Power Hardware-in-the-Loop

Closed-loop Test Benches, and Their Considerations, Solutions and Applications

Sebastian Hubschneider
R&D Engineer at
OPAL-RT TECHNOLOGIES

POWER ELECTRONICS

Power Electronics & Energy Storage event

27 juni 2023 | 1931 Congrescentrum ‘s-Hertogenbosch

ENERGY STORAGE

WHO WE ARE & WHAT WE DO

Established in 1997
Montréal, Canada

400+ employees
worldwide

20 - 30 % of revenue
reinvested in R&D

- Developing real-time digital simulators based on **PC and FPGA** topologies, for **Control Prototyping** and **(Power) Hardware-in-the-Loop**
- Offering scalable hardware solutions, from compact **portable devices** to large **integrated HIL test benches**
- Providing **high-fidelity**, **fast**, and **accurate** simulation models and solvers

Pictures: OPAL-RT TECHNOLOGIES.

TT&MS
total test and measurement support

OPAL-RT TECHNOLOGIES

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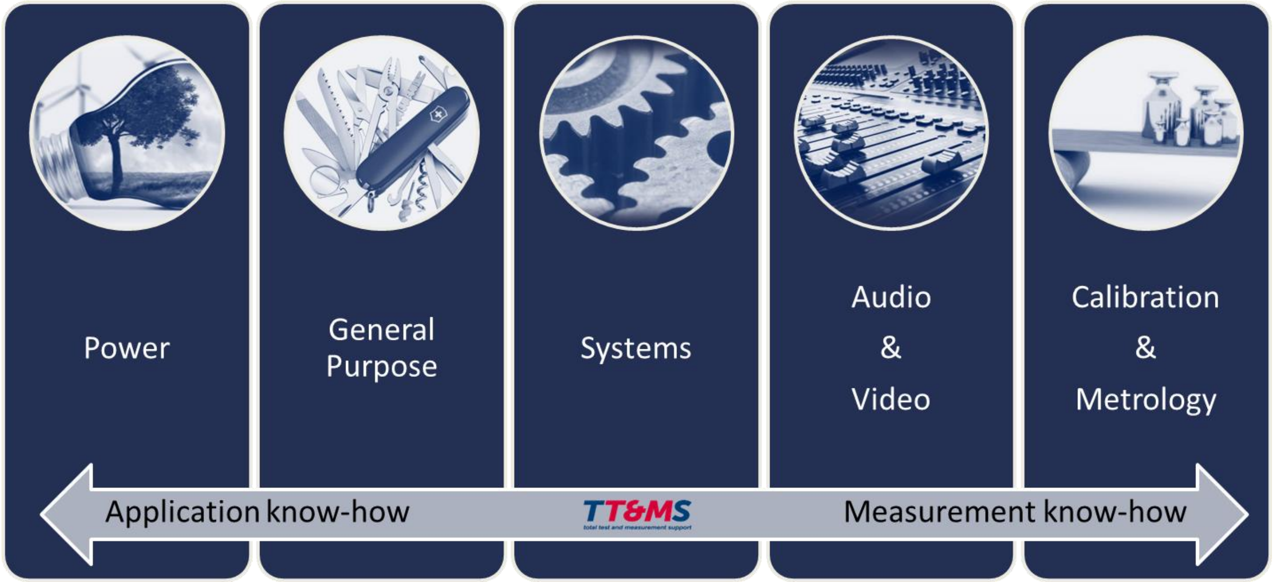
SIEMENS
Valeo
VOLVO
MR
REN Redes Energéticas Nacionais
KTH
Enel
HITACHI
ROLLS ROYCE
Aalborg University Denmark
Hydro Québec
Politecnico di Torino
KEYSIGHT TECHNOLOGIES
Schneider Electric
UCD Dublin
KIT Karlsruhe Institute of Technology
GE Energy
Rte Réseau de transport d'électricité
L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille
JRC European Commission
Imperial College London
The University of Nottingham UNITED KINGDOM · CHINA · MALAYSIA
国家电网 State Grid 中国电力科学研究院 China Electric Power Research Institute
eDF
EPFL École Polytechnique Fédérale de Lausanne
Fraunhofer
ALSTOM
ABB

TT&MS total test and measurement support

OPAL-RT TECHNOLOGIES

Pictures: OPAL-RT TECHNOLOGIES.

ON BEHALF OF TT&MS

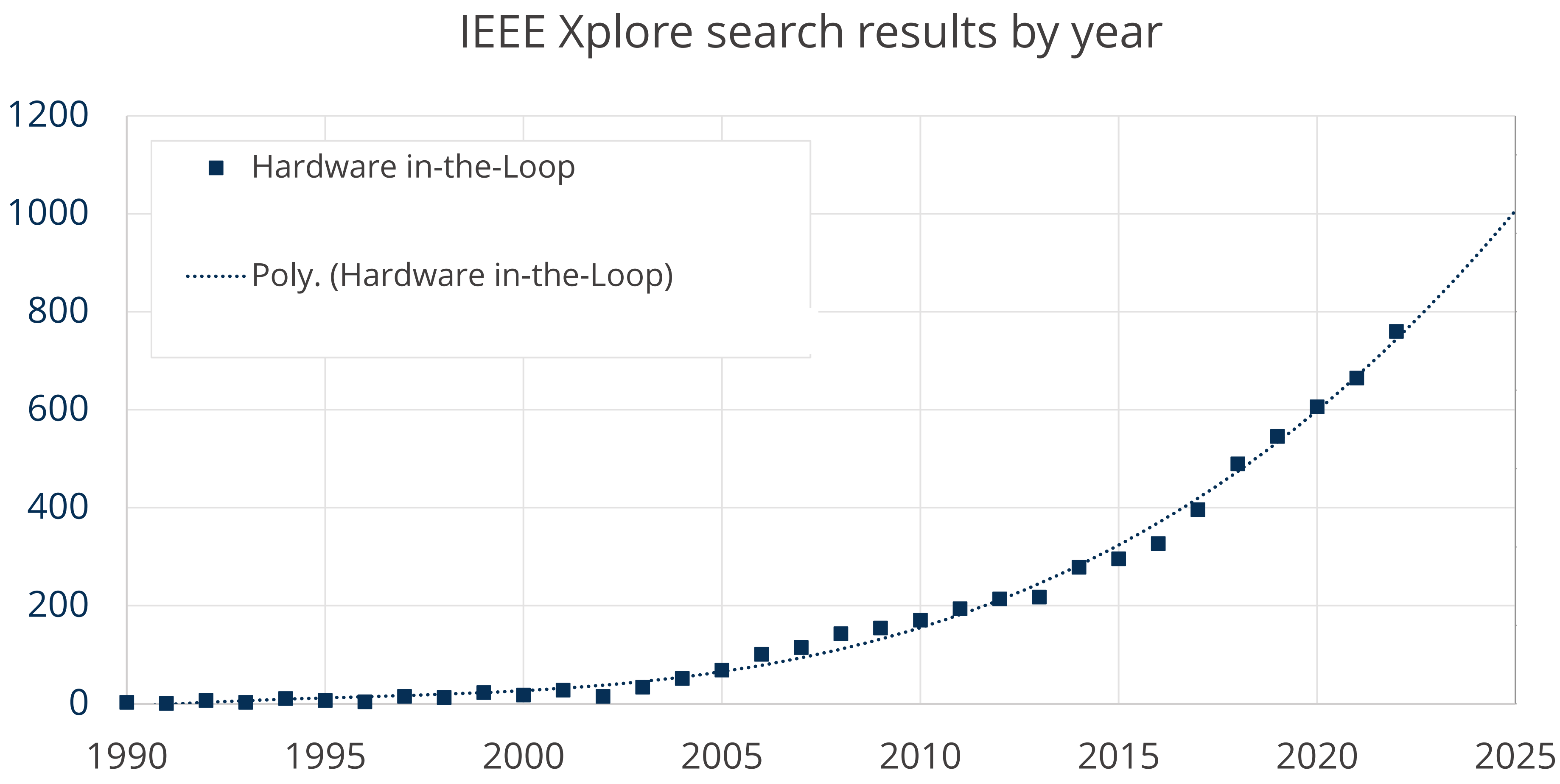


TT&MS

T&M Consulting	Training	In-House Repair Service	Rental	Extensive Network	Flexibele Purchasing

- Founded in 2003
- Largest product portfolio of power related instrumentation
- Supplier of high quality test and measurement equipment

(POWER) HARDWARE-IN-THE-LOOP



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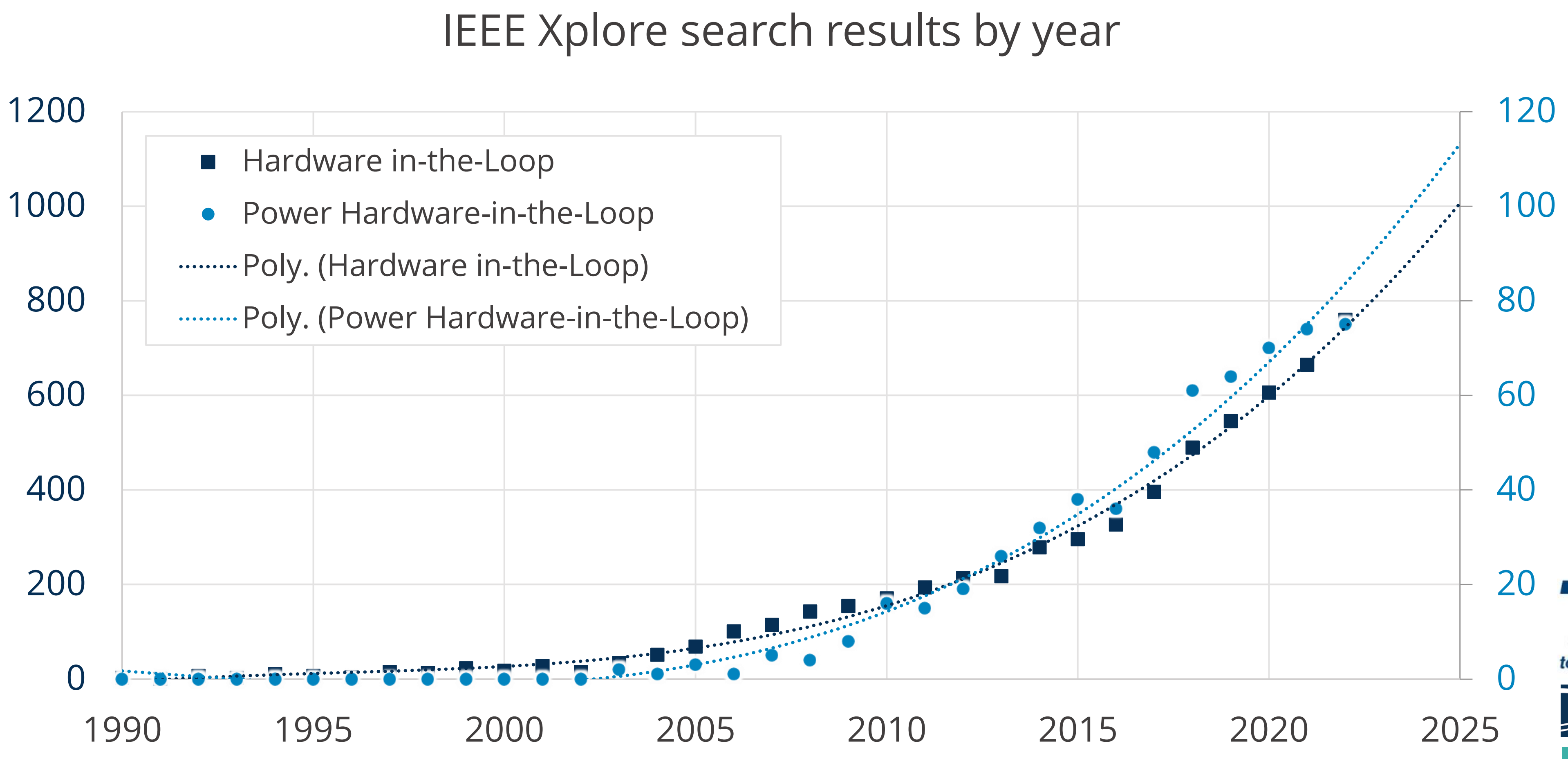


AGENDA

- Power Hardware-in-the-Loop (PHIL)
- Setting Up a PHIL Environment
- Interface Algorithms – a Comparison
- Exemplary Laboratory Applications
- Conclusions – PHIL Now and in Future

IN-THE-LOOP SYSTEMS

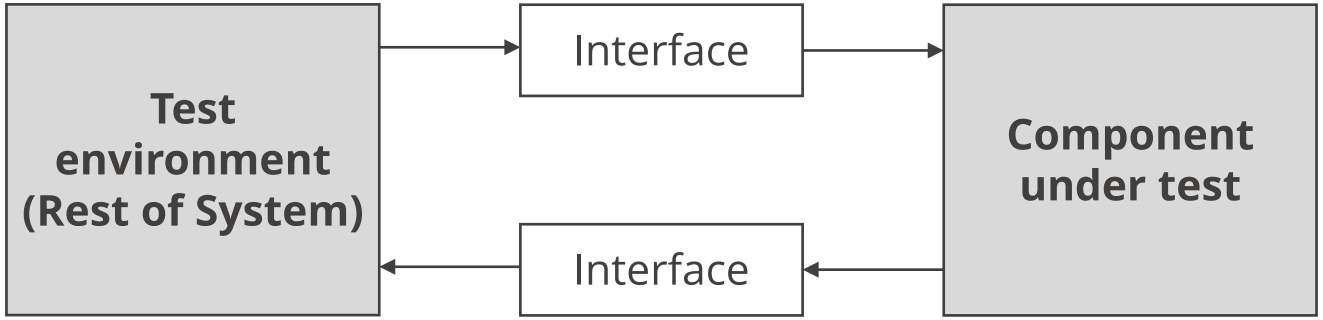
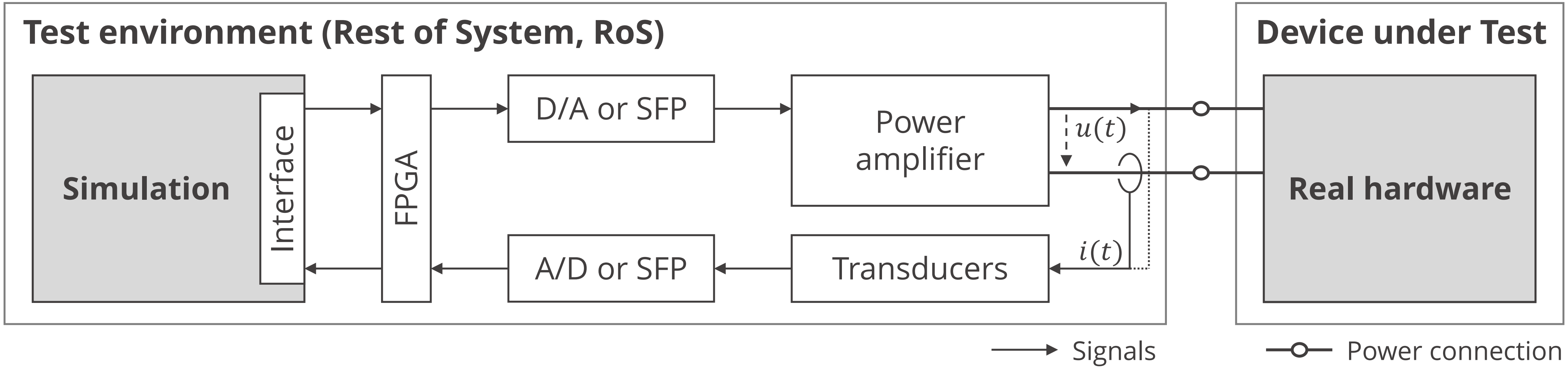


Figure: adapted from [1, 2]. Table: adapted from [1].

POWER HARDWARE-IN-THE-LOOP SYSTEMS



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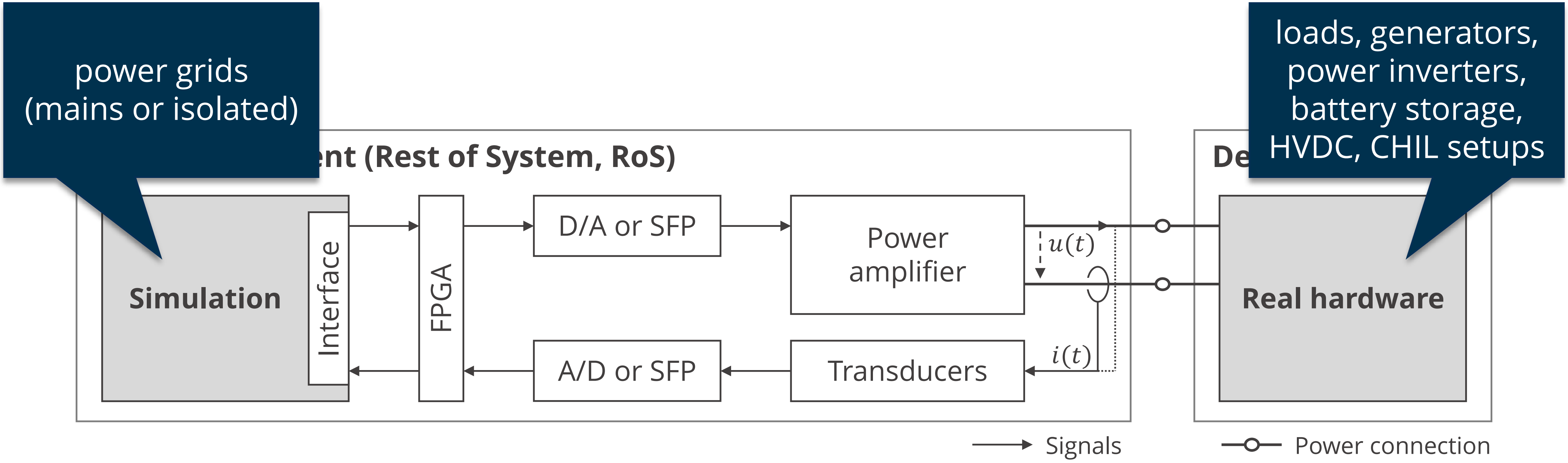

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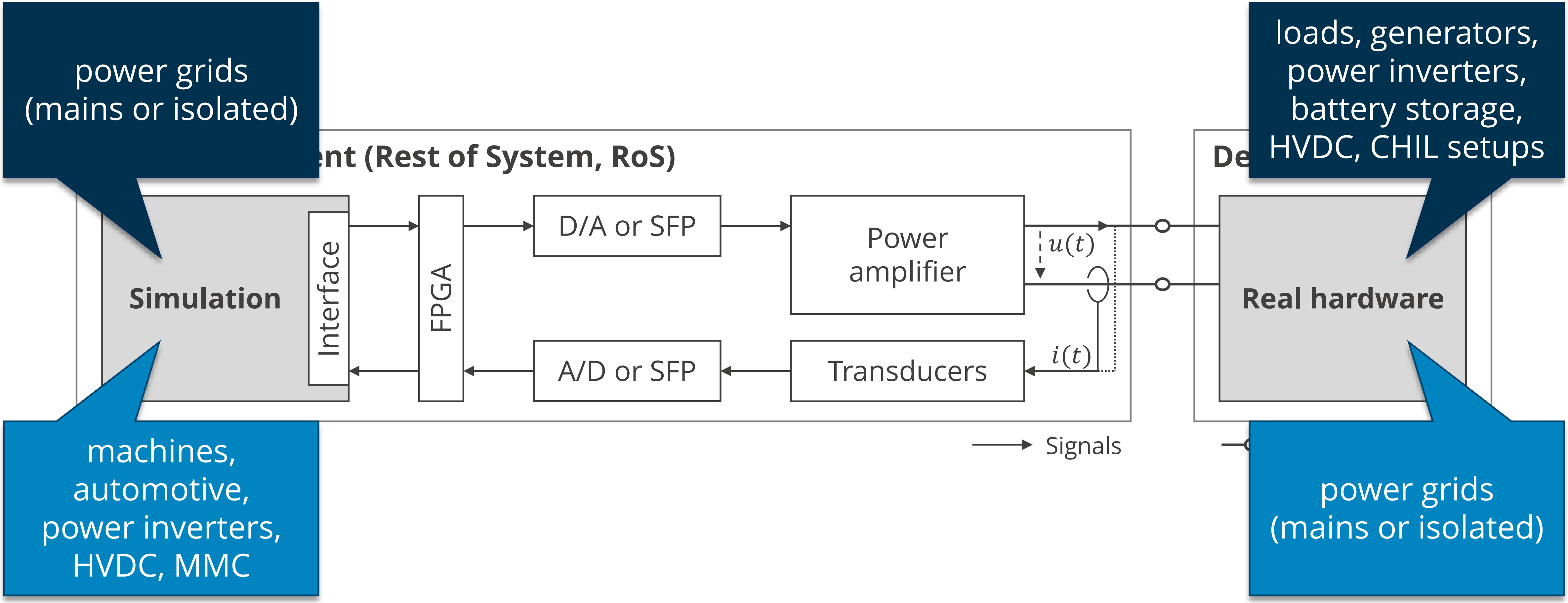

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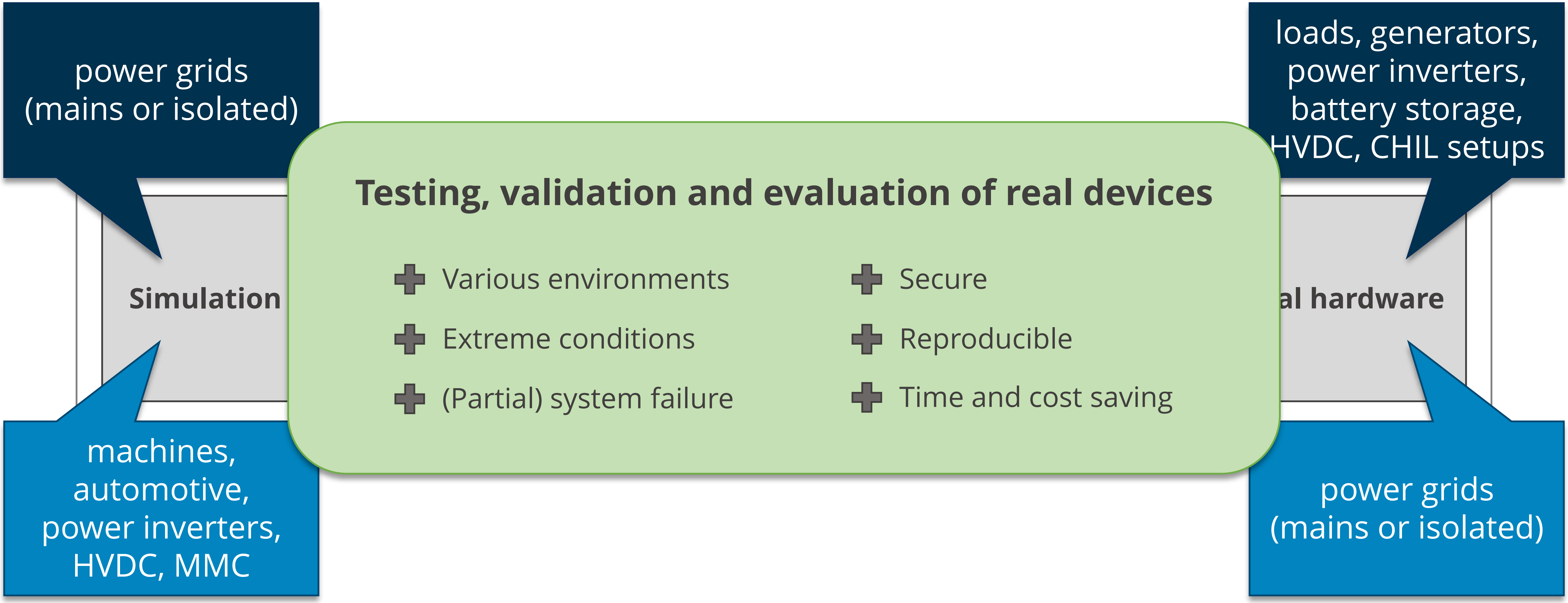
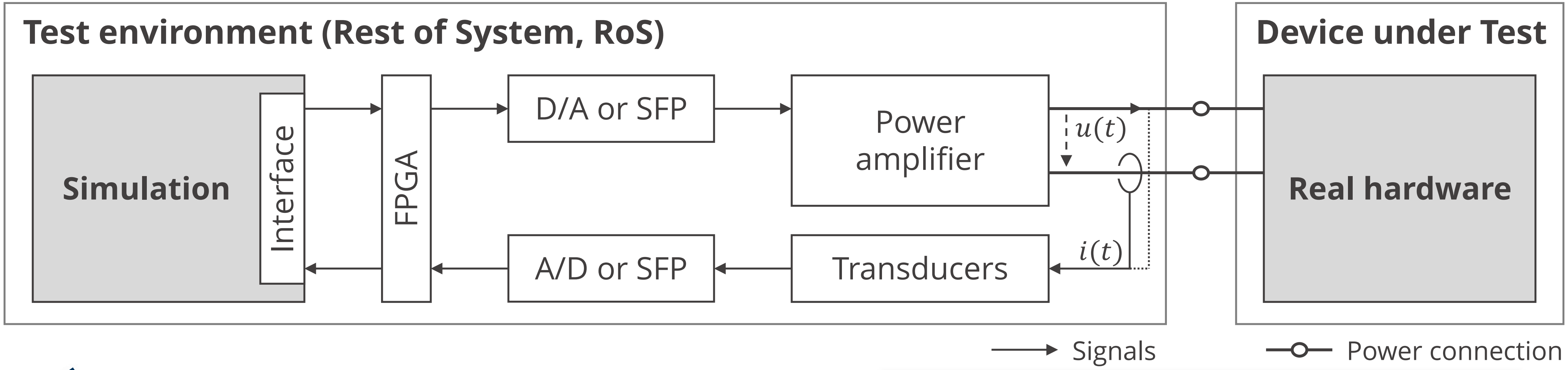


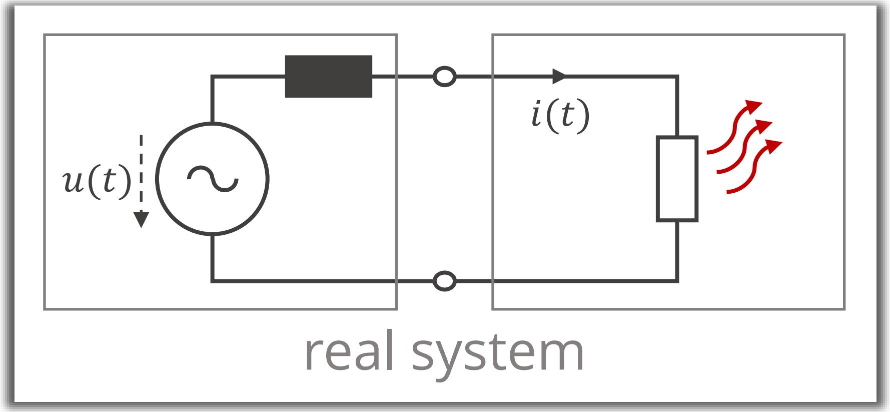
Figure: adapted from [1, 2]. Table: adapted from [1].

POWER HARDWARE-IN-THE-LOOP SYSTEMS

- Optimal PHIL system requirements



- Cover all relevant system dynamics
- Detailed models of all components
- Stable (quasi-continuous) test environment



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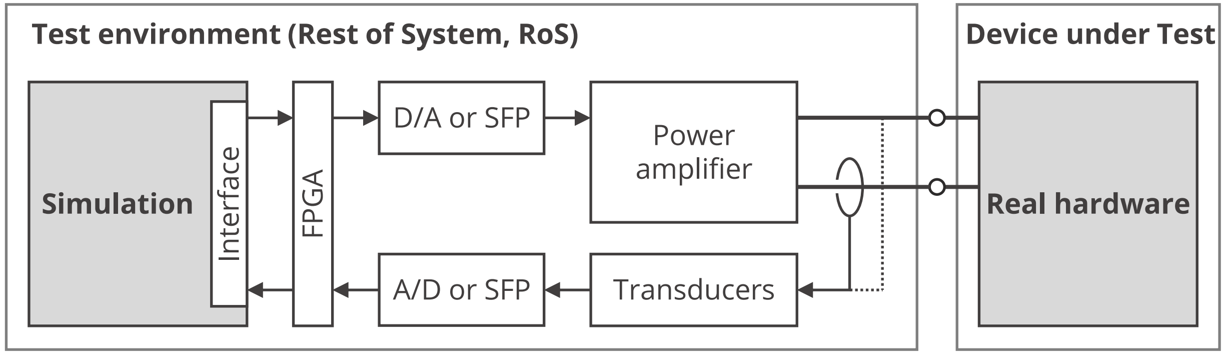


- Cover all relevant system **dynamics**
- Detailed **models** of all components
- **Stable** (quasi-continuous) test environment

- Realistic PHIL system conflict

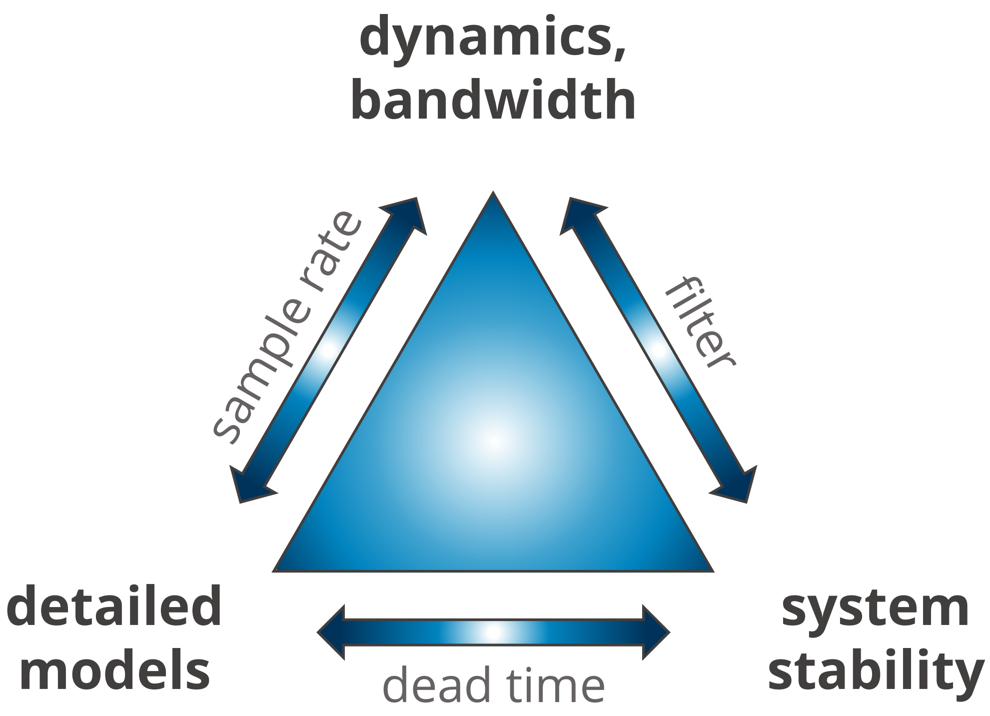
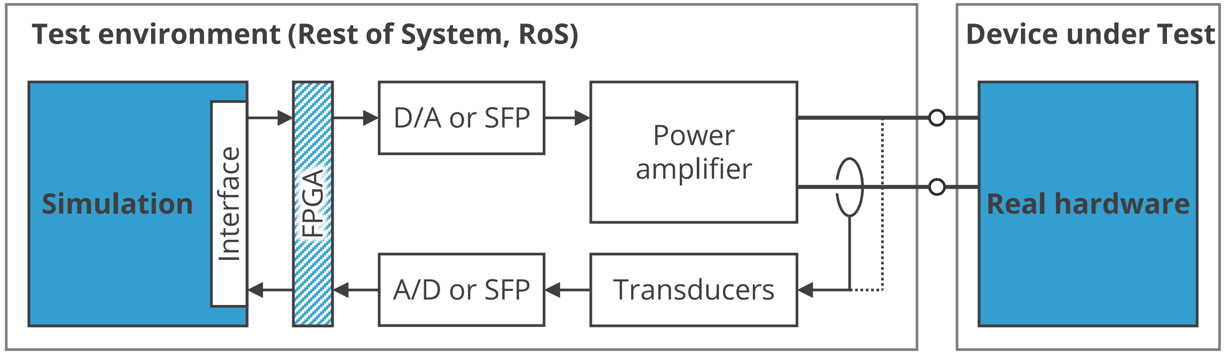


Figure left: adapted from [1, 2]. Figure right: adapted from [1].

SETTING UP A PHIL ENVIRONMENT

- 1st: Define use cases and requirements



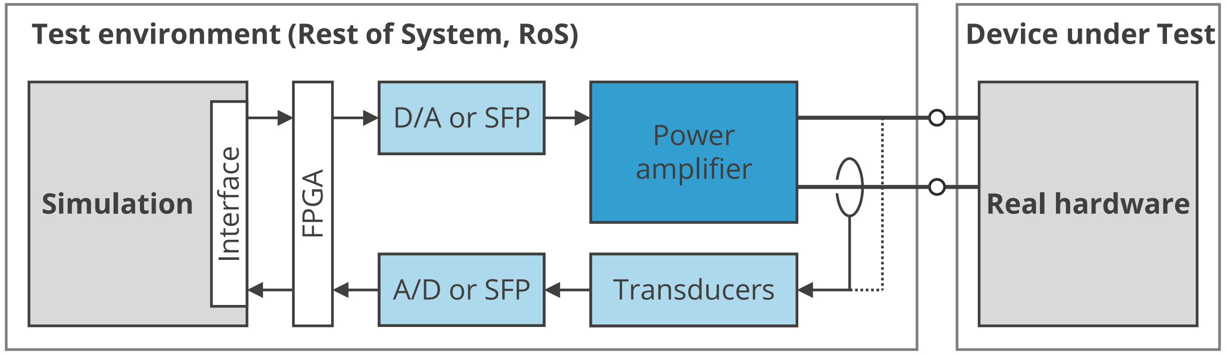
- What to consider?
  - Scope of PHIL experiments (type of DuT)
  - Challenges/incidents/events of interest
  - Given characteristics of the Device under Test
  - Required characteristics of the simulation environment, required level of detail

	Open loop	Closed loop
Grid	Interconnected Strong, high inertia	Islanded Weak, low inertia
Phasor co-simulation	Secondary reserve Tertiary reserve	Grid optimization Voltage support
Static	Under-/overvoltages Droop control $P(f)$	Phase balancing $Q(U)$, $\cos\varphi\,(P)$
Dynamic	Fault ride through Mains signaling	Harmonics Grid stability
Transient	Transients, e. g. LI/SI Cond. disturbances	Active fault clearance Transient stability

Figure: adapted from [1, 2]. Table: adapted from [2].

SETTING UP A PHIL ENVIRONMENT

- 2nd: Decide for a hardware interface



- What to consider?
  - Type of communication between RTS and PA (lab environment: physical distance, disturbances)
  - Amplifier bandwidth, dynamics and signal quality
  - Maximum time delay suitable for dynamic events
  - Required transducer bandwidth and acceptable noise

- Power amplifier
  - Crucial impact on bandwidth and dynamics
  - Typ. transfer function: $G_{\mathrm{PA}}(s) = \frac{1}{1+\alpha s+\beta s^2} \cdot e^{-sT_{\mathrm{PA}}}$
  - Fundamental decision required
    - Linear amplifier (class-A/B/AB)
    - Switching amplifier (class-D)

Figure: adapted from [1, 2].

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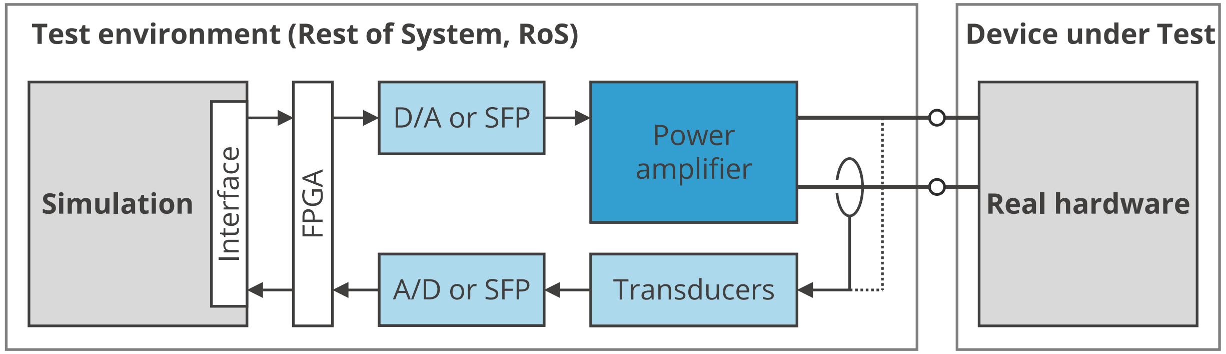

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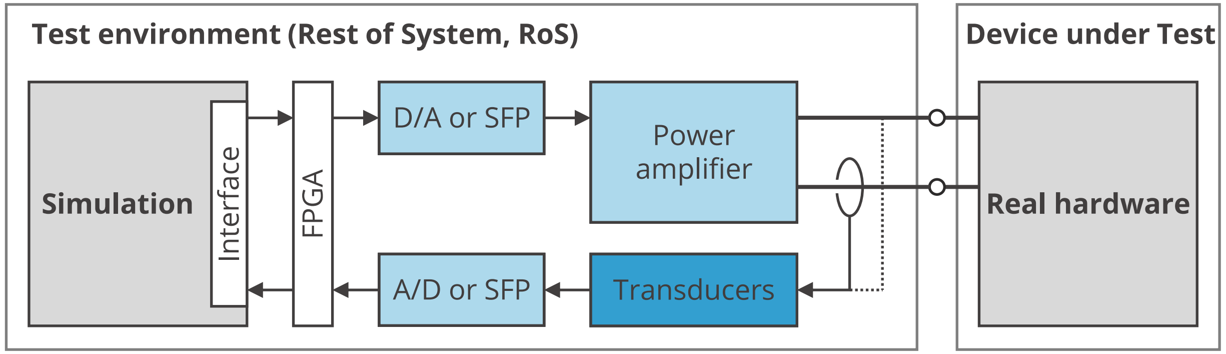
    - Linear amplifier (class-A/B/AB)
      - + signal quality
      - + bandwidth
      - + dynamics
      - + crest factor
    - Switching amplifier (class-D)
      - + 4-quadrant operation
      - + maximum system power
      - + feedback capability
      - + operating temperature
      - + efficiency
      - + weight, size

Figure: adapted from [1, 2]. Content basing on [1, 3, 4, 5].

SETTING UP A PHIL ENVIRONMENT

- 2nd: Decide for a hardware interface



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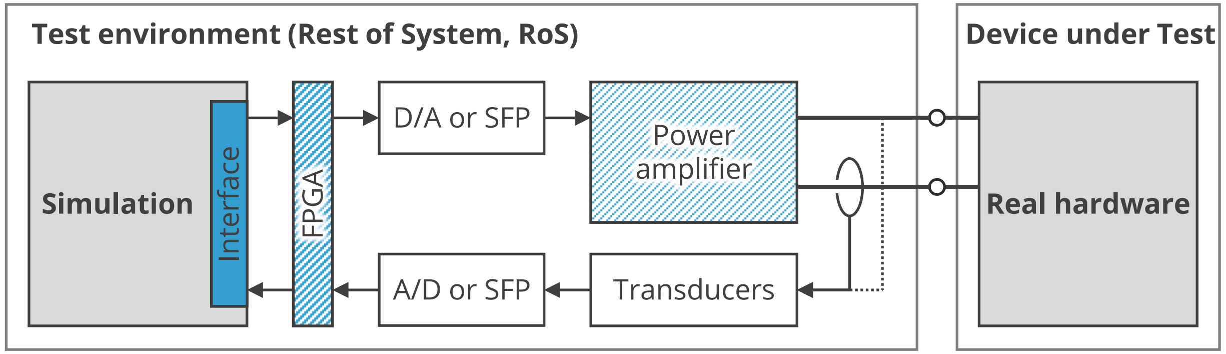
  - Fundamental decision required
    - Linear amplifier (class-A/B/AB)
    - Switching amplifier (class-D)
- Current/voltage transducers
  - Typically sufficient bandwidth and dynamics
  - Noise and error can have a crucial impact
  - High signal-to-noise ratio over entire signal range
- Analog or digital (electrical or optical) communication interface

Figure: adapted from [1, 2]. Content basing on [1, 3, 4, 5].

SETTING UP A PHIL ENVIRONMENT

- 3rd: Implement suitable Interface Algorithm (IA)



- What to consider?
  - Required bandwidth and dynamics
  - Minimum calculation time for environment simulation
  - Utilized amplifier and transducers (transfer functions)
  - RoS/DuT impedances at all points of operation (ratio)
  - Compromise between conflictive requirements

- Where to implement the IA?
  - In dependance of the use case
    - CPU realtime simulator
    - FPGA realtime simulator
    - (FPGA power amplifier)
  - Multiple IAs might be used (CPU ⇌ FPGA ⇌ DuT)

Figure: adapted from [1, 2].

SETTING UP A PHIL ENVIRONMENT

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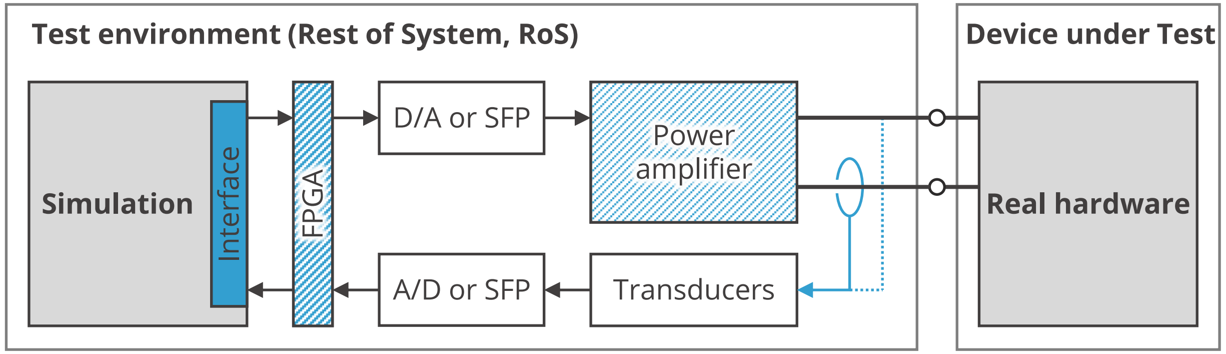

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- How to (further) stabilize a closed loop?
  - Use of electrically long conductors for compensation of delays and dead times
  - Damping of the closed loop (software and/or hardware)
    - Snubbers or inductive components
    - Lowpass filters

Figure: adapted from [1, 2].

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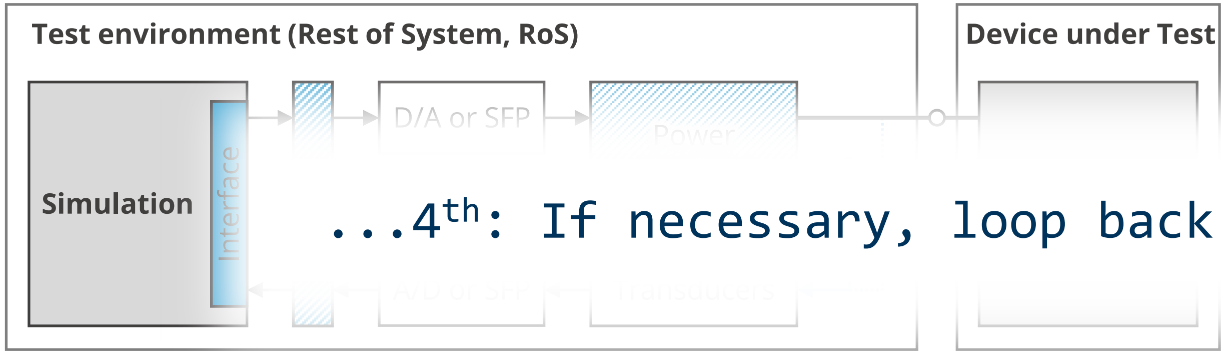

...4th: If necessary, loop back to 1st step and adjust...

- What to consider?
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FOCUS: INTERFACE ALGORITHMS – A COMPARISON

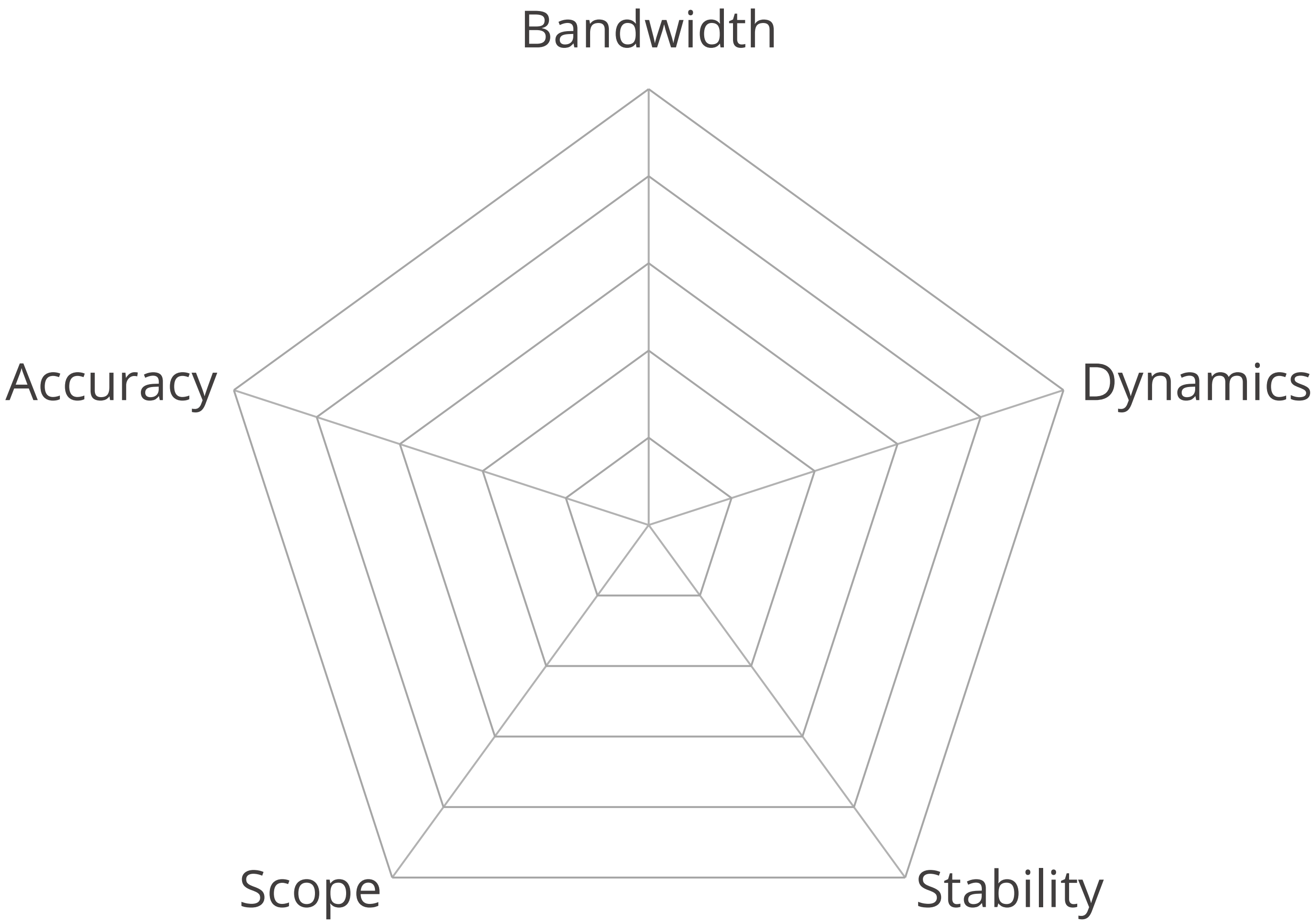

Figure adapted from [1], basing on [6, 7, 8, 9, 10].

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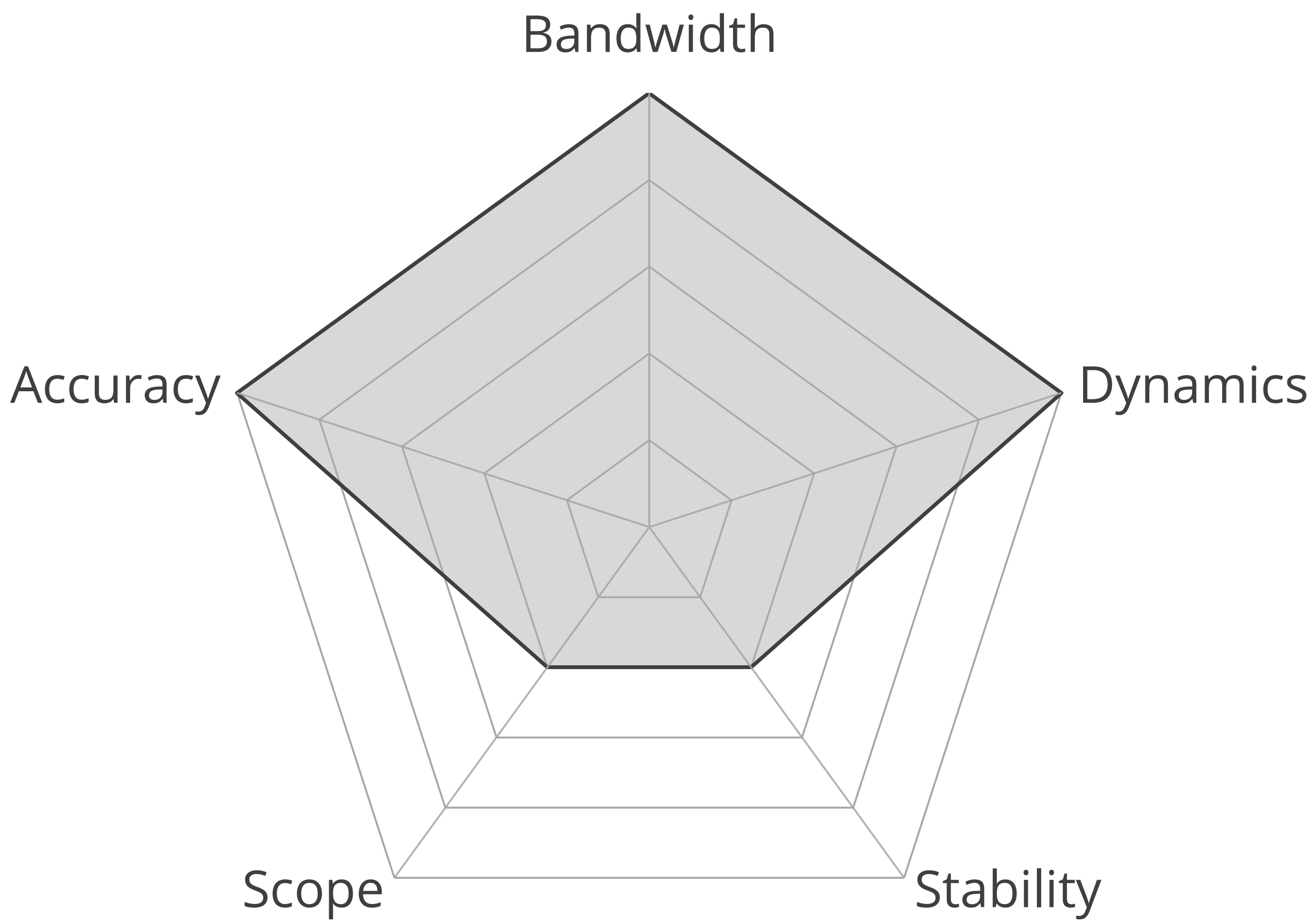

ITM — Direct dependence on the ratio of Impedances Z_{S} and Z_{H}

Figure adapted from [1], basing on [6, 7, 8, 9, 10].

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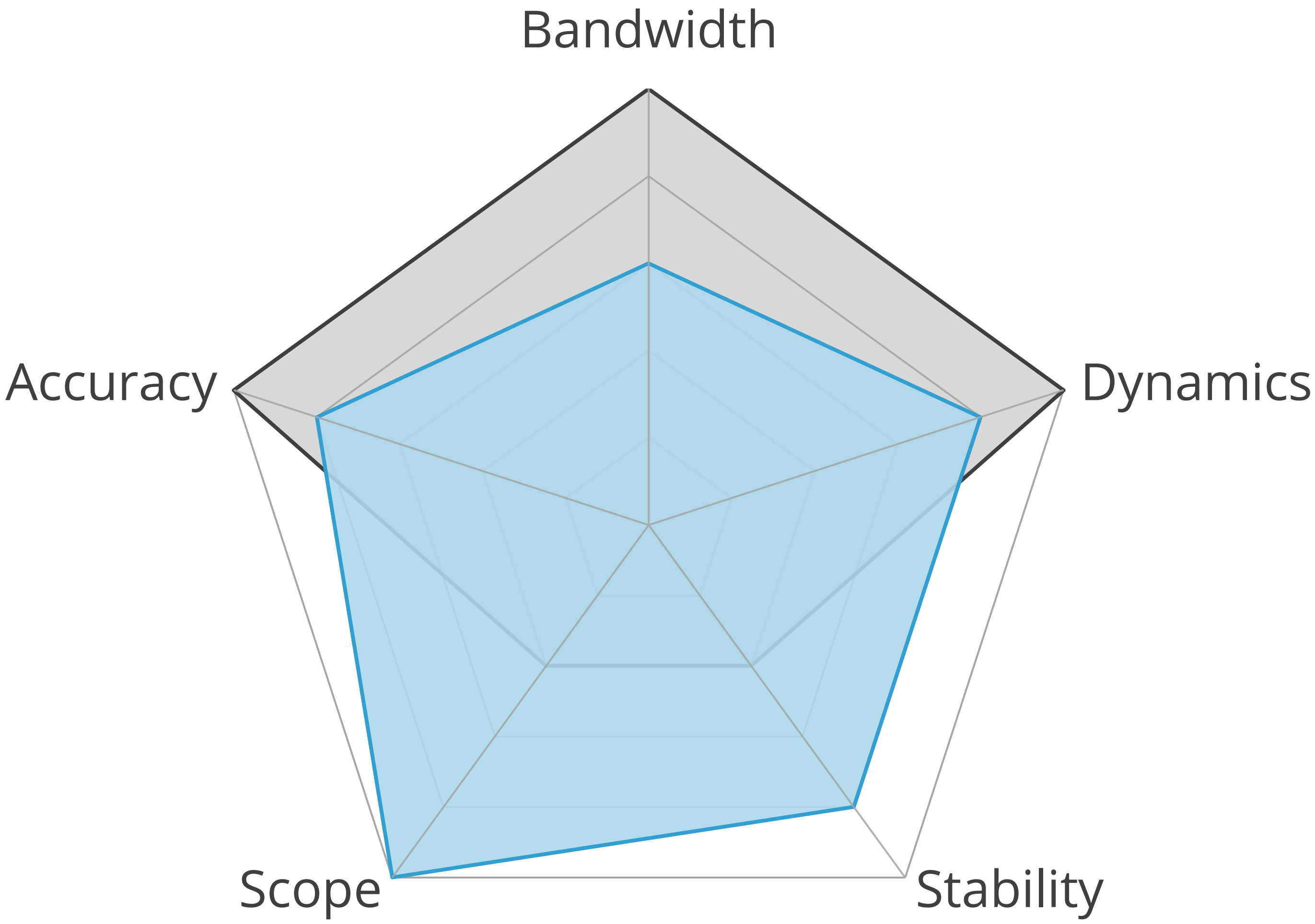

ITM — Direct dependence on the ratio of Impedances Z_S and Z_H

FITM* — Filter increases stability, dampens and limits the system

Figure adapted from [1], basing on [6, 7, 8, 9, 10].

*Filtered ITM: lowpass filter in transducer signal feedback path

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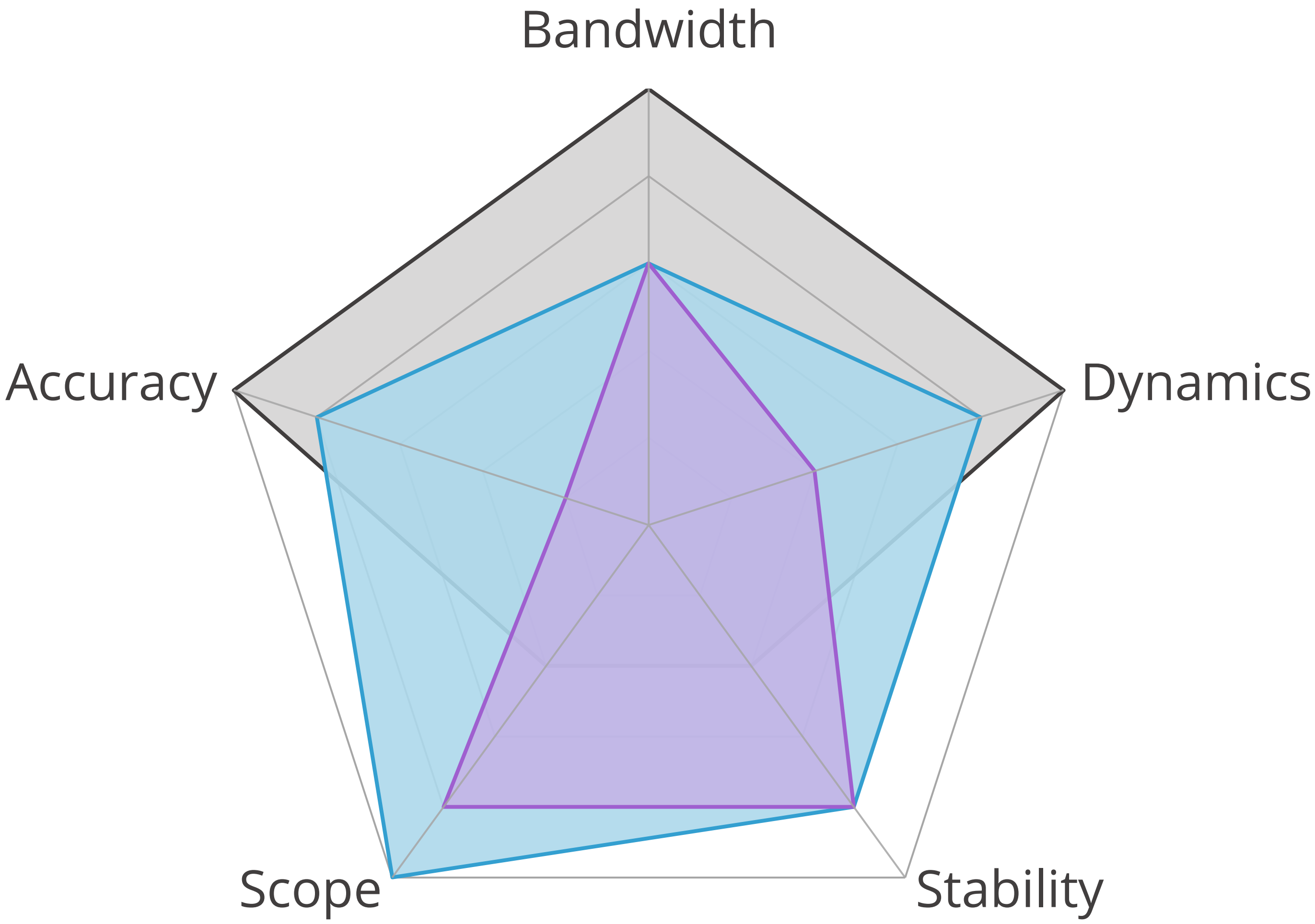

- ITM — Direct dependence on the ratio of Impedances Z_{S} and Z_{H}
- FITM* — Filter increases stability, dampens and limits the system
- PCD — Improvement if large usable impedance Z_{SH} in real system

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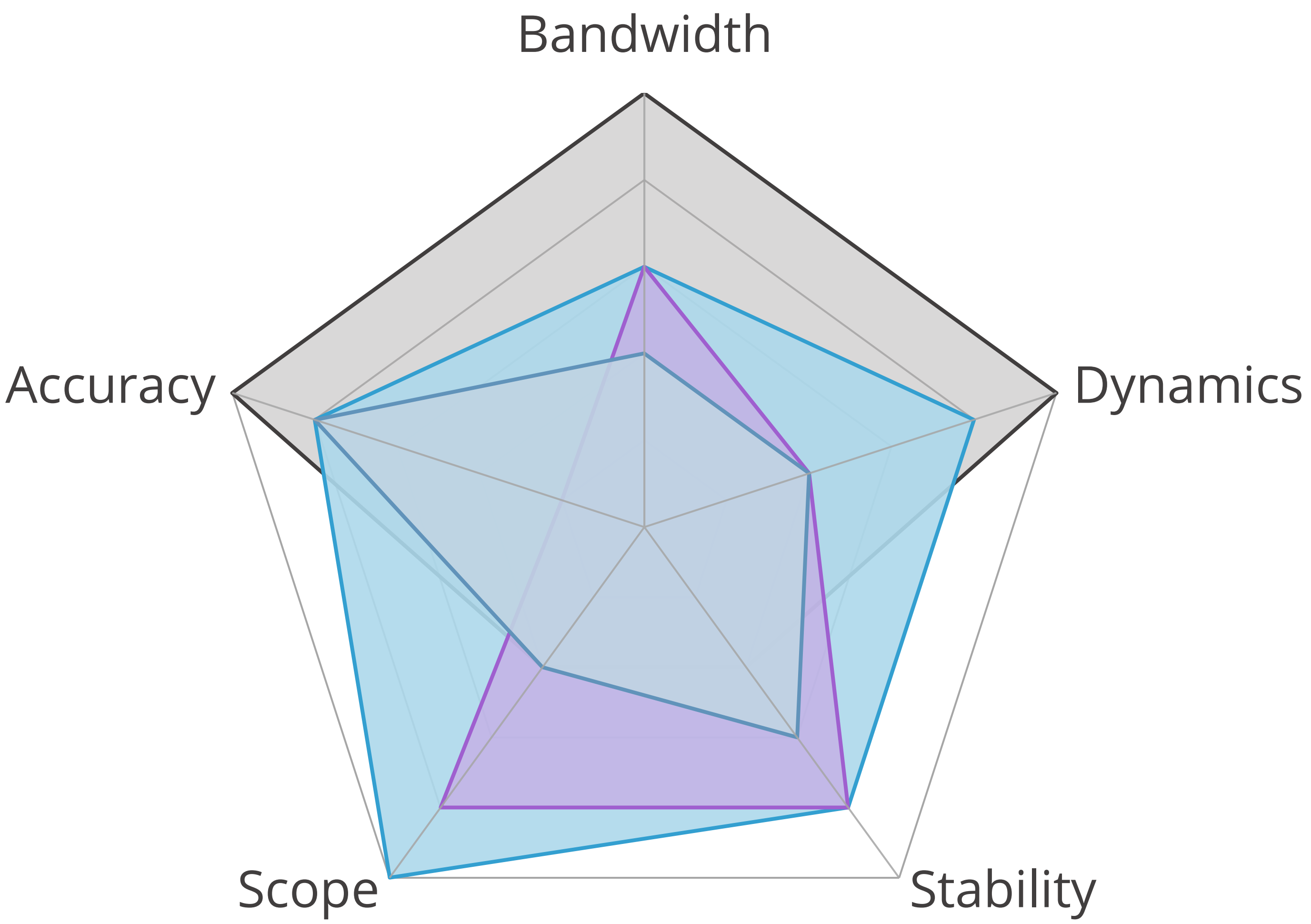

ITM	Direct dependence on the ratio of Impedances Z_S and Z_H
FITM*	Filter increases stability, dampens and limits the system
PCD	Improvement if large usable impedance Z_{SH} in real system
DIM	Impedances Z_{SH} increse stability at the expense of accuracy

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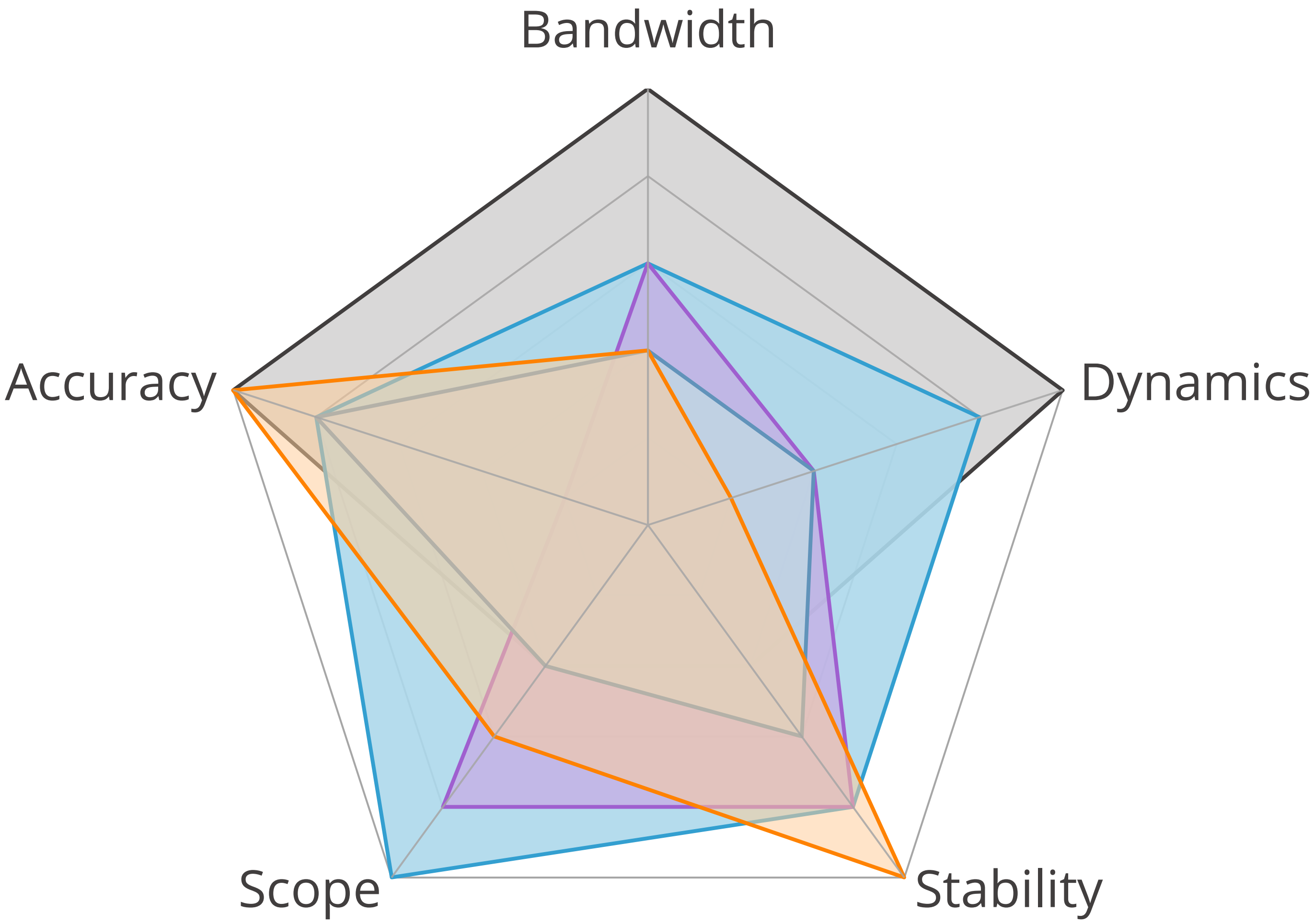

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- **DIM** – Impedances Z_SH increse stability at the expense of accuracy
- **MDIM** – Complex adaptive impedance Z^* estimation increases stability

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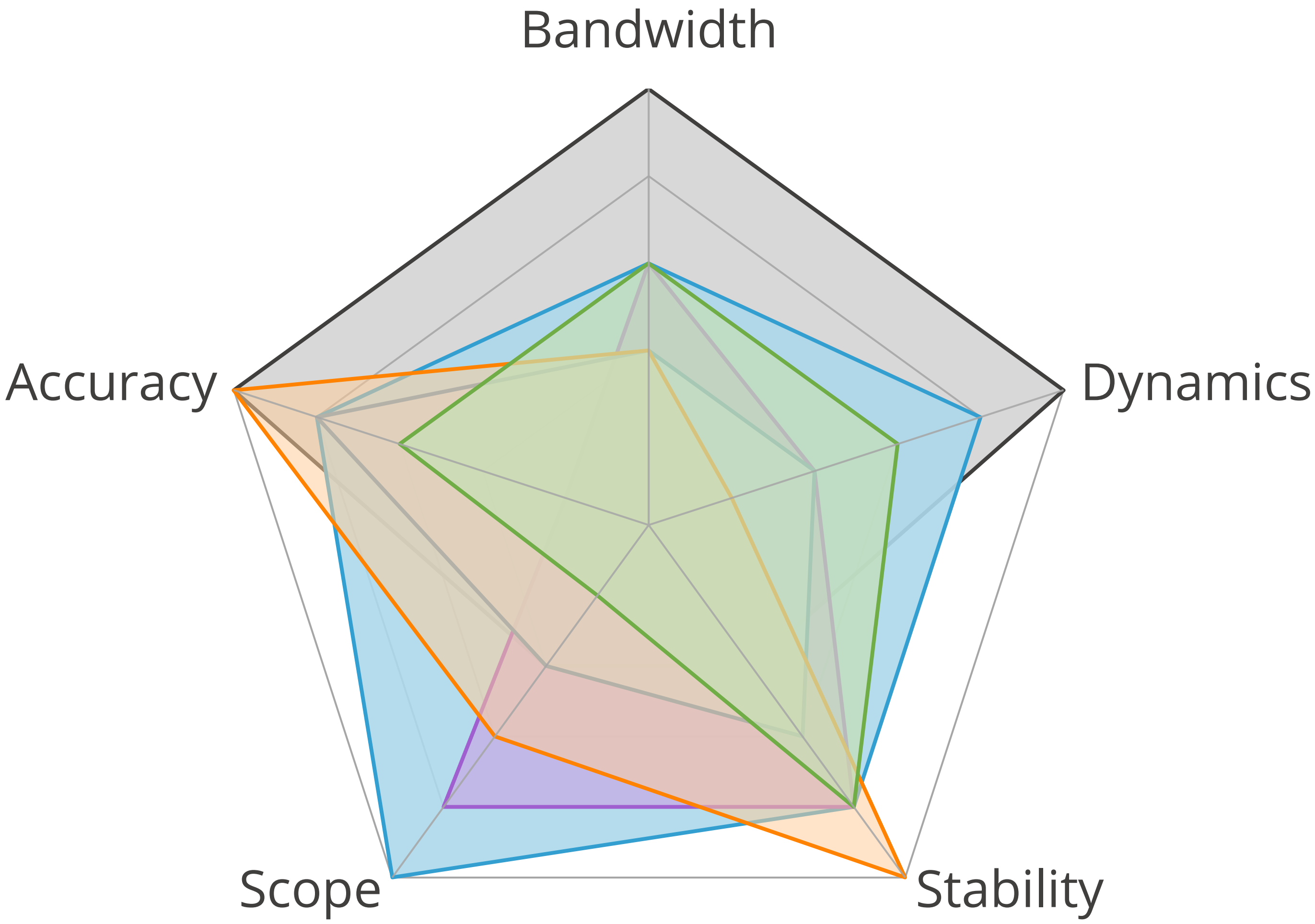

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TLM	Only for DuTs connected via an electrically long conductor, otherwise bad accuracy

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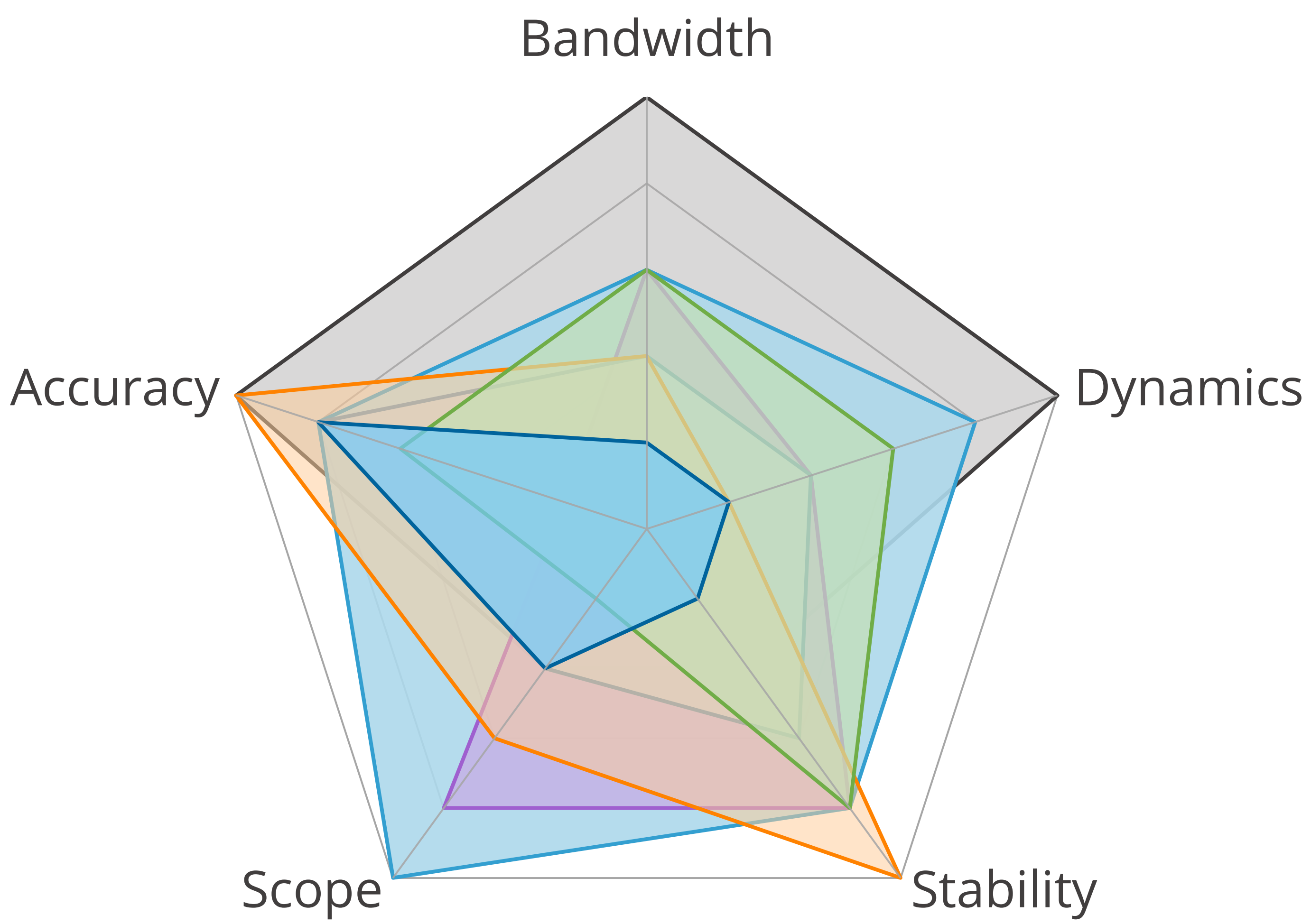

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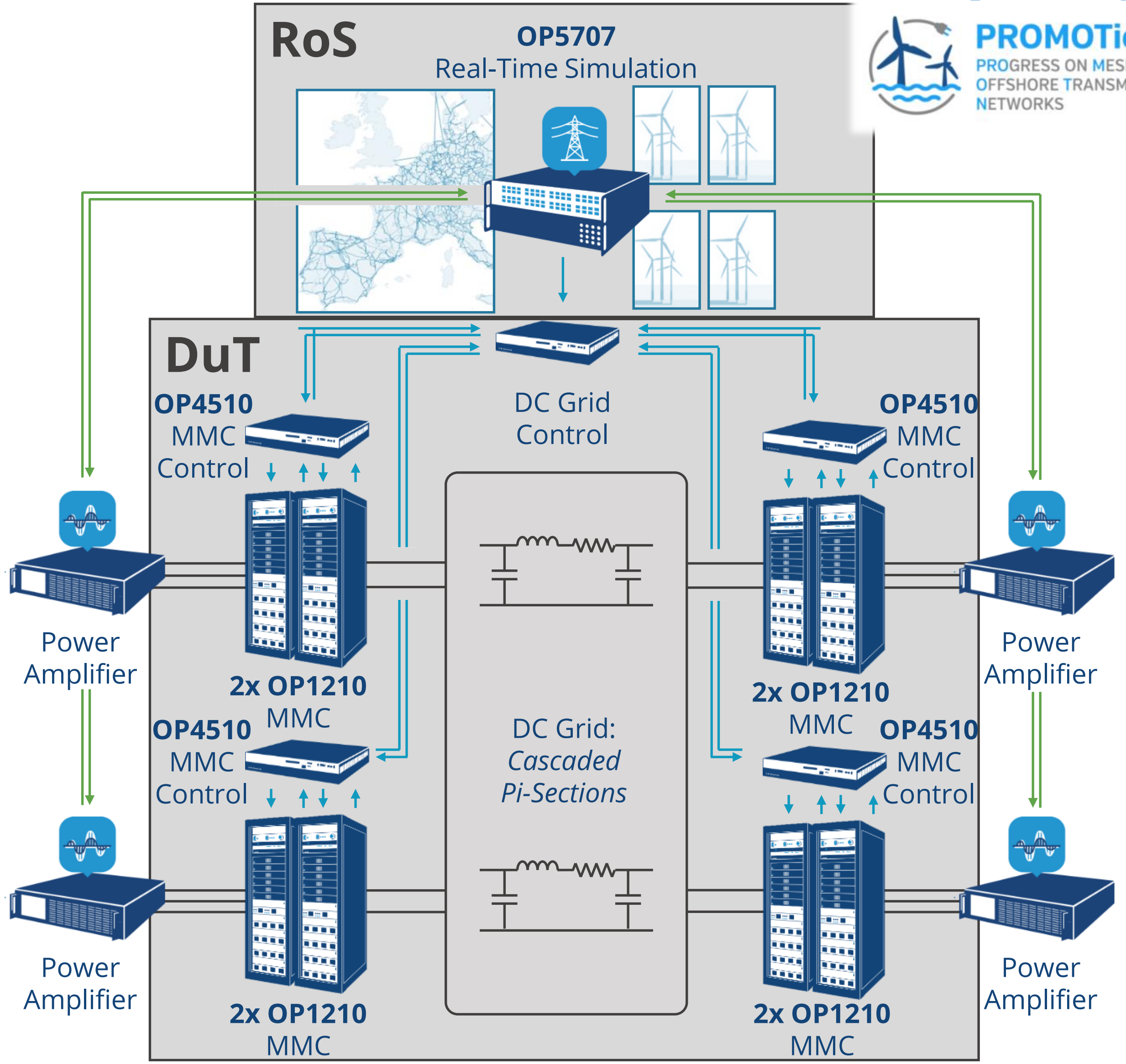
DIM	Impedances Z_SH increse stability at the expense of accuracy
MDIM	Complex adaptive impedance Z^* estimation increases stability
TLM	Only for DuTs connected via an electrically long conductor, otherwise bad accuracy
TFA	Accurate for linear loads, basing on a predictive first order estimation

*Filtered ITM: lowpass filter in transducer signal feedback path

Figure adapted from [1], basing on [6, 7, 8, 9, 10].

A – PHIL AT RWTH AACHEN

- Lab scale MMC test bench
  - Operation and control of meshed offshore HVDC systems using (P)HIL
  - Controllability and interoperability, fault handling and AC grid support
  - Resonance phenomena and harmonic interaction of active components
- Exemplary use case
  - Offshore wind park integration in AC grids
  - Start-up sequences, change of wind speed



Picture: RWTH Aachen [12]. Figure: [13]. Further information given in [12, 13].

B – PHIL AT KARLSRUHE INSTITUTE OF TECHNOLOGY

- **Energy Lab 2.0**

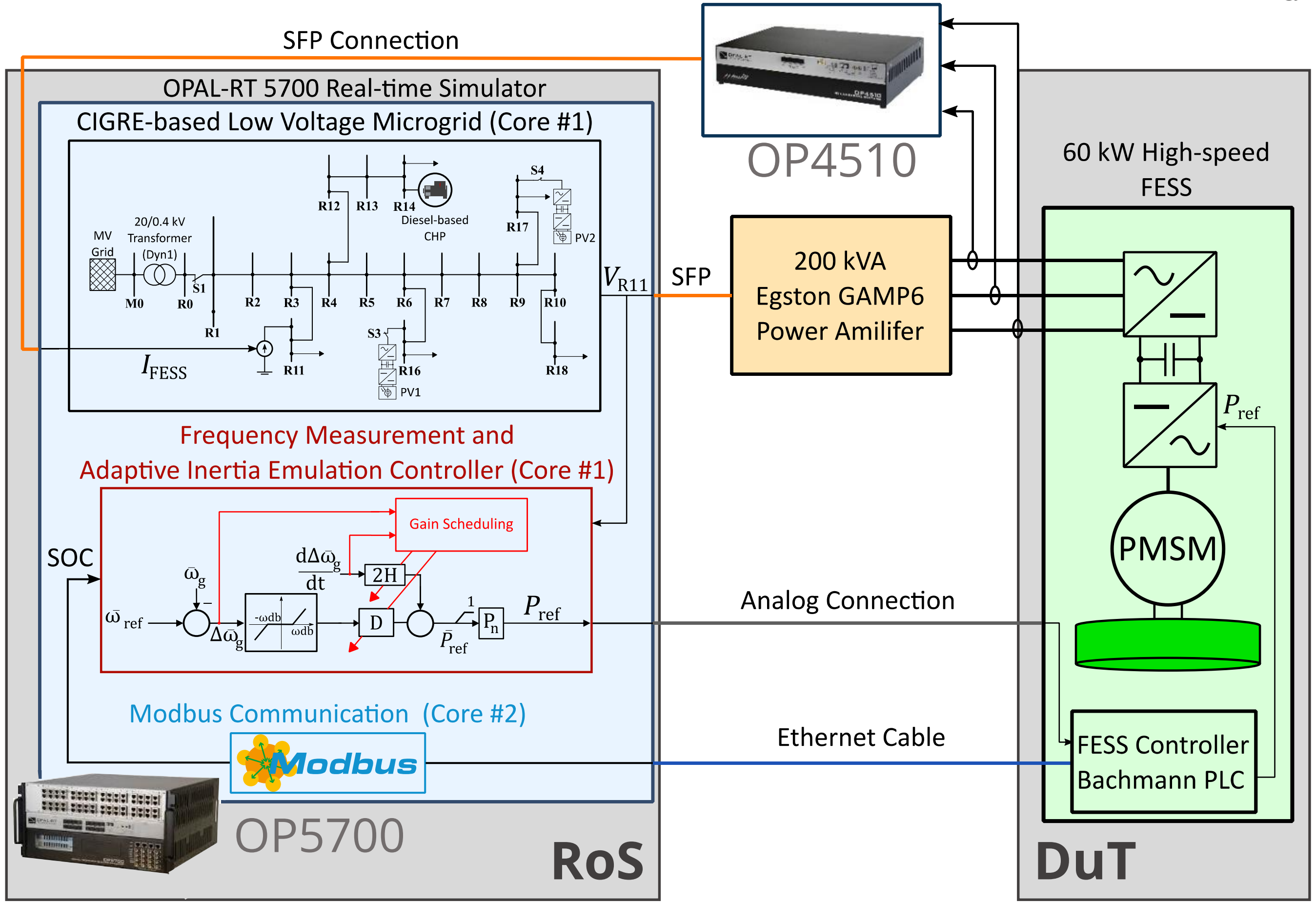
  Large-scale research infrastructure with 20+ OPAL-RT cores and a 1 MVA, 1.5 kV power amplifier

  Multimodal development, testing and grid integration of new technologies: DC grids, storage systems and superconductivity

- **Exemplary use case**

  Flywheel Energy Storage System (FESS)

  Development and validation of adaptive grid-synchronous controllers



Pictures: KIT. Further information given in [14, 15].

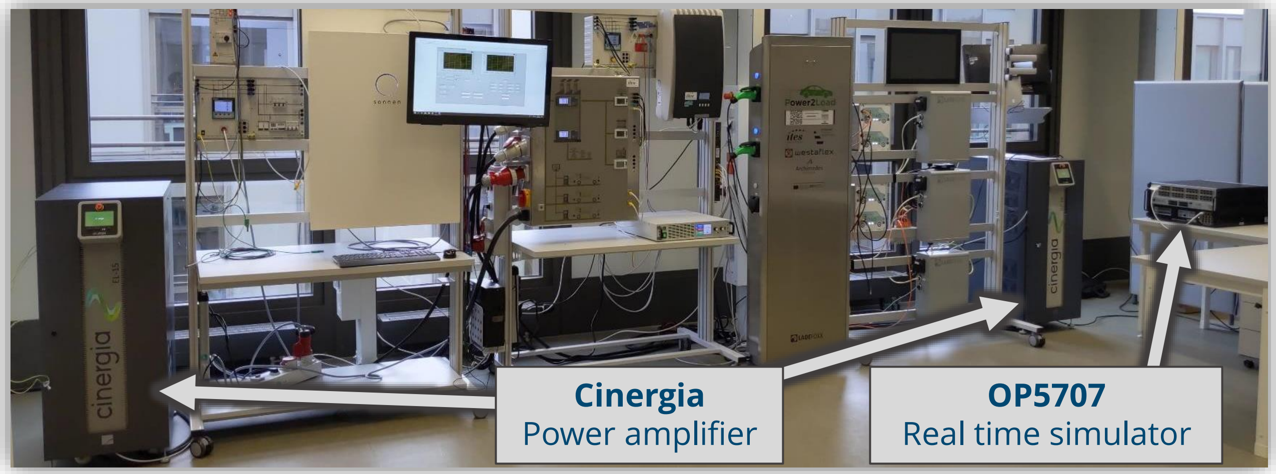
C – PHIL AT BIELEFELD UNIV. OF APPLIED SCIENCES

FH Bielefeld
University of
Applied Sciences

AGNES

ites
Institut der HSBI

SEAp



- Smart Energy Application Lab

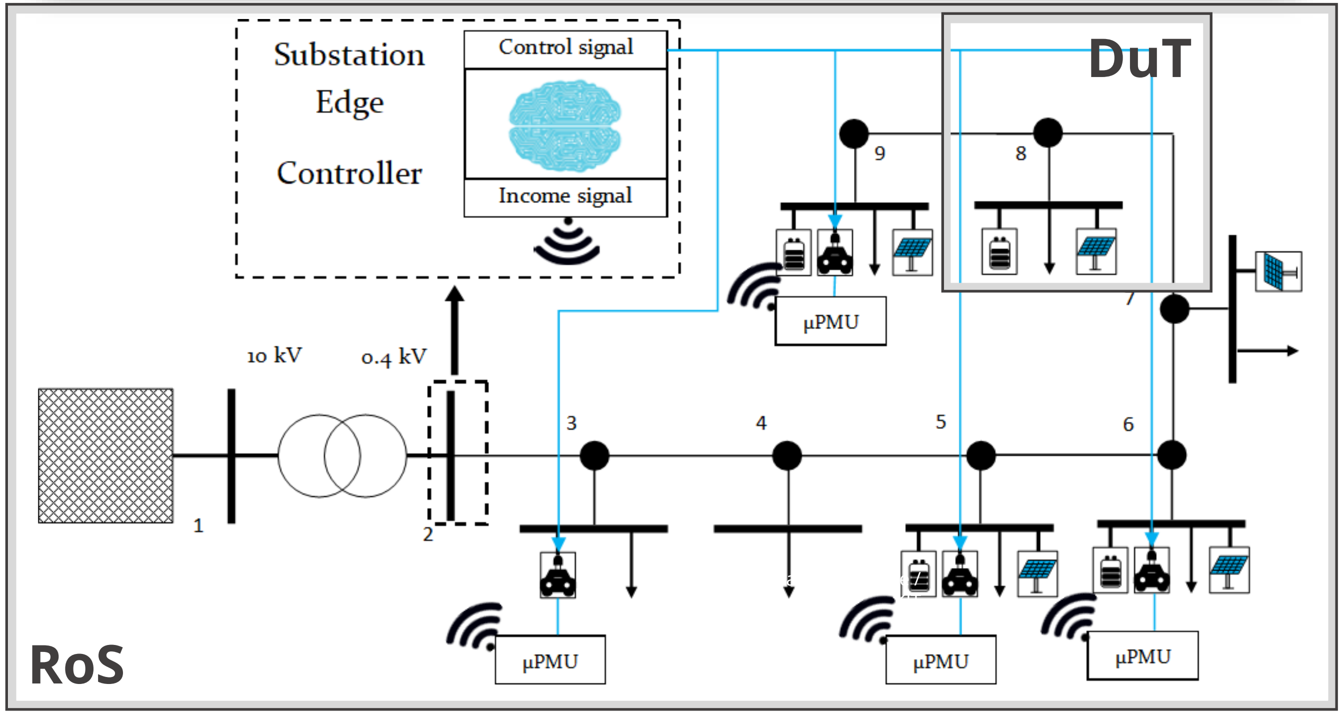
  Development and validation of intelligent algorithms and methods for control and monitoring of electrical grids

  (P)HIL test bed for future energy systems: PV and Wind, CHP, EV charging and BES

- Exemplary use case

  AI grid controller for low voltage grids

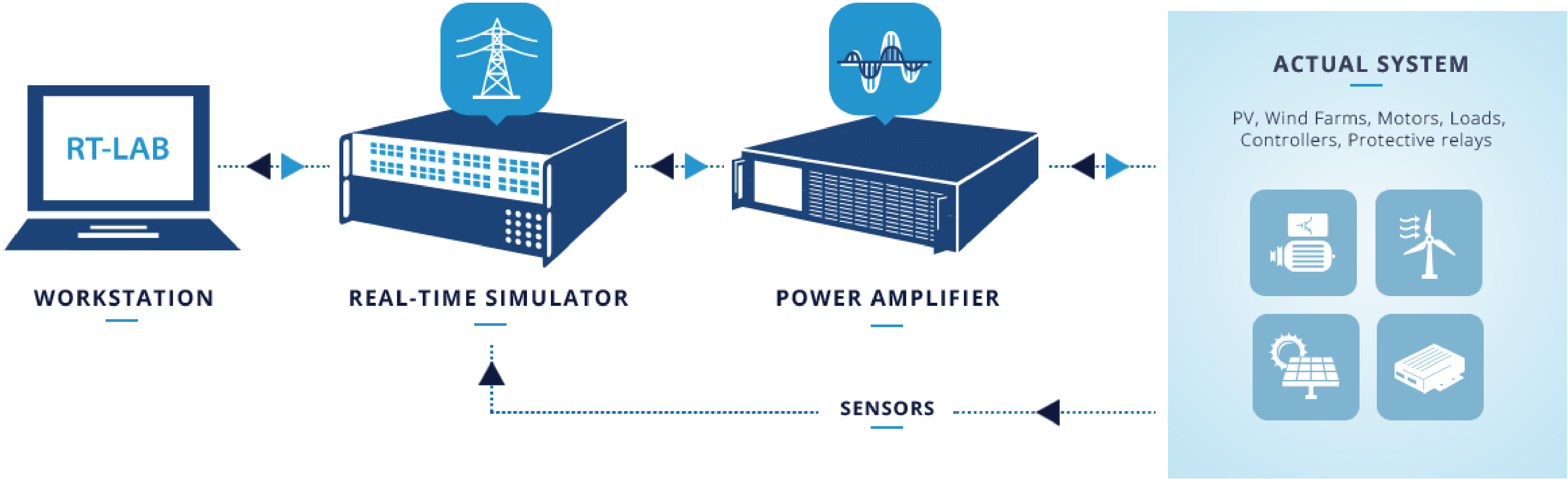
  Reinforced learning based control of a digital twin integrating real power hardware



Pictures: TU Bielefeld. Further information given in [16, 17].

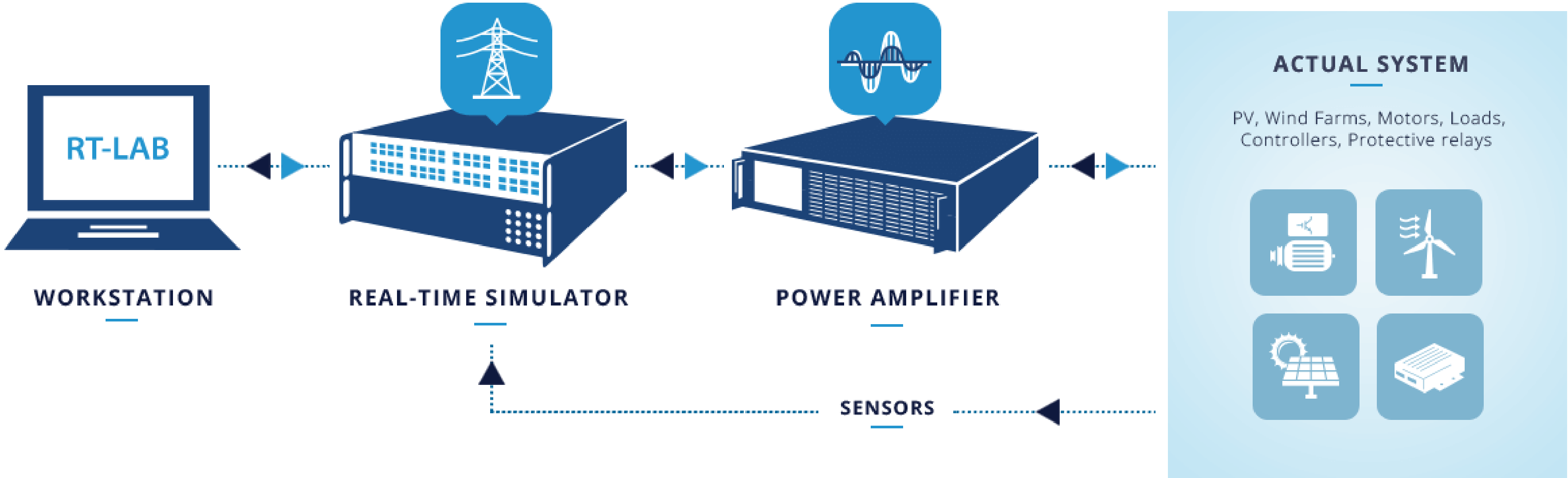
CONCLUSIONS – PHIL NOW AND IN FUTURE

- Mighty tool for development, testing, validation and evaluation of power grids and its components
- A careful system layout is mandatory, compromises must be made
- An optimum for test beds and respective use cases must be engineered



Picture: OPAL-RT TECHNOLOGIES.

CONCLUSIONS – PHIL NOW AND IN FUTURE



- Further developments towards turnkey solutions for PHIL setups
- Research on Interface Algorithms and minimization of the necessary compromise
- Customized engineering and test bed integration by specialists

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Picture: OPAL-RT TECHNOLOGIES.

PHIL AMPLIFIERS AT THE STAND

- **Cinergia GE/EL 30+ vAC/DC**
  - Complete regenerative DC Load/Source
  - Full 4 quadrant AC Grid Emulator and Electronic Load
  - Power Amplifier for Power HIL
- **Special features**
  - Battery Emulation and Testing
  - PV Panel Emulation
- **Specification**
  - 7.5 kW to 160 kW models, up to 2 MW parallel
  - AC voltage from 20 V to 277 V_{rms} (optional 295 $V_{l\text{-}n}$)
  - DC voltage from 20 V to 750 V_{dc} (optional 800 V_{dc})
  - Peak power: 200 % of rated power

PHIL AMPLIFIERS AT THE STAND

- Itech IT7800

  Regenerative grid simulator

  Full 4 quadrant AC&DC power Source/Load

  Professional islanding test mode,
  support R, L, C and active, reactive power settings

  4 output modes of AC/DC/AC+DC/DC+AC can be realized

- Special features

  Harmonic simulation and analysis function up to 50 times, built-in IEC61000-3-2/3-12

  Simulation of arbitrary waveform output, supports CSV file import waveform

- Specification

  High power density, up to 15 kVA for 3U

  Master and slave equal flow, parallel machines up to 960 kVA

Visit us at stand 21

TT&MS

total test and measurement support

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OPAL-RT TECHNOLOGIES

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CITED SOURCES

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D – PHIL AT HAMBURG UNIVERSITY OF TECHNOLOGY

TUHH PHILs Lab

- ACIE Lab: Microgrids and battery systems
  (Un-)intentional islanding and grid synchronity
  Provision of frequency containment reserve (FCR)
- DiCIE Lab: Stability of (isolated) DC grids
  Influence of DC loads on DC system performance
  Short circuit behavior, oscillations and grounding
- Exemplary use case
  PHIL testing of ship DC grids with oscillating loads
  Fault behavior and clearance, oscillations up to 30 kHz

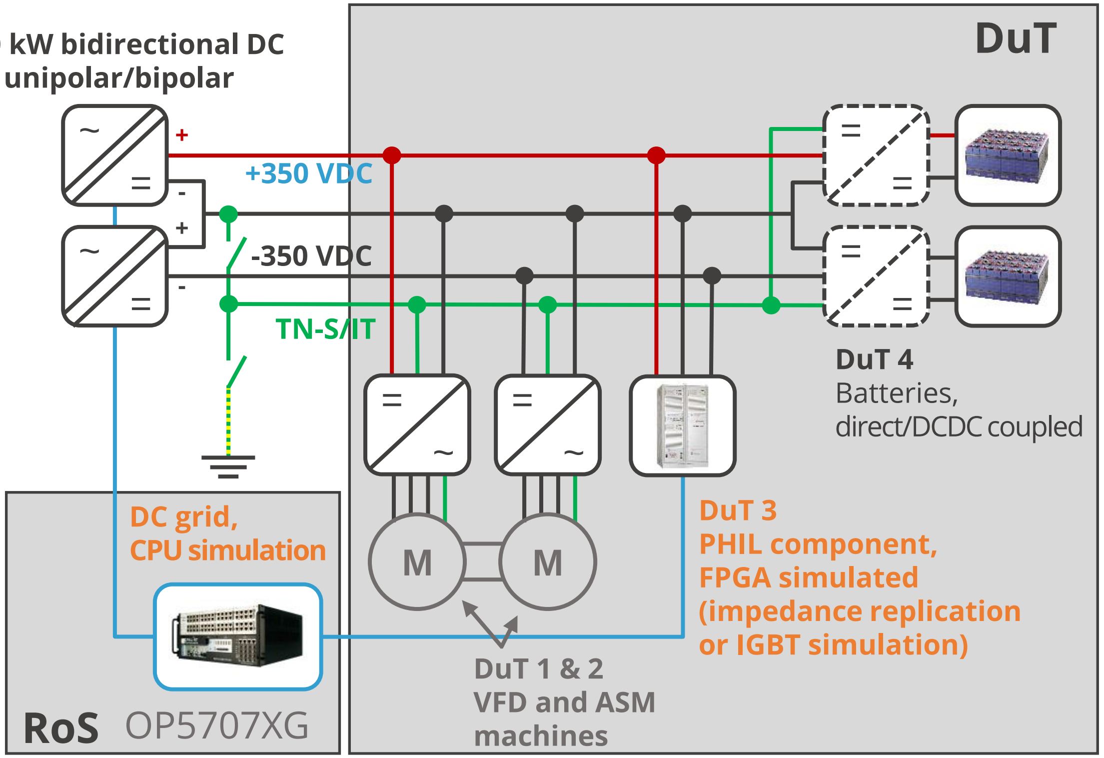


Figure: Hamburg University of Technology. Further information given in [11].

FOCUS: INTERFACE ALGORITHMS

- Voltage type Ideal Transformer Method (ITM): circuit, closed loop and stability analysis

schematically

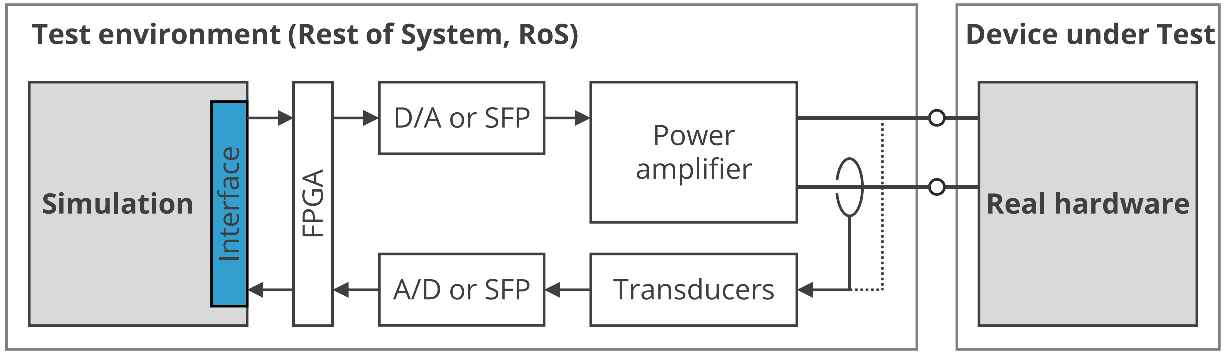
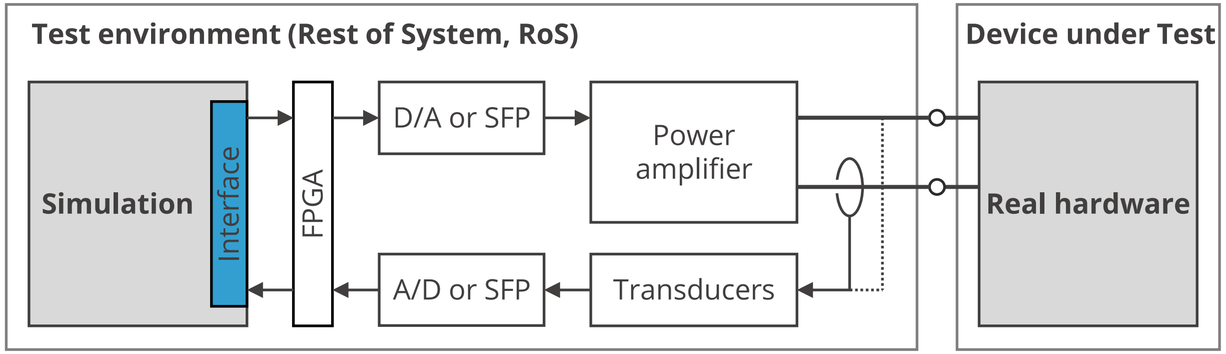


Figure: adapted from [1, 2].

FOCUS: INTERFACE ALGORITHMS

- Voltage type Ideal Transformer Method (ITM): circuit, closed loop and stability analysis

schematically



equivalent circuit

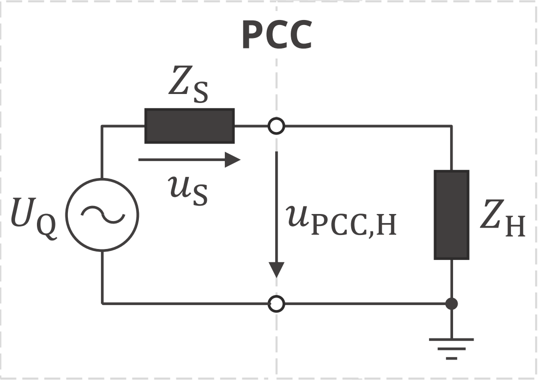
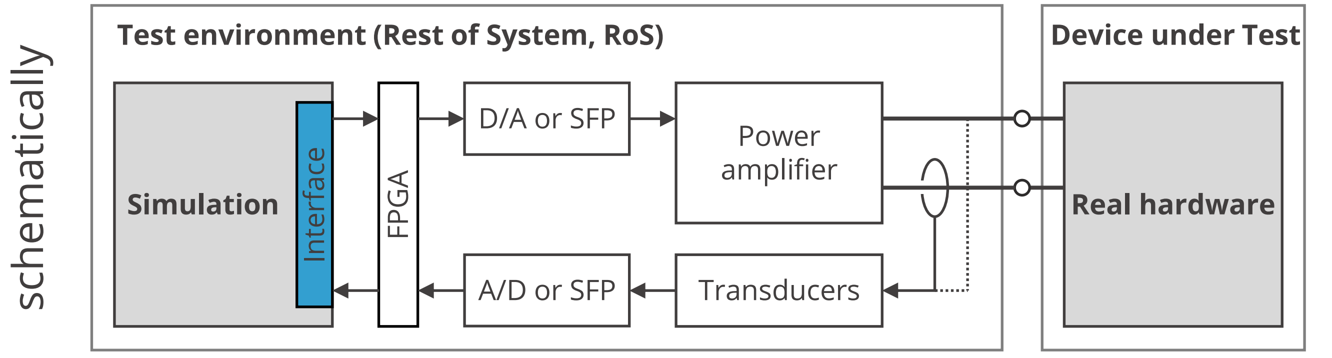


Figure top left: adapted from [1, 2]. Figure bottom left: adapted from [1].

FOCUS: INTERFACE ALGORITHMS

- Voltage type Ideal Transformer Method (ITM): circuit, closed loop and stability analysis



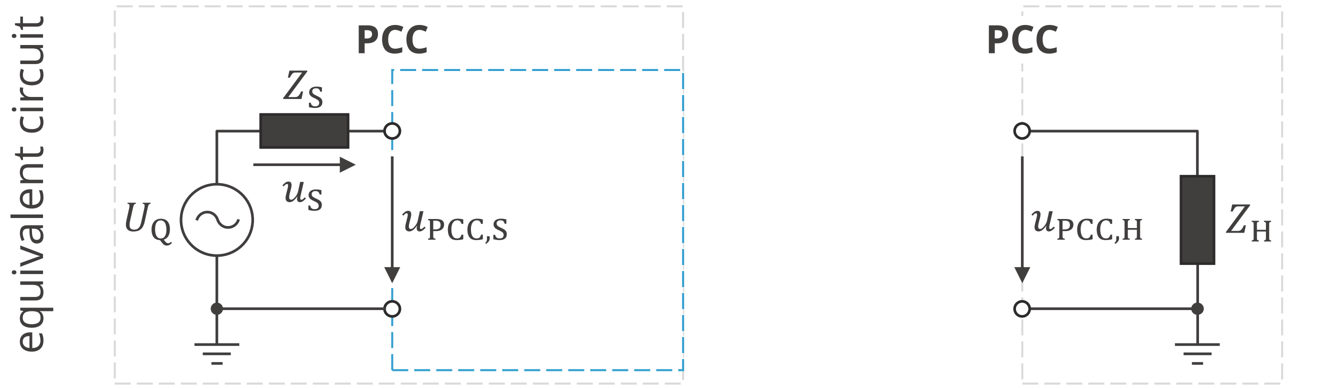


Figure top left: adapted from [1, 2]. Figure bottom left: adapted from [1].

FOCUS: INTERFACE ALGORITHMS

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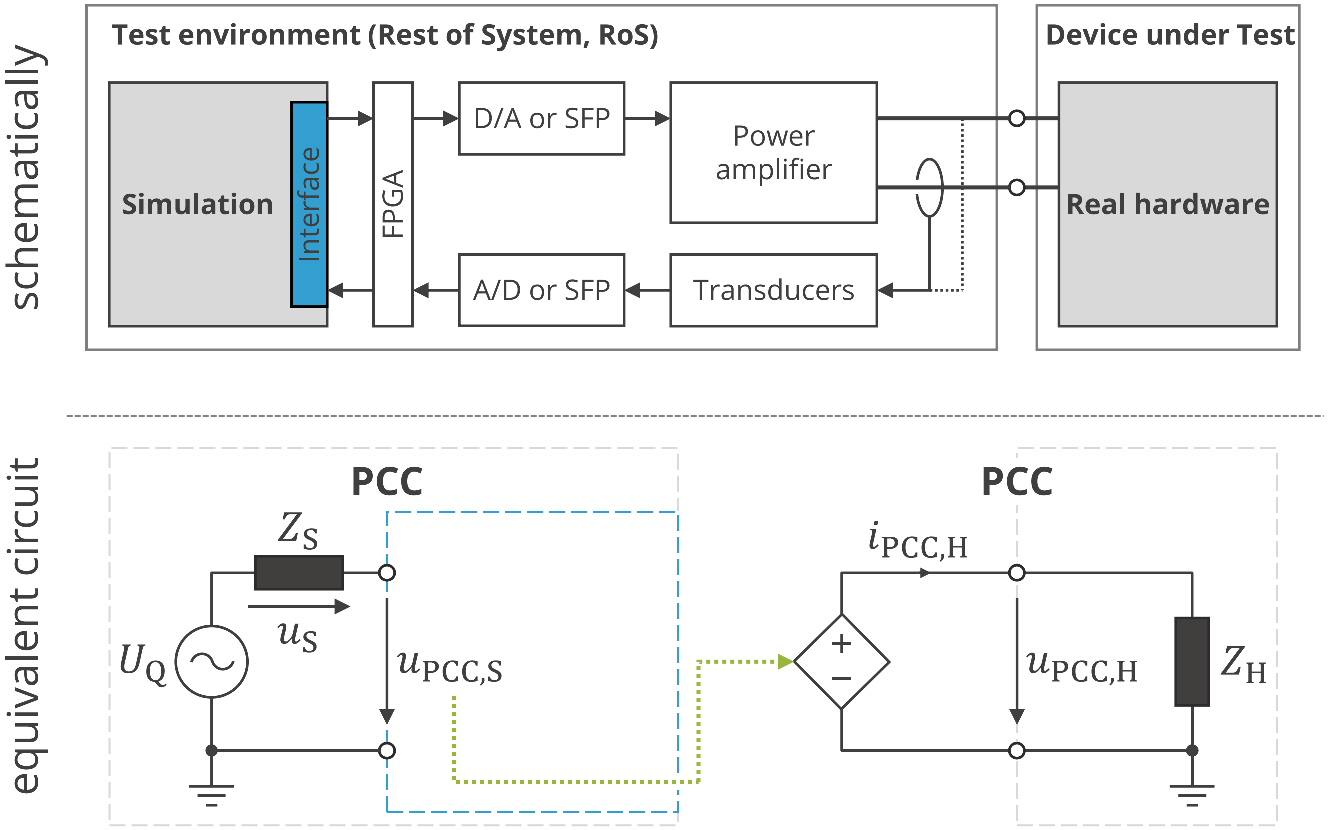

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FOCUS: INTERFACE ALGORITHMS

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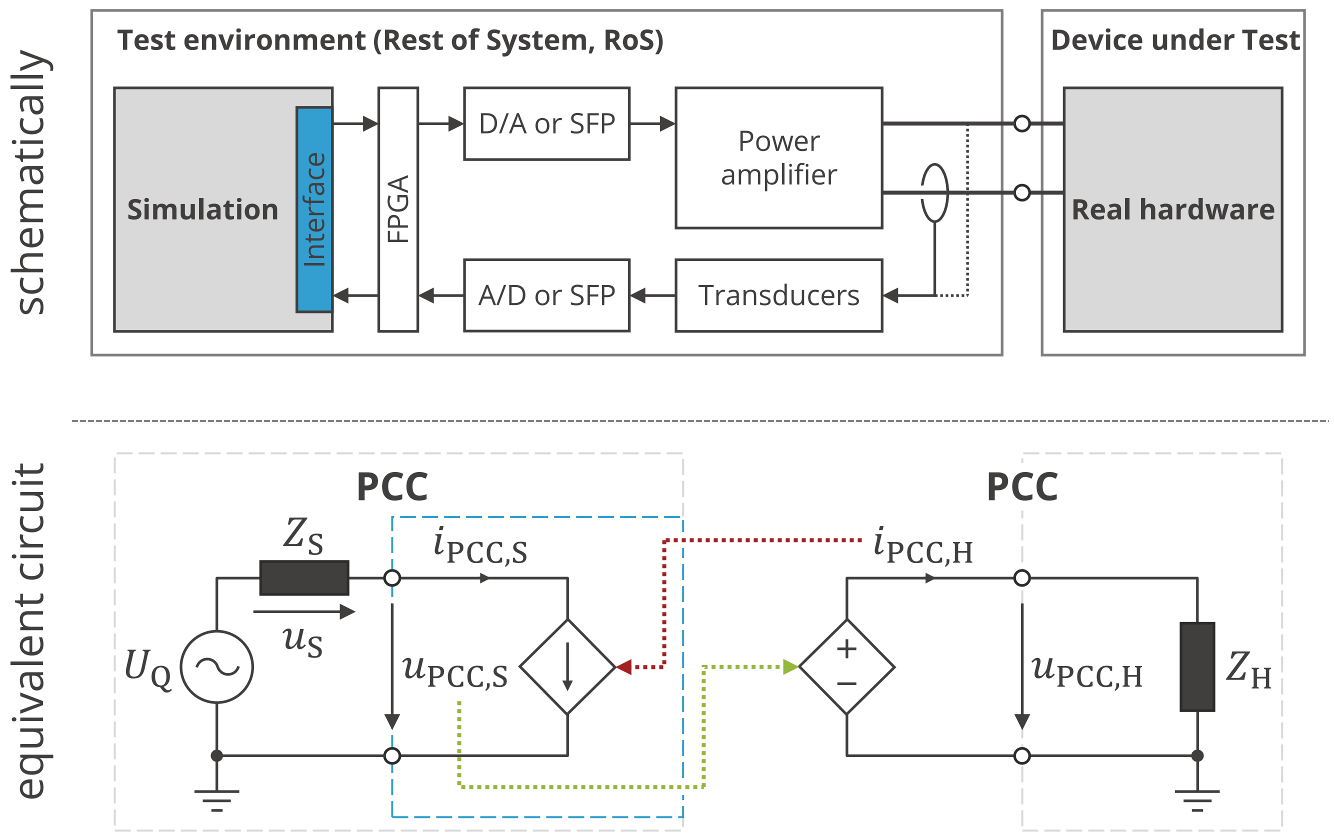
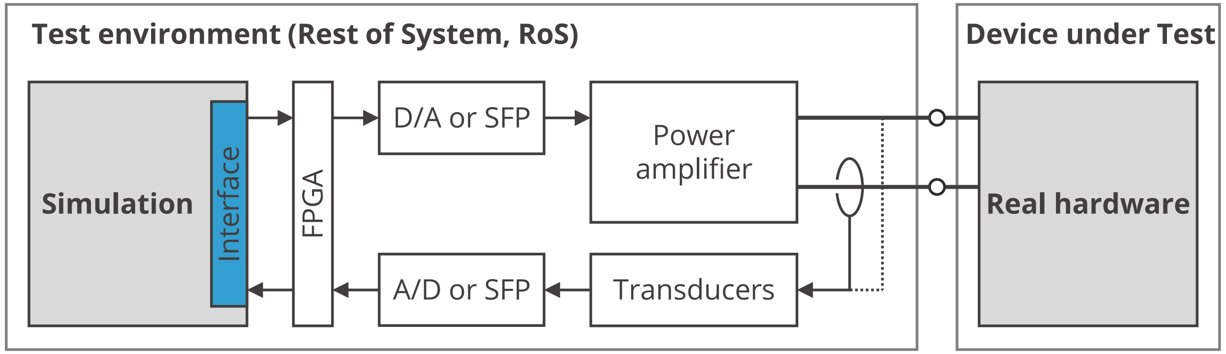


Figure top left: adapted from [1, 2]. Figure bottom left: adapted from [1].

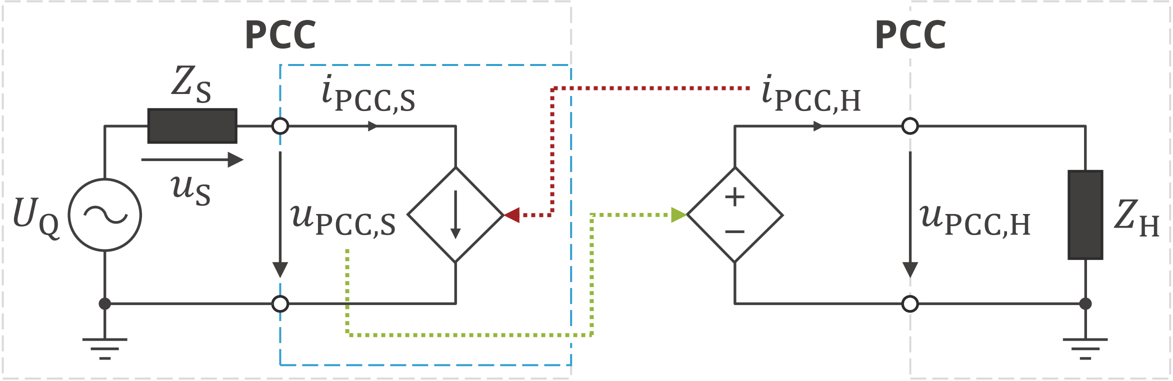
FOCUS: INTERFACE ALGORITHMS

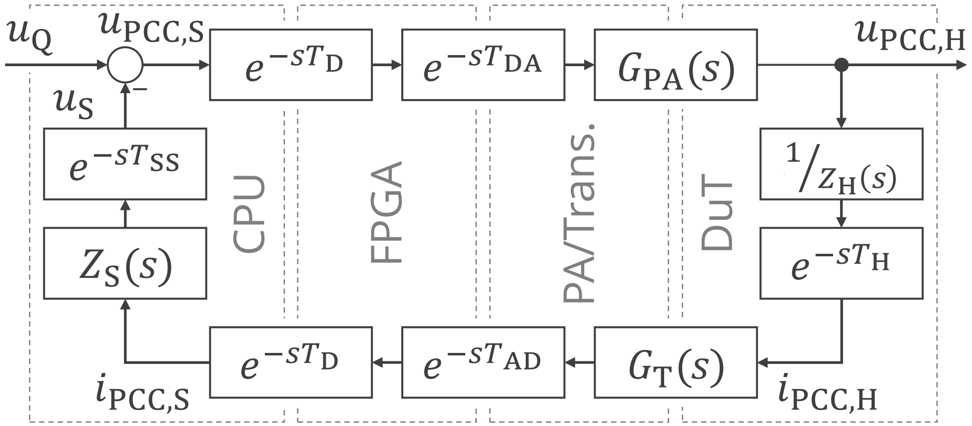
- Voltage type Ideal Transformer Method (ITM): circuit, closed loop and stability analysis

schematically



equivalent circuit





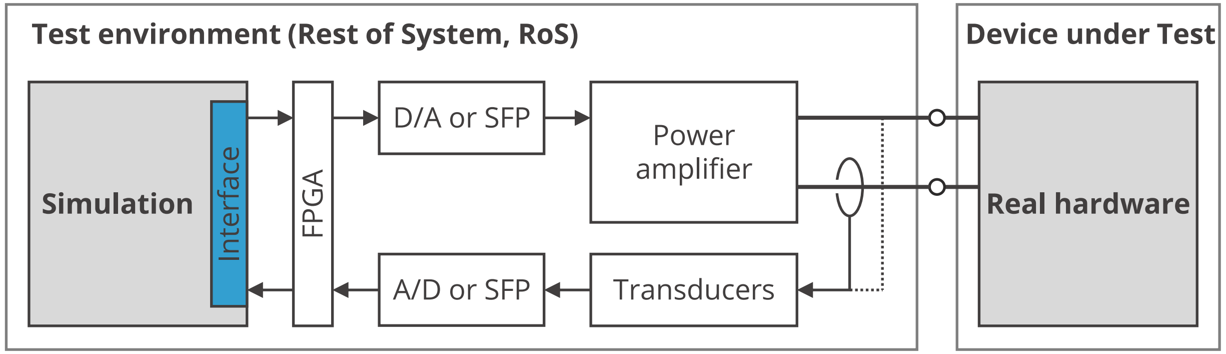
closed loop

Figure top left: adapted from [1, 2]. Figures bottom left, top right: adapted from [1].

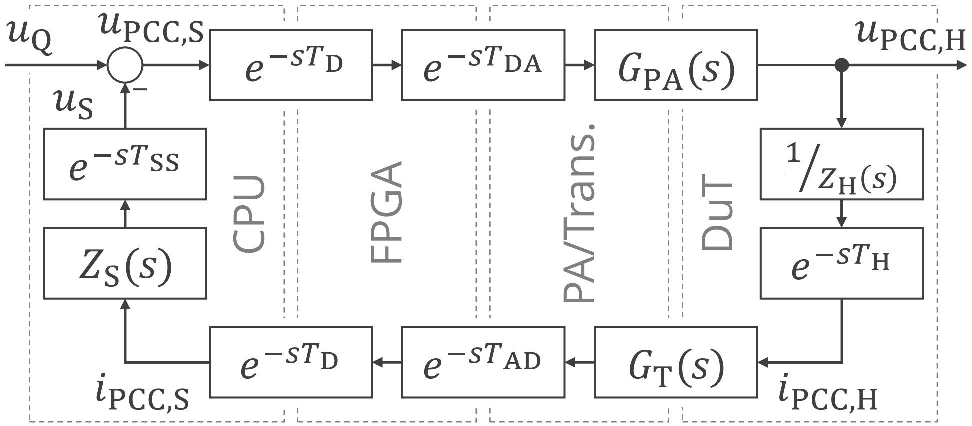
FOCUS: INTERFACE ALGORITHMS

- Voltage type Ideal Transformer Method (ITM): circuit, closed loop and stability analysis

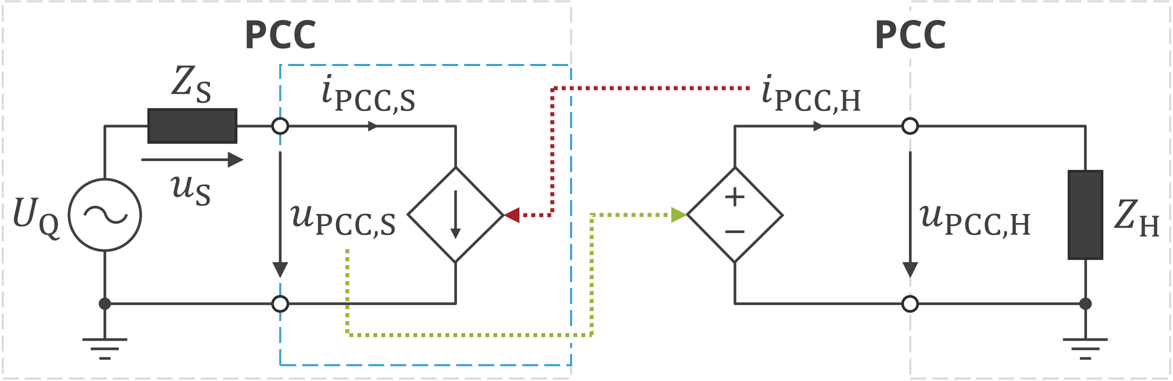
schematically



closed loop



equivalent circuit



stability

$$T_T = T_D + T_{DA} + T_{PA} + T_H + T_T + T_{AD} + T_D + T_{SS}$$

$$G_{OL,ITM}(s) = \underbrace{G_{PA}(s)}_{\approx 1} \cdot \underbrace{G_T(s)}_{\approx 1} \cdot \frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T}$$

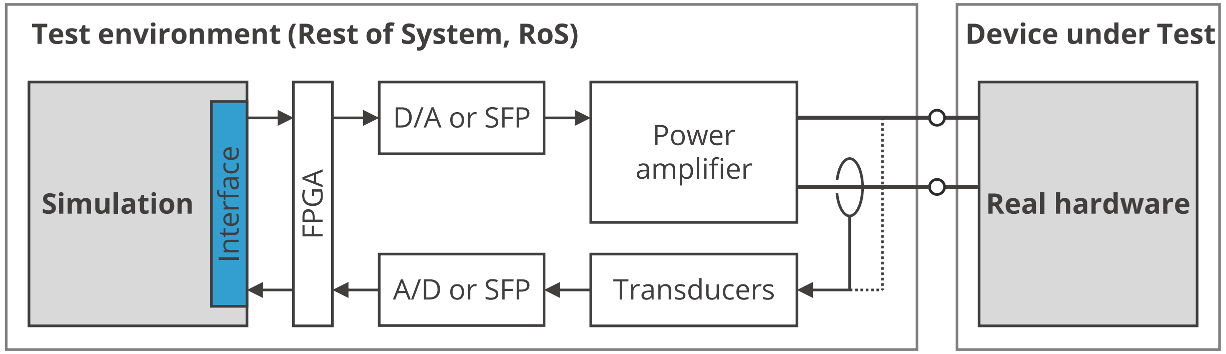
$$= \frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T}$$

Figure top left: adapted from [1, 2]. Figures bottom left, top right: adapted from [1]. Equation basing on [6].

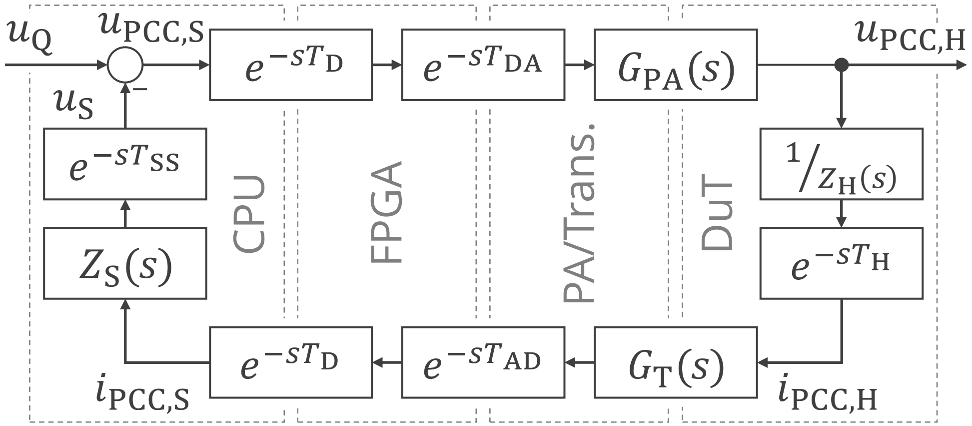
FOCUS: INTERFACE ALGORITHMS

- Voltage type Ideal Transformer Method (ITM): circuit, closed loop and stability analysis

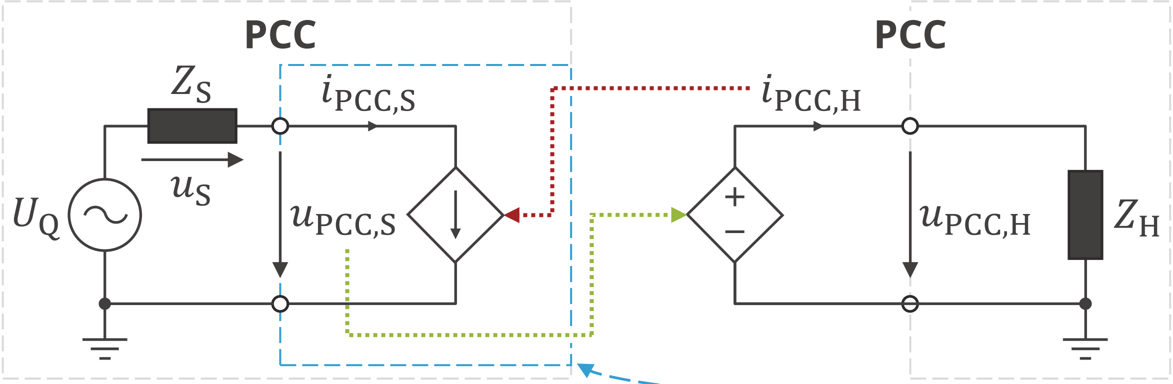
schematically



closed loop



equivalent circuit



stability

$$T_T = T_D + T_{DA} + T_{PA} + T_H + T_T + T_{AD} + T_D + T_{SS}$$

$$G_{OL,ITM}(s) = \underbrace{G_{PA}(s)}_{\approx 1} \cdot \underbrace{G_T(s)}_{\approx 1} \cdot \frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T}$$

$$= \frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T} \cdot H_{LP}(s)$$

Figure top left: adapted from [1, 2]. Figures bottom left, top right: adapted from [1]. Equation basing on [6].

FOCUS: INTERFACE ALGORITHMS – A COMPARISON

- Open loop transfer functions: $G_{OL}(s) = G_{PA}(s) \cdot G_T(s) \quad \ldots$

Ideal Transformer Method (ITM) $\ldots \cdot \frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T}$

Filtered Ideal Transformer Method (FITM) $\ldots \cdot H_{LP}(s) \cdot \frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T}$

Partial Circuit Duplication (PCD) $\ldots \cdot \frac{Z_S(s)\,Z_H(s)}{(Z_S(s)+Z_{SH}(s))\,(Z_H(s)+Z_{SH}(s))} \cdot e^{-sT_T}$

Damping Impedance Method (DIM) $\ldots \cdot \frac{Z_S(s)\,(Z_H(s)-Z^*(s))}{(Z_H(s)+Z_{SH}(s))\,(Z_S(s)+Z_{SH}(s)+Z^*(s))} \cdot e^{-sT_T}$

Modified Damping Impedance Method (MDIM) $\ldots \cdot \frac{Z_S(s)\,(Z_H(s)-Z^*(s))}{(Z_H(s)+Z_{SH}(s))\,(Z_S(s)+Z_{SH}(s)+Z^*(s))} \cdot e^{-sT_T}$, $Z^*(s)$ variable

Transmission Line Model (TLM) $\ldots \cdot \frac{Z_S(s)-R_{SH}}{Z_S(s)+R_{SH}} \cdot \frac{Z_H(s)-R_{SH}}{Z_H(s)+R_{SH}} \cdot e^{-2sT_T}$, $R_{SH} = \frac{L}{T_T}$ or $R_{SH} = \frac{T_T}{C}$

Time-variant First-order approximation (TFA) $\ldots \cdot \frac{Z_S(s)}{R_H+sL_H} \cdot \left(1-\frac{sT_T}{2}\right)$

Transfer functions from [1], basing on [6, 7, 8, 9, 10].