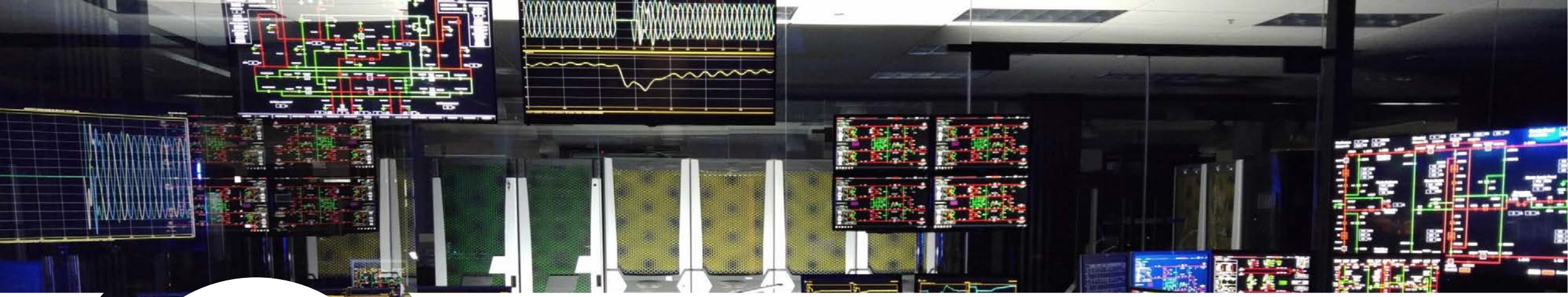


IREQ PHIL SIMULATOR PROJECT UPDATE:
Small-Scale Closed-Loop Testing Advancements and Full-Scale Amplifier

Olivier Tremblay, D. Rimorov, K. Slimani, P. Giroux, Y. Brissette, R. Gagnon

Hydro-Québec Research Institute (IREQ)

H. Fortin-Blanchette

École de Technologie Supérieure (ÉTS)

5th International Workshop on Grid Simulator Testing of Energy Systems and Wind Turbine Powertrains

Florida State University (FSU) Center for Advanced Power Systems (CAPS)
November 15-16, 2018 - Tallahassee, Florida, USA

Objective

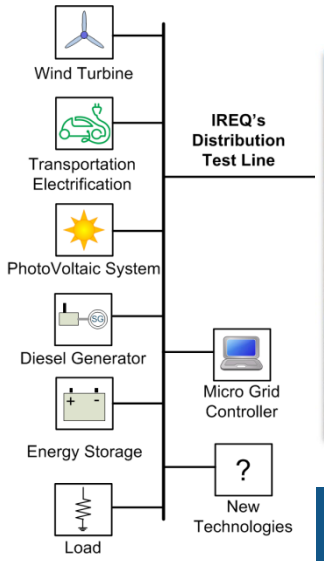
Lead the energy transition at Hydro-Québec by developing a hybrid (virtual and real) T&D laboratory to study and integrate :

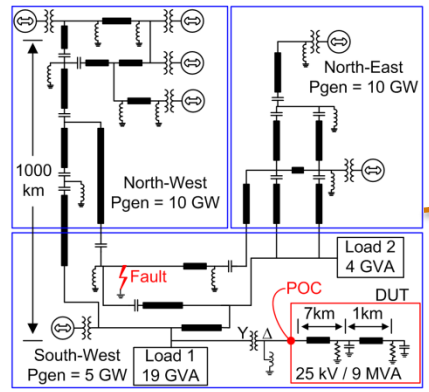
- Distributed Energy Resources
- Smart grids
- Microgrids

Large-scale transmission system simulated in real-time (Hypersim)

Distribution test line
25 kV 10 MVA

Power amplifier
25 kV 10 MVA





Challenge:

Design and operation of a real distribution network connected in closed-loop EMT to a simulated transmission system

Project milestones

Design of the power amplifier (PA) topology

Cascaded H-Bridge

Transformerless

High bandwidth

25 kV, 10 MVA

Development of the reduced-scale version of the PA

Cascaded H-Bridge

Transformerless

High bandwidth

208 V, 3 kVA

Design of a general closed-loop interface

Stable

Precise

High bandwidth

Making a single full-scale H-Bridge

Experimental H-Bridge

1 kV, 100 kW

Overload capability: 10x nominal current

Complete the PA

3-phase

2 PU overvoltage capability

10 PU overcurrent capability

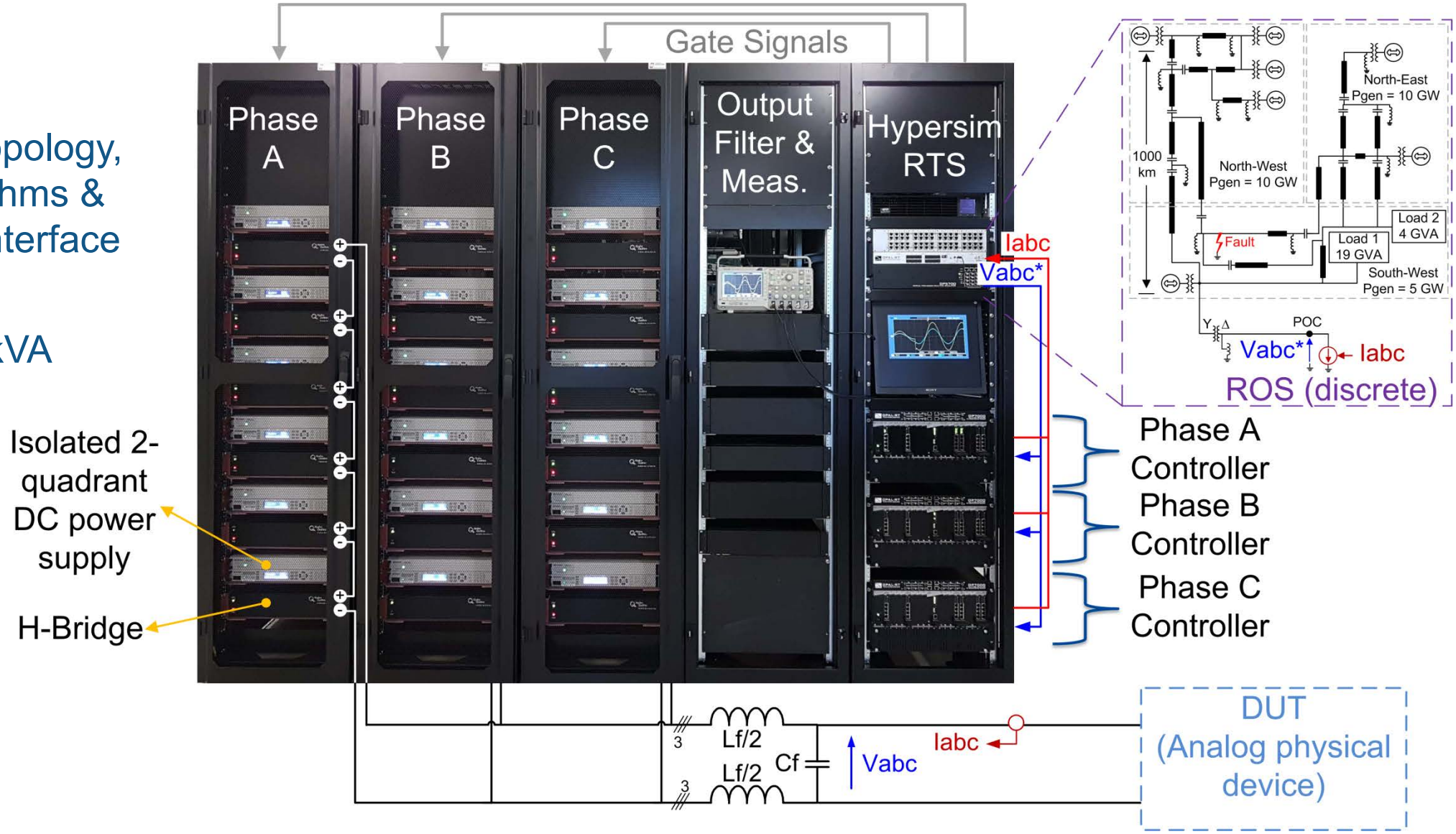
DC to 1 kHz in closed-loop

Reduced-scale power amplifier

Goal:

Validate the PA topology, the control algorithms & the closed-loop interface

Rating: 208 V, 3 kVA



Project milestones

Design of the power amplifier (PA) topology

Cascaded H-Bridge

Transformerless

High bandwidth

25 kV, 10 MVA

Development of the reduced-scale version of the PA

Cascaded H-Bridge

Transformerless

High bandwidth

208 V, 3 kVA

Design of a general closed-loop interface

Stable

Precise

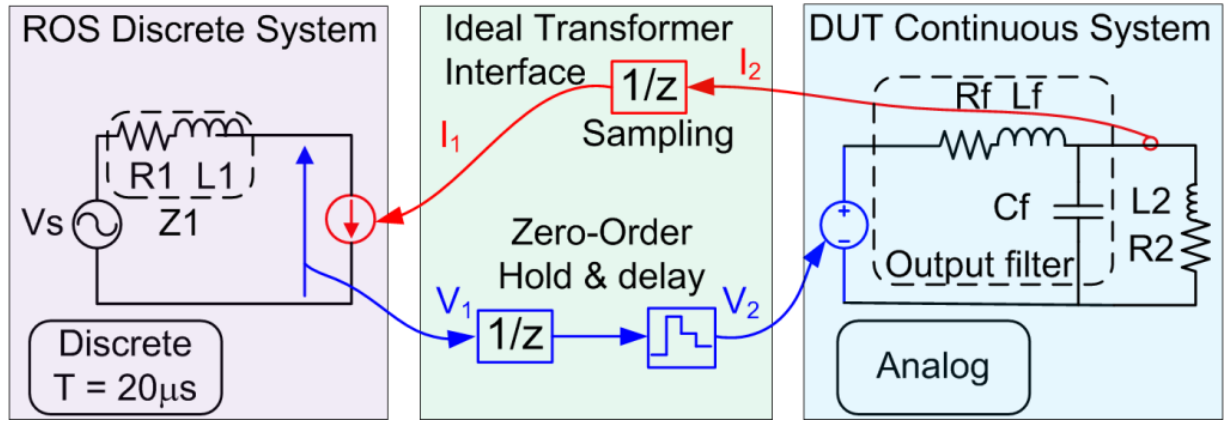
High bandwidth

Stability issues in PHIL system

Ideal Transformer Method (ITM) is one of the most convenient interface methods:

- PA is a voltage source
- DUT current is injected in the simulator

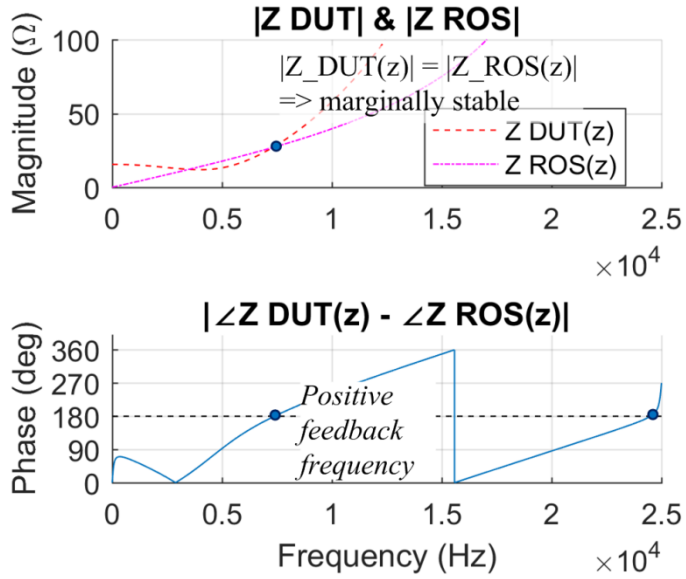
The stability of this interface method is related to the impedance ratio between the ROS and the DUT taking in to account the hybrid nature of the system (i.e. continuous – discrete)



Closed-loop system stable if [1] **:**

$$|Z\_ROS(z)| < |Z\_DUT(z)|$$
when
$$\angle Z\_DUT(z) - \angle Z\_ROS(z) = 180°$$

Example for a resistive DUT



Stable only if the Short Circuit Ratio (SCR) is > 50:

- R1 = 0.21 Ω
- L1 = 0.55 mH
- R2 = 14.4 Ω
- L2 = 15 µH
- Rf = 0.05 Ω
- Lf = 50 µH
- Cf = 22 µF

[1] O. Tremblay, H. Fortin-Blanchette, R. Gagnon and Y. Brissette, "Contribution to stability analysis of power hardware-in-the-loop simulators," in IET Generation, Transmission & Distribution, vol. 11, no. 12, pp. 3073-3079, 24 8 2017.

Relevance of the closed-loop PHIL

If the simulated network needs to be 50 times stronger than a resistive DUT, the impact of the DUT on the ROS will be negligible (only 2% of impact).

⇒ closed-loop simulation is irrelevant using an infinite bus power system. Similar to open loop testing…

Relevant closed-loop tests should be able to represent high penetration of DUTs on the ROS:

⇒ Short-circuit ratio between 1 and 10 times the DUT power level

➢ **The ITM is not appropriate for closed-loop PHIL!**

The interface method must be energy conservative to ensure stability

⇒ Why not use a method that has been proven for more than 20 years in RTS to separate computation tasks?

Traveling wave

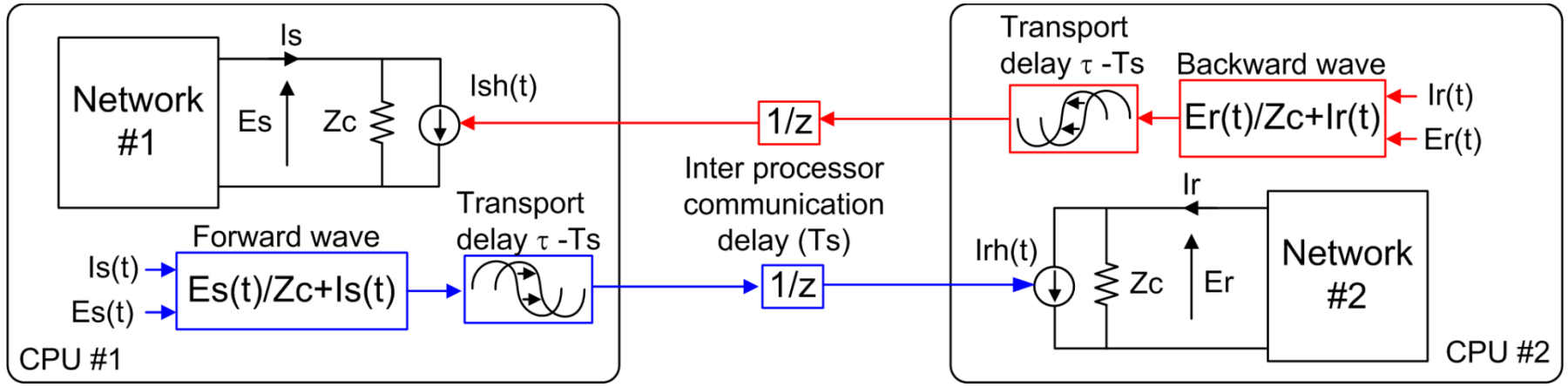
Traveling wave interface method (Bergeron Line Model)

The secret behind real-time simulator

- A part of natural propagation delay of a transmission line is absorbed by the communication time between two processors

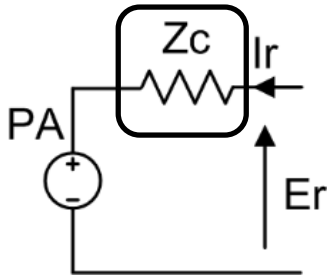
⇒ Large system impedance matrix can be divided into multiple smaller matrices that can be solved in parallel on many processors without numerical error.

The closed-loop system is stable since the trapezoidal integration method is used



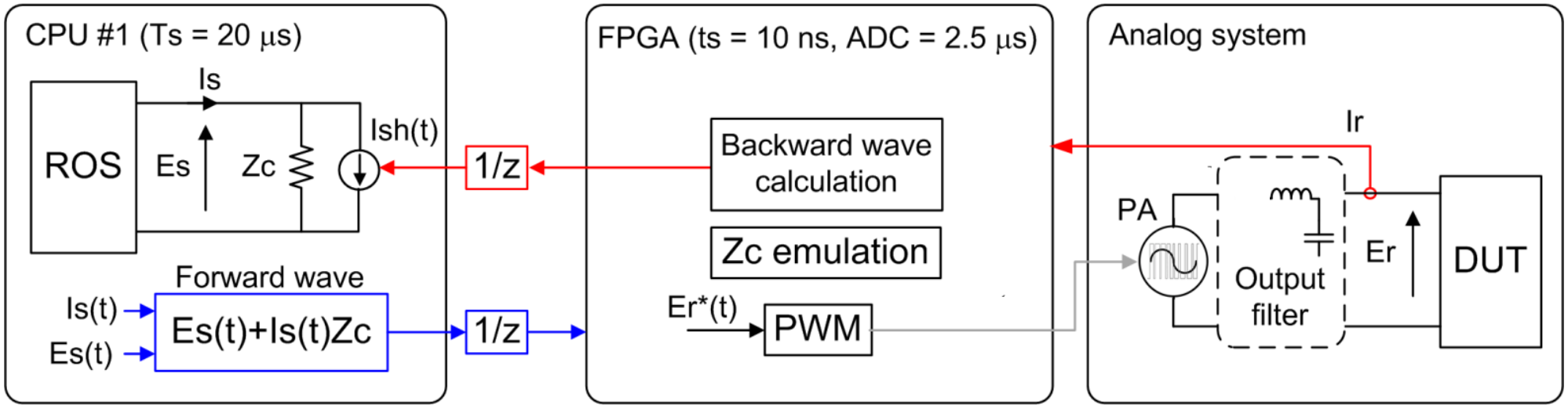
Traveling wave interface method for PHIL

For PHIL, it is possible to add an artificial line (StubLine) between the ROS and DUT with exactly one time step propagation delay. However, there is a major drawback:

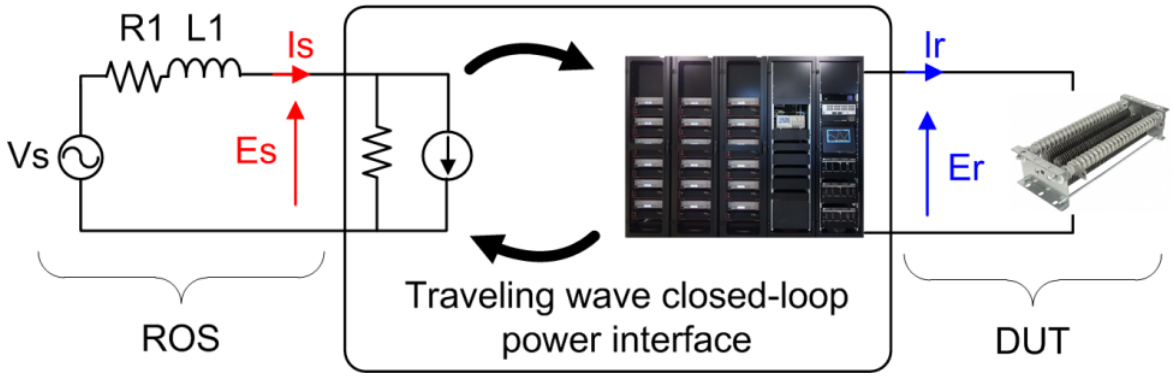


- It is required to add a real resistor Zc at the output of the PA
  - High power losses in Zc must be considered (sizing of the PA, sizing and cooling of Zc)
  - Reduced voltage range at the output (voltage drop across Zc)
  - Zc cannot be changed easily (hardware)

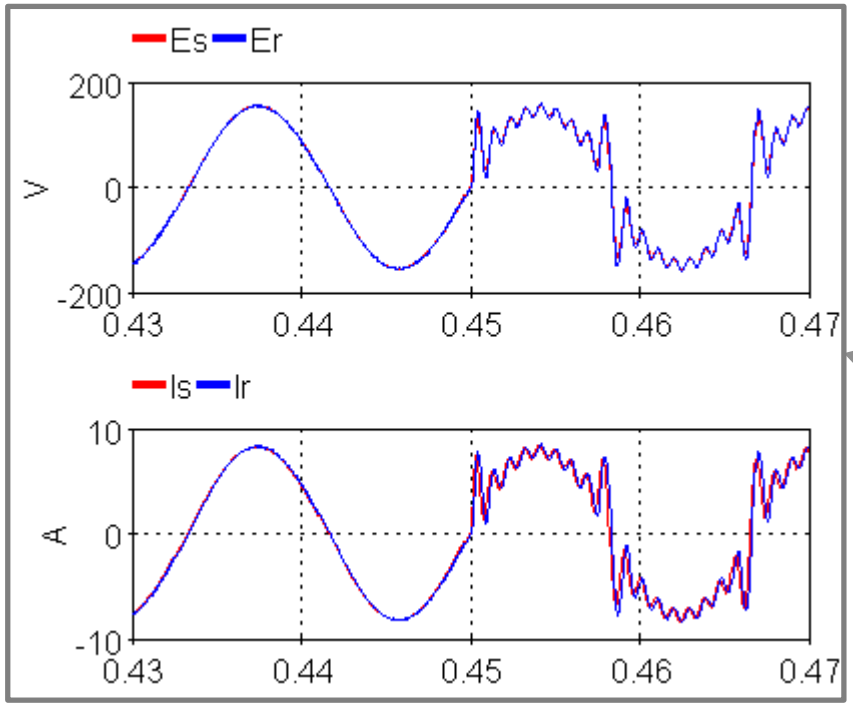
Instead of a real resistor, a fast speed control loop is used to emulate the behaviour of Zc:



Experimental validation (resistive load 20Ω)

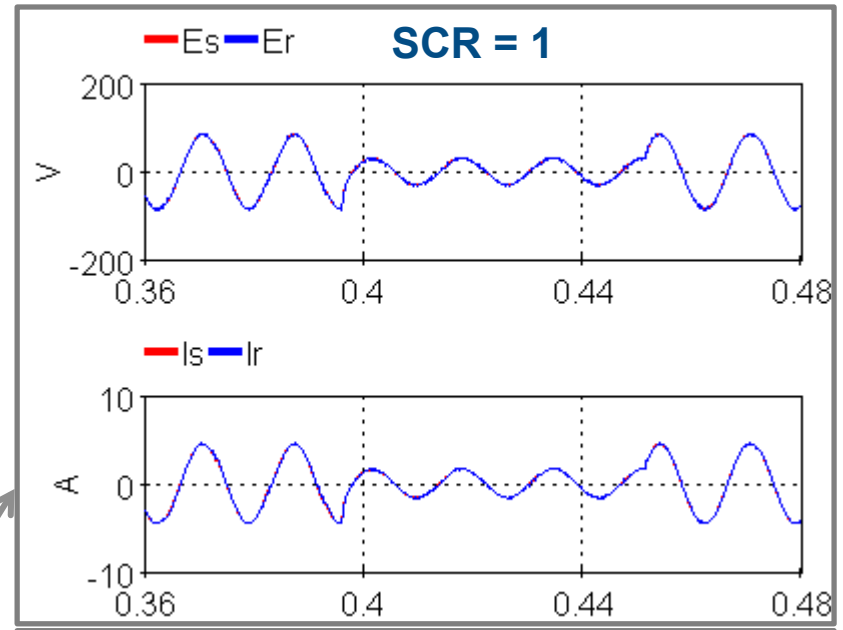


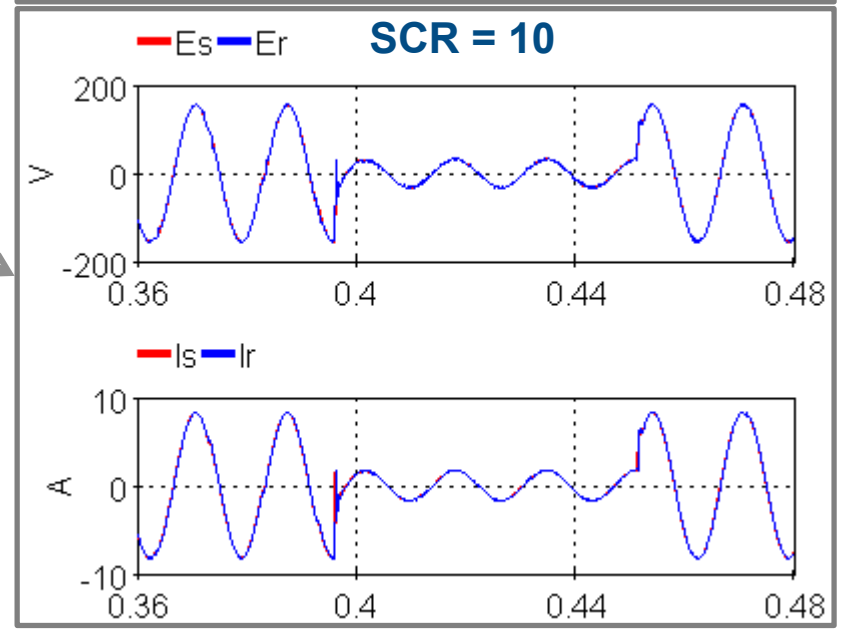
In an ideal world, the power interface should not alter the E & I signals : Es = Er, Is = Ir



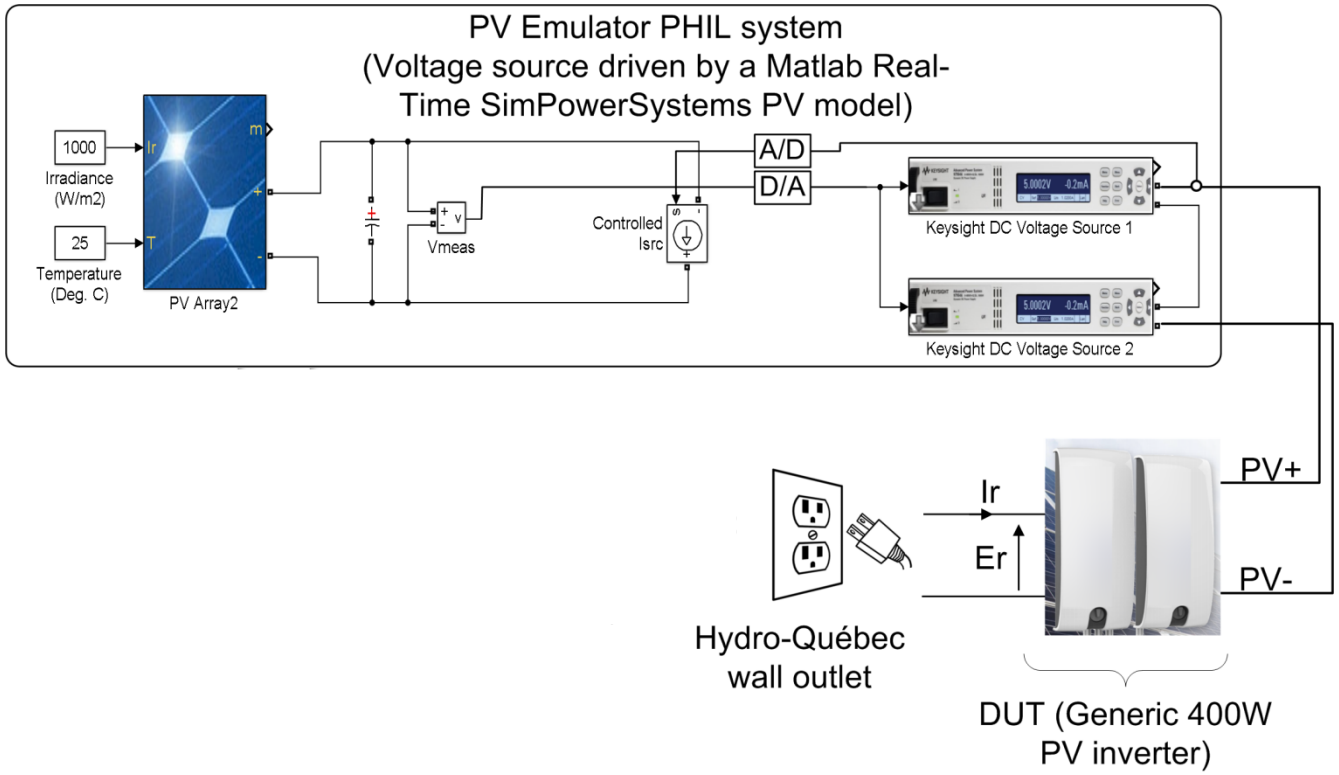
Voltage sag during 3 cycles
(Vs = 120Vrms, 60 Hz)

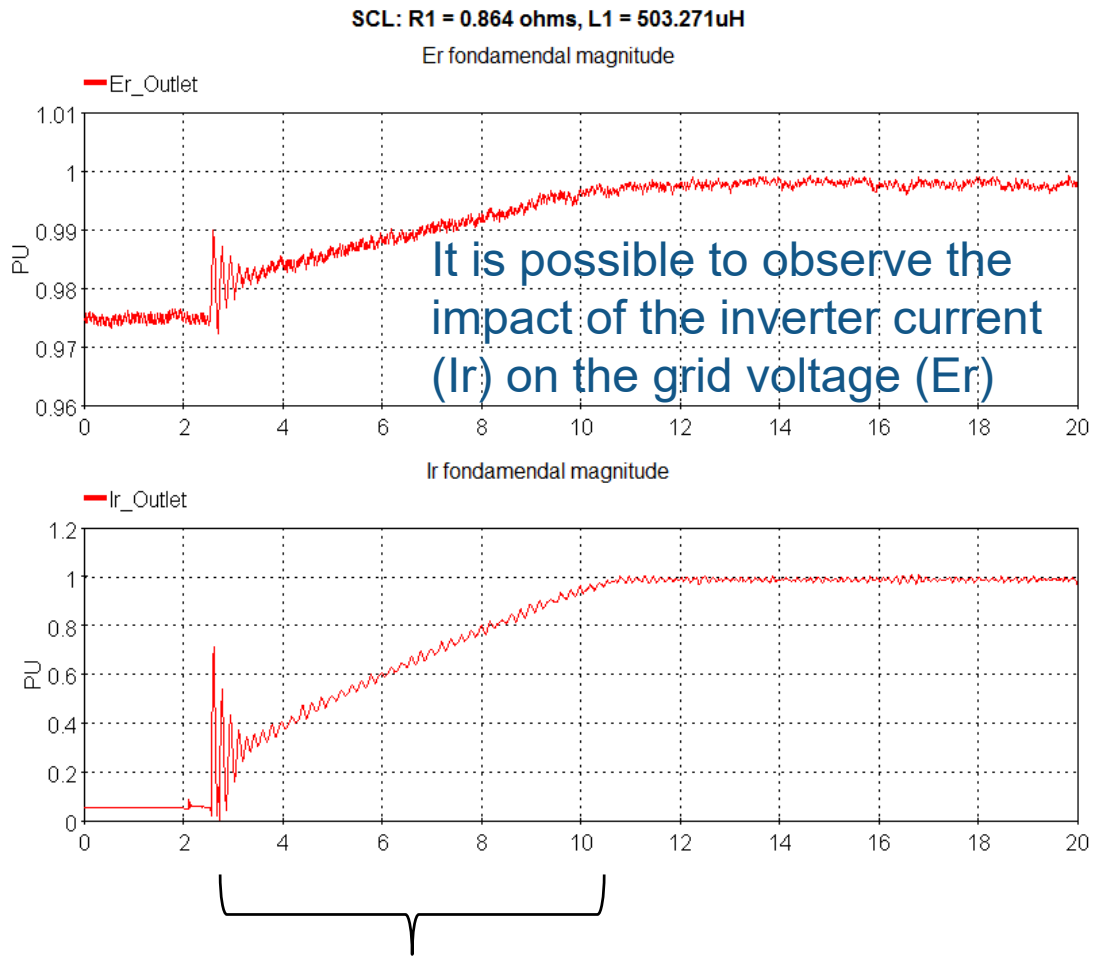
Harmonics generation at Vs:
harmo rank = 3,5,7,9,11,13,15,17
(Vs = 120Vrms, 60 Hz, SCR = 10)



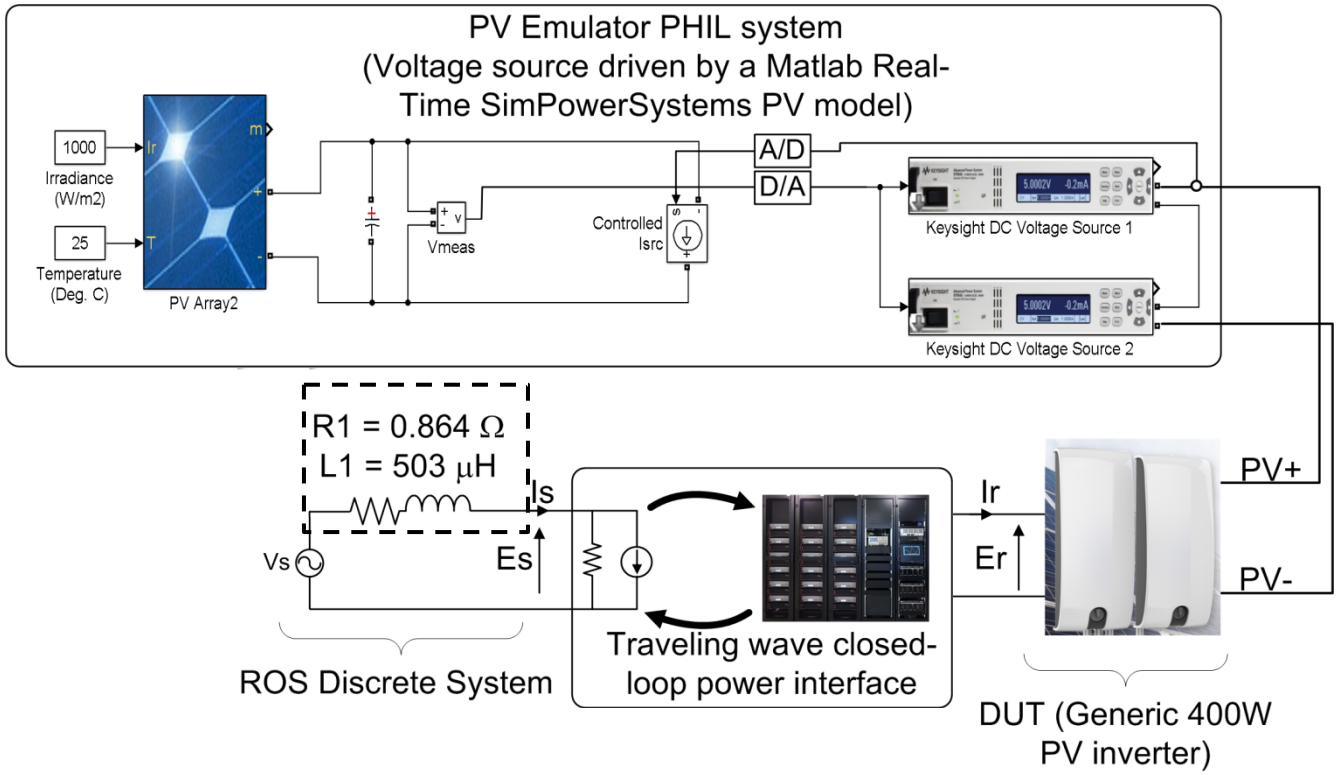


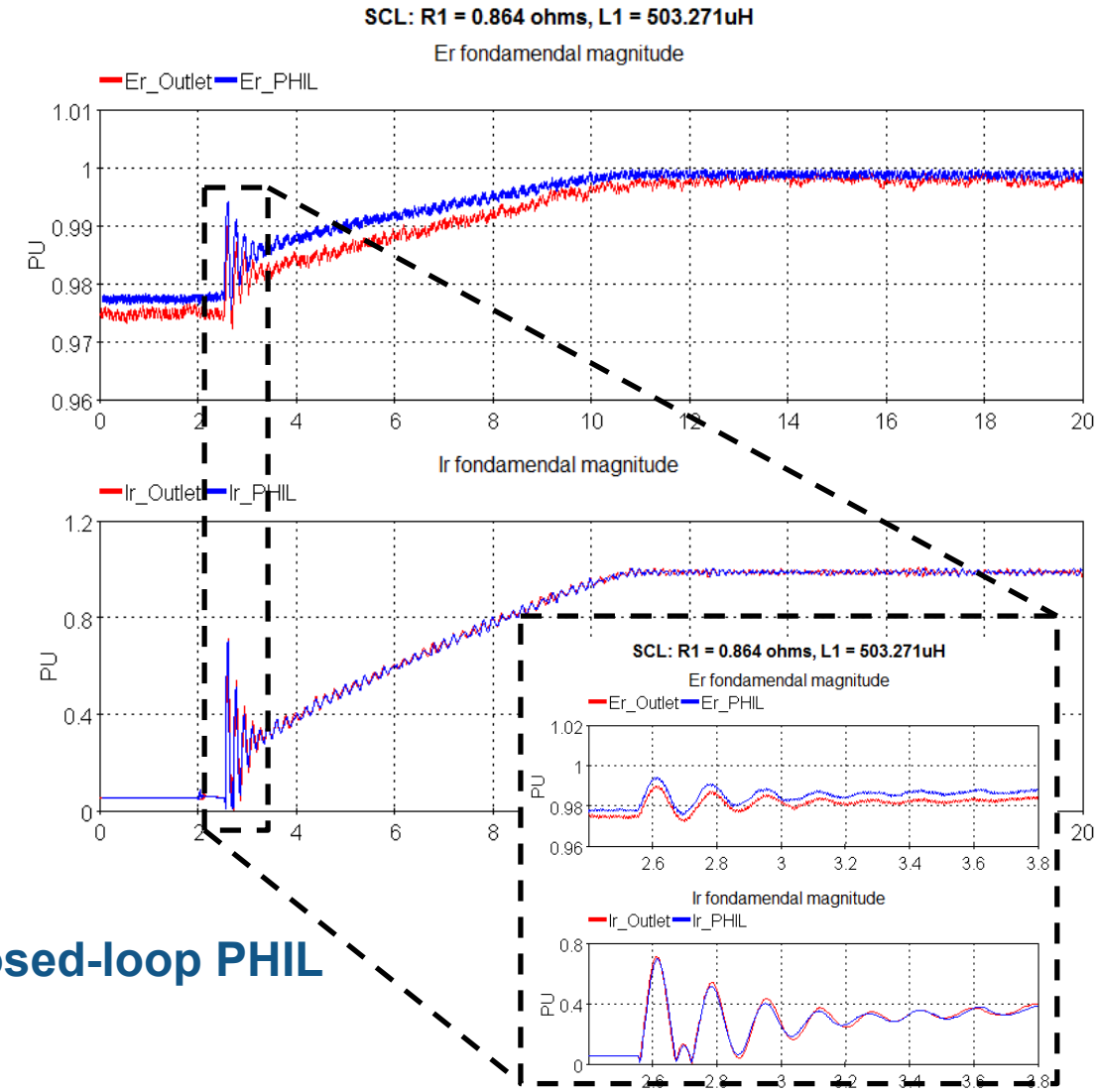
Experimental validation (PV inverter startup) – Wall outlet





Experimental validation (PV inverter startup) – PHIL



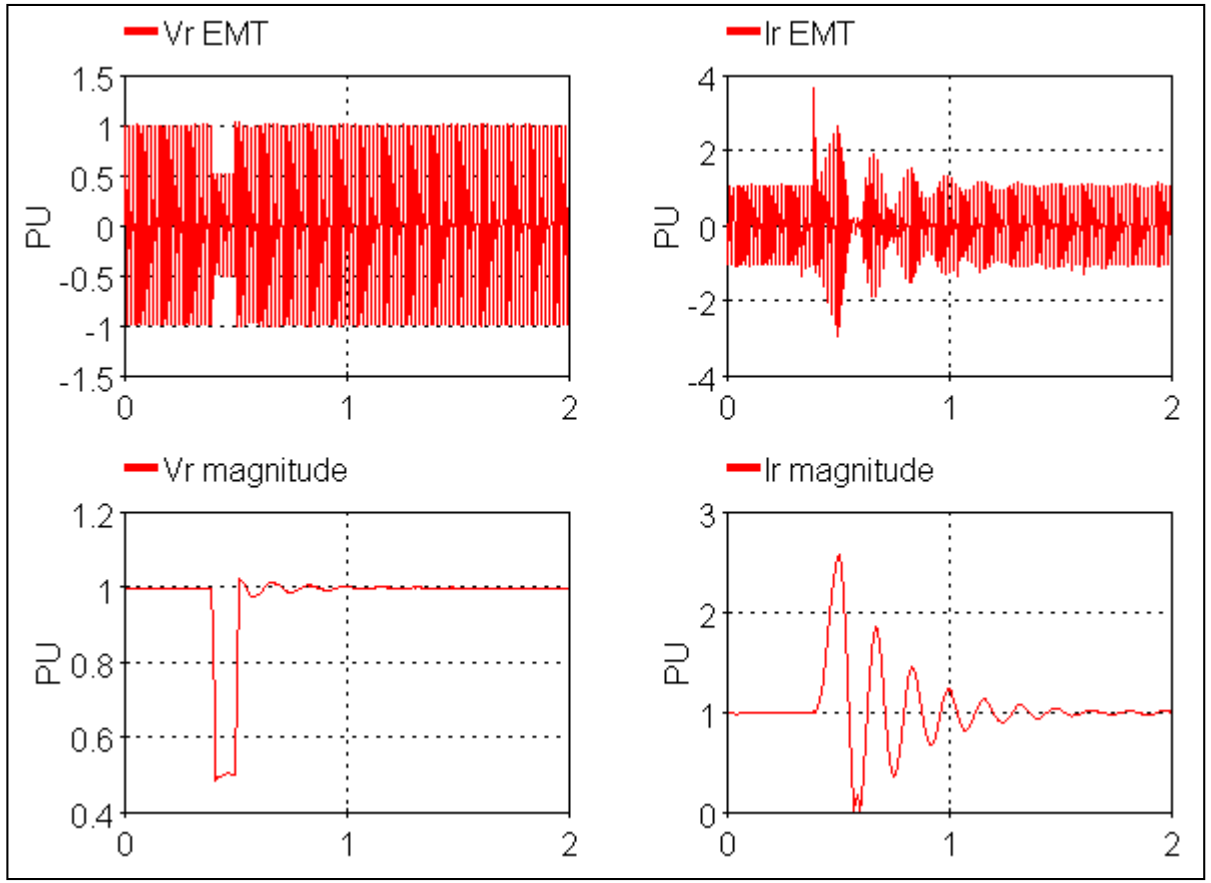


Very good results, closed-loop PHIL interface works well.

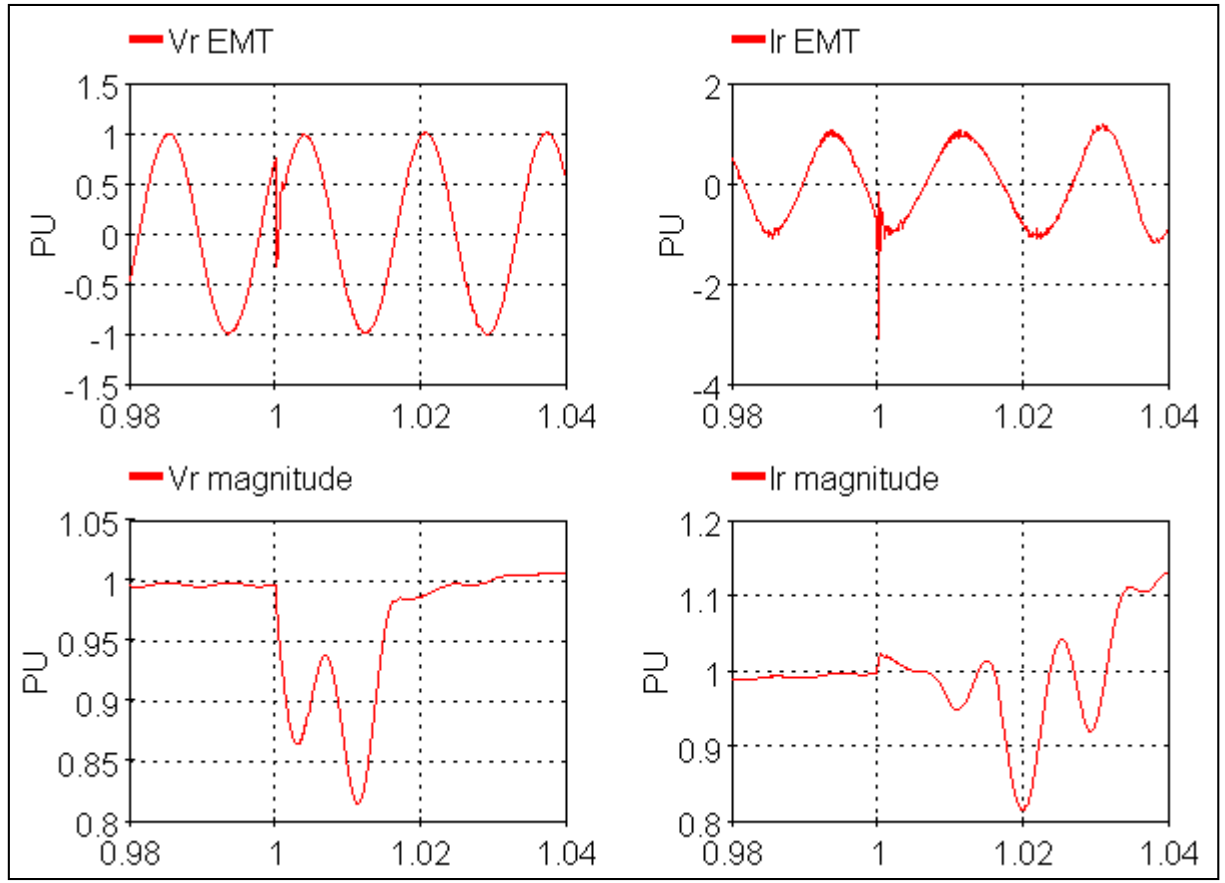
Experimental validation (PV inverter) – PHIL

Now, let's play with the system by doing events that are impossible to do with the wall outlet!

50 % Voltage sag



45-degree Phase shift



Project milestones

Design of the power amplifier (PA) topology

Cascaded H-Bridge

Transformerless

High bandwidth

25 kV, 10 MVA

Development of the reduced-scale version of the PA

Cascaded H-Bridge

Transformerless

High bandwidth

208 V, 3 kVA

Design of a general closed-loop interface

Stable

Precise

High bandwidth

Making a single full-scale H-Bridge

Experimental H-Bridge

1 kV, 100 kW

Overload capability: 10x nominal current

Making a full-scale H-Bridge (Hardware)

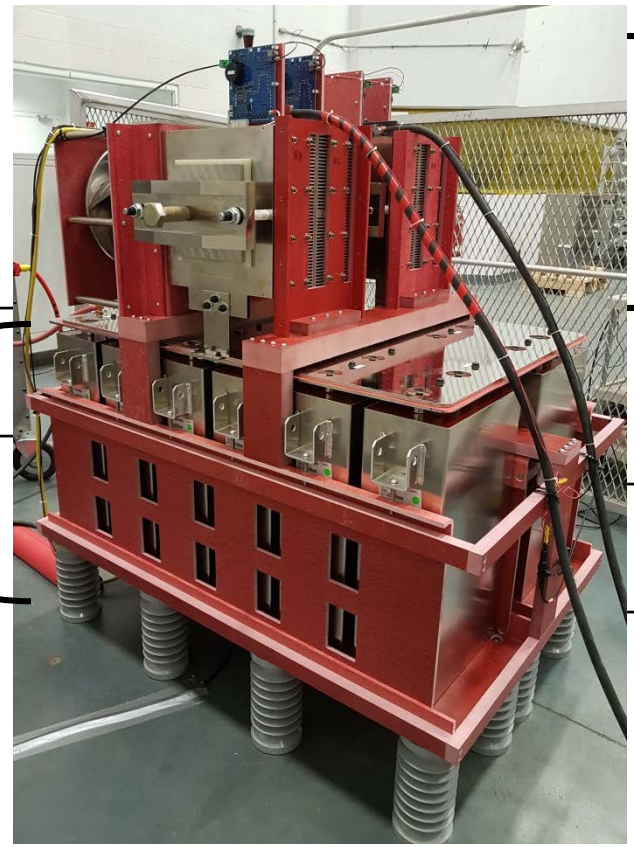
Goal:

Build an experimental cell to optimize the final design (100 kW, 1kV)

1 kV, 100 kVA, Bi-directional Active Front End

↑ Vdc

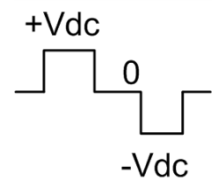
Configurable DC-link capacitor bank (ratio energy stored / power rating = 4 to 44 cycles of 60 Hz)



1 kV, 100 kW H-Bridge

H-Bridge: 4x 4500V, 3000A StakPak IGBT

↑ Vac

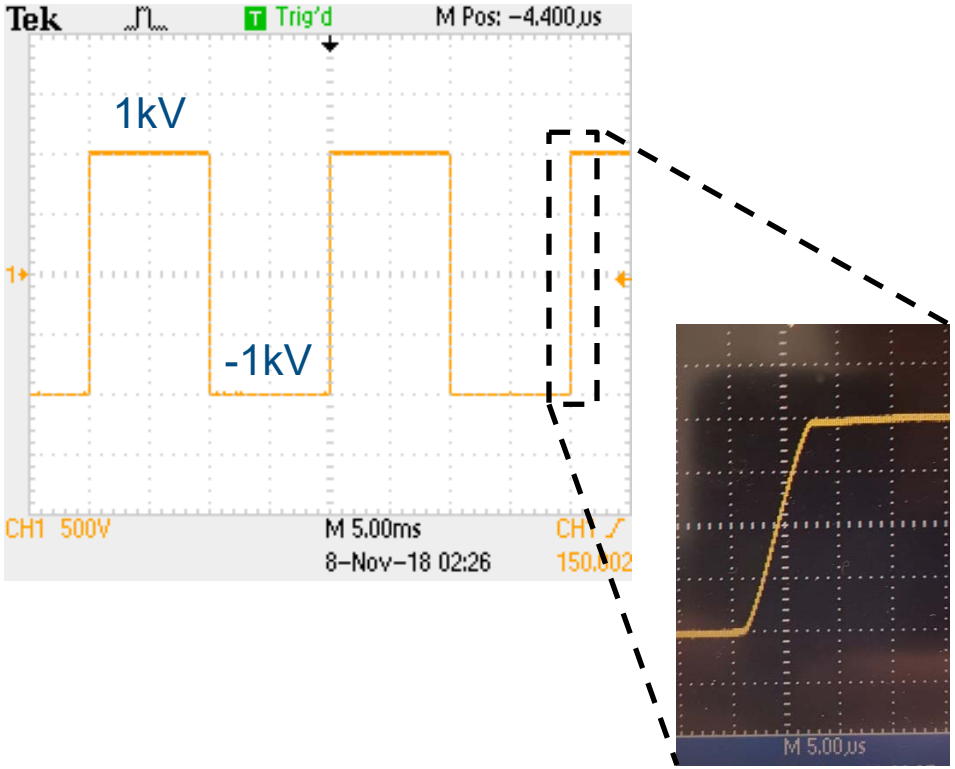


1 kV, 150 kW Load

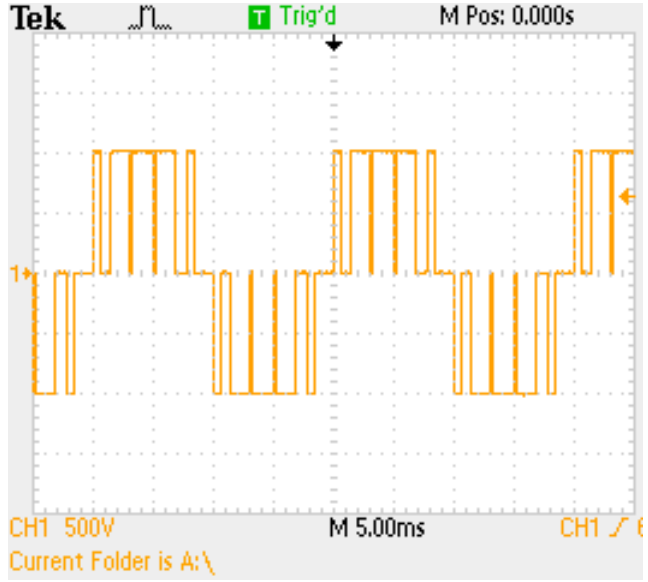
Making a full-scale H-Bridge (experimental results)

Smooth and fast switching, stable voltage

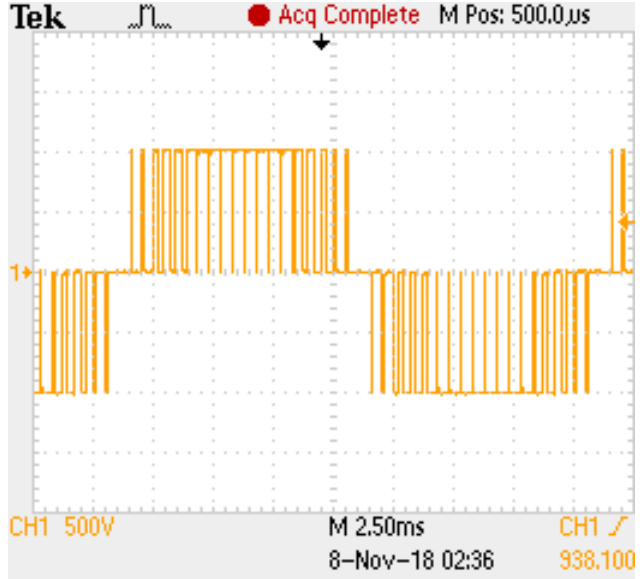
Square wave 50 Hz
P = 100 kW



Sine wave 50 Hz (PWM = 250 Hz), 707 Vrms, 50 kW



Sine wave 50 Hz (PWM = 1000 Hz), 707 Vrms, 50 kW



Full voltage inversion at nominal power in less than 10 µs.

Project milestones

Design of the power amplifier (PA) topology

Cascaded H-Bridge

Transformerless

High bandwidth

25 kV, 10 MVA

Development of the reduced-scale version of the PA

Cascaded H-Bridge

Transformerless

High bandwidth

208 V, 3 kVA

Design of a general closed-loop interface

Stable

Precise

High bandwidth

Making a single full-scale H-Bridge

Experimental H-Bridge

1 kV, 100 kW

Overload capability: 10x nominal current

Complete the PA

3-phase

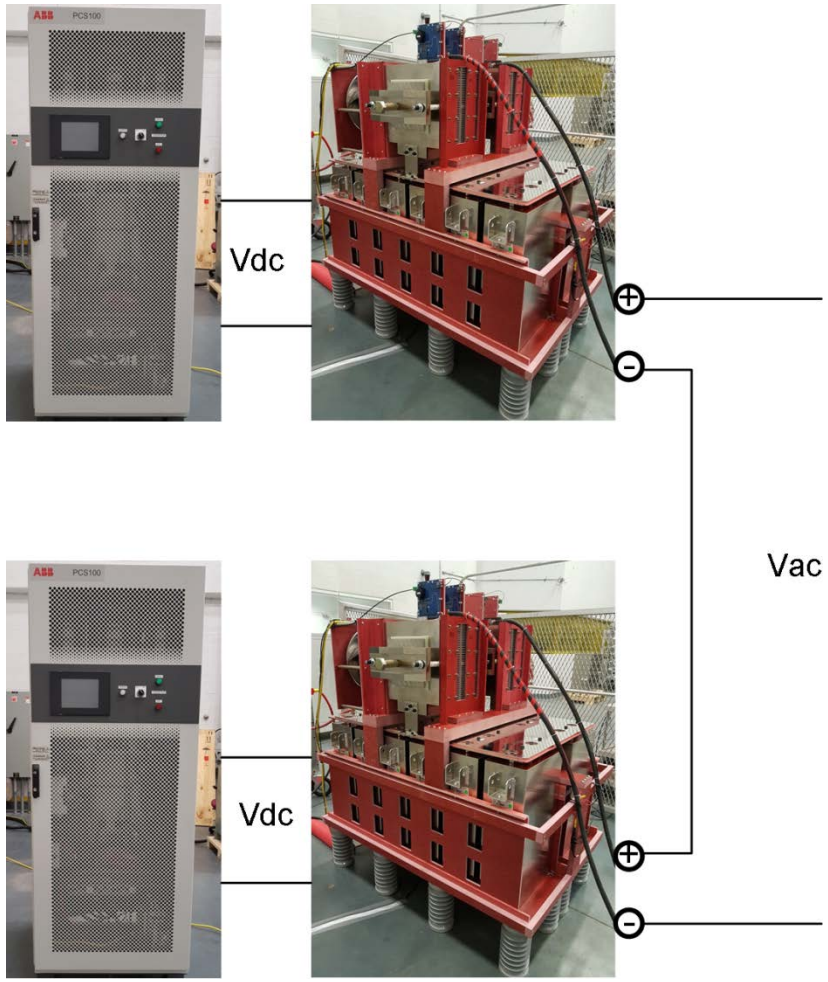
2 PU overvoltage capability

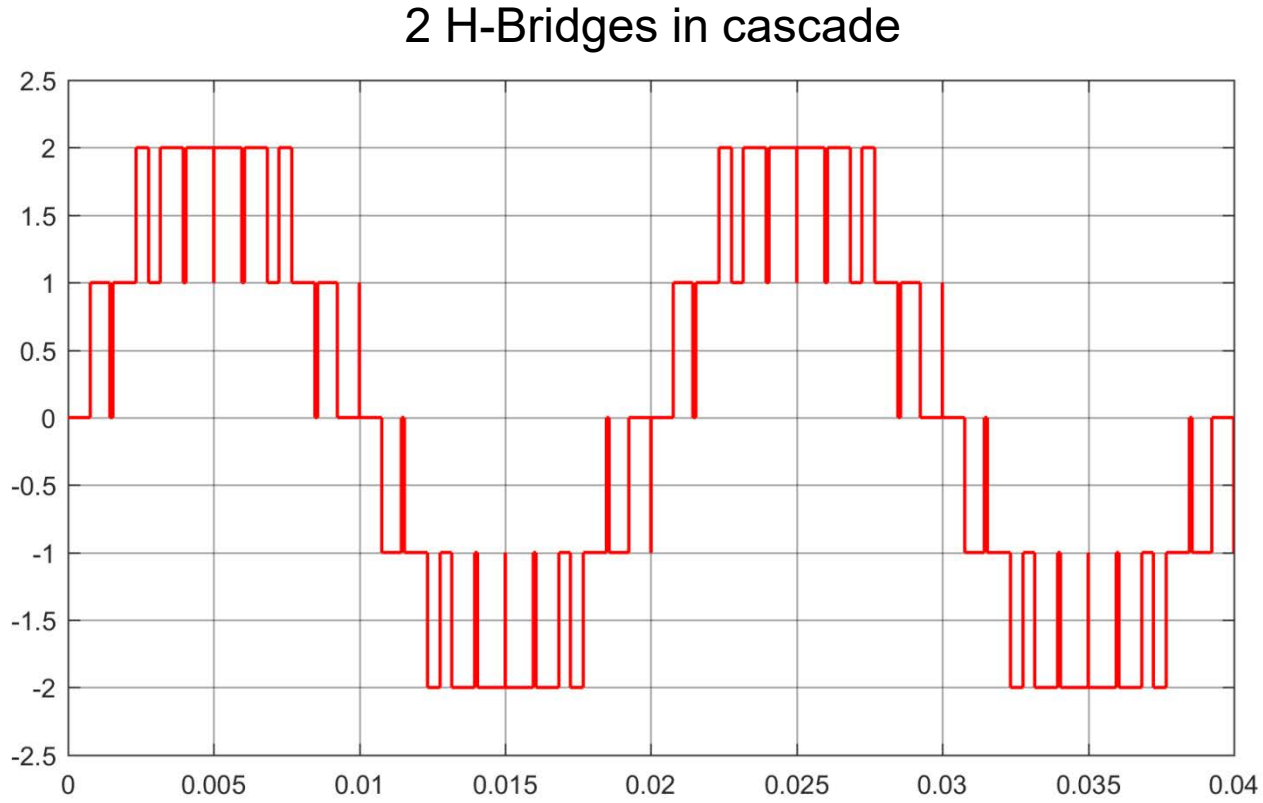
10 PU overcurrent capability

DC to 1 kHz in closed-loop

Next step: complete the Power Amplifier

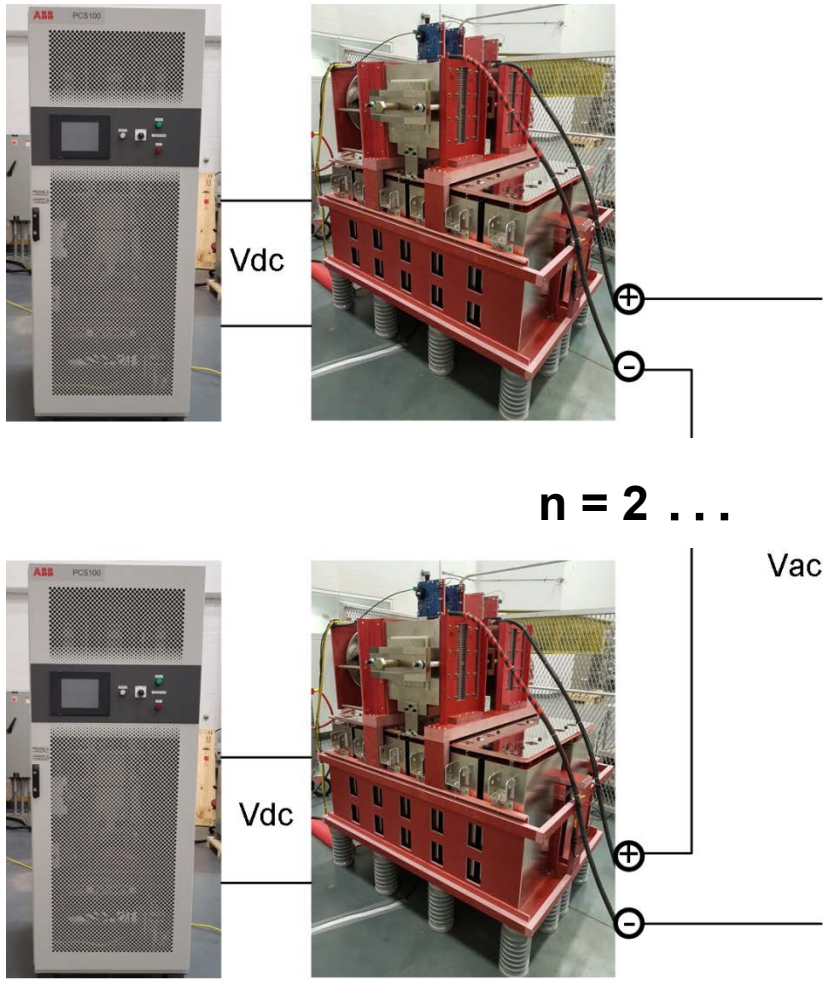
Optimize the design and connect the H-Bridges in cascade

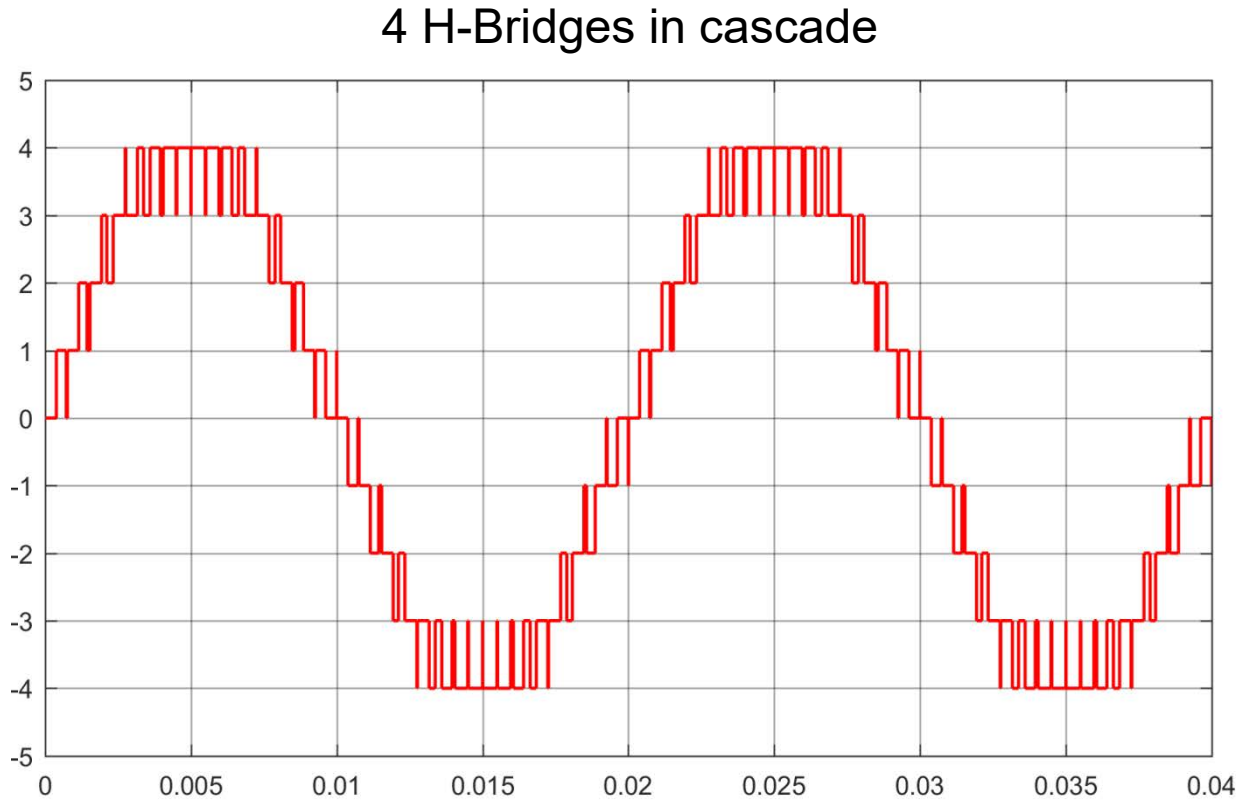




Next step: complete the Power Amplifier

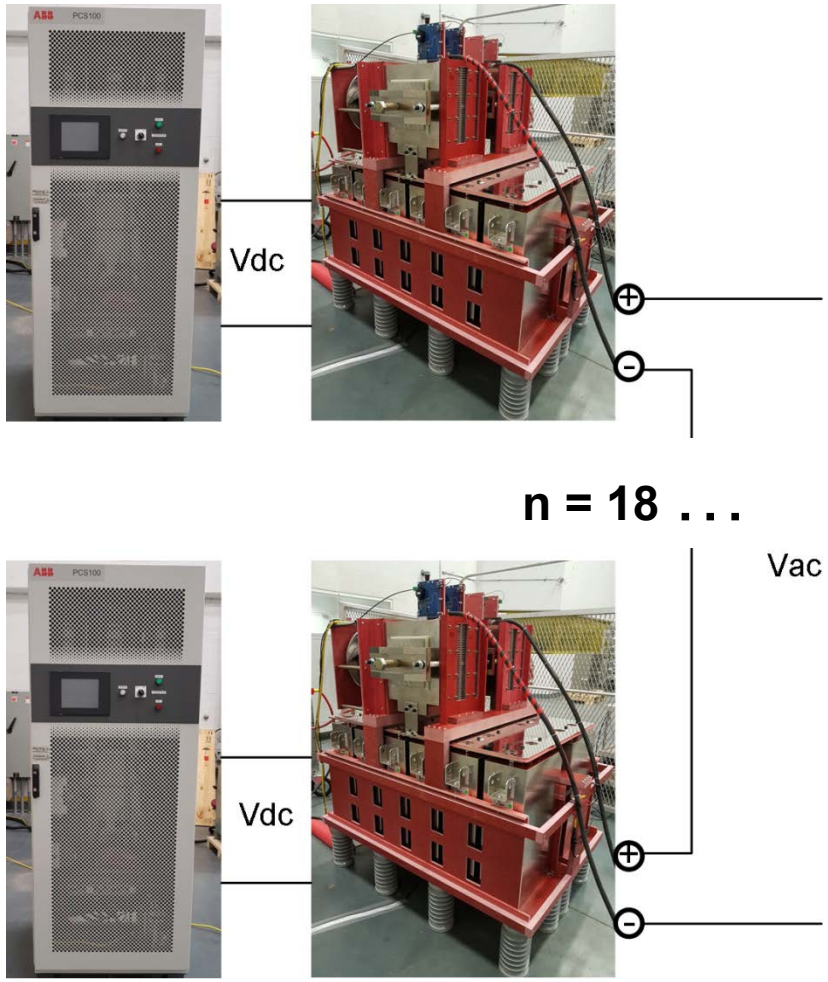
Optimize the design and connect the H-Bridges in cascade

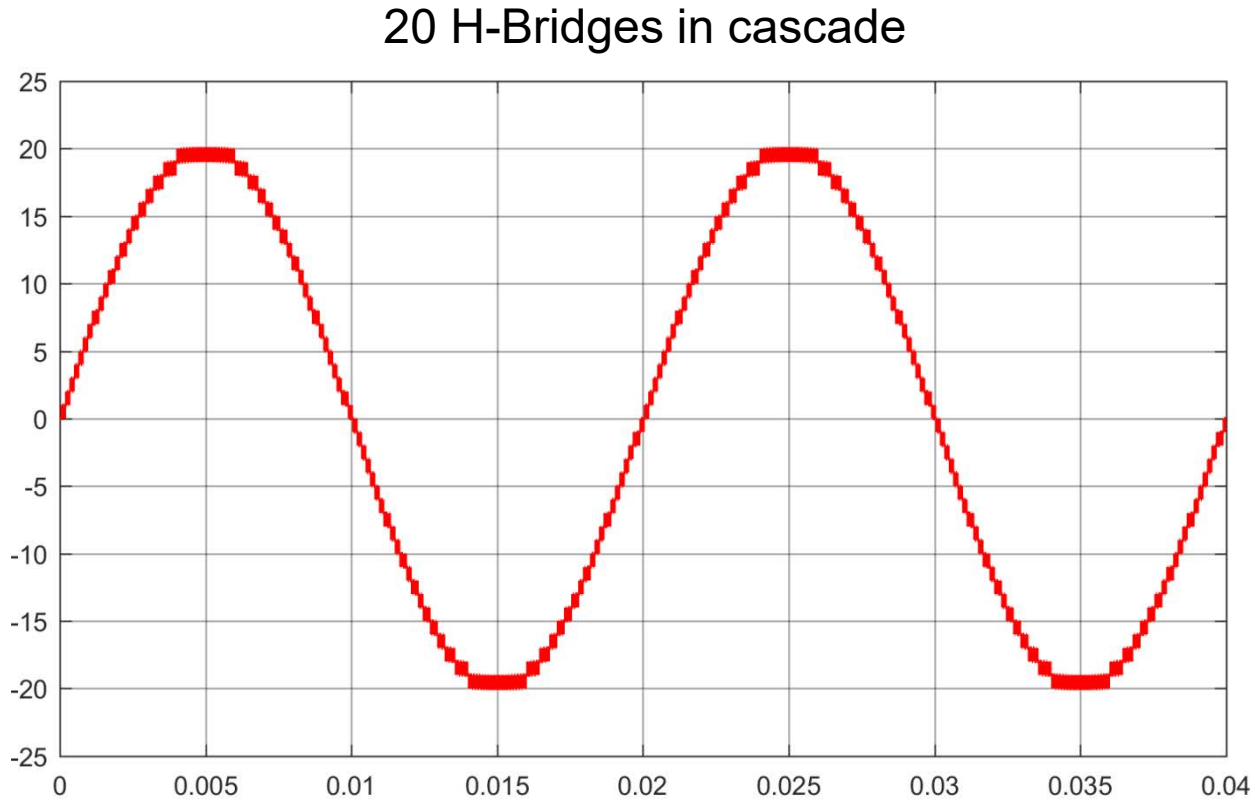




Next step: complete the Power Amplifier

Optimize the design and connect the H-Bridges in cascade





Conclusion

IREQ PHIL simulator, a unique research & testing infrastructure to prepare the energy transition of Hydro-Québec.

To realize this system, full control of every technical aspects is required:

- Simulator's development to integrate seamless interface algorithms (traveling wave)
- FPGA technologies to implement fast control-loops (Zc emulation)
- Reduced-scale prototype to prove the concept
- Experimental bench for the hardware design of the full-size power amplifier


Hydro
Québec