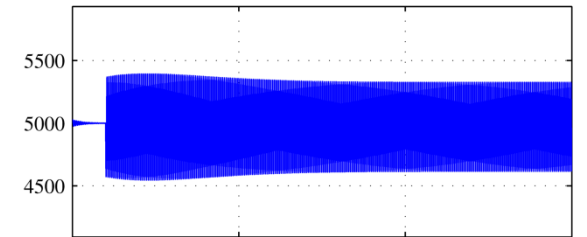
Symbol	Parameter	Value
E_c	critical current criterion	10^{-4} V/m
I_{c0}	tape critical current @77 K	300 A
n_0	power law exponent @77 K	21
L_{sc}	tape length	100 m
n_t	nb of tapes in parallel	2
R_{sh}	shunt resistance	50 m Ω



$P_s = 2.0$ MW: **stable**



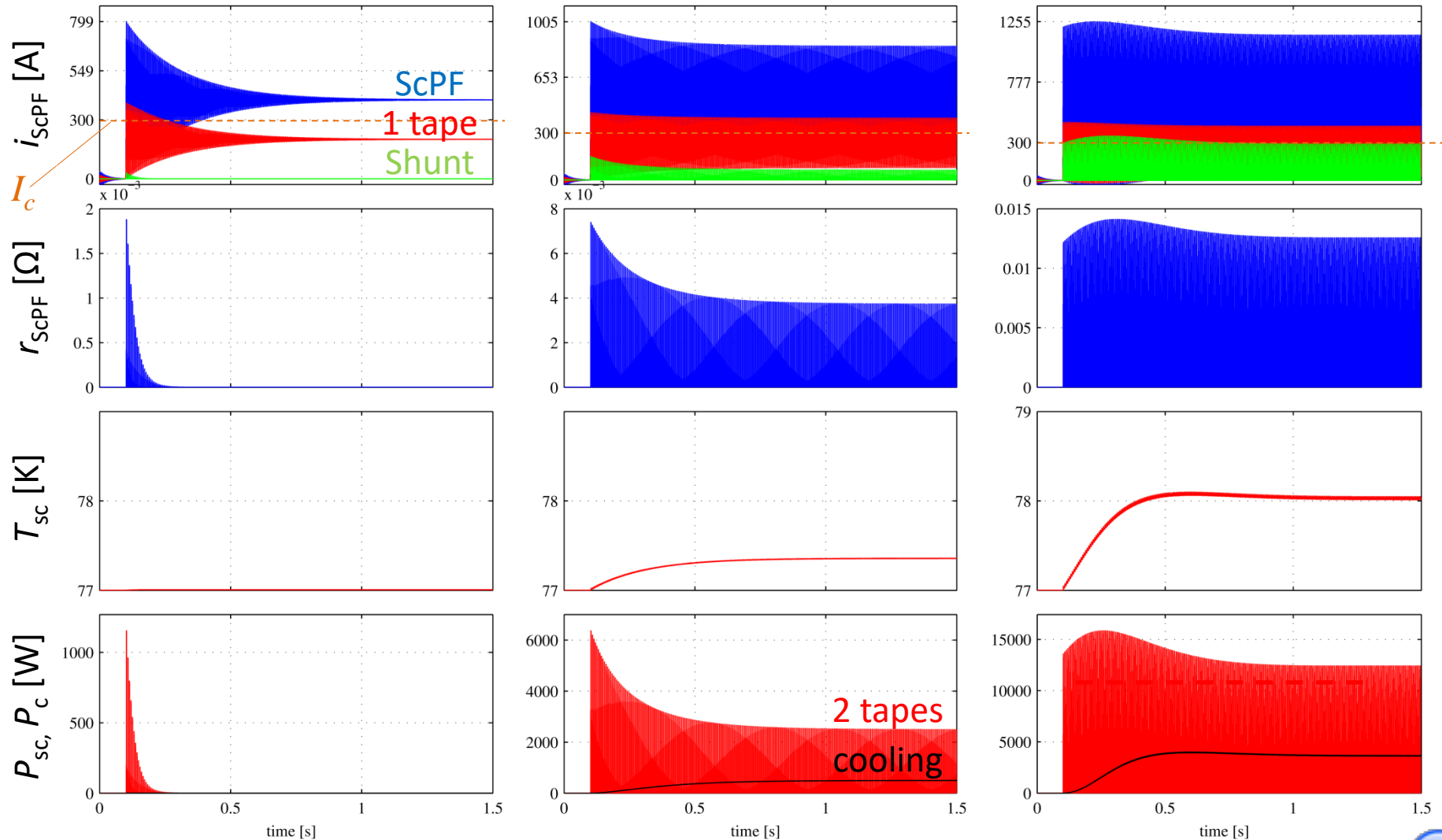
$P_s = 2.5$ MW: **stable**



$P_s = 3.0$ MW: **stable**



ScPF behavior



$P_s = 2.0$ MW: no losses

$P_s = 2.5$ MW: some losses

$P_s = 3.0$ MW: more losses

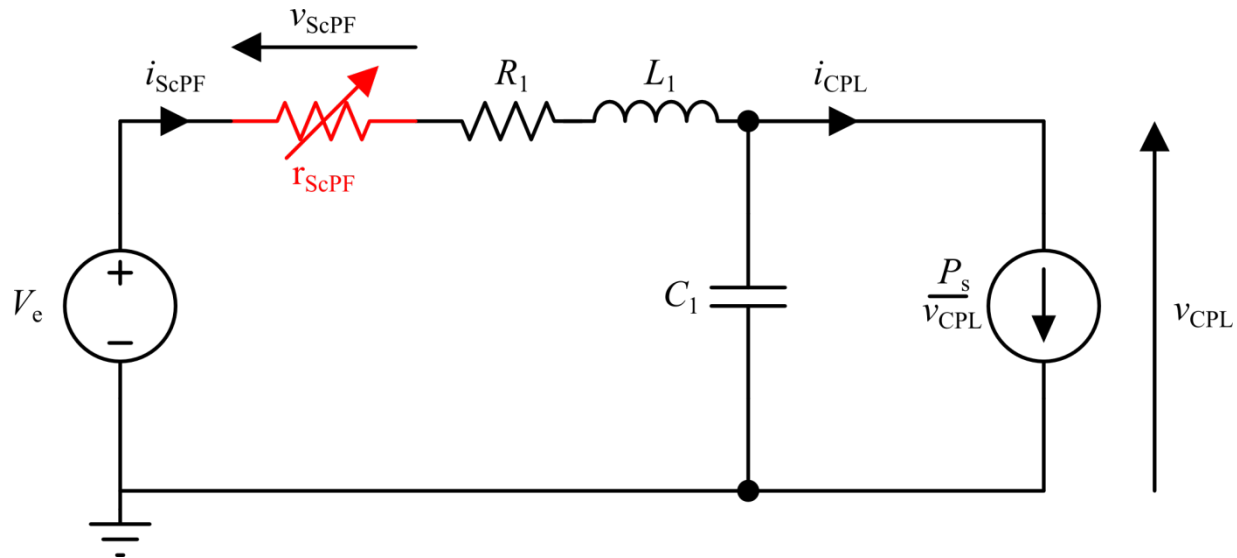


III. Towards an experimental proof of concept

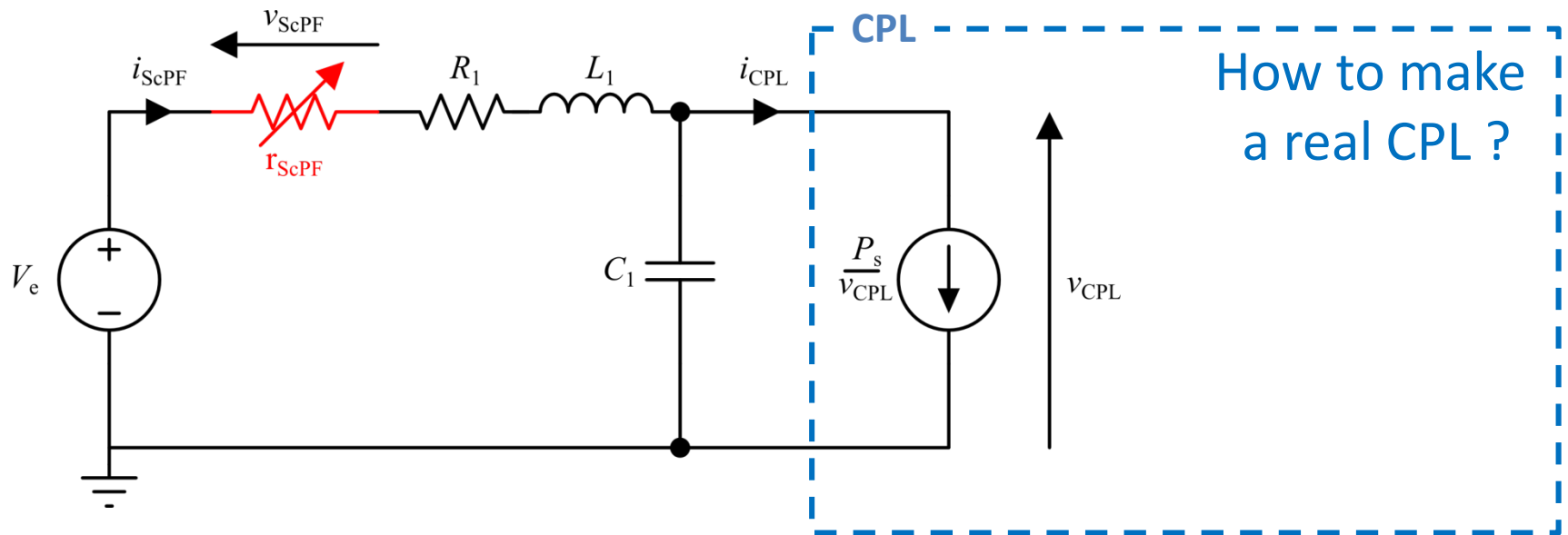
III. Towards an experimental proof of concept

1. DC100 testbench at GeePs

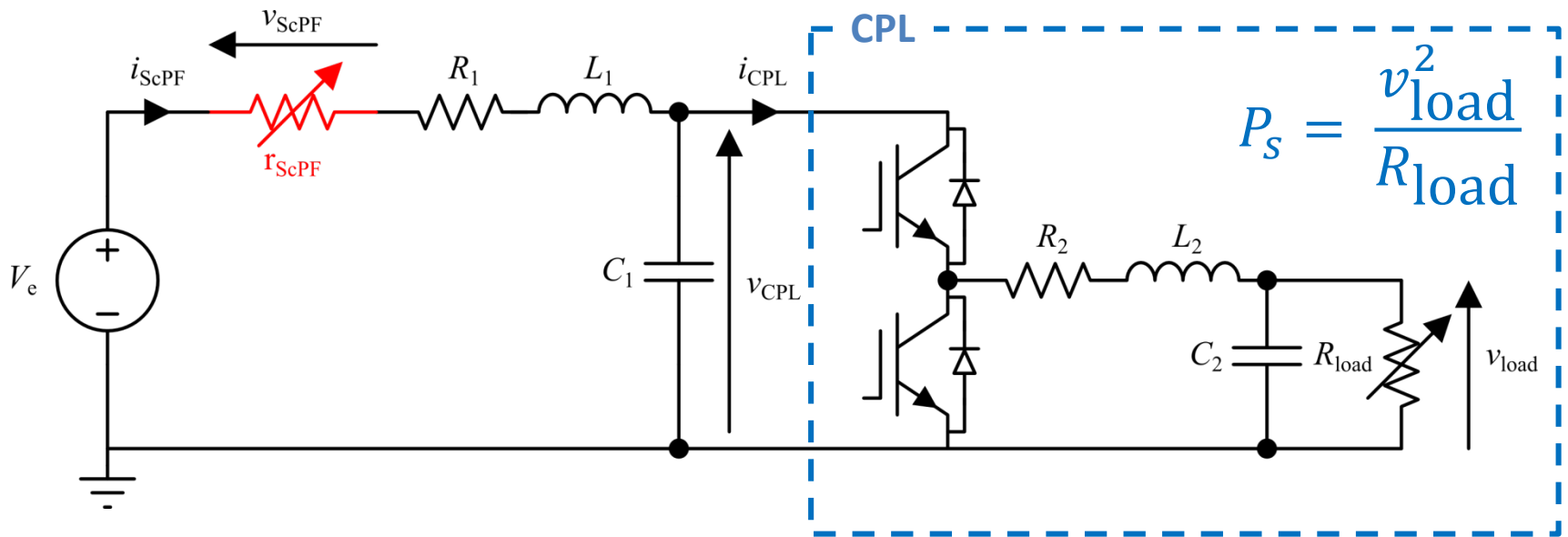
Overview of DC100 testbench



Overview of DC100 testbench

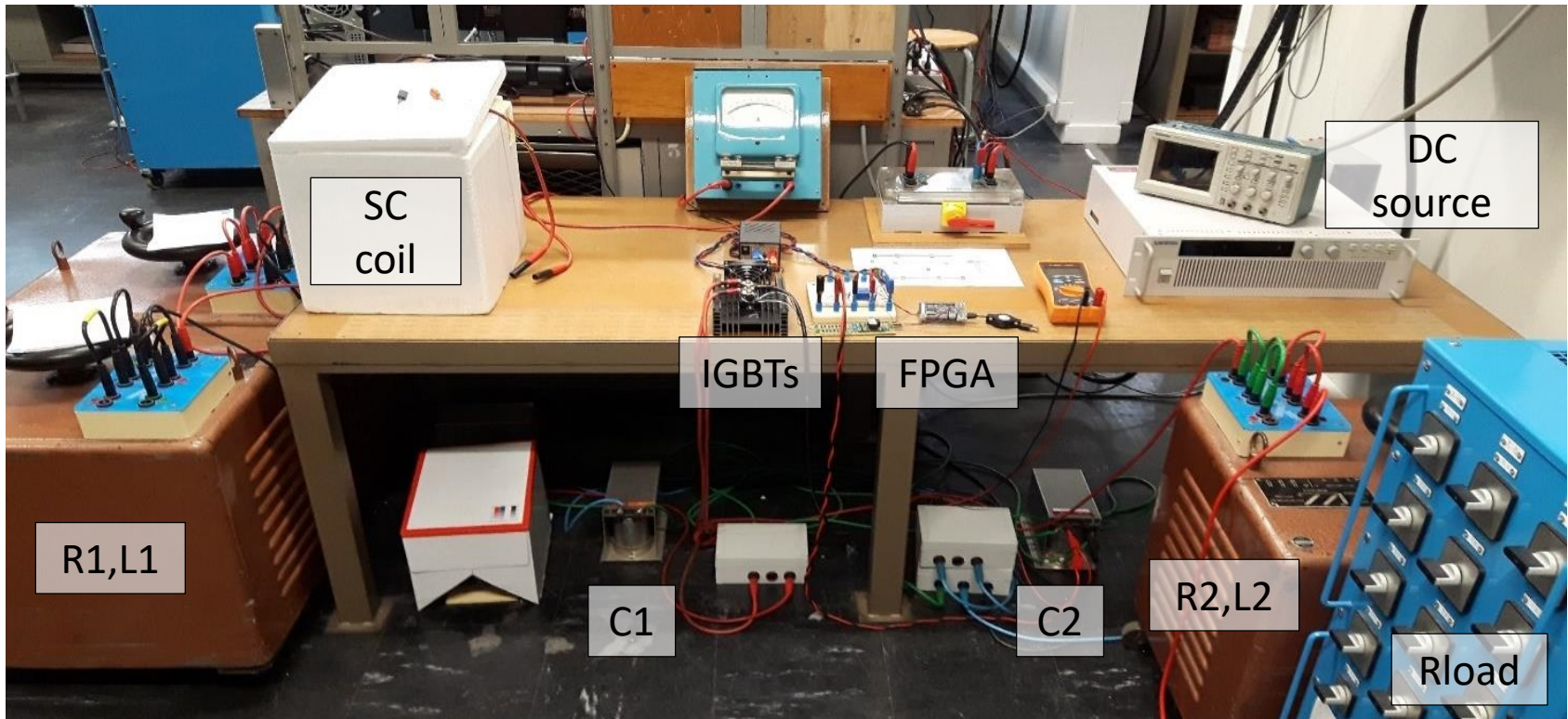
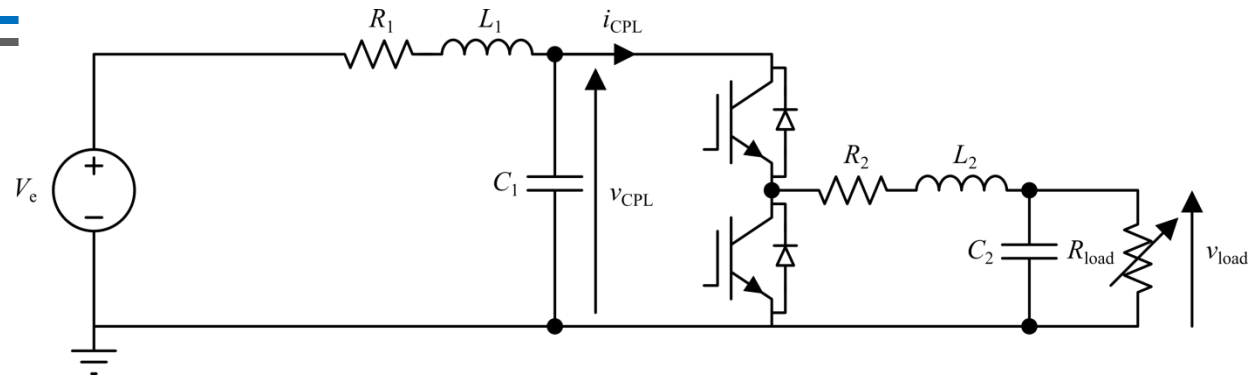


Overview of DC100 testbench



v_{load} is kept constant by controller $\leftrightarrow P_s$ is kept constant (CPL)

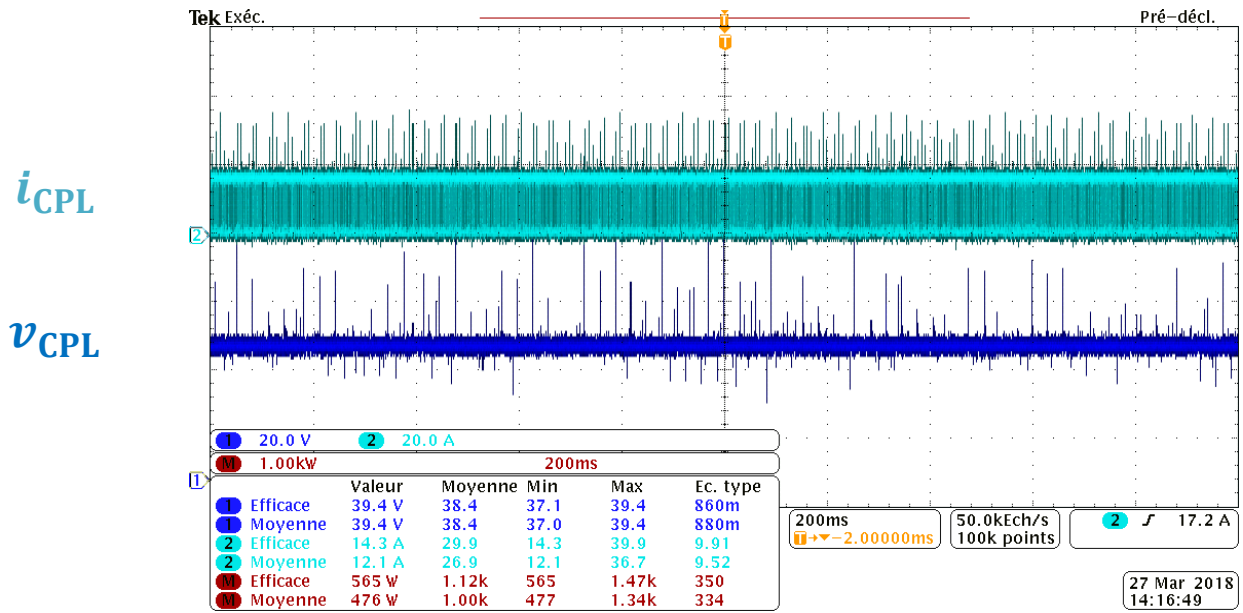
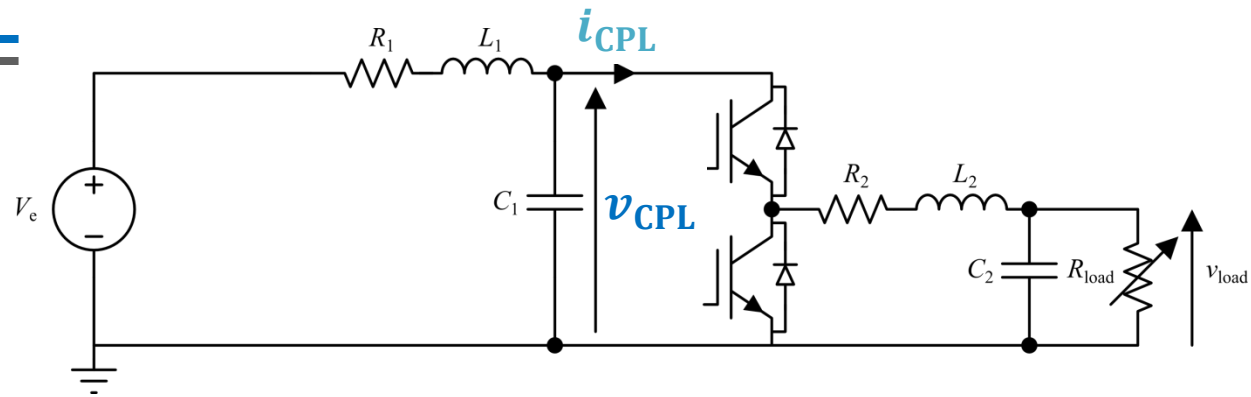
DC100 testbench



[1] H. Hallak, M. Martial, "Stabilisation d'un réseau DC en utilisant une bobine supraconductrice," Rapport de projet de Master 2 PIE-PDE, GeePs, Univ. Paris-Saclay, Gif-sur-Yvette, 2018.

[2] B. Hamard, "Méthodes et outils SIMULINK pour la conversion en langage VHDL d'une commande continue ou discrète" Rapport de projet de Magister, GeePs, Univ. Paris-Saclay, Gif-sur-Yvette, 2018.

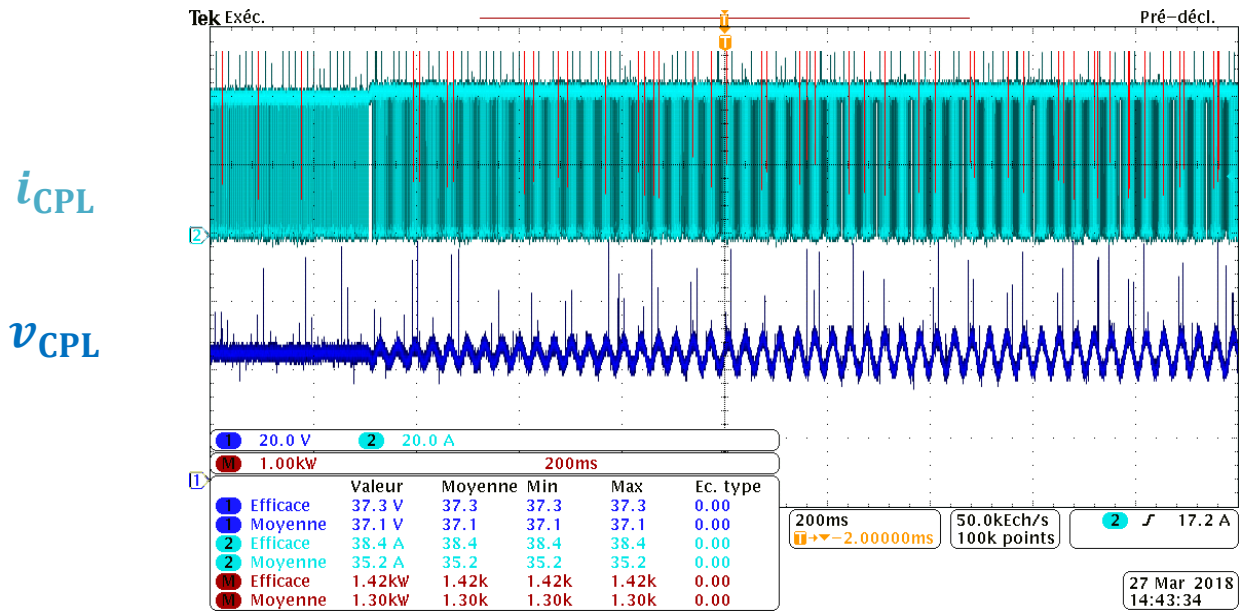
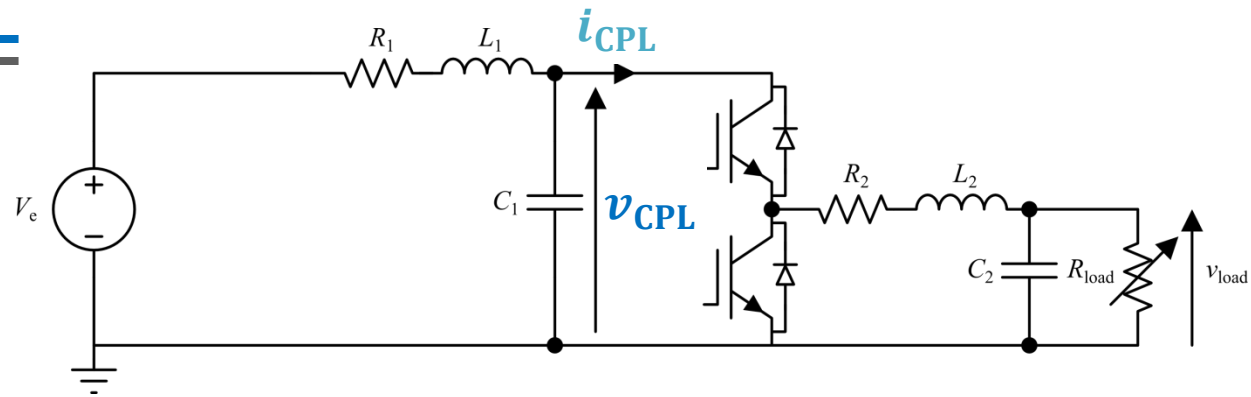
Stable operation (no ScPF)



$P_s = 476 \text{ W}$
stable

[1] H. Hallak, M. Martial, "Stabilisation d'un réseau DC en utilisant une bobine supraconductrice," Rapport de projet de Master 2 PIE-PDE, GeePs, Univ. Paris-Saclay, Gif-sur-Yvette, 2018.

Unstable operation (no ScPF)



$P_s = 1305 \text{ W}$
unstable

[1] H. Hallak, M. Martial, "Stabilisation d'un réseau DC en utilisant une bobine supraconductrice," Rapport de projet de Master 2 PIE-PDE, GeePs, Univ. Paris-Saclay, Gif-sur-Yvette, 2018.

III. Towards an experimental proof of concept

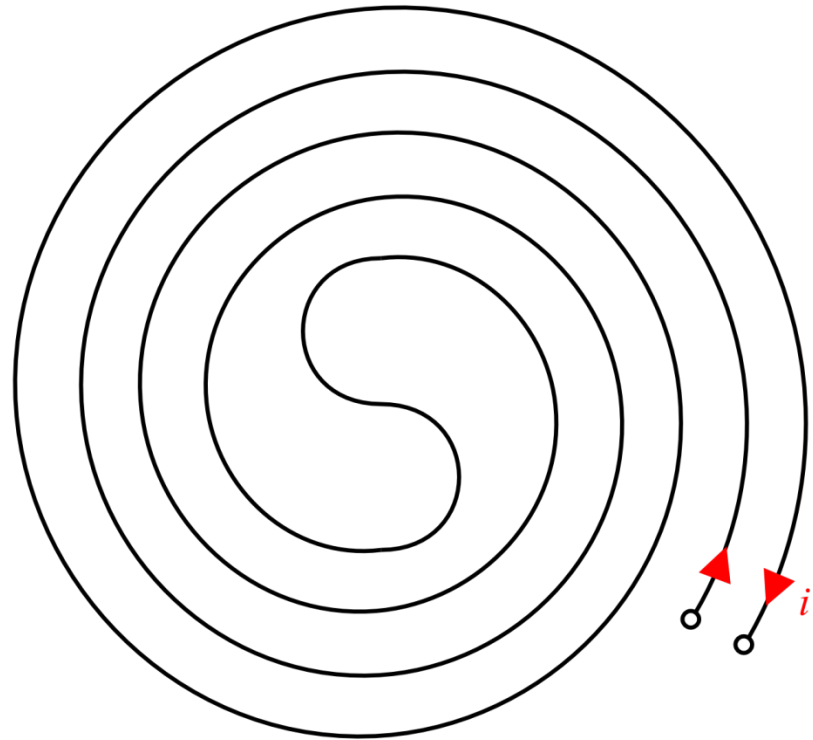
2. ScPF prototypes

Specifications

- Non-inductive coil

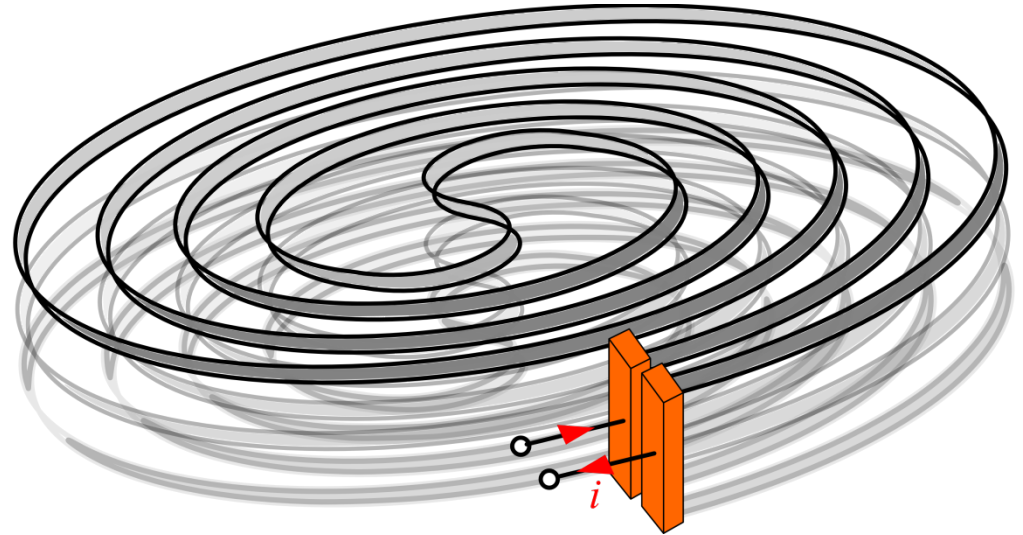
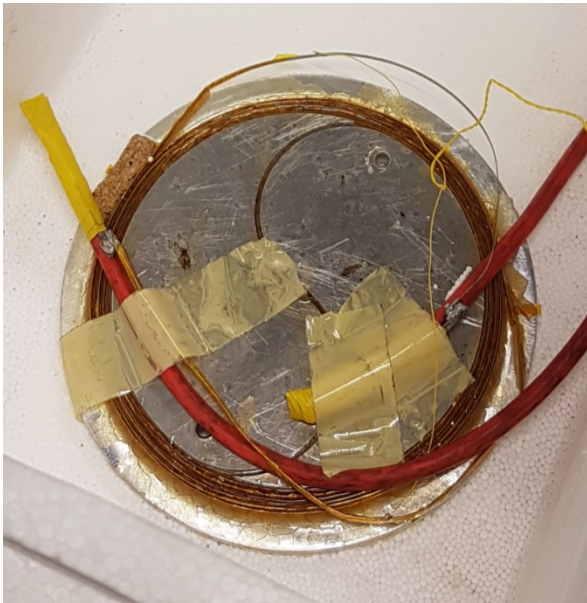
$$P_s \leq \frac{RC}{L} V_e^2$$

- BSCCO or YBCO (77 K)



Prototype ScPF#1

- BSCCO
- $I_c = 63 \text{ A}$
- $L_{sc} = 5.2 \text{ m}$

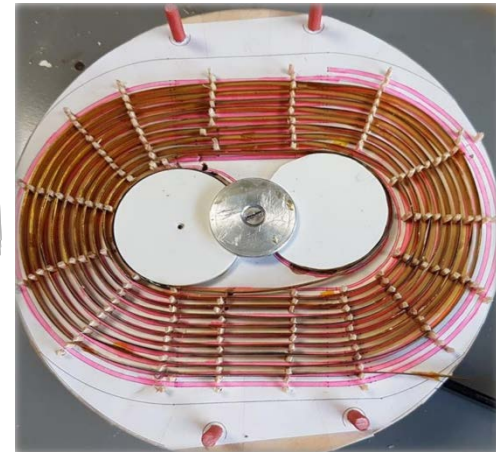
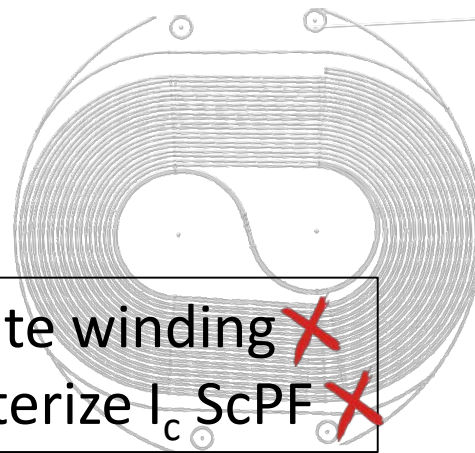
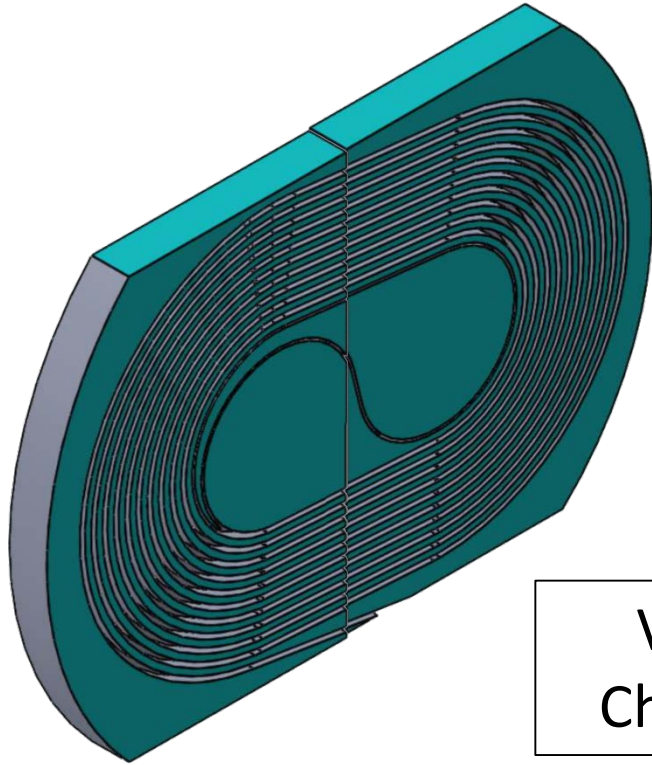


Validate winding ✓
Characterize I_c ScPF ✓

[1] G.B. Huang, B. Douine, K. Berger, G. Didier, I. Schwenker, J. L ev eque, "Increase of stability margin in embedded DC electric grid with superconducting stabilizer," *IEEE Trans. on Applied Superconductivity*, vol. 26, no. 4, June 2016.

Prototype ScPF#2

- ReBCO (Shanghai SC)
- $I_c < 90 \text{ A}$
- $L_{sc} = 9 \text{ m}$

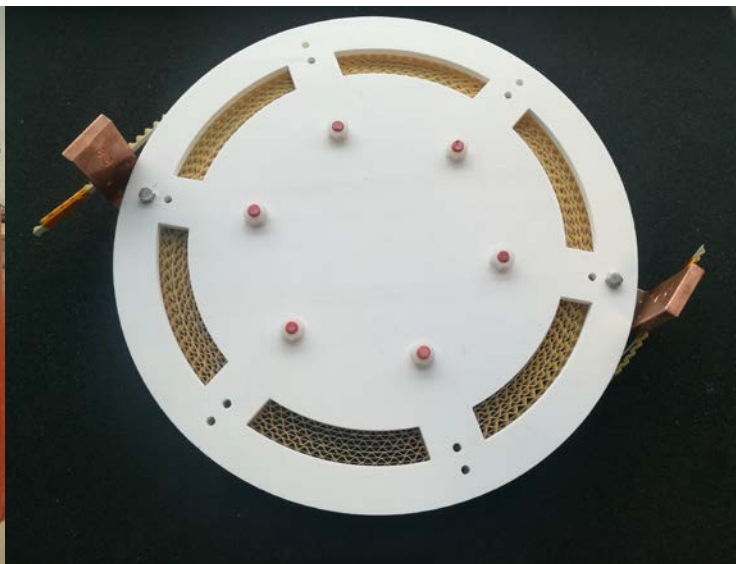
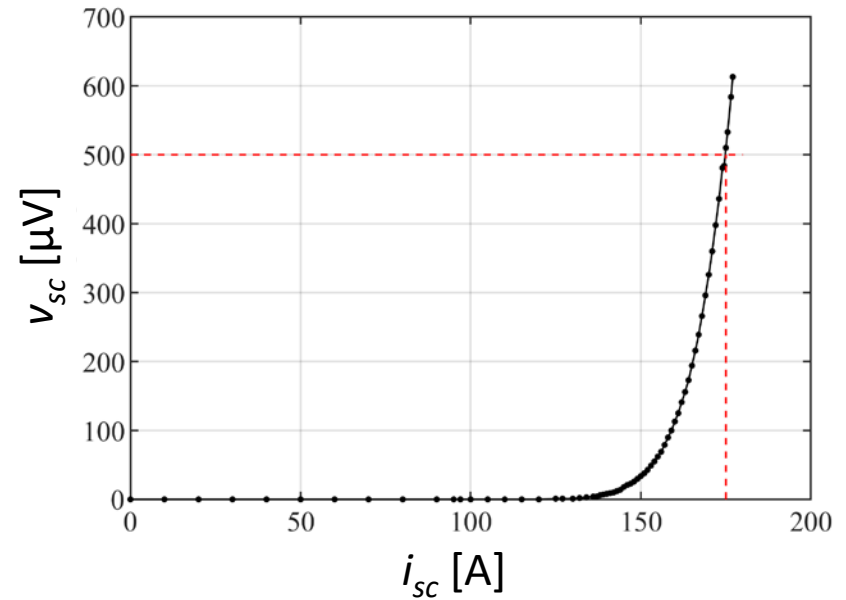


Validate winding ~~X~~
Characterize I_c ScPF ~~X~~

[1] El Harouch Abdessamad, Ikram Hamdaoui Aloui, "Réalisation et caractérisation d'une bobine supraconductrice non inductive," Rapport de projet de fin d'étude de Master, GREEN, Univ. of Lorraine, Nancy, 2018.

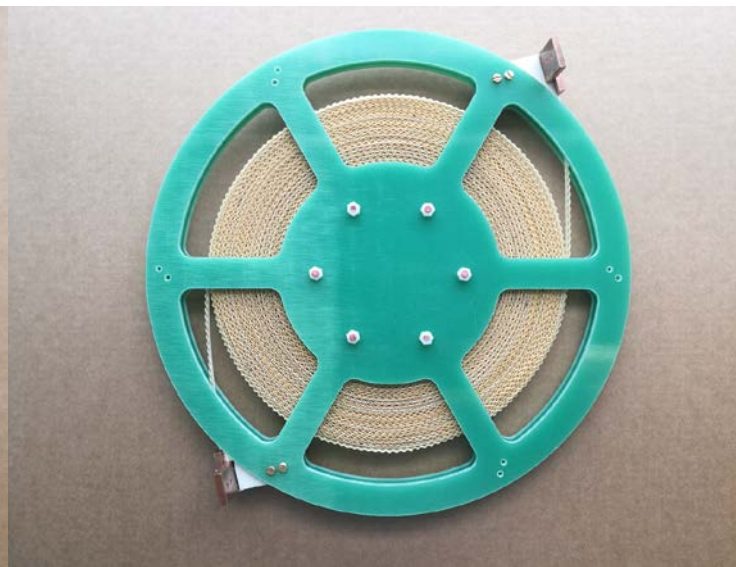
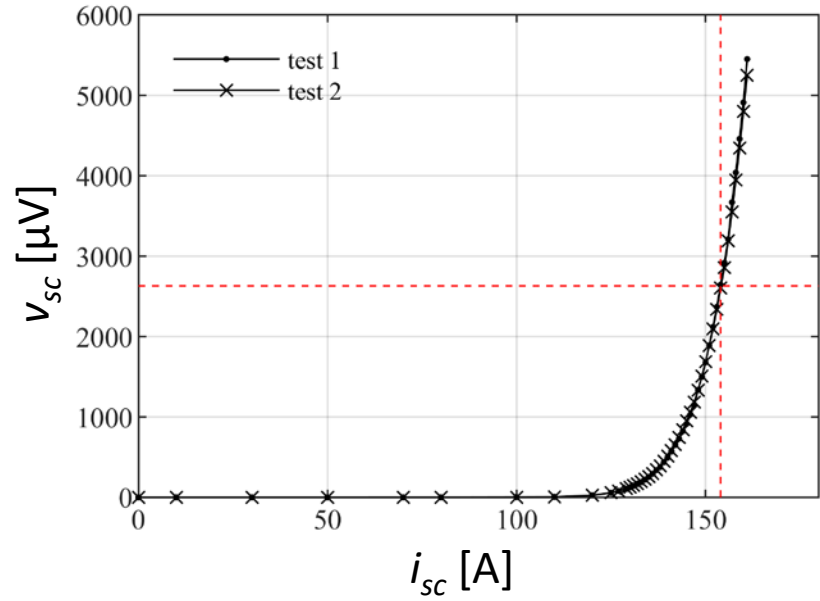
Prototype ScPF#3a

- BSCCO (Sumitomo)
- $I_c = 175$ A (datasheet 170 A)
- $L_{sc} = 5$ m



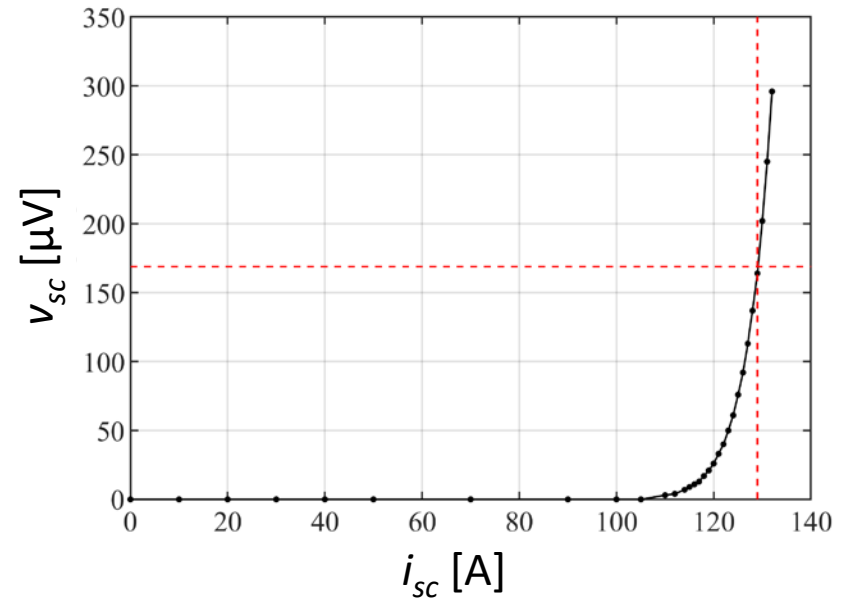
Prototype ScPF#3c

- BSCCO (Sumitomo)
- $I_c = 154$ A (datasheet 170 A)
- $L_{sc} = 25$ m

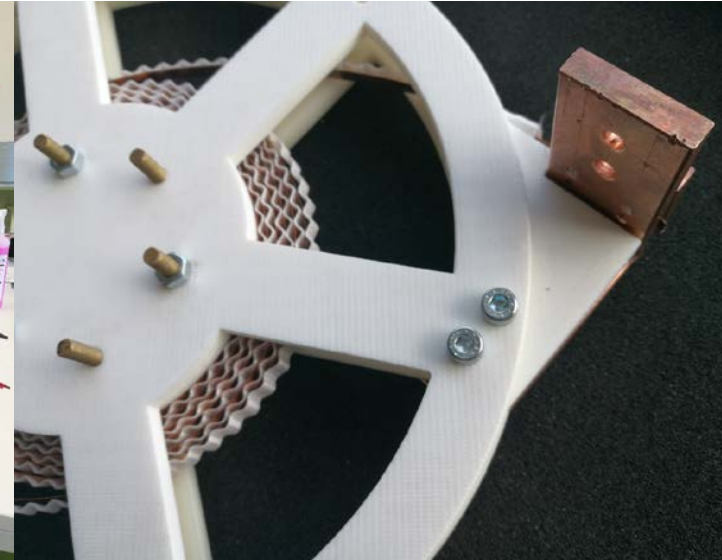
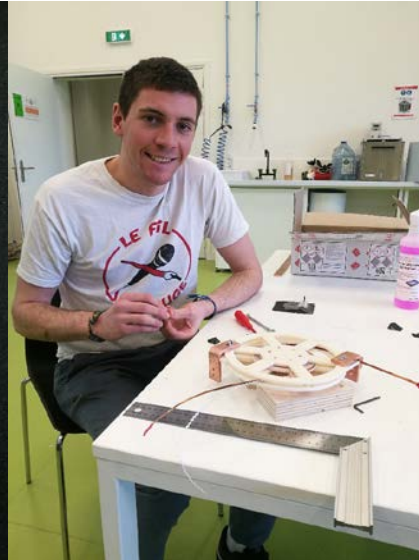
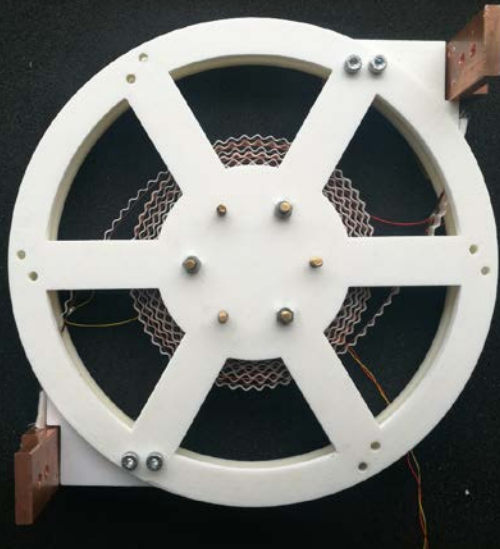


Prototype ScPF#4a

- ReBCO (SuNAM)
- $I_c = 129 \text{ A}$ (datasheet: 199 A)
- $L_{sc} = 2 \text{ m}$

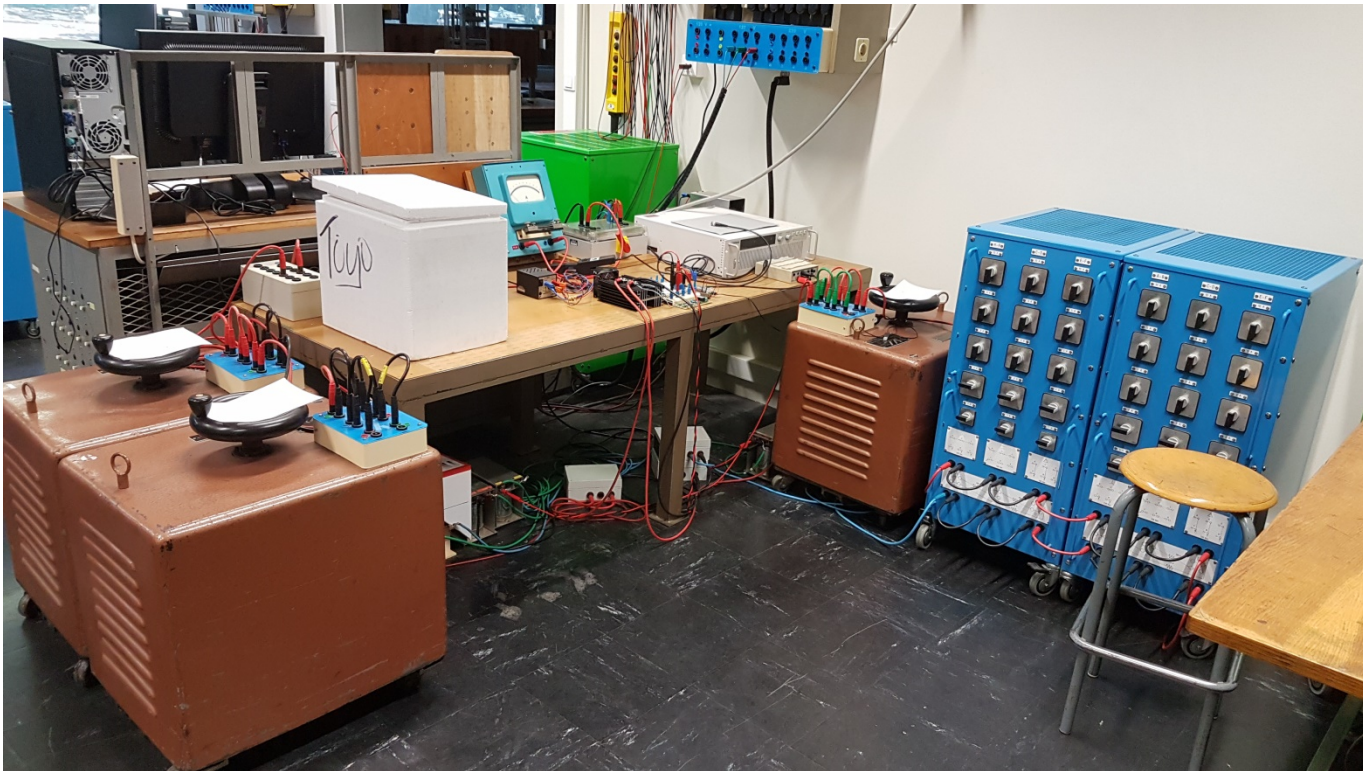


[1] V. Naude, T. Benramdane, "Etude de faisabilité d'un filtre supraconducteur pour les réseaux à courant continu haute tension," Projet 3A, GeePs, CentraleSupélec, 2020.



Future works

- Winding and characterization of a ScPF made of 100 m of BSCCO
- Experimental proof-of-concept of the proposed function



IV. Conclusion

Conclusion

- A new application of HTS technology is introduced. The device referred to as "Superconducting power filter" (ScPF) aims at increasing the stability of DC grids by adding a current-dependent resistance to a classical RLC filter.
- In comparison with other stabilization techniques, a ScPF achieves a fully passive stabilization without decreasing the energy transferred to the load in nominal operation.
- To clarify its operation, a simple DC circuit with a controlled power load (CPL) and a ScPF was considered. Using an thermo-electric lumped-parameter model of the ScPF, the stability of the DC grid was assessed for a given test case.
- Efforts are underway to provide an experimental proof of concept.

References

- [1] G.B. Huang, B. Douine, K. Berger, G. Didier, I. Schwenker, J. Lévêque, “Increase of stability margin in embedded DC electric grid with superconducting stabilizer,” *IEEE Trans. on Applied Superconductivity*, vol. 26, no. 4, 2016.
- [2] L. Quéval, F. Trillaud, B. Douine, “DC grid stabilization using a resistive superconducting fault current limiter,” *Intl. Conf. on Components and Systems for DC grids (COSYS-DC 2017)*, Grenoble, France, March 2017.
- [3] J.J. Pérez-Chávez, F. Trillaud, L.M. Castro, L. Quéval, A. Polasek, R. de Andrade Junior, “Modelling of (Re)BCO resistive superconducting fault current limiters with application to an AC electric power circuit,” *13th European Conf. on Applied Superconductivity (EUCAS 2017)*, Geneva, Switzerland, Sept. 2017.
- [4] L. Quéval, F. Trillaud, J.J. Pérez-Chavez, B. Douine, “Superconducting power filter for DC electrical grids,” *13th European Conf. on Applied Superconductivity (EUCAS2017)*, Geneva, Switzerland, Sept. 2017.
- [5] L. Quéval, F. Trillaud, B. Douine, “Progress towards the realization of a DC superconducting power filter,” *14th European Conference on Applied Superconductivity (EUCAS2019)*, id. 3-LO-TG-05S, Glasgow, UK, Sept. 2019.
- [6] L. Quéval, O. Despouys, F. Trillaud, B. Douine, “Feasibility study of a superconducting power filter for HVDC grids,” *22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe)*, Lyon, France, Sept. 2020.
- [7] F. Trillaud, B. Douine, L. Quéval, “Superconducting power filter for aircraft electric DC grids,” *Applied superconductivity conference (ASC 2020)*, Online, Oct. 2020.

Merci !

