Update on IREQ PHIL simulator: prototype and stability analysis

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National Renewable Energy Laboratory (NREL) and Clemson University (CU)

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NREL's Energy Systems Integration Facility (ESIF), Golden, Colorado USA

Hydro Québec

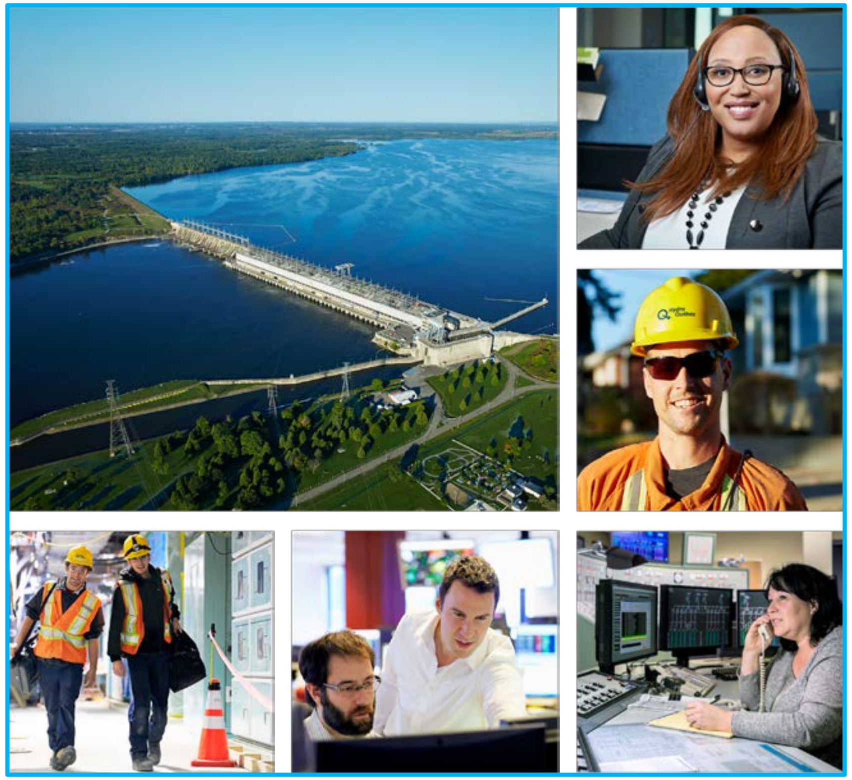
Innovation, équipement et services partagés

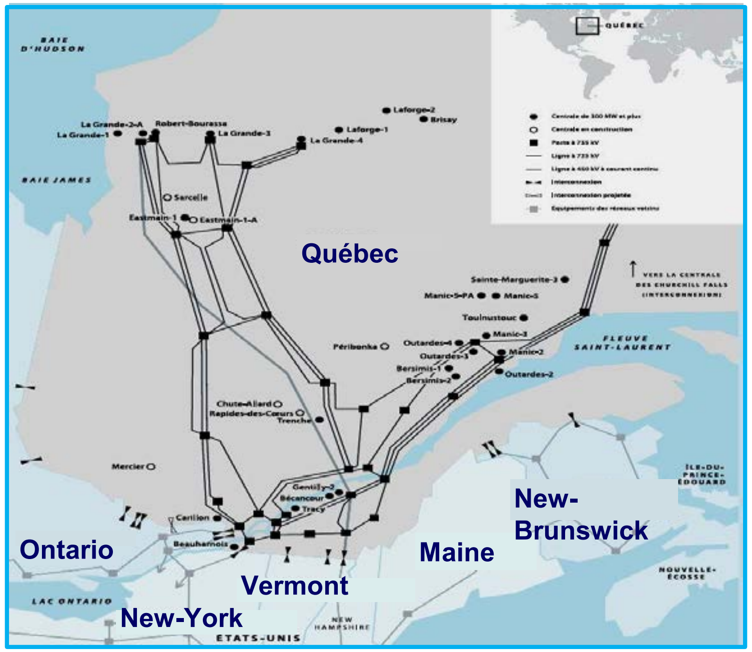
Presentation overview

- Introduction to Hydro-Québec Research Institute (IREQ)
- Concept of the SimP project
- Stability Analysis of PHIL
- Prototype of the power amplifier
- Next steps
- Concluding remarks

Introduction

Hydro-Québec Key Figures





Hydro-Québec generates, transmits and distributes electricity. Its sole shareholder is the Québec government. It uses mainly renewable generating options, in particular large hydro, and supports the development of other technologies—such as wind energy and biomass.

KEY FIGURES* (2016)

Total assets: $75,2 billion	Net income: $2.9 billion	Energy portfolio: **99%** renewable
3,700 MW of wind power on the grid	**34,300 km** of high-voltage lines	Québec market: **4.2** million customers
Generating capacity: 36,900 MW	Total workforce: 19,550 employees	15 interconnections
Residential rate: 7.23¢/kWh** (lowest in North America)	Hydro-Québec Annual Report	COMPARISON OF ELECTRICITY PRICES IN NORTH AMERICA

*Financial data expressed in Canadian dollars.
**Rate in effect April 1, 2016, for monthly consumption of 1,000 kWh (taxes not included)

Introduction

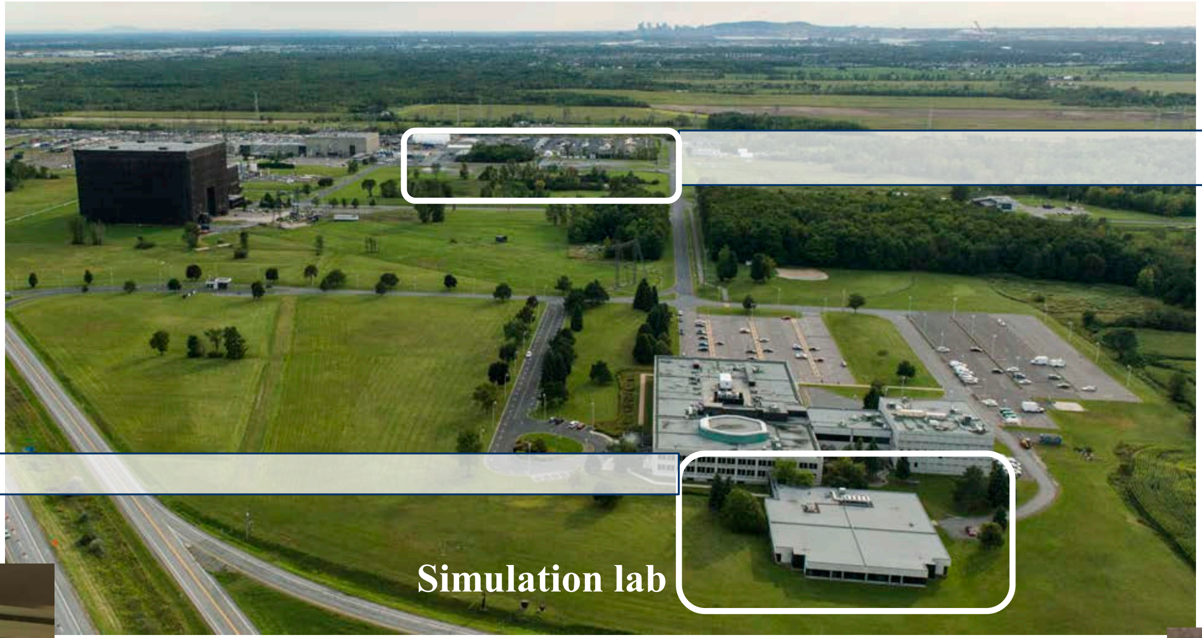
Hydro-Québec Research Institute (IREQ)

526 employees including
267 scientists
125 technicians

128 partnerships

850 patents

$100-million R&D Budget



Full-scale 25-kV distribution test line

Large-scale real-time simulator

Power amplifier
25 kV
10 MVA

Power Simulator (SimP)

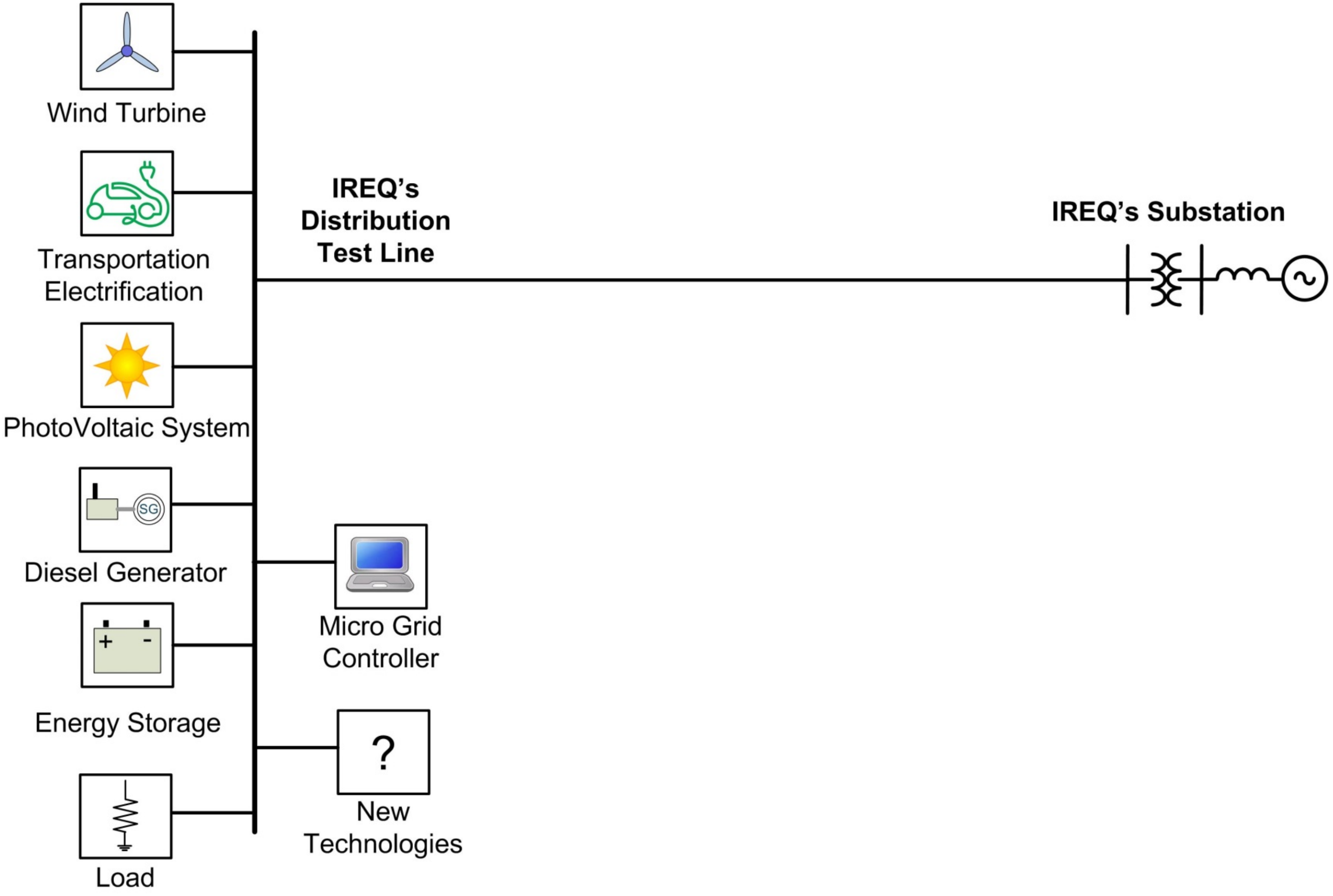
SimP at a glance

- **SimP, for doing what?**
  - Development and validation of the technologies for the power systems of the future
  - Validation of simulation models of equipment (10 MVA @ 25 / 34.5 kV)
  - Study the dynamic behavior of electrical equipment connected to their power system (global behavior power system + equipment)
  - Scope: renewable energy integration, microgrid, smart grid, energy storage, ground transportation electrification, all-electric ship, more electric aircraft

- **Status of the project**
  - Implementation of a small scale prototype of SimP (3 kVA)
  - Design of the 10 MVA power amplifier
  - Development of algorithms for closed-loop operating mode

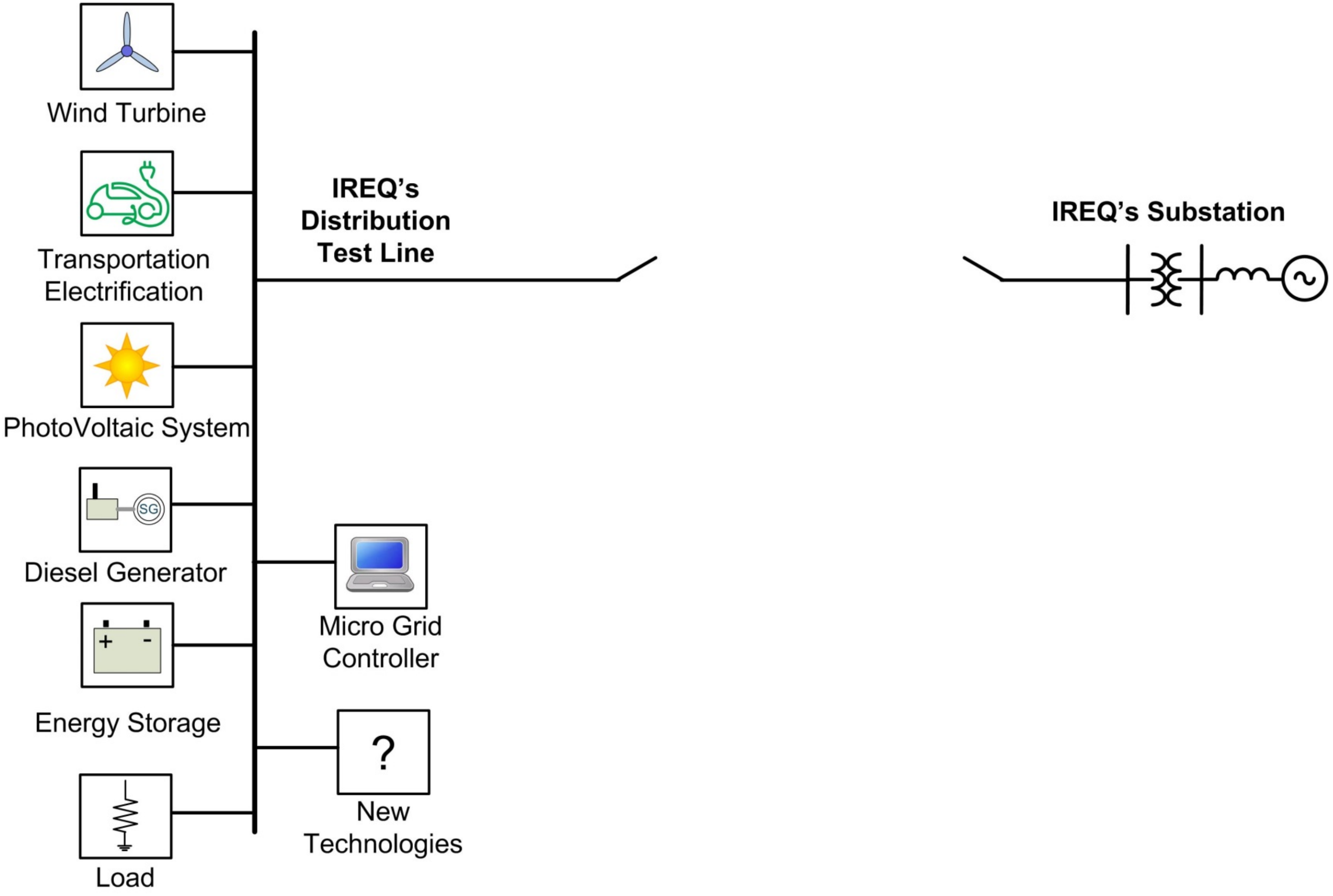
Concept of SimP

Current Distribution Test Line Configuration



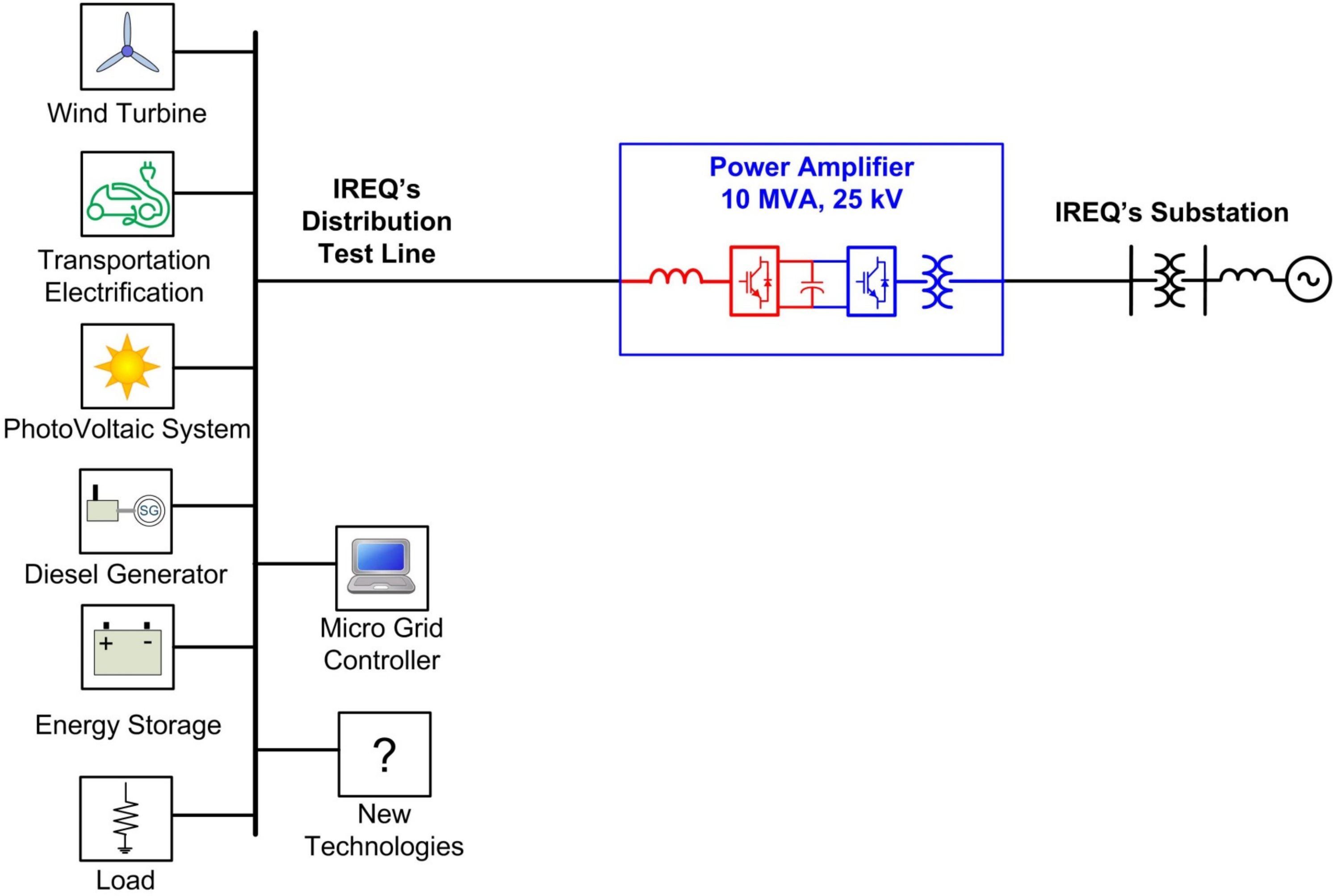
Concept of SimP

Opening the line to insert the amplifier of SimP



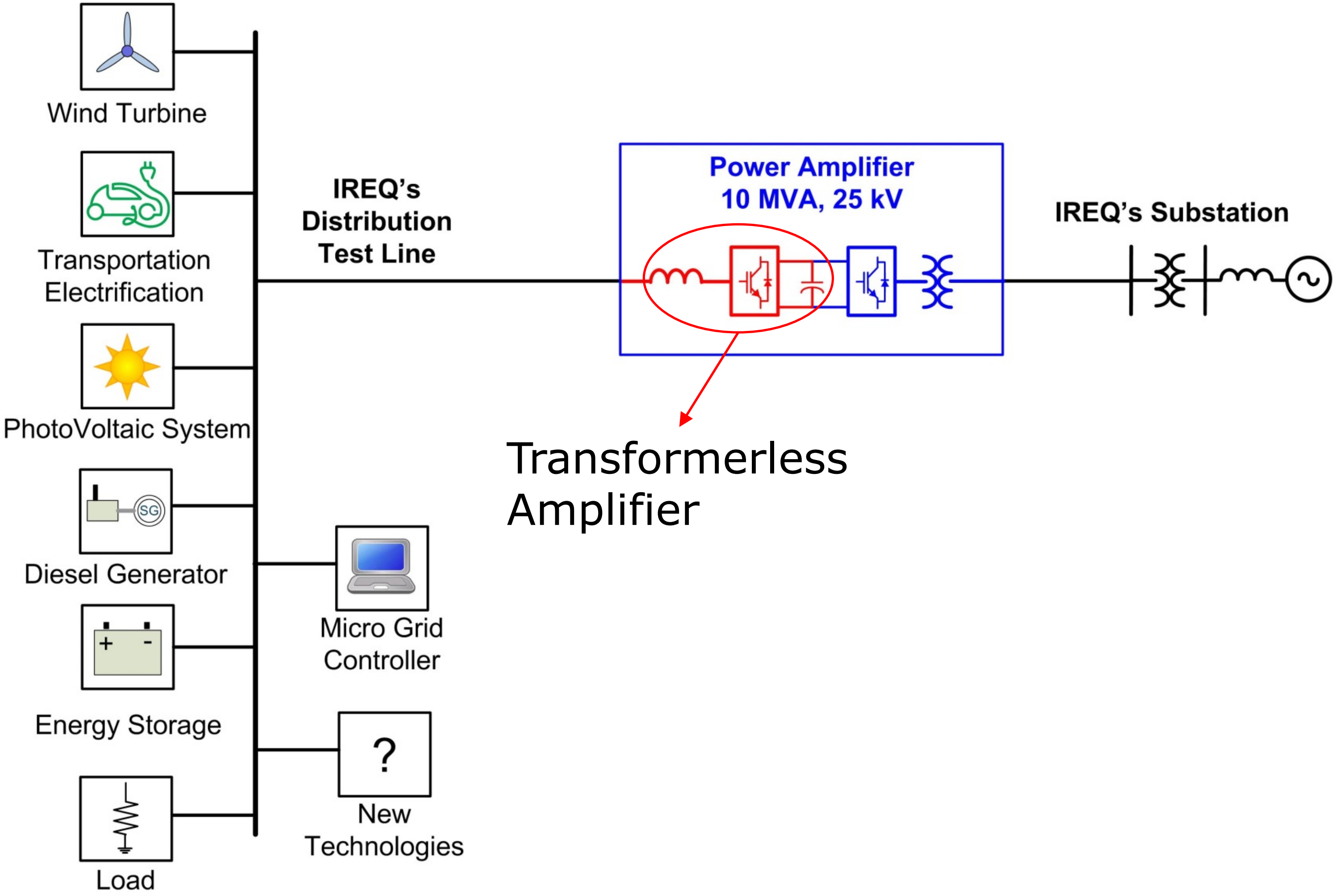
Concept of SimP

Inserting the amplifier



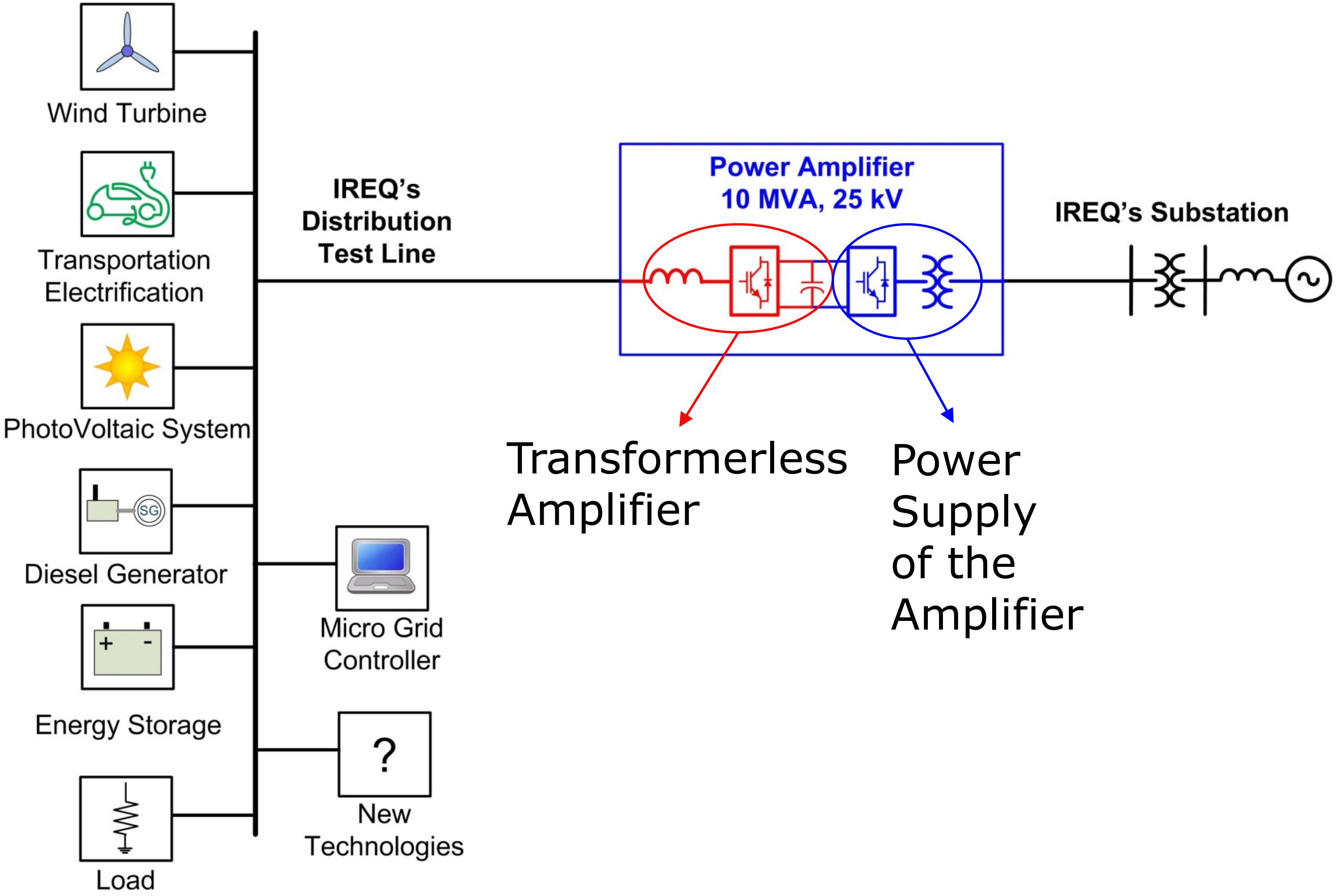
Concept of SimP

Inserting the amplifier



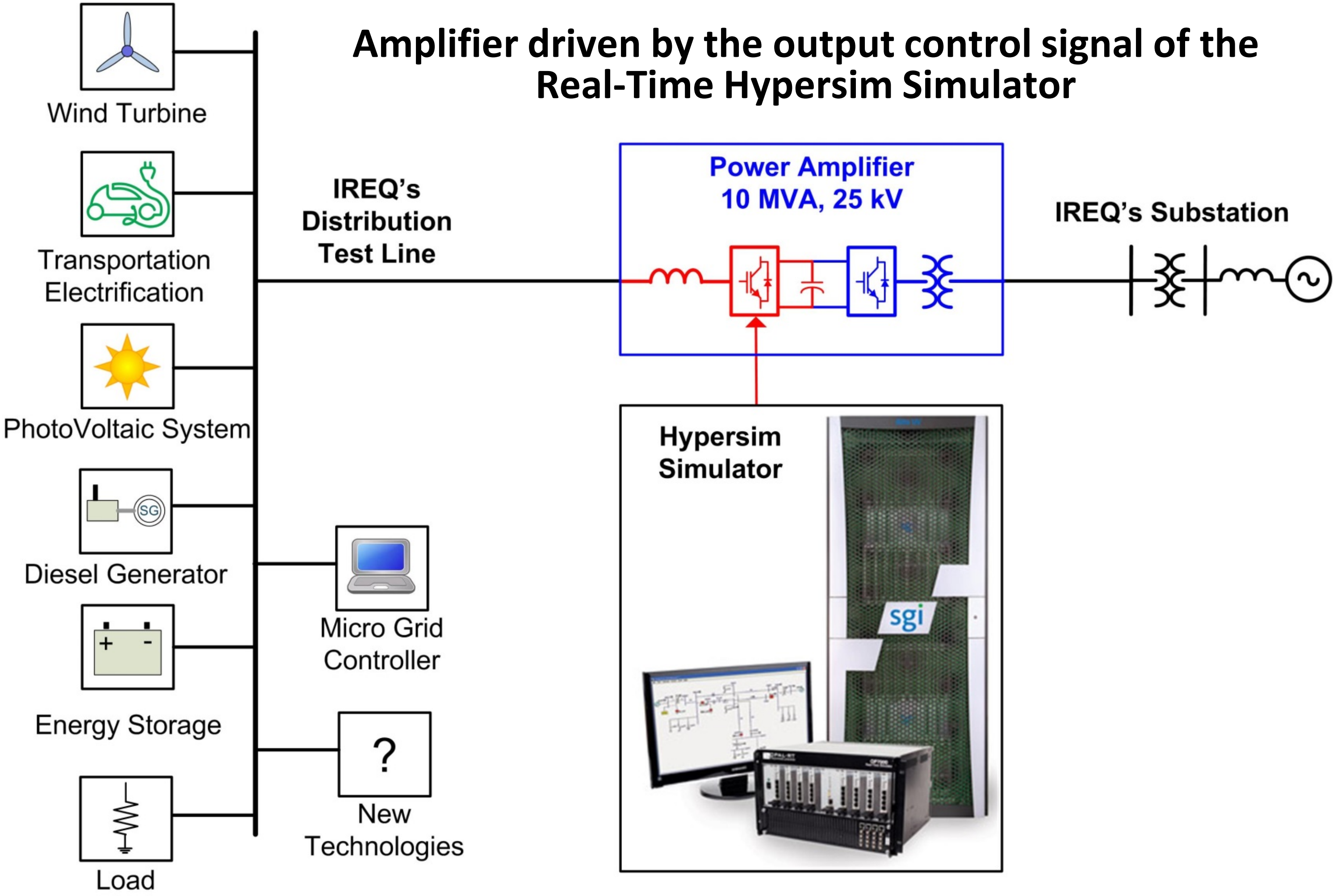
Concept of SimP

Inserting the amplifier



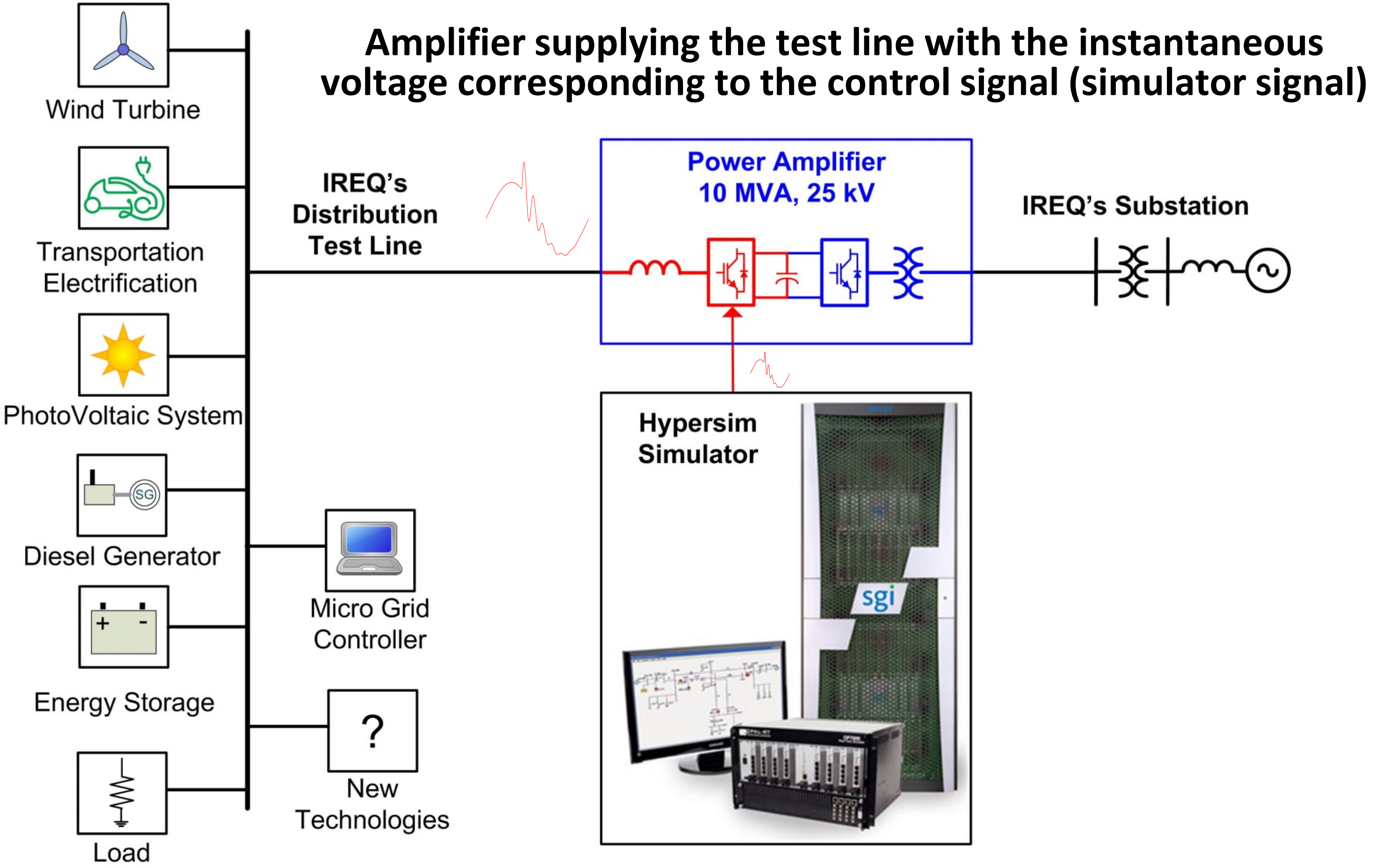
Concept of SimP

Voltage reference given by Hypersim



Concept of SimP

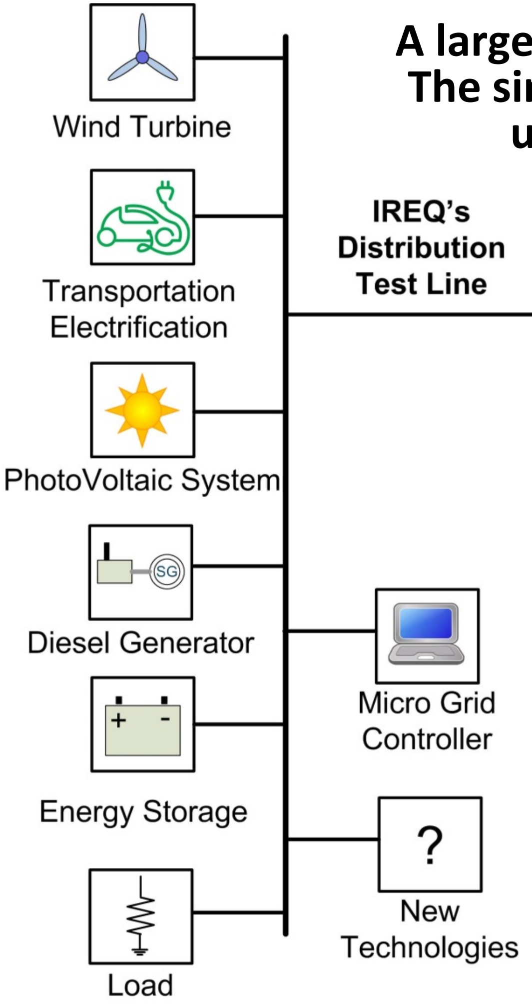
Open-Loop operation

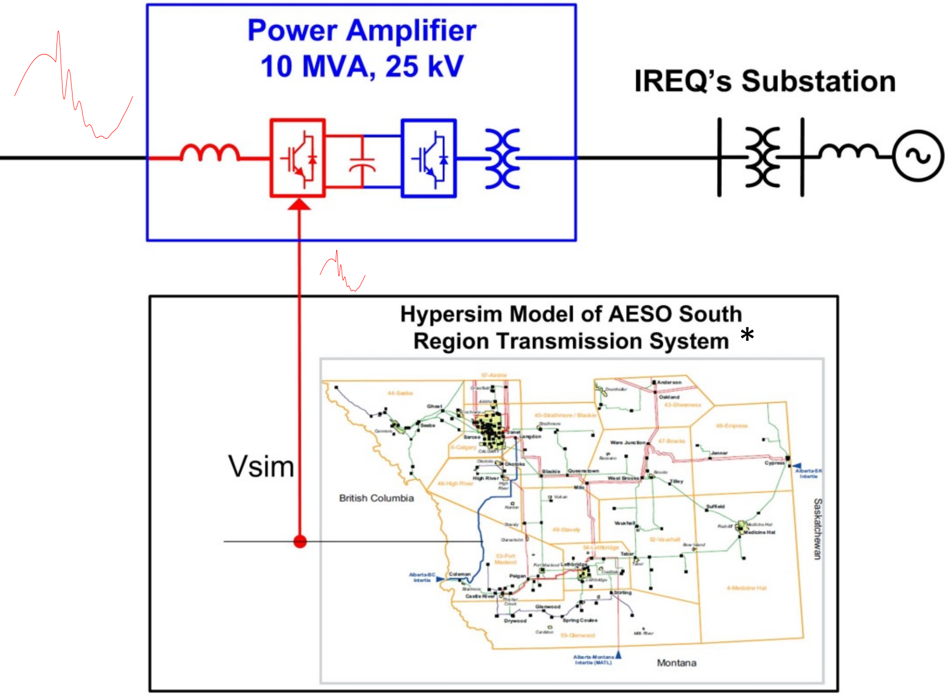


Concept of SimP

Open-Loop operation

A large-scale T&D system is simulated in real-time. The simulated voltage (Vsim) at a bus (any bus) is used as control signal for the amplifier.

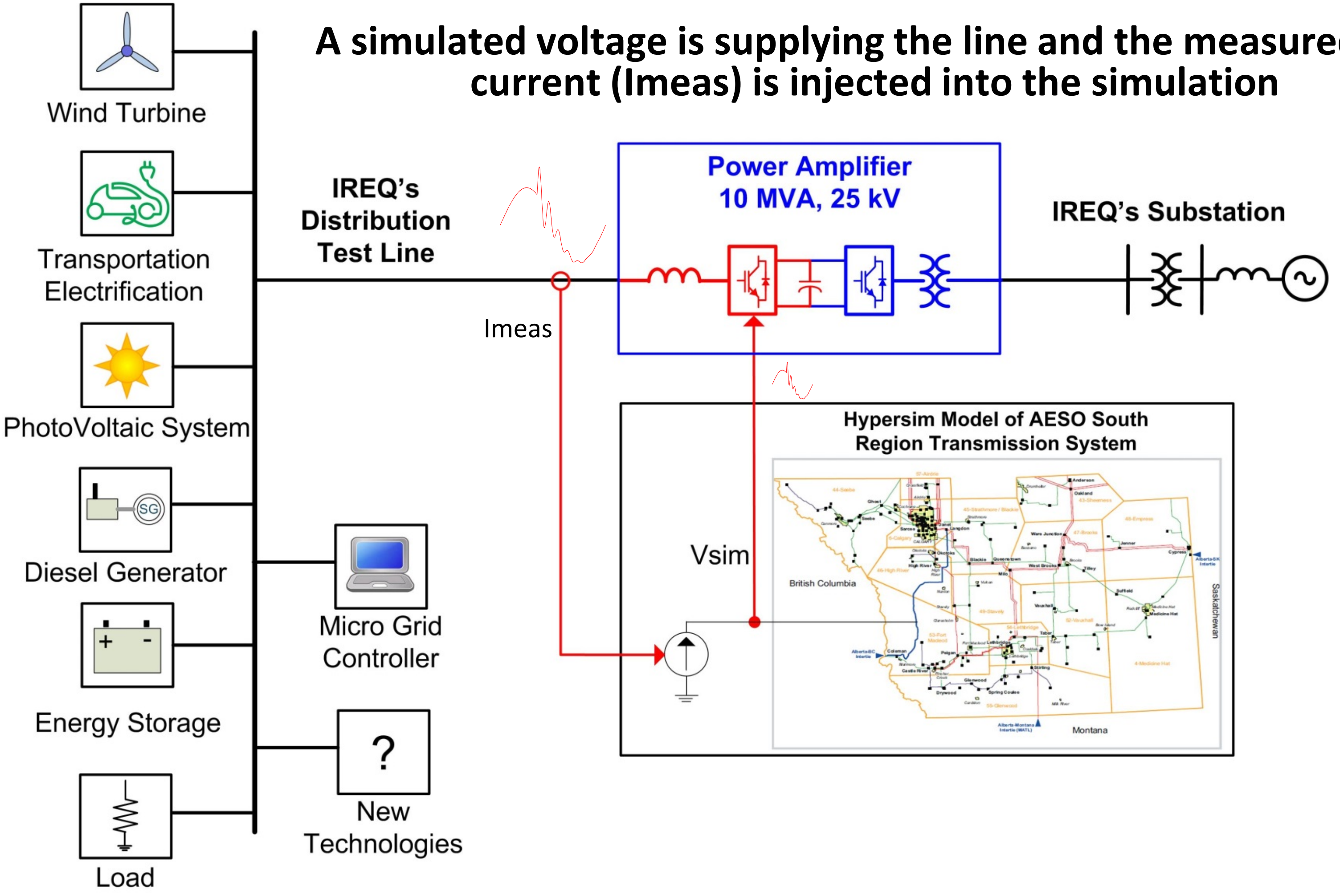




* AESO 2013 Long-term Transmission Plan
Filed January 2014
https://www.aeso.ca/grid/long-term-transmission-plan/

Concept of SimP

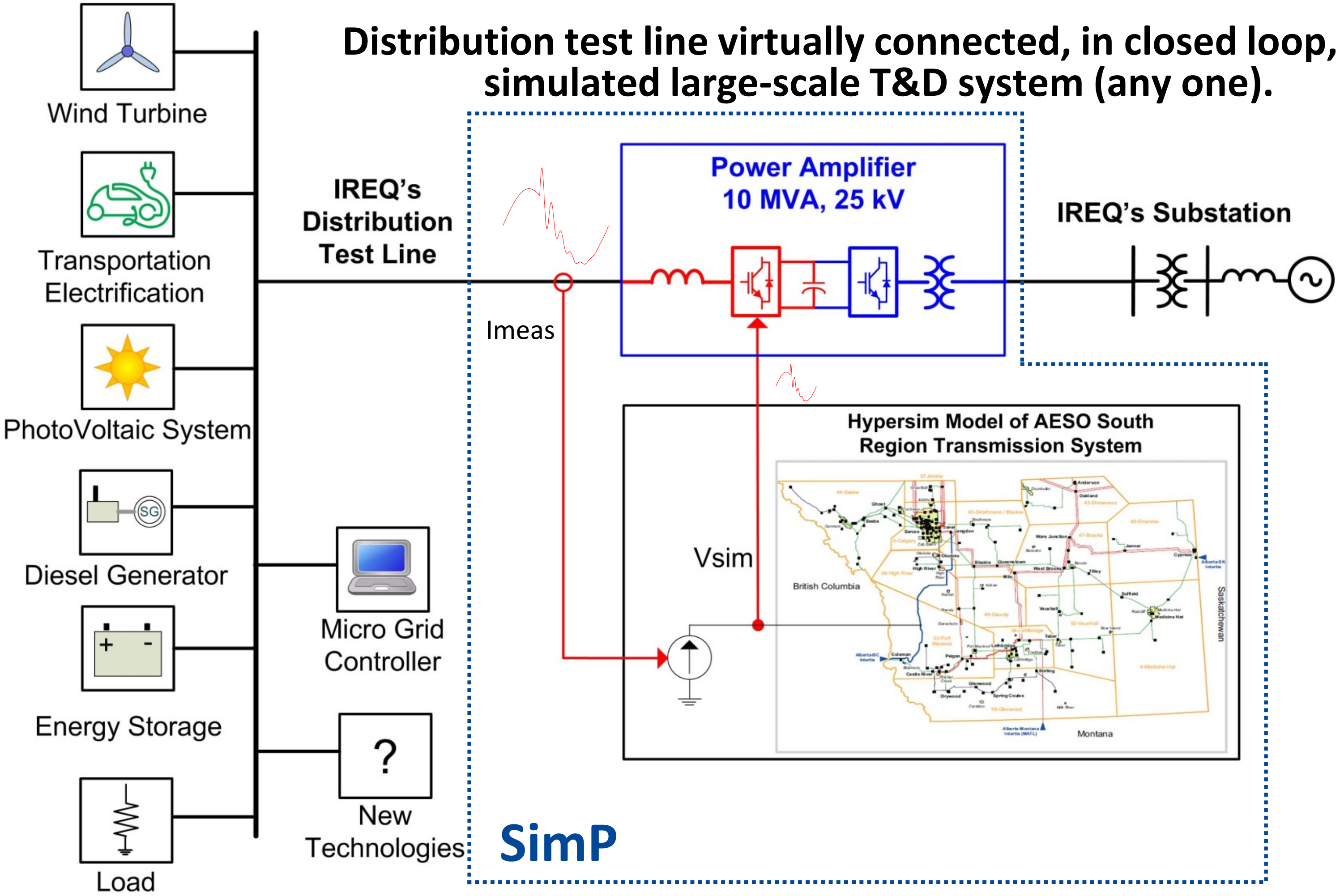
Closed Loop operation



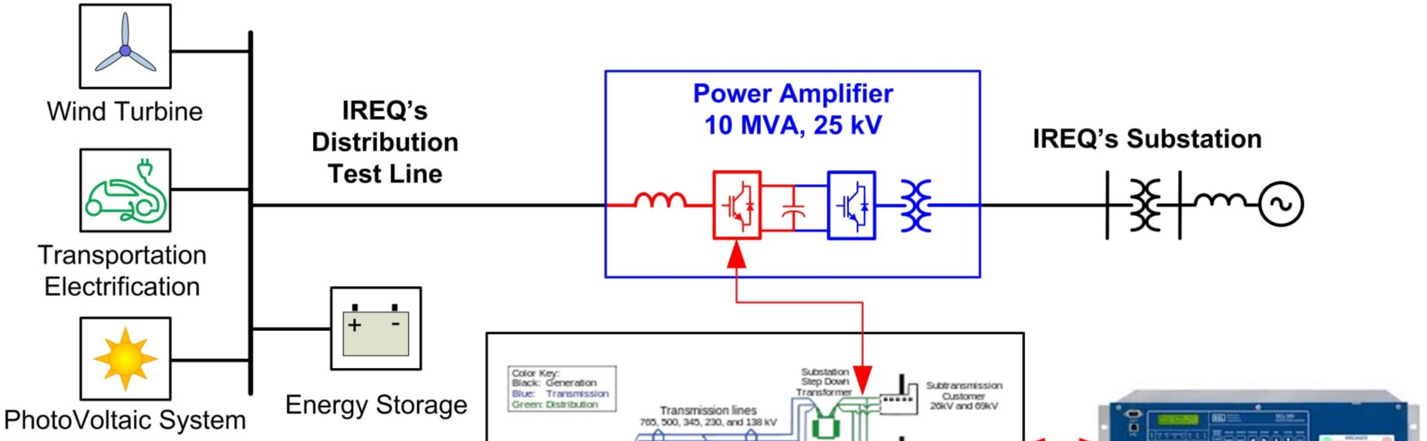
Concept of SimP

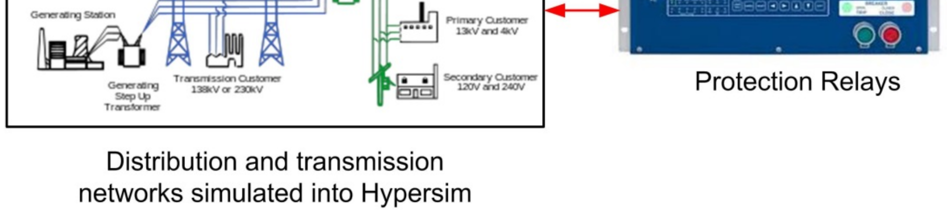
Closed Loop operation

Distribution test line virtually connected, in closed loop, to a simulated large-scale T&D system (any one).



Example: Development of the network of the future
Transmission & Distribution





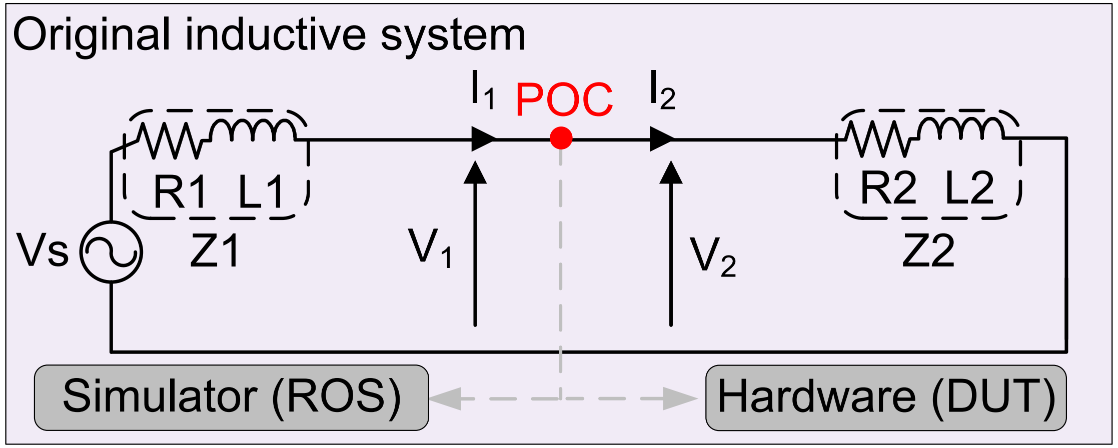
- Full-sized, realistic and flexible controlled environment
- Pre-deployment technology development: reliability and cost savings
- Power system protection studies
- Power quality studies
- New operating mode studies
- Simulation model validation

- Development of microgrid
- Development of remote off-grid power systems
- Ancillary services: voltage regulation & frequency control
- LVRT, HVRT
- Geomagnetically induced currents (GIC) studies
- Phase balancing

Stability Analysis of PHIL

Stability issues in PHIL system

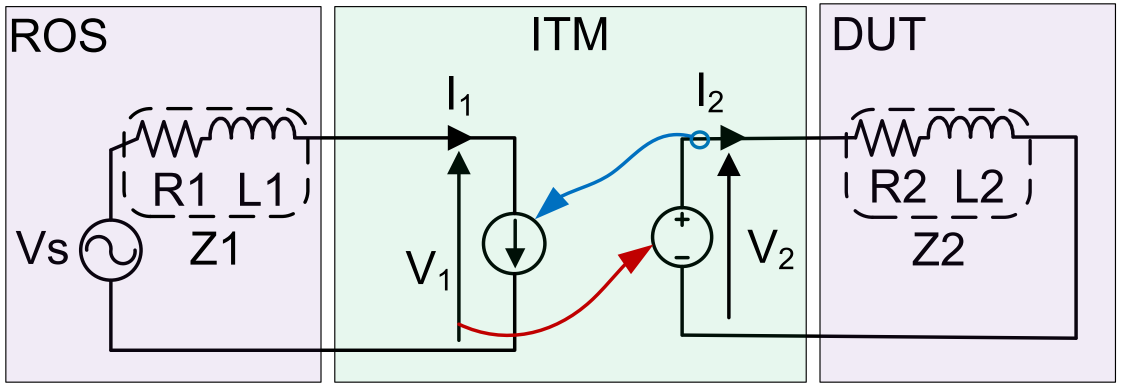
Problem definition



Stable system

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

- **Power amplifier is a voltage source**
- **DUT current is injected in the simulator**



Stable system if $|Z1| < |Z2|$

New method for assessing PHIL-system stability

Hybrid system representation

In fact, it is required to take into account the hybrid (continuous – discrete) nature of the system

- For the long story, we have developed a new method [1] for assessing the stability of a PHIL system. The detailed explanation can be found here:

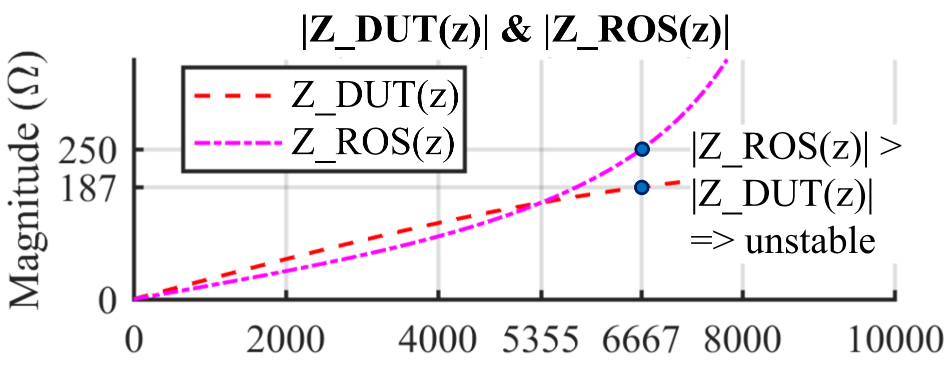
  [1] Tremblay, O., Fortin-Blanchette, H., Gagnon, R., Brissette, Y. : 'A Contribution to Stability Analysis of Power Hardware-In-the-Loop Simulators', IET Generation, Transmission & Distribution (ACCEPTED MANUSCRIPT)

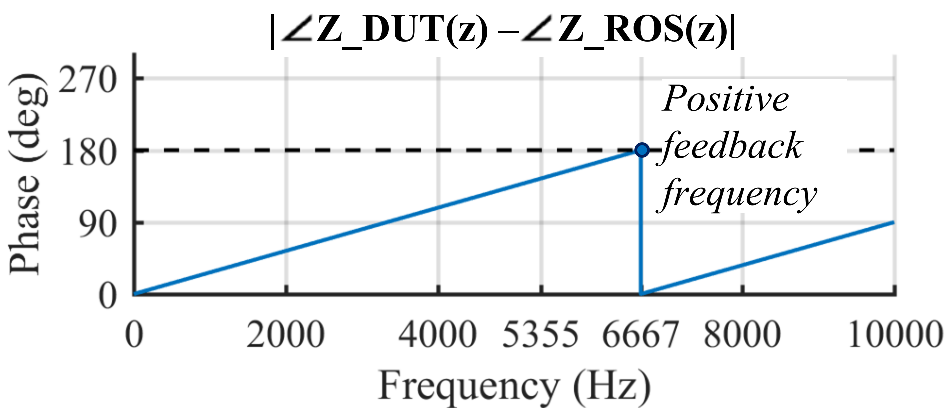
- For the short story, it is an impedance ratio issue:
  - The simulator increases the impedance magnitude at the POC
  - The sampling-and-hold of the DUT decreases the impedance magnitude at the POC and adds a phase-shift due to the delay

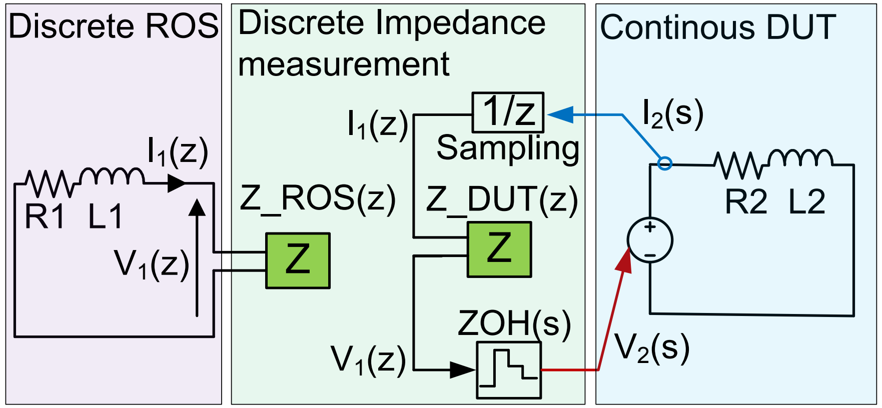
New method for assessing PHIL-system stability

Frequency response stability criteria

|Z1| = 0.67|Z2|:
Unstable simulation results







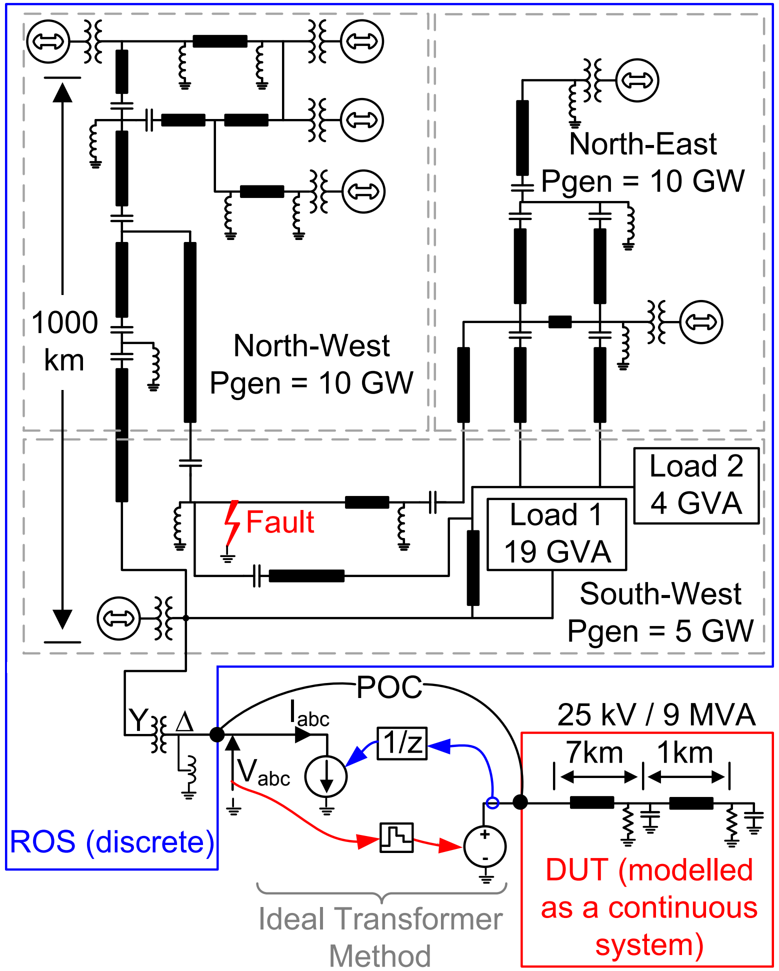
Closed-loop system stable if:

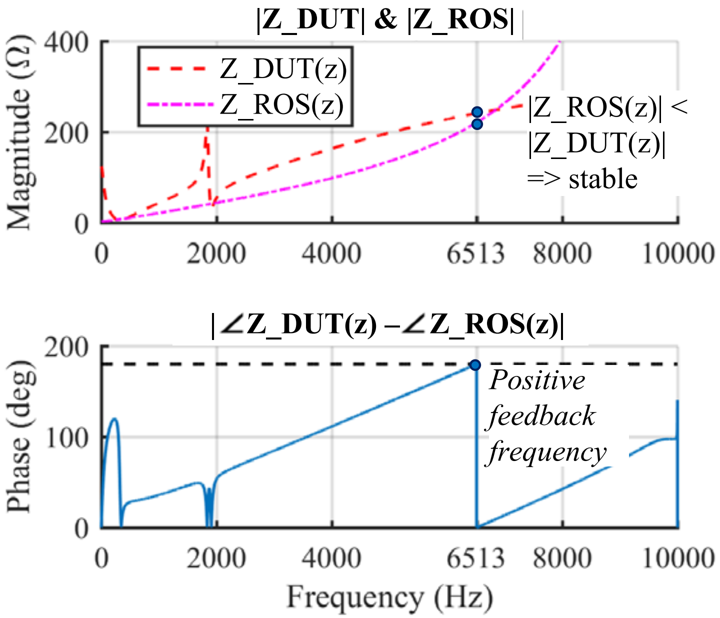
$$|Z\_ROS(z)| < |Z\_DUT(z)|$$

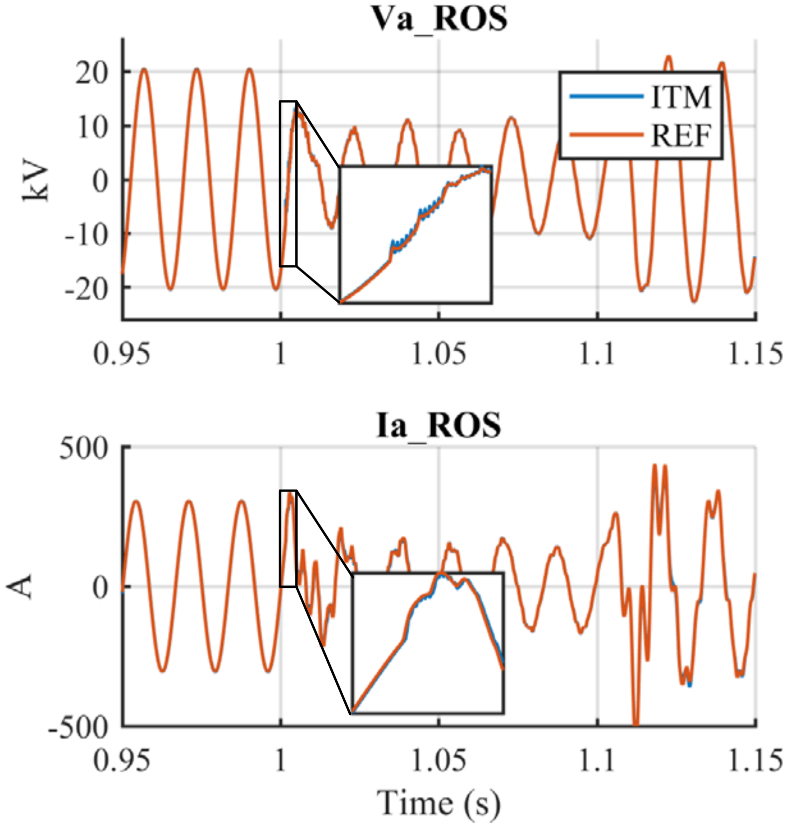
$$\text{when } \angle Z\_ROS(z) - \angle Z\_DUT(z) = 180°$$

New method for assessing PHIL-system stability

Simulation results for a large-scale PHIL system





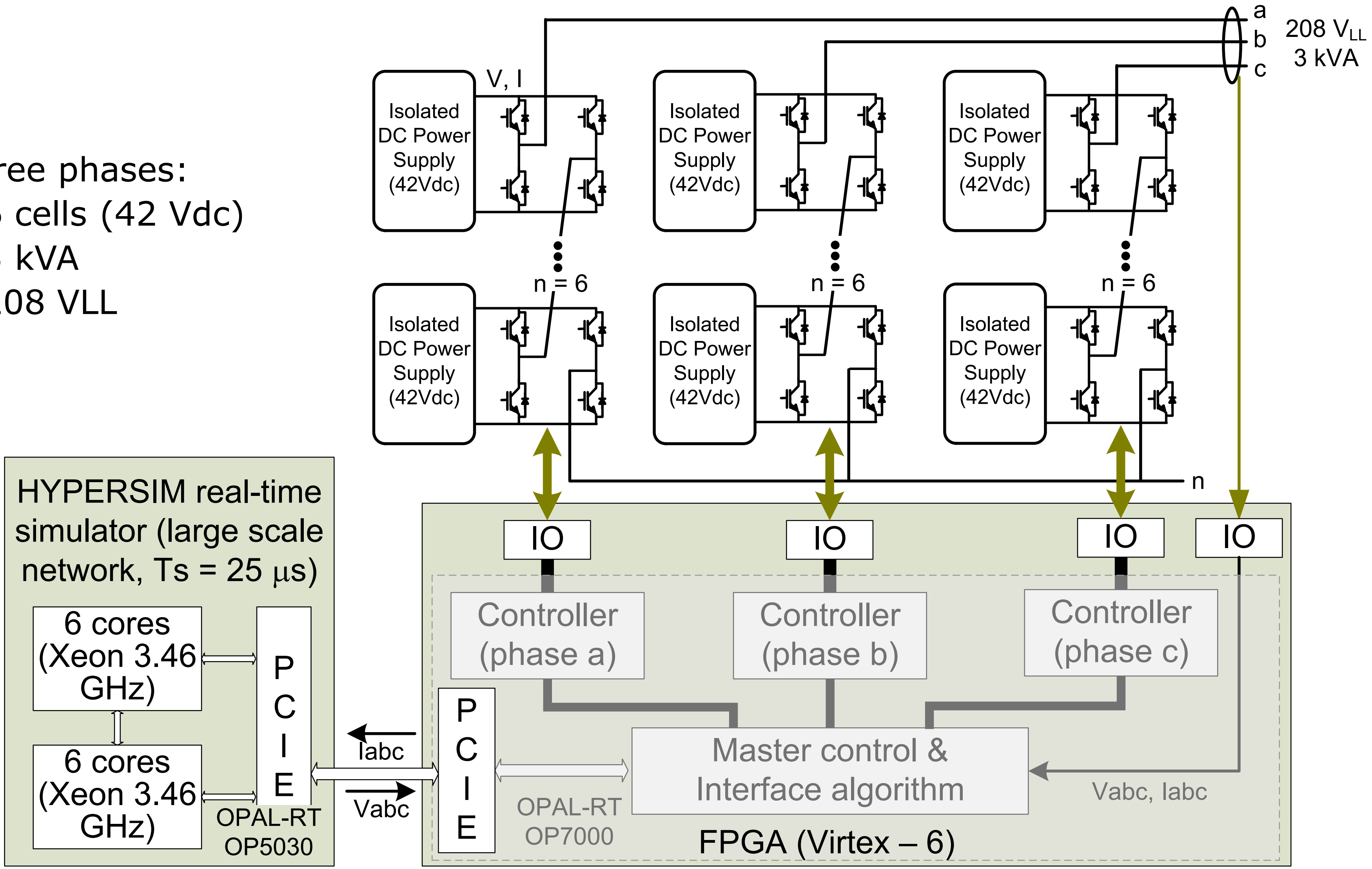


Prototype of the power amplifier

Prototype of the power amplifier

Reduced-scale system

Three phases:
- 6 cells (42 Vdc)
- 3 kVA
- 208 VLL



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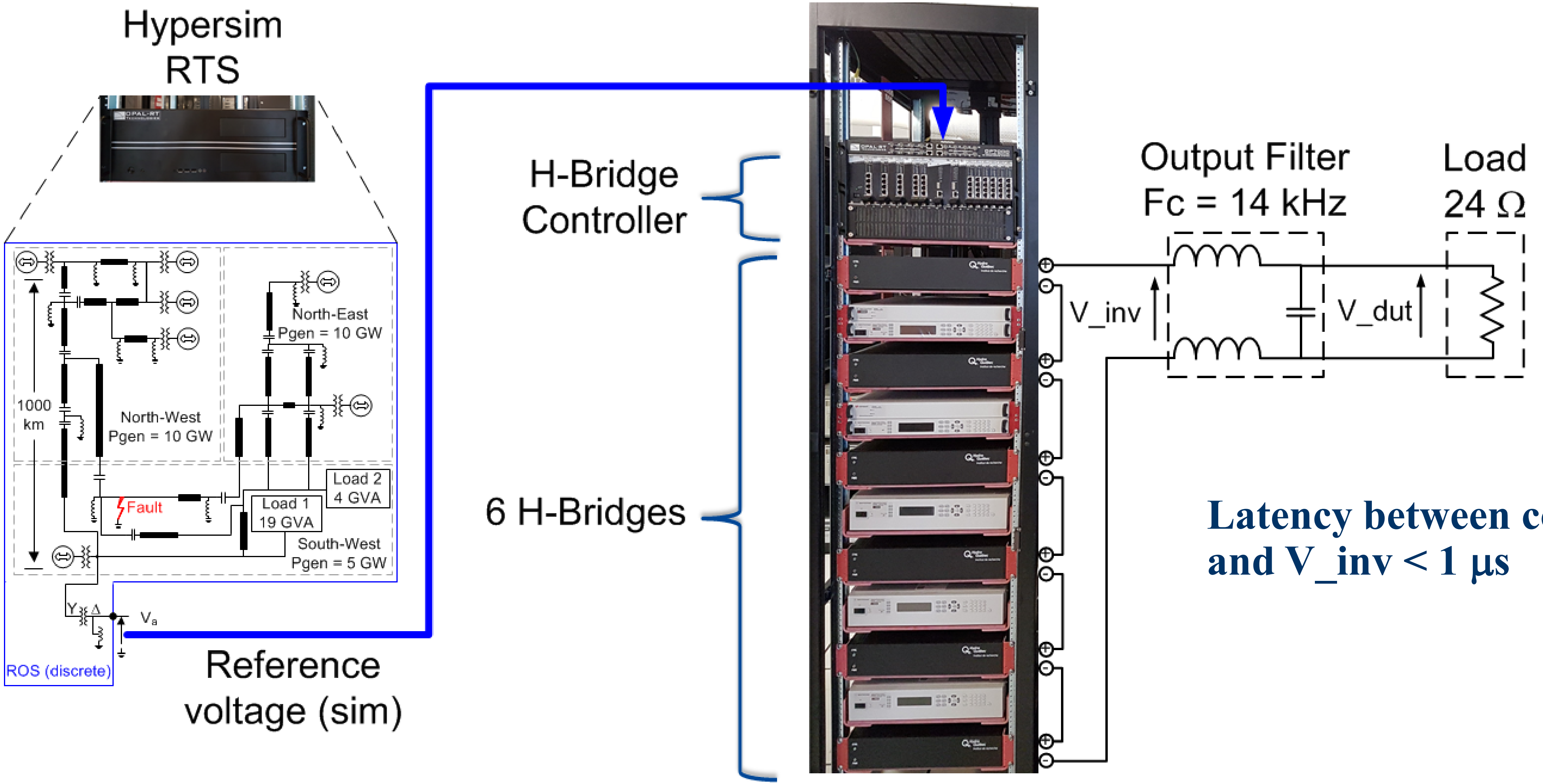
Prototype of the power amplifier

The 1st version (1 phase)



Latency between controller and V_inv < 1 µs

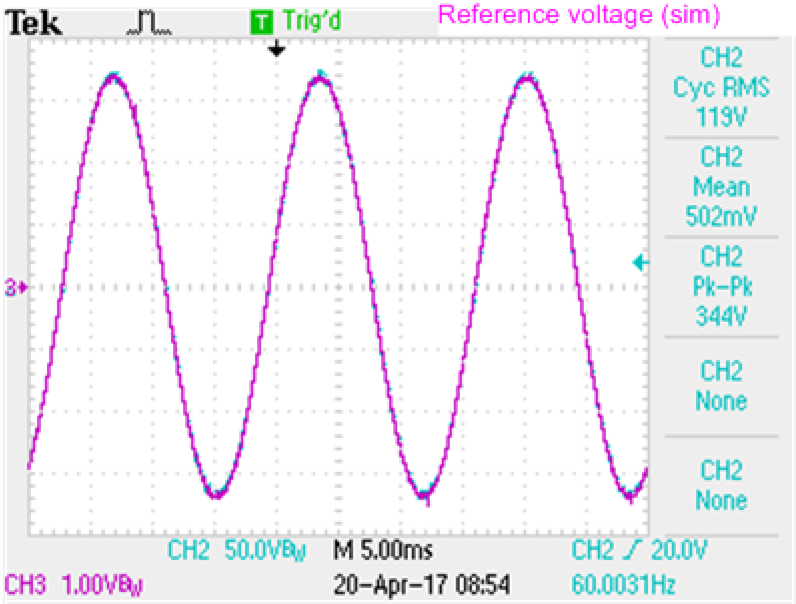
Prototype of the power amplifier

Open-Loop experimental results

Pure 120V- 60 Hz Sine Wave

Load voltage (DUT)

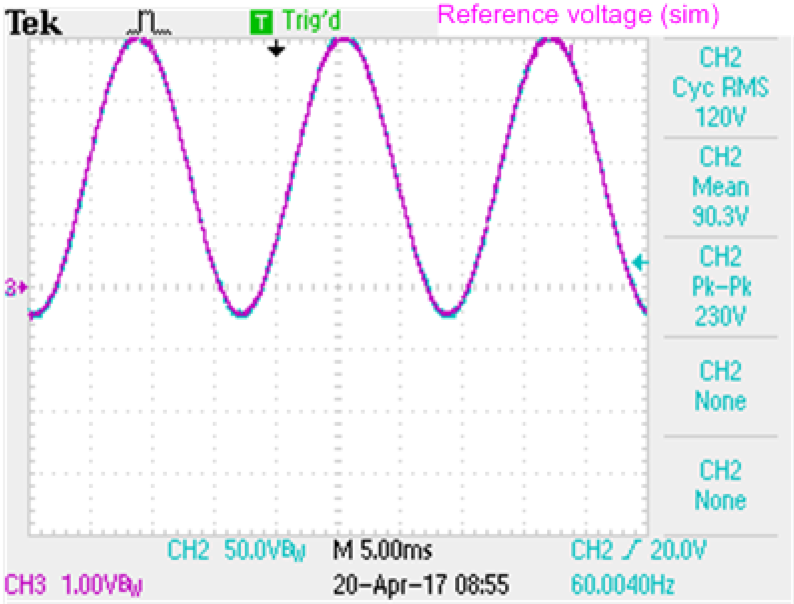
Reference voltage (sim)



120V- 60 Hz Sine Wave + DC

Load voltage (DUT)

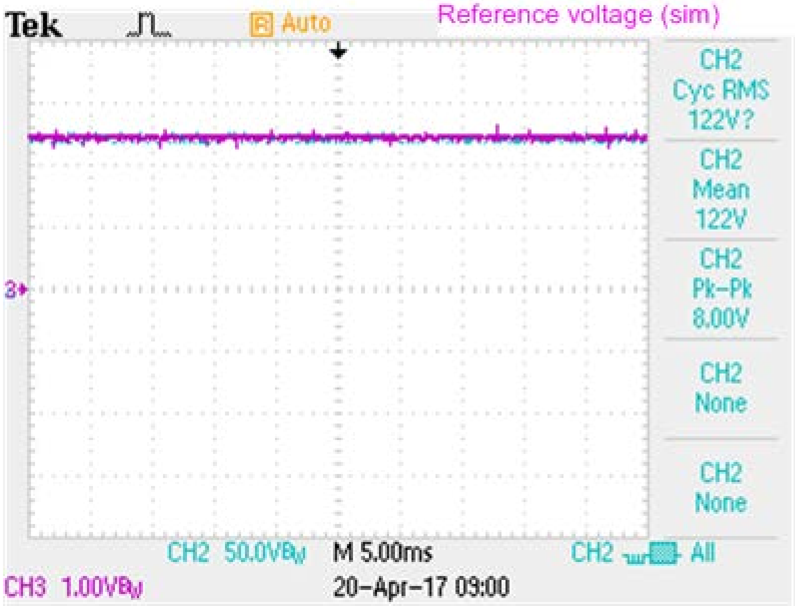
Reference voltage (sim)



120VDC

Load voltage (DUT)

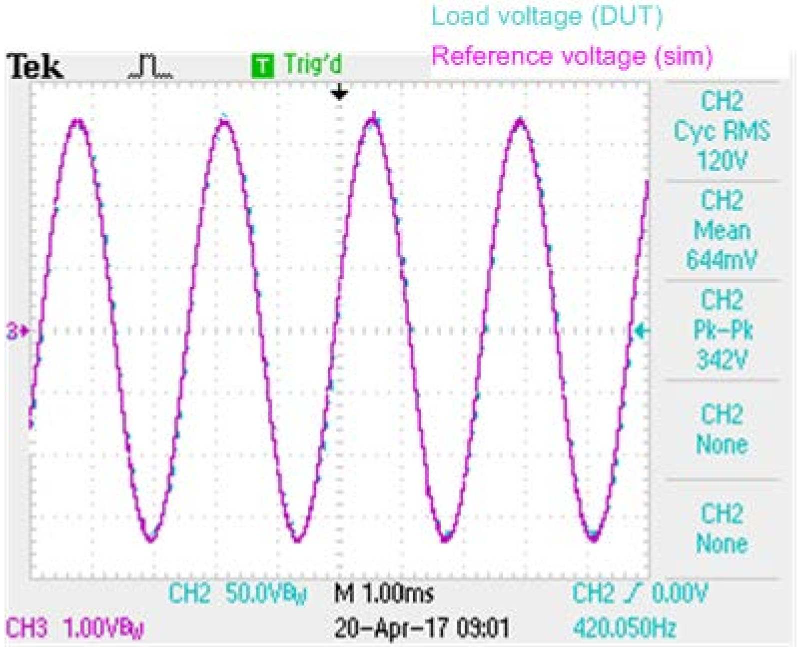
Reference voltage (sim)



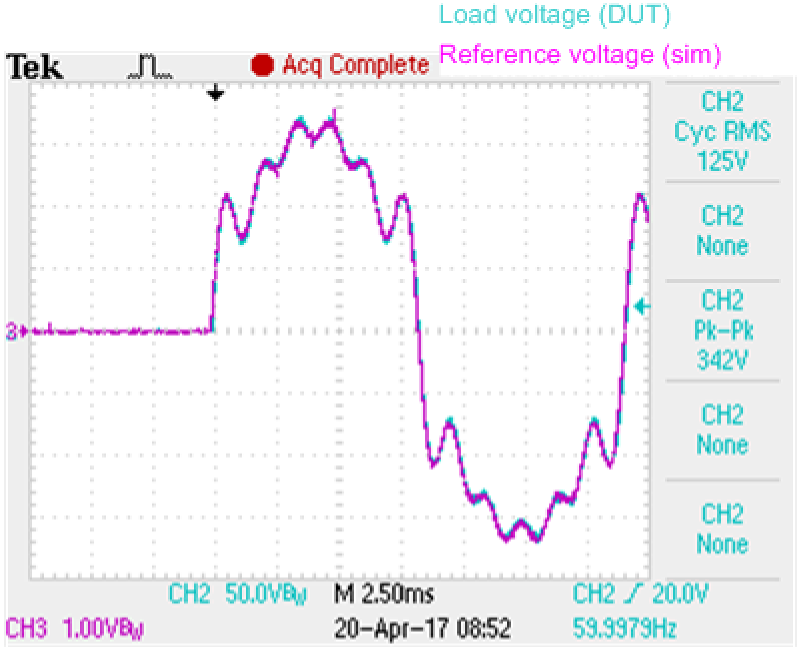
Prototype of the power amplifier

Open-Loop experimental results

Pure 120V- 420 Hz Sine Wave



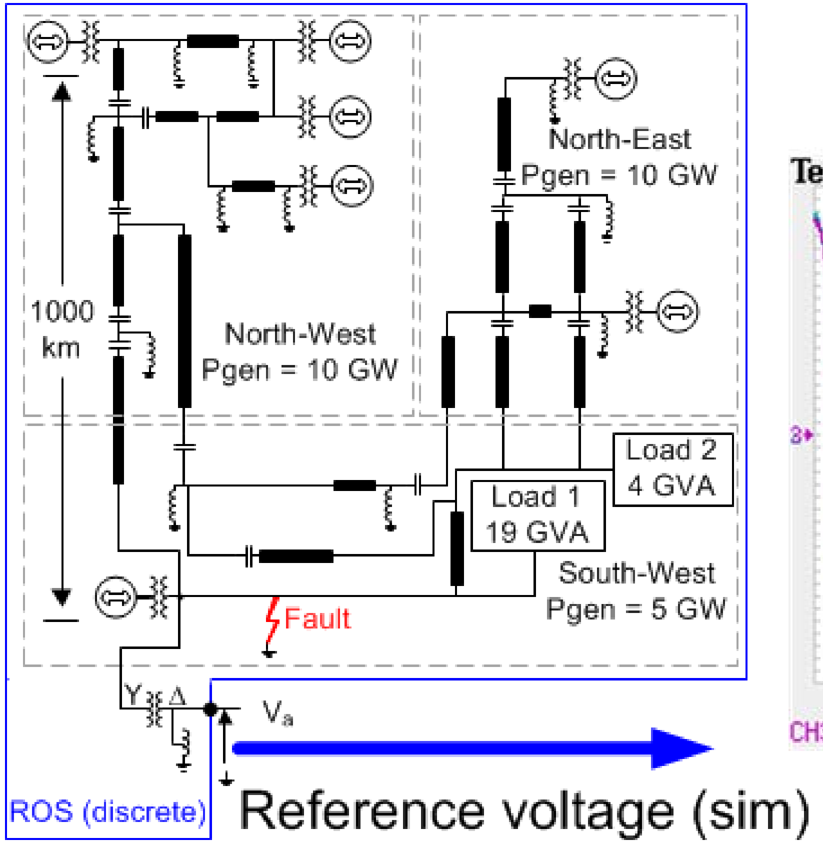
Fault + Harmonics (3,5,7,9,11)



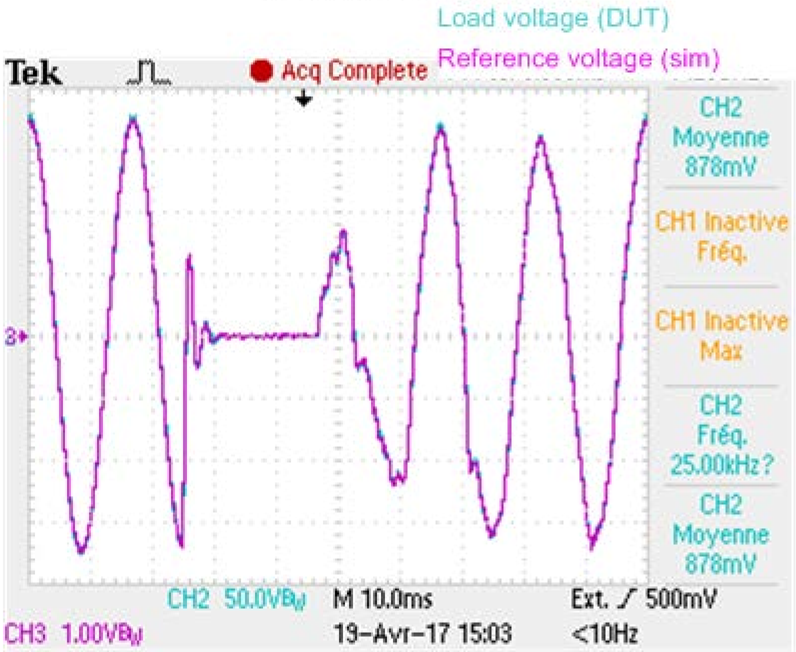
Prototype of the power amplifier

Open-Loop experimental results

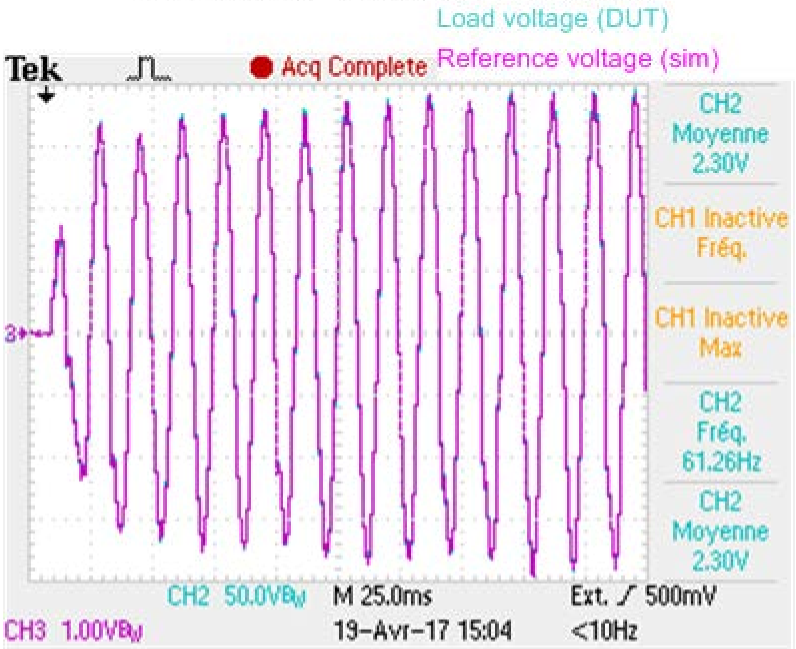
Simulation results for a large-scale EMT PHIL system



10 mSec fault

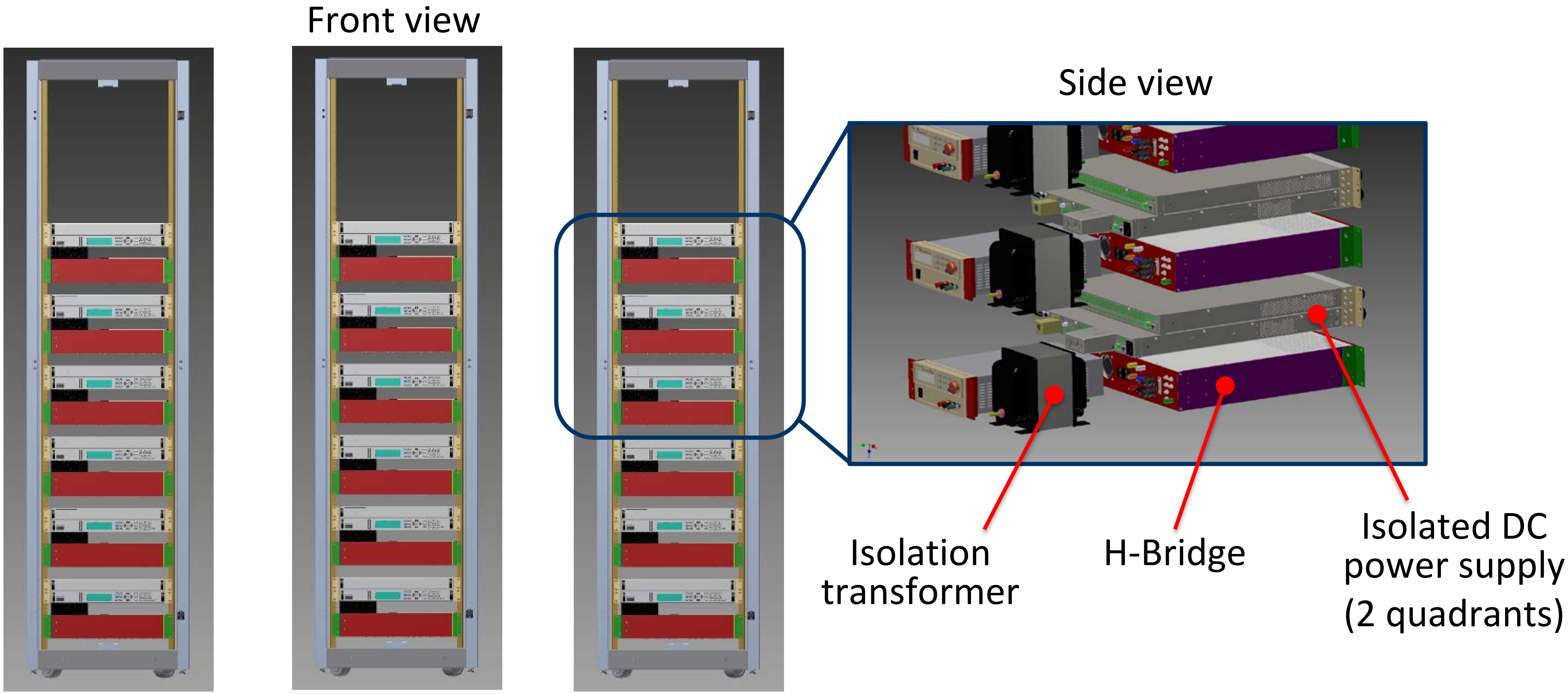


10 mSec fault (post fault)



Prototype of the power amplifier

Next step: 3-phase system



Power Simulator

Next steps

- Development of numerical interface between simulator and power amplifier in order to close the loop stably and precisely
- Real-time simulation of the power amplifier to validate the controller and interface method
- Design and realization of the 10-MVA amplifier
- Secure the financing of the project:
  - Internal (business case)
  - Federal government
  - Partnership
  - ….

Conclusion

Power Simulator

Strategic research & testing infrastructure :
Development and validation of the technologies for the power systems of the future

- Reliability of the integration of new renewable energy sources
- Development and optimization of the smart grid and microgrids: storage, V2G, etc.
- Expertise: modeling / simulation (PHIL), equipment, testing
- Partnerships
- IREQ, a showcase for new technology demonstration

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