Investigation of PHIL Simulation Stability and Accuracy Analysis

Comparison of Real World Setup with Simulation

OPAL-RT TECHNOLOGIES

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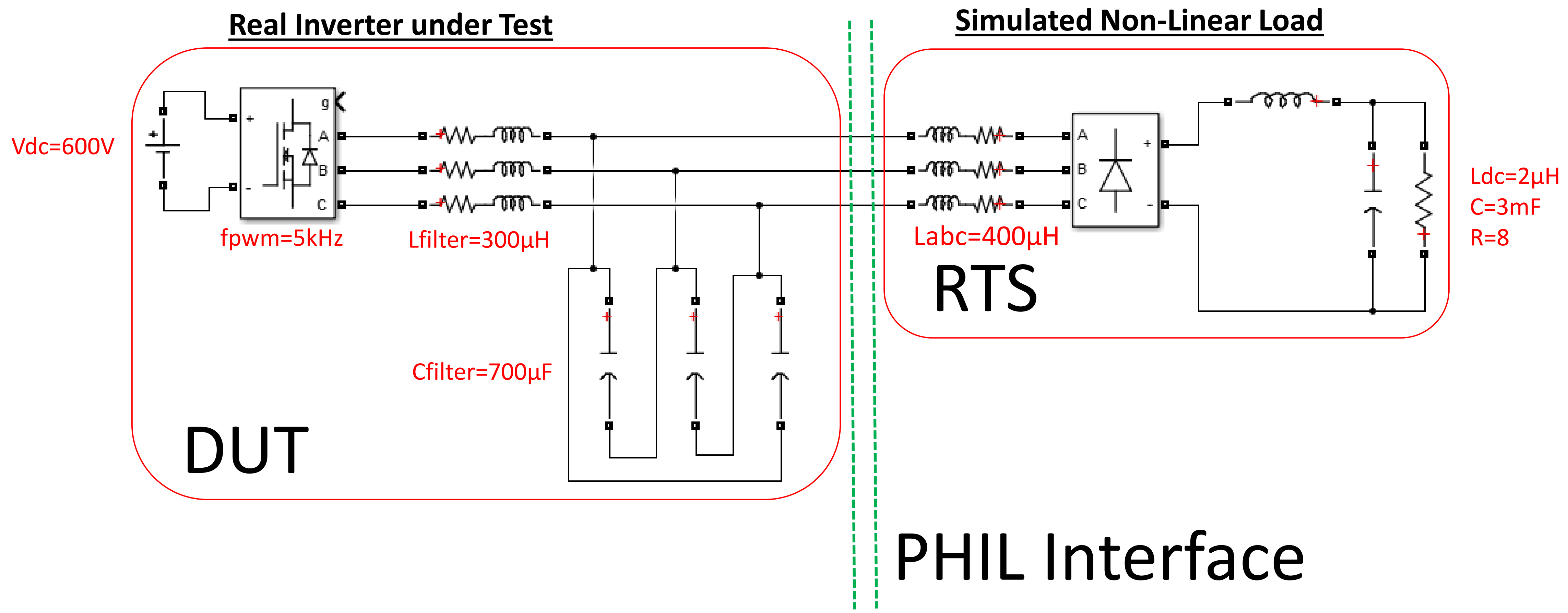
Presentation Overview

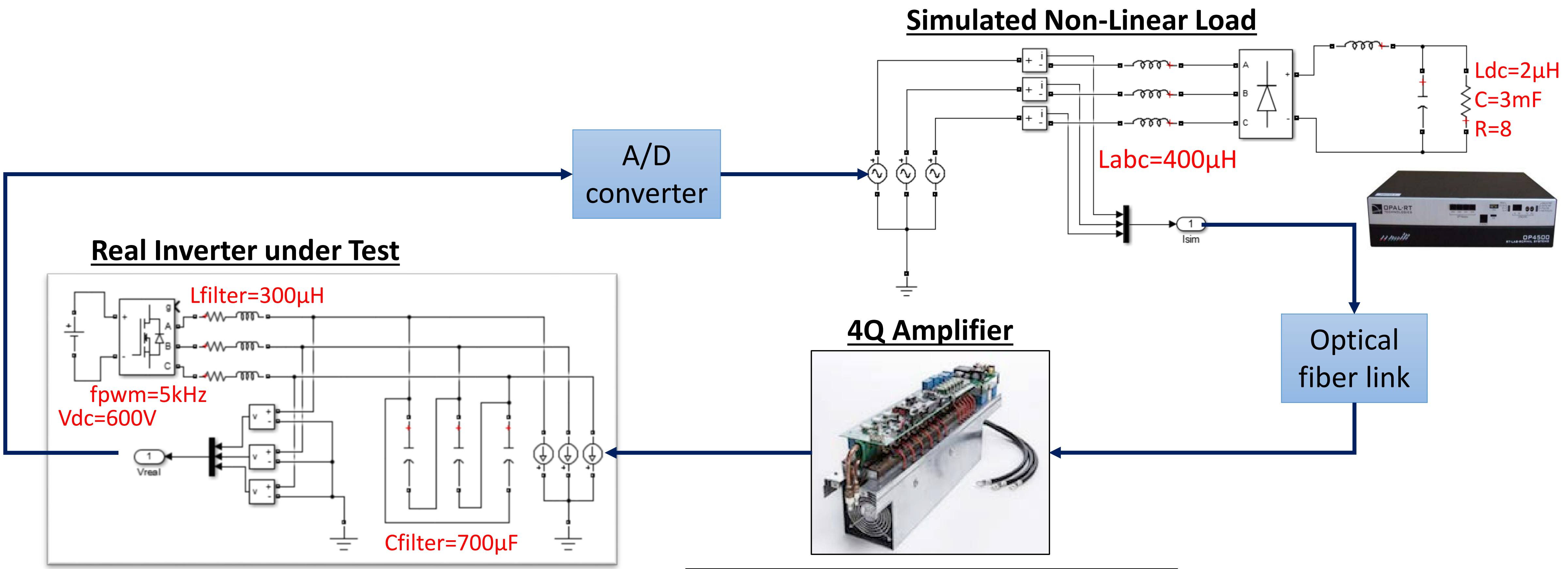
- Presentation of the Test Case
  - Test Circuit Diagram for Theoretical Analysis
  - PHIL Setup
- Stability Analysis, Gain Margin, Phase Margin
- Accuracy (and Stability) Analysis VS System Poles Location
- Simulation of the PHIL Setup
- Conclusions (Part 1)

- Comparison of lab results with simulation
- Conclusion (Part 2)

Test Circuit Schematic Diagram



Power Hardware-in-the-Loop Setup



$$f_{ampli}(s) = \frac{(2 \cdot \pi \cdot f_n)^2}{s^2 + 2 \cdot \xi \cdot 2 \cdot \pi \cdot f_n + (2 \cdot \pi \cdot f_n)^2}$$

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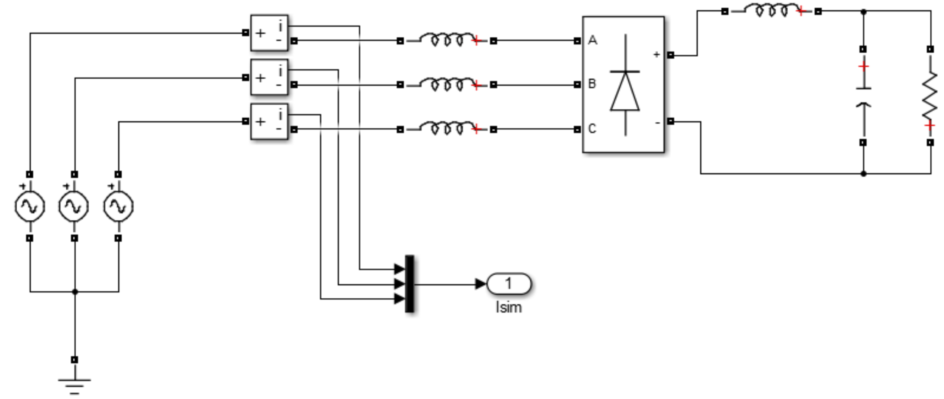
Stability Analysis – Transfer Functions

Simulated model



$$I1_{Sim} = C_{I1}(AX + BU) + D_{I1}U$$

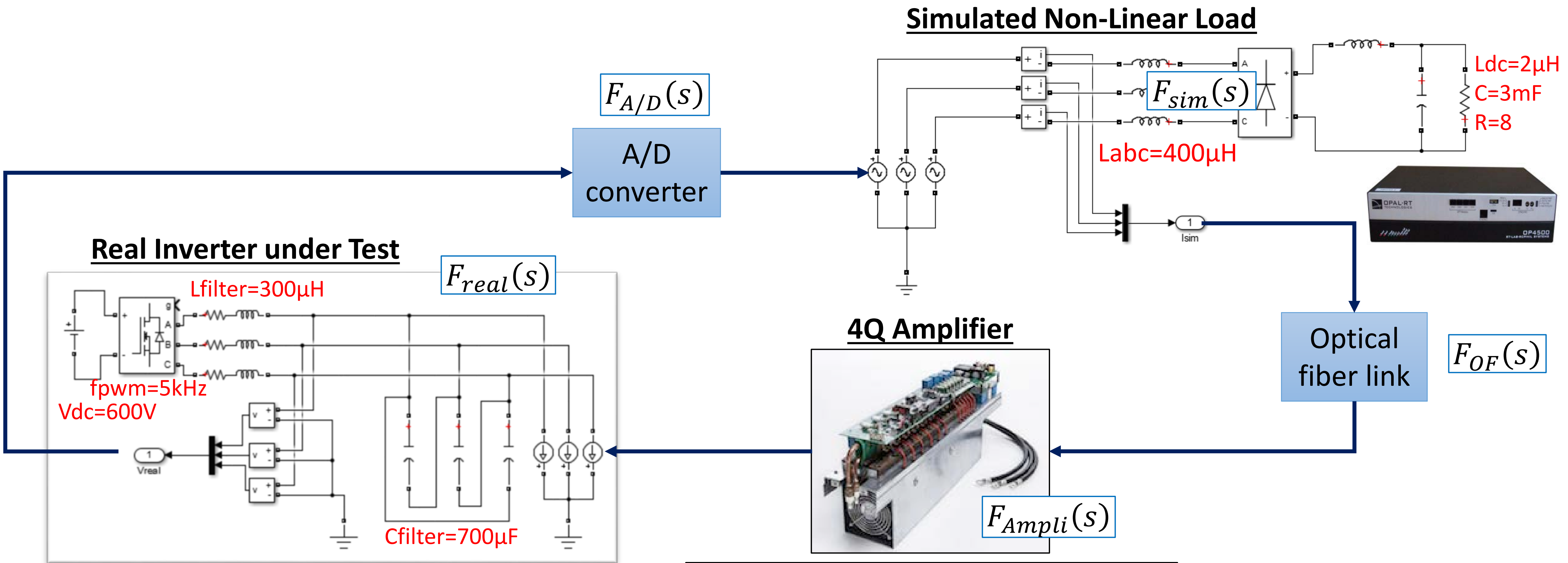
Where X and U are vectors

This system can be analysed as a multiple inputs single output system; current measurement I1.

$$I1_{Sim} = C_{I1}AX + C_{I1}B_{V1,V2,V3}\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} + D_{I1}\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} \Rightarrow I1_{Sim} = C_{I1}A_{V1}X + C_{I1}B_{V1}V1 + D_{V1}V1$$

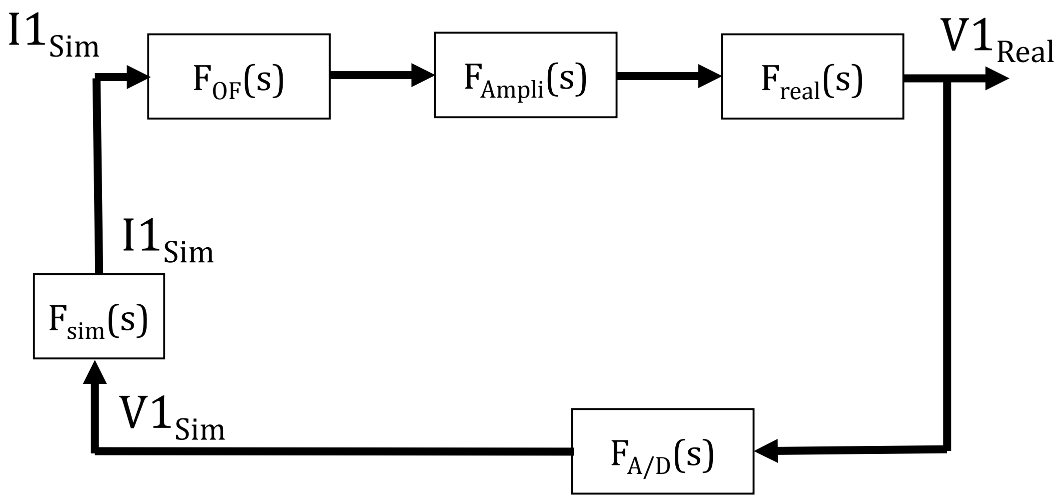
$$F_{sim} = H(s) = \frac{Y(s)}{U(s)} = C_{I1}(sI - A_{V1})^{-1}B_{V1} + D_{I1}$$

Stability Analysis – Transfer Functions

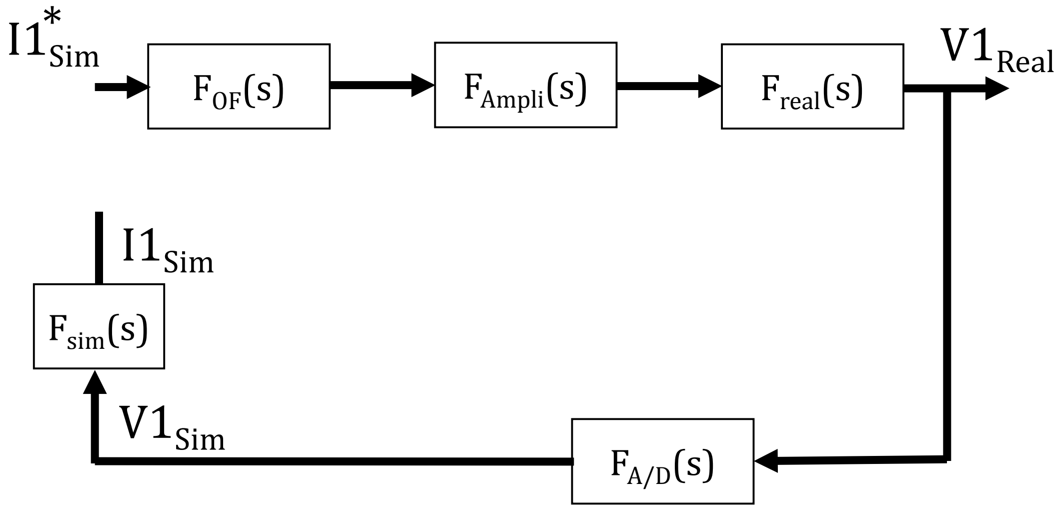


$$f_{ampli}(s) = \frac{(2 \cdot \pi \cdot f_n)^2}{s^2 + 2 \cdot \xi \cdot 2 \cdot \pi \cdot f_n + (2 \cdot \pi \cdot f_n)^2}$$

Stability Analysis – Transfer Functions

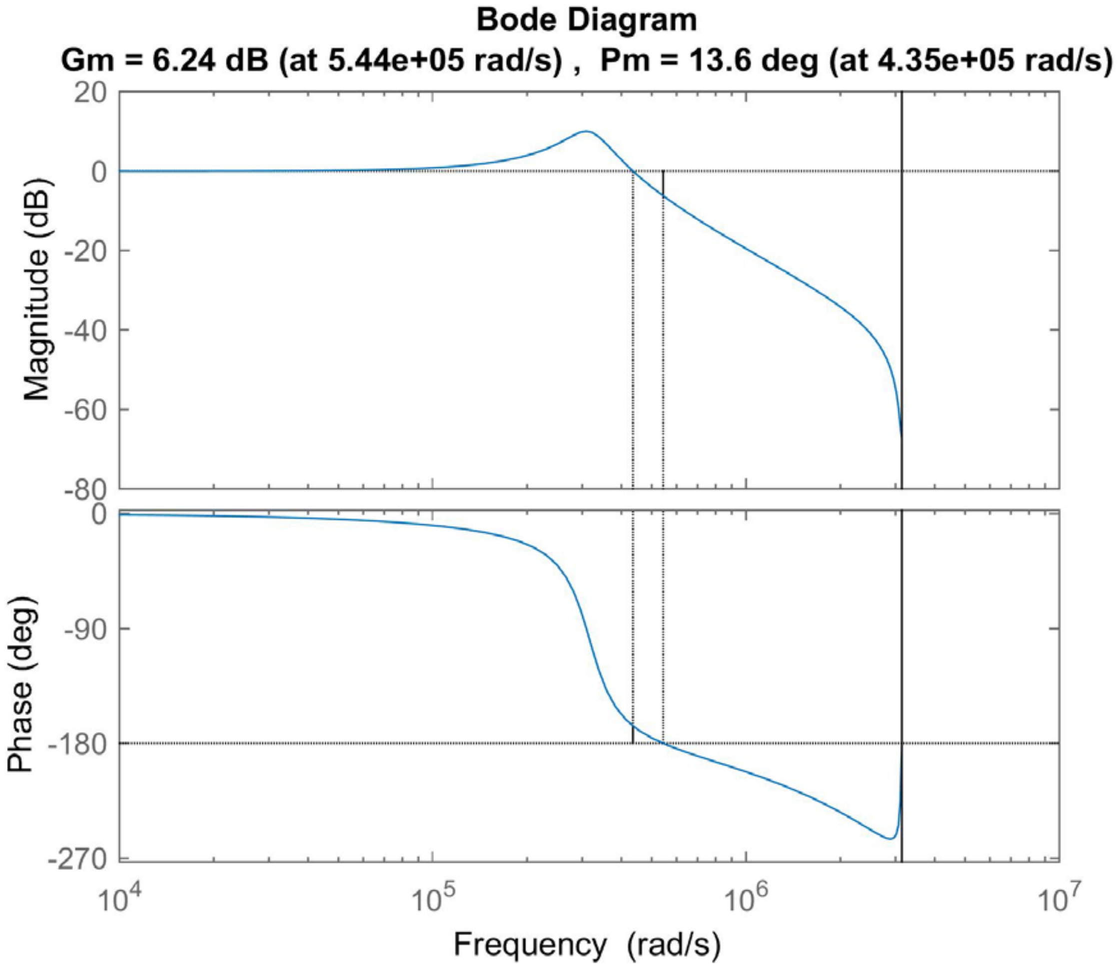


Stability Analysis – Transfer Functions

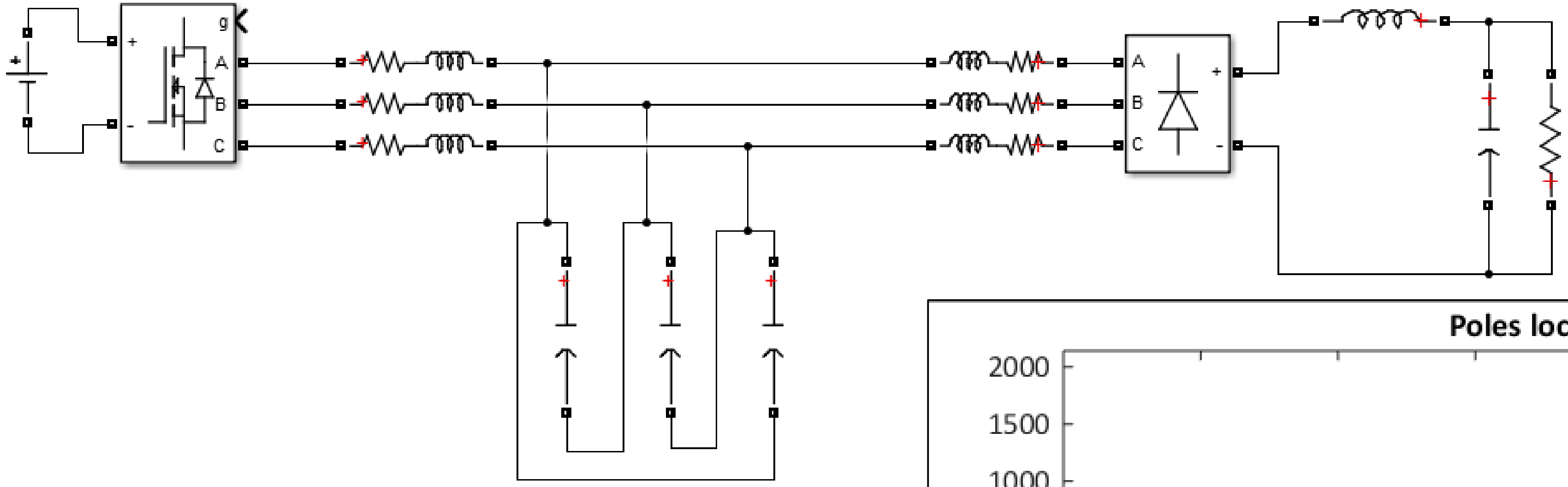


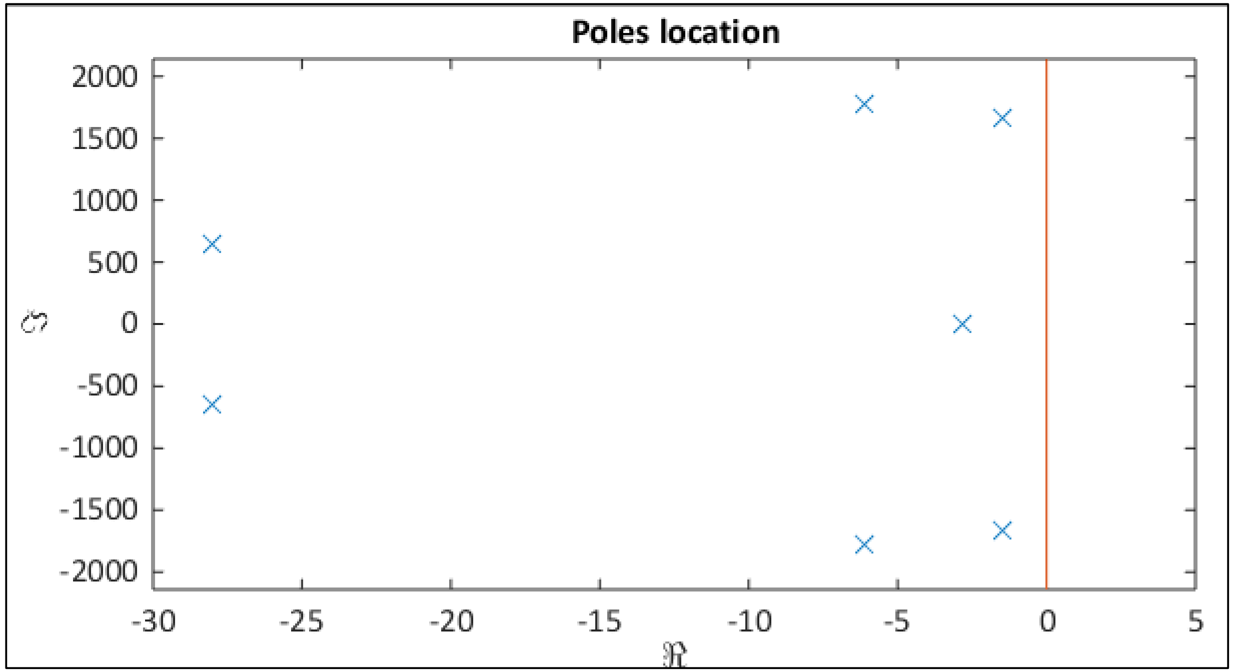
$$\frac{I1^*_{sim}}{I1_{sim}} = F_{OF}(s) \cdot F_{Ampli}(s) \cdot F_{real}(s) \cdot F_{A/D}(s) \cdot F_{sim}(s)$$

Stability Analysis – Bode Diagram, GM and PM

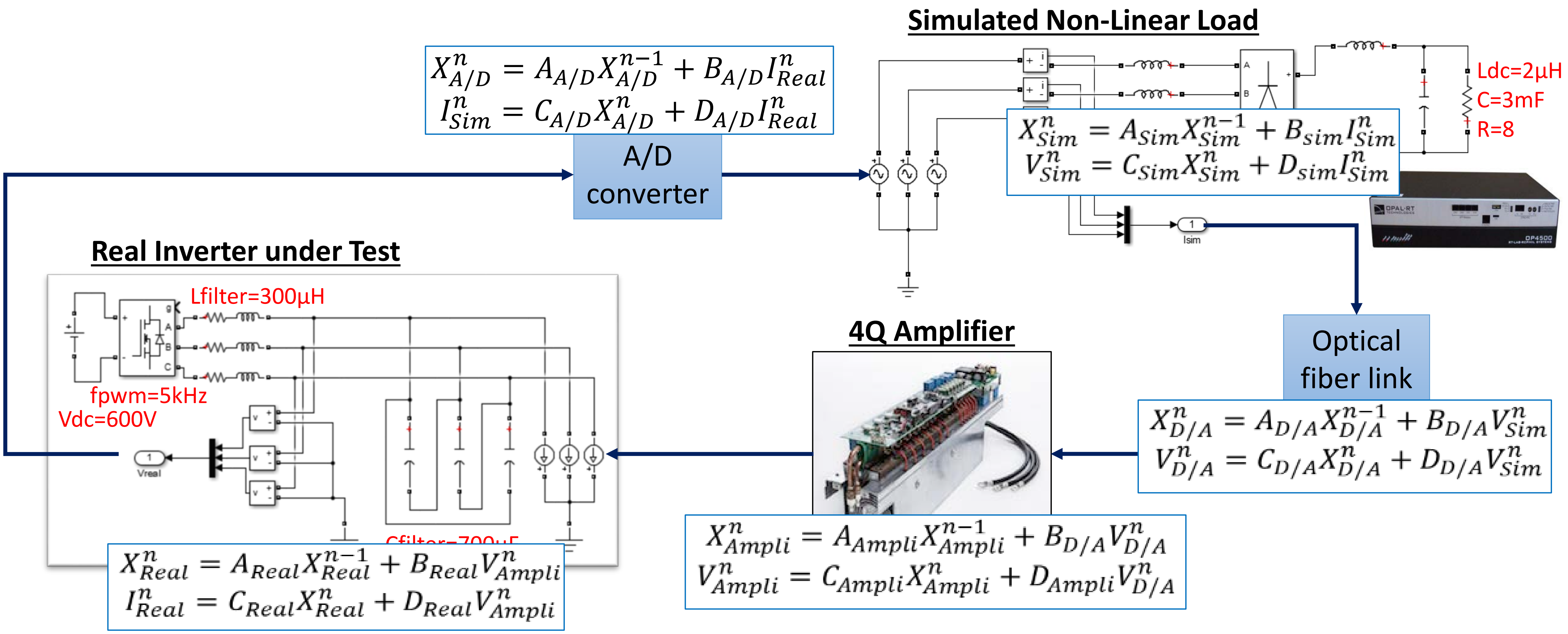


Accuracy Analysis – Continuous Poles of the "Ideal" System





Accuracy Analysis – Discrete State-Spaces (Multi-Rate)



Accuracy Analysis – Discrete State-Spaces (Multi-Rate)

$$
\begin{bmatrix} X_{Sim}^{n} \\ I_{Sim}^{n} \\ X_{OF}^{n} \\ I_{OF}^{n} \\ X_{Ampli}^{n} \\ V_{Ampli}^{n} \\ X_{Real}^{n} \\ V_{Real}^{n} \\ X_{A/D}^{n} \\ V_{Sim}^{n} \end{bmatrix}
=
\overbrace{\begin{bmatrix}
A_{Sim} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{sim} \\
C_{sim}A_{sim} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{sim}B_{sim} + D_{sim} \\
0 & B_{OF} & A_{OF} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & C_{OF}B_{OF} + D_{OF} & C_{OF}A_{OF} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & B_{Ampli} & A_{Ampli} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & C_{Ampli}B_{Ampli} + D_{Ampli} & C_{Ampli}A_{Ampli} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & B_{Real} & A_{Real} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & C_{Real}B_{Real} + D_{Real} & C_{Real}A_{Real} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{A/D} & A_{A/D} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & C_{A/D}B_{A/D} + D_{A/D} & C_{A/D}A_{A/D} & 0
\end{bmatrix}}^{A_{PHIL}}
\begin{bmatrix} X_{Sim}^{n-1} \\ I_{Sim}^{n-1} \\ X_{OF}^{n-1} \\ I_{OF}^{n-1} \\ X_{Ampli}^{n-1} \\ V_{Ampli}^{n-1} \\ X_{Real}^{n-1} \\ V_{Real}^{n-1} \\ X_{A/D}^{n-1} \\ V_{Sim}^{n-1} \end{bmatrix}
$$

Accuracy Analysis – Discrete State-Spaces (Linearizing at Single-Rate)

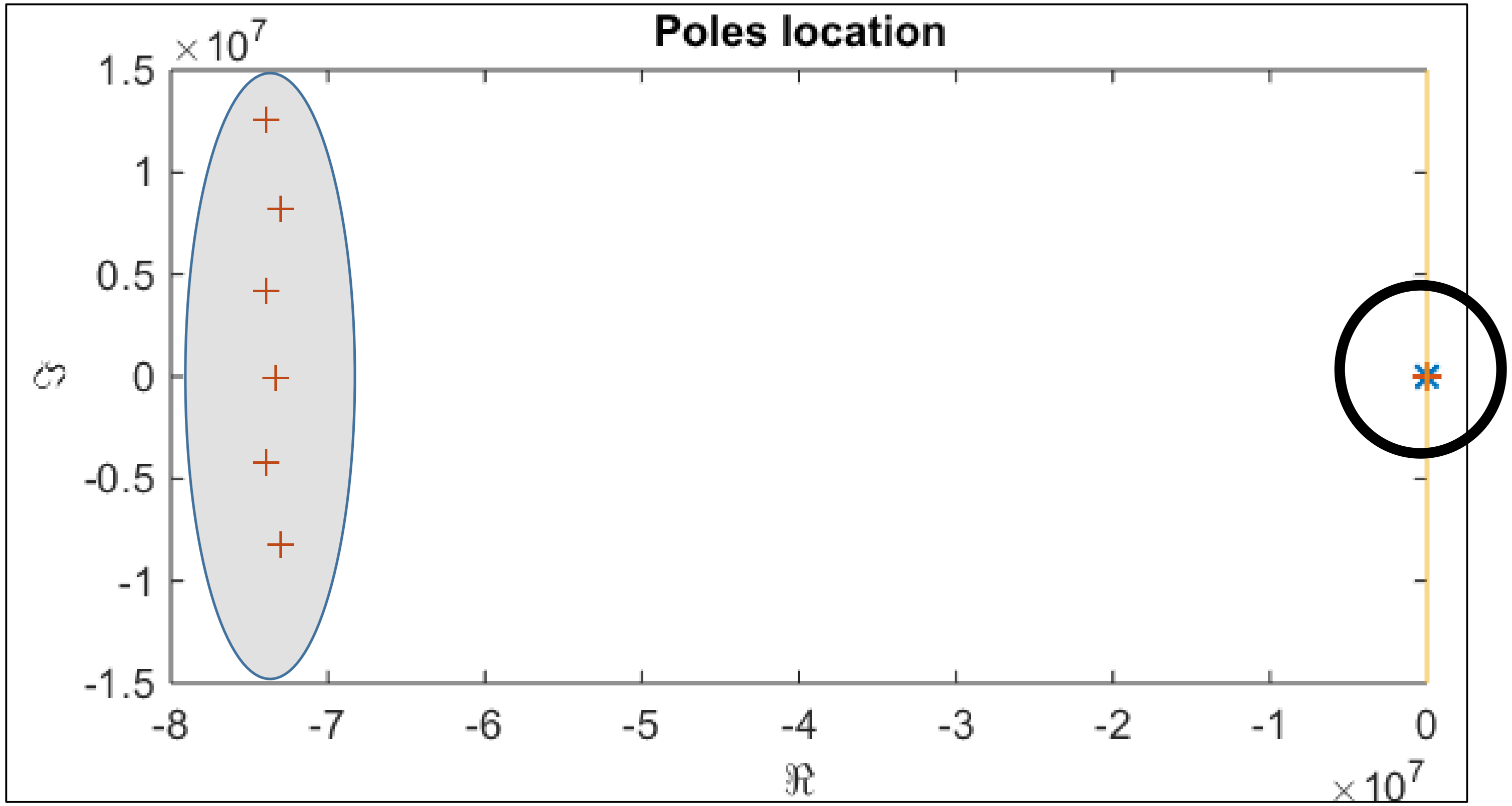
$$\begin{matrix} T_{Sim} \\ \\ T_{OF} \\ \\ T_{Ampli} \\ \\ T_{Real} \\ \\ T_{A/D} \\ \\ \end{matrix} \quad \begin{bmatrix} X_{Sim}^{n} \\ I_{Sim}^{n} \\ X_{OF}^{n} \\ I_{OF}^{n} \\ X_{Ampli}^{n} \\ V_{Ampli}^{n} \\ X_{Real}^{n} \\ V_{Real}^{n} \\ X_{A/D}^{n} \\ V_{Sim}^{n} \end{bmatrix} = A_{PHIL}^{MR} \begin{bmatrix} X_{Sim}^{n-1} \\ I_{Sim}^{n-1} \\ X_{OF}^{n-1} \\ I_{OF}^{n-1} \\ X_{Ampli}^{n-1} \\ V_{Ampli}^{n-1} \\ X_{Real}^{n-1} \\ V_{Real}^{n-1} \\ X_{A/D}^{n-1} \\ V_{Sim}^{n-1} \end{bmatrix}$$

$$A_{PHIL}^{SR} = M_{\varrho} A_{PHIL}^{MR} + I - M_{\varrho}$$

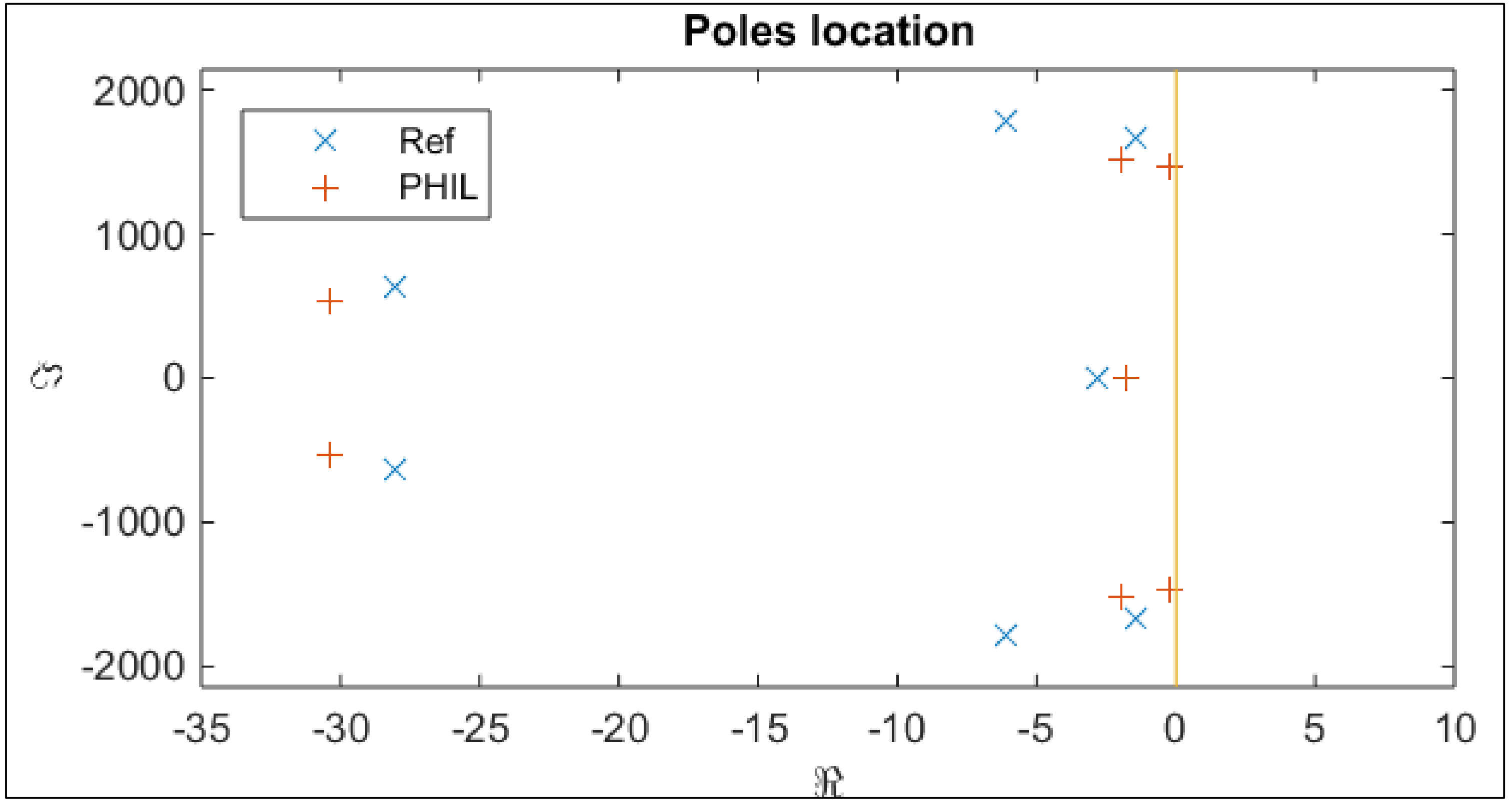
$$M_{\varrho} = \begin{bmatrix} \frac{T_{Real}}{T_{Sim}} & 0 & 0 & 0 & 0 \\ 0 & \frac{T_{Real}}{T_{OF}} & 0 & 0 & 0 \\ 0 & 0 & \frac{T_{Real}}{T_{Ampli}} & 0 & 0 \\ 0 & 0 & 0 & \frac{T_{Real}}{T_{Real}} & 0 \\ 0 & 0 & 0 & 0 & \frac{T_{Real}}{T_{A/D}} \end{bmatrix}$$

L. A. Gregoire; H. Fortin-Blanchette; J. Belanger; K. Al-Haddad, "A Stability and Accuracy Validation Method for Multi-Rate Digital Simulation," in IEEE Transactions on Industrial Informatics , vol.PP, no.99, pp.1-1

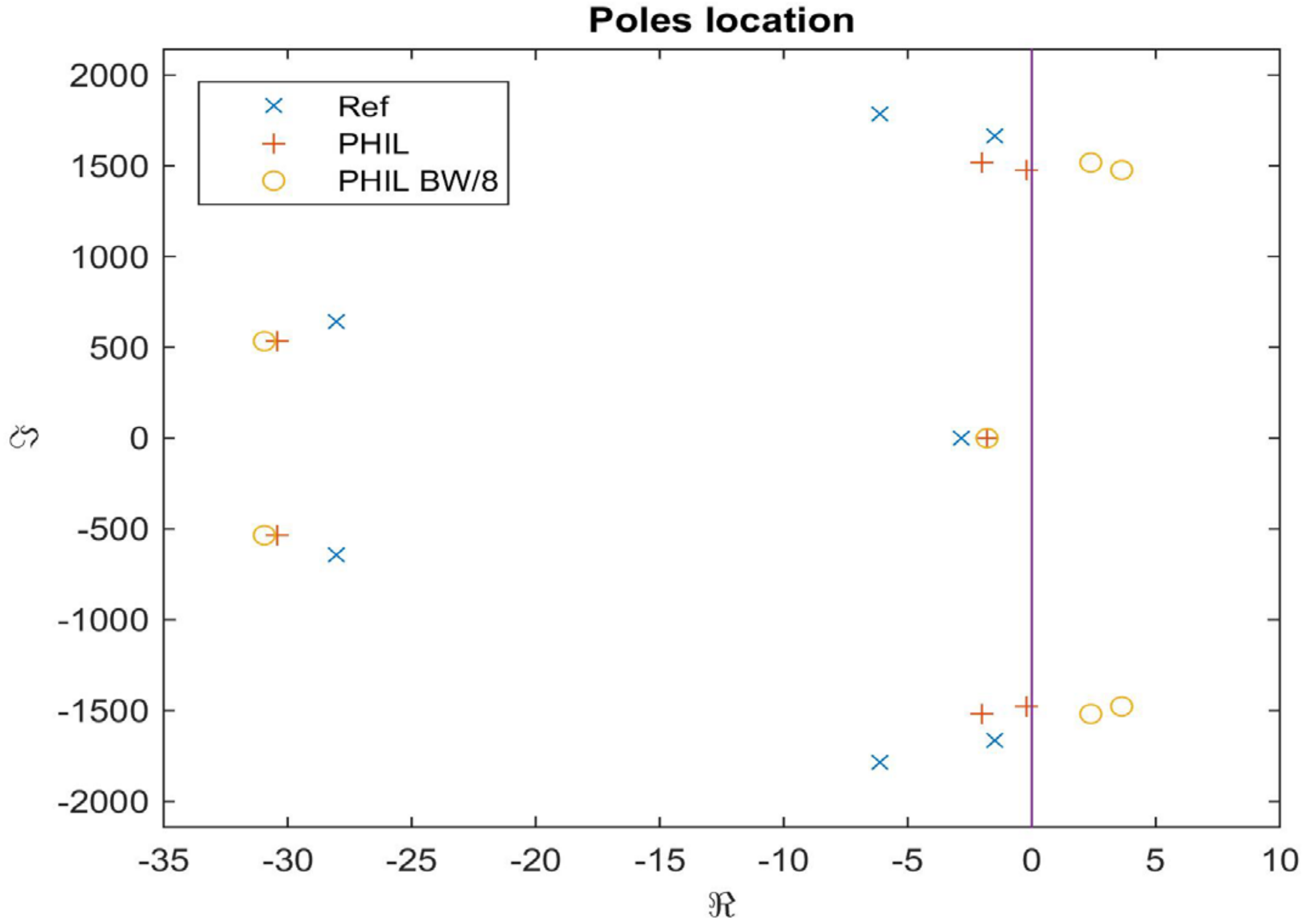
Accuracy Analysis – Equiv. Continuous Poles of the PHIL Setup



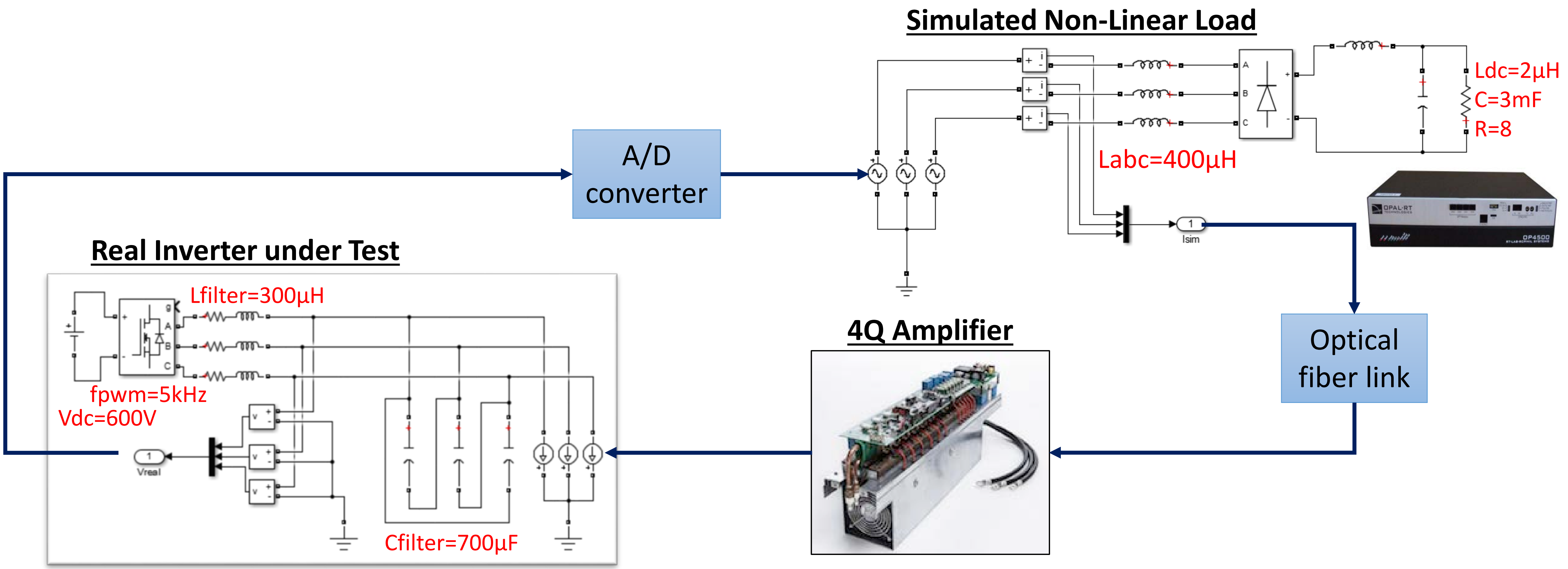
Accuracy Analysis – Ideal VS PHIL Simulation Poles



Accuracy Analysis – Ideal VS PHIL Poles (Effect of 4Q Amp BW)

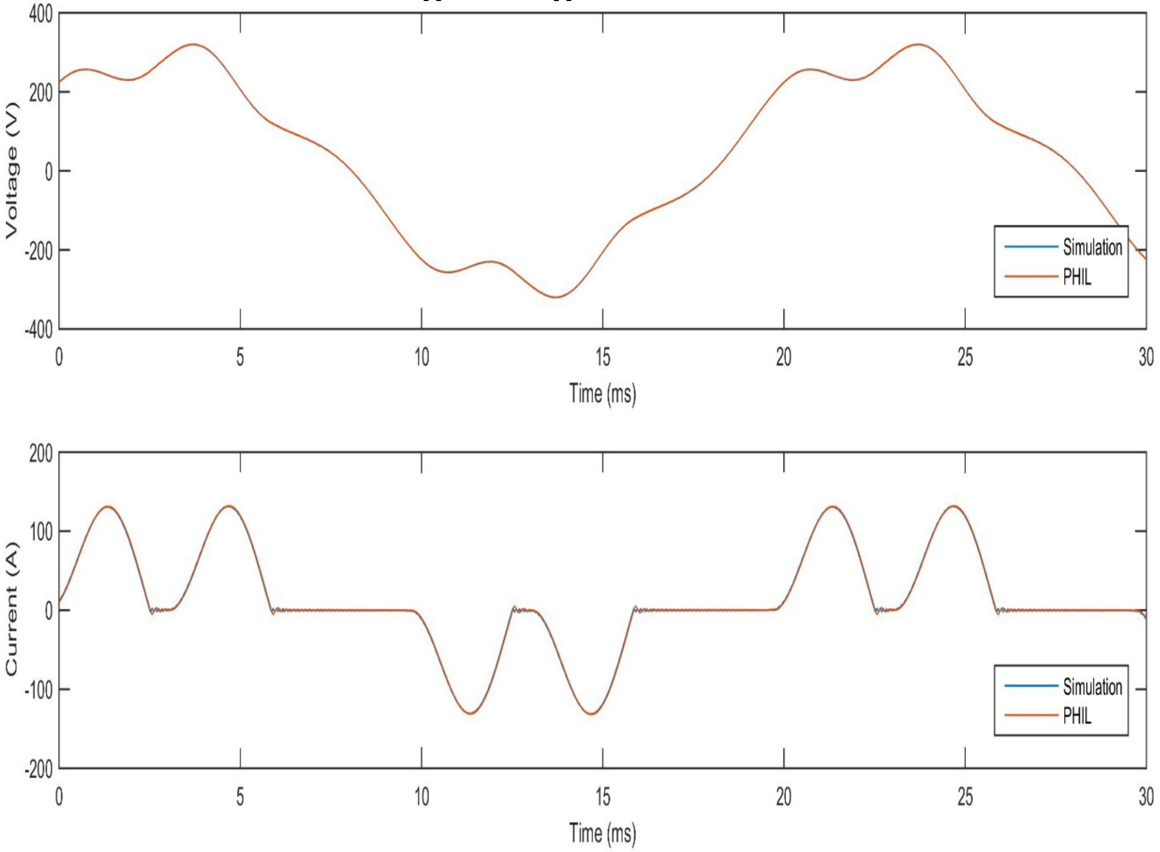


Time domain simulation of the PHIL Setup

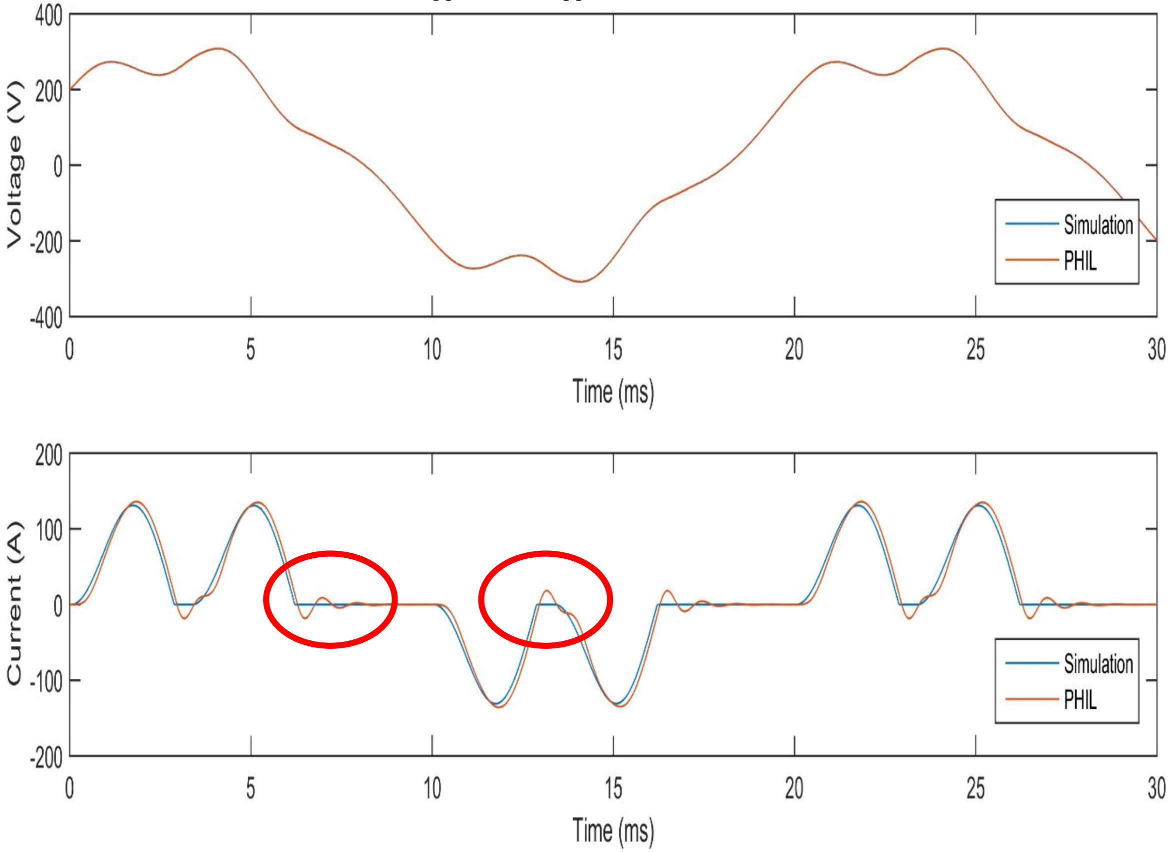


Simulation of the PHIL setup for Validation of Design Criteria

Bandwidth ($f_n = \omega_n/(2\pi)$) = 4 kHz

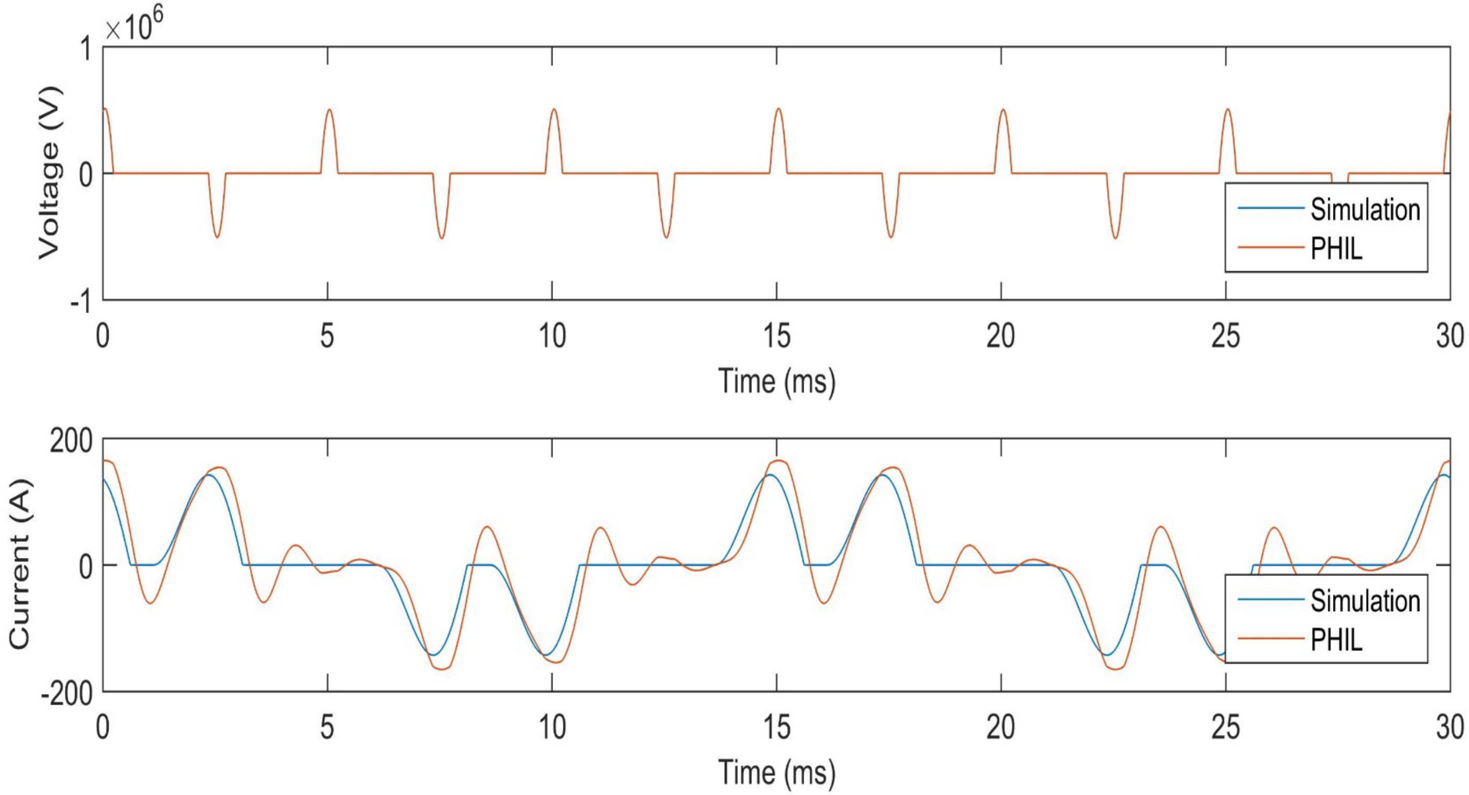


Bandwidth ($f_n = \omega_n/(2\pi)$) = 2 kHz



Simulation of the PHIL setup for Validation of Design Criteria

Bandwidth ($f_n = \omega_n/(2\pi)$) = 500 Hz



Conclusions (Part 1)

- Stability and accuracy analysis could be done using PM, GM and pole location assessment and possibly other analytical techniques
- But stability and accuracy are best assessed through simulation of the PHIL setup
  - The different sampling rates are taken into account
  - The delays are taken into account
- Amplifier bandwidth has an important impact on system accuracy, but also stability
  - Same for delays in the loop

eHS all-software simulation
VS
eHS-driven real-world emulation

Comparison of simulation and measured results

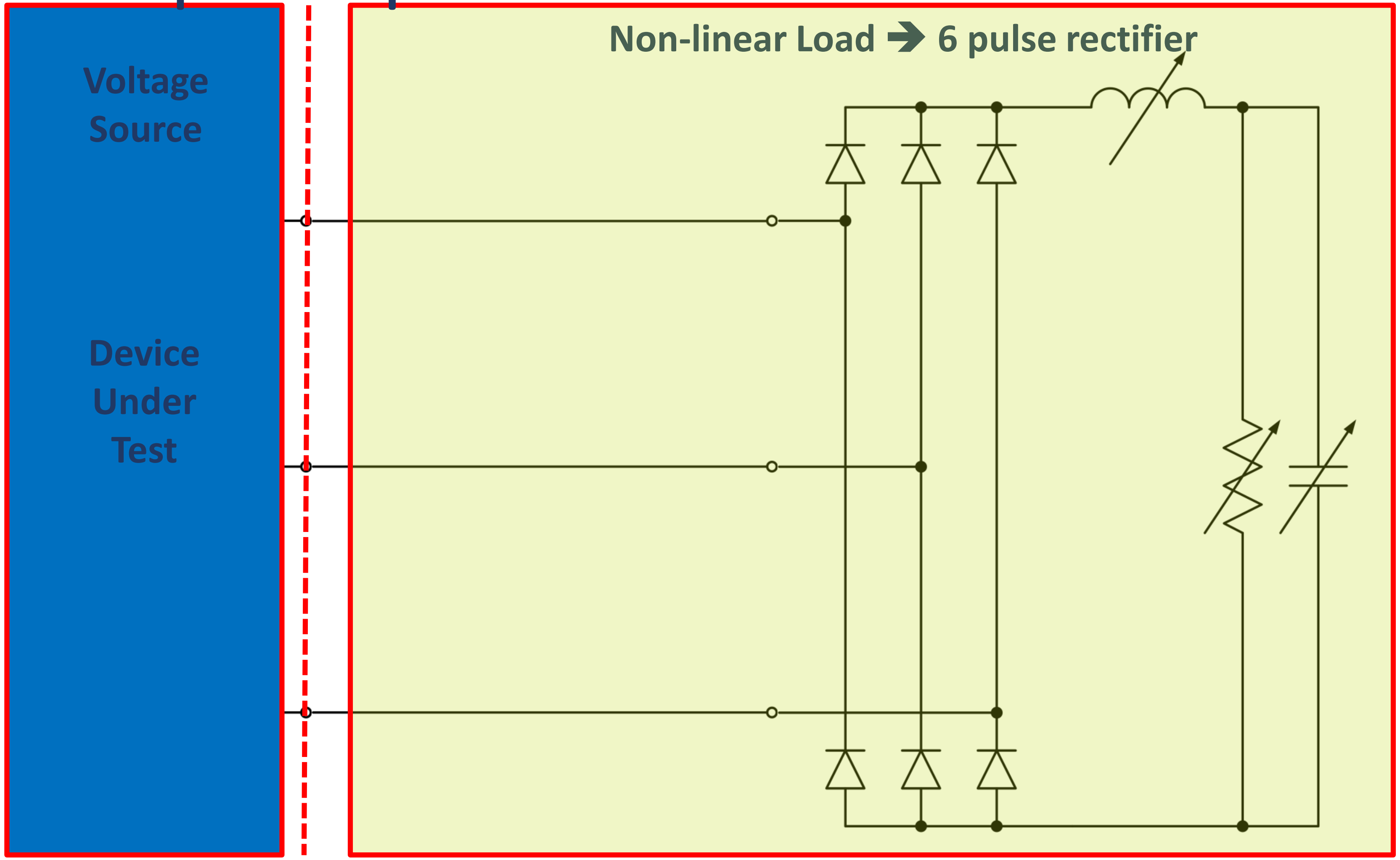
PHIL practical case study in a nutshell

- Case study: highly non-linear load P-HIL emulation:
- A comparison between simulation and a P-HIL emulation with a 100 kVA high bandwidth power amplifier
- Conclusions: simulation VS measured results

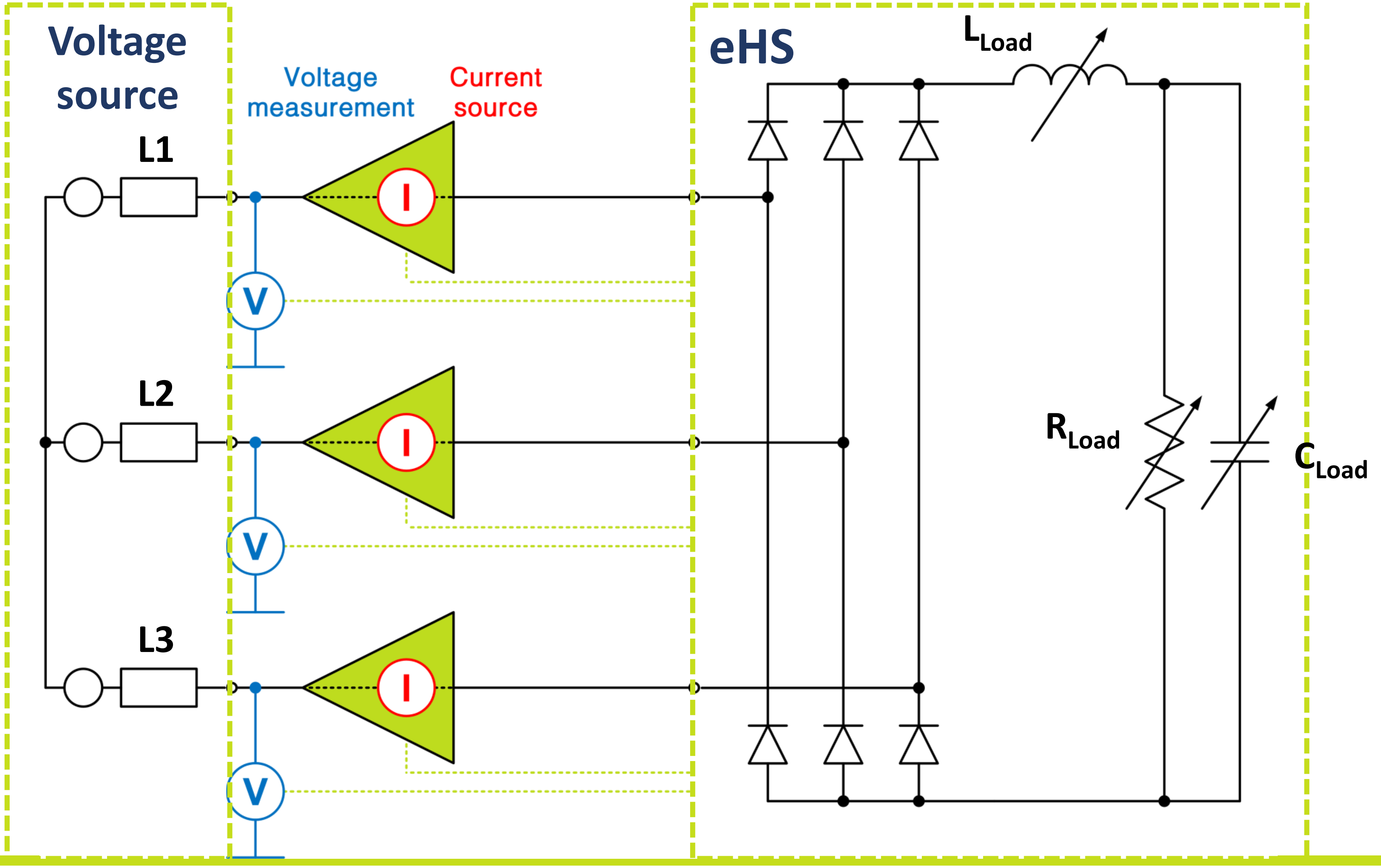
Scope of experimental work

- **Requirements**
  - Emulation of a highly non-linear load
  - Simple model / tradition topology
  - Adjustable distortions
- **Selected topology**
  - 6-pulse rectifier
- **Goal**
  - Demonstrate a feasible operation area
  - Show limitations & restrictions
- **Use case**
  - Test tolerance of real world devices in realistic scenarios when operated with non-linear load

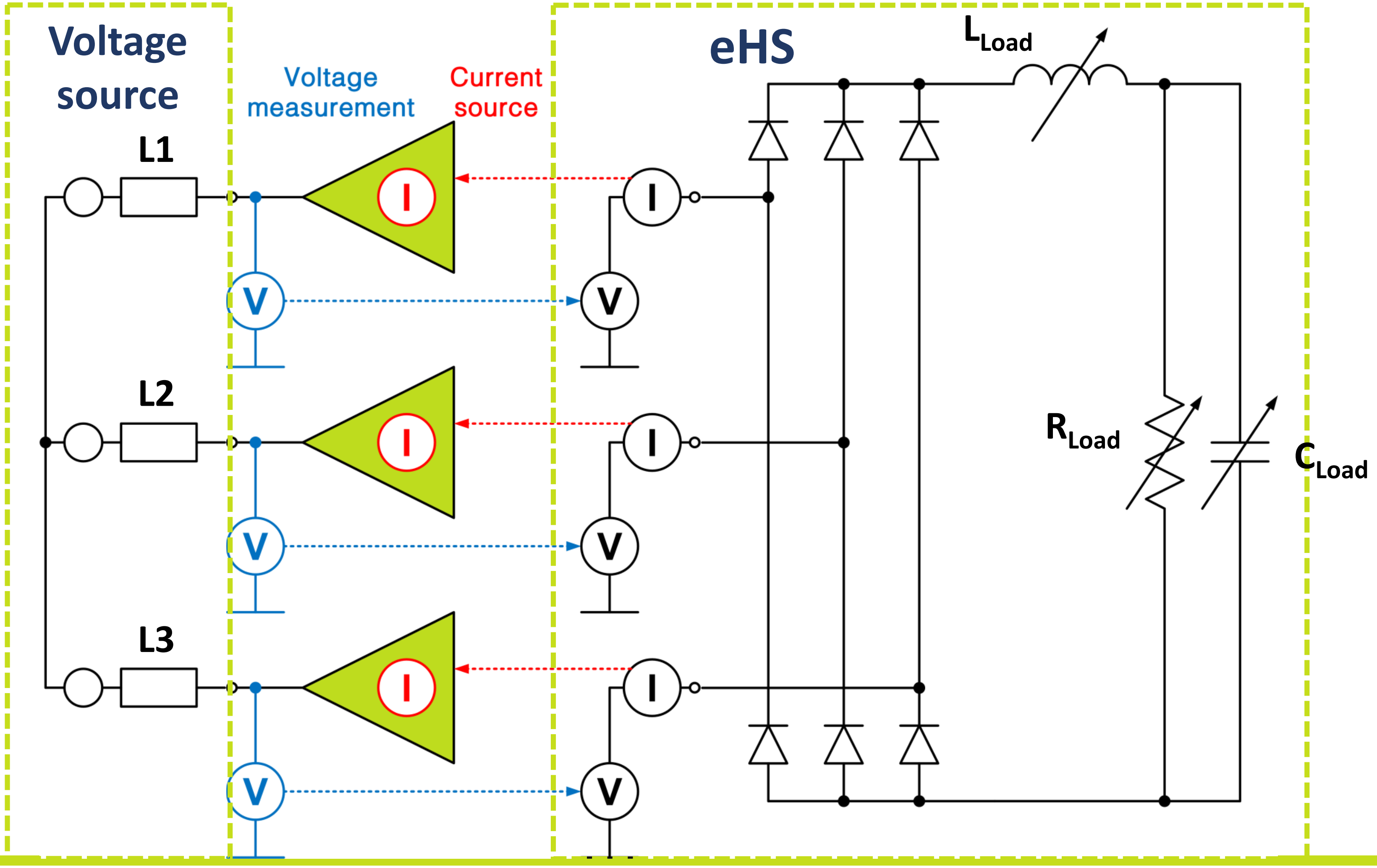
P-HIL Test Setup - simplified



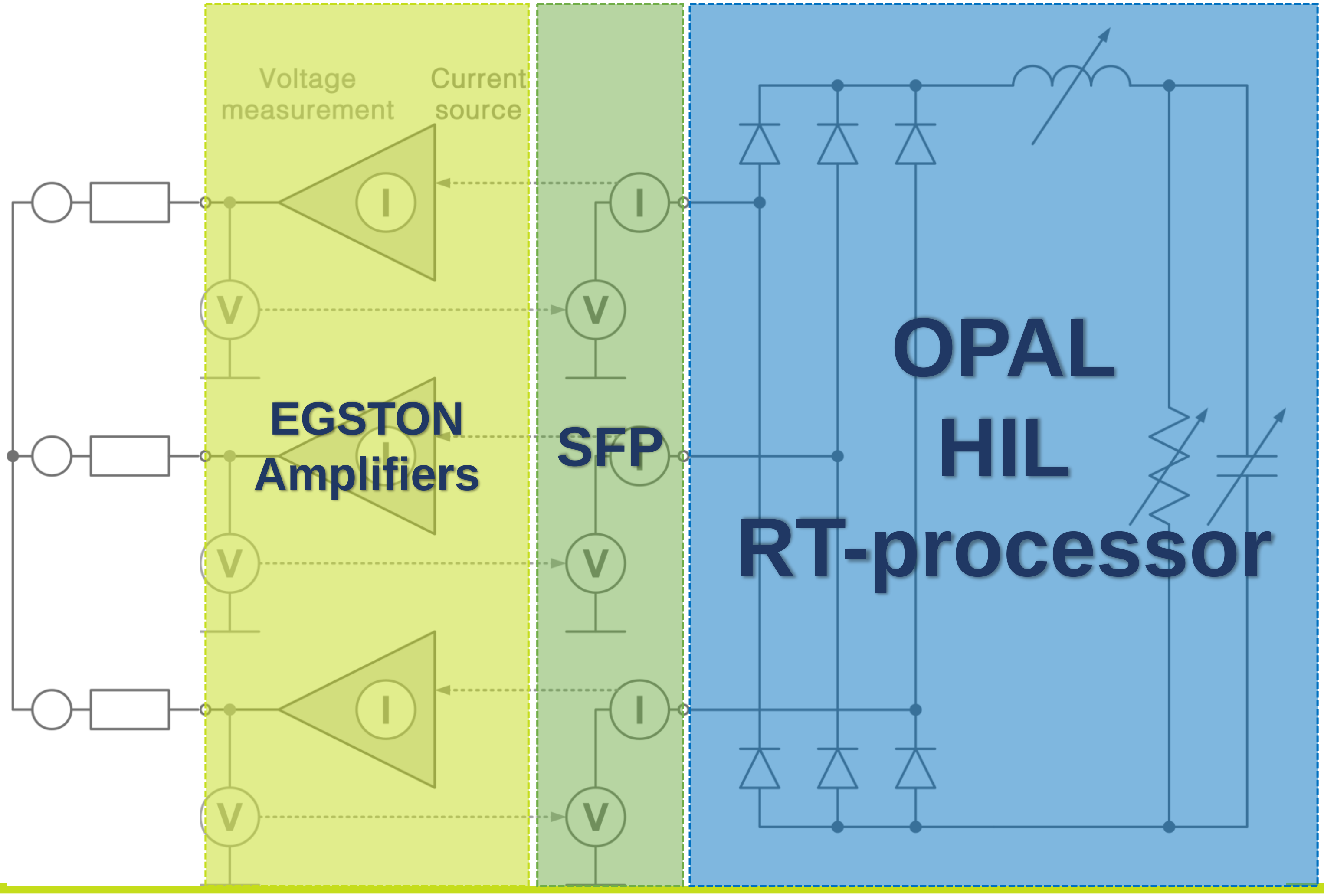
P-HIL Test Setup with eHS simulation



P-HIL Test Setup with eHS simulation



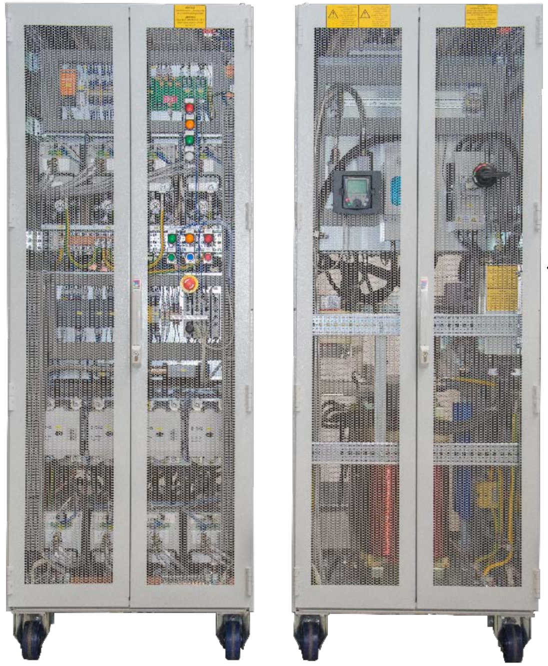
P-HIL Test Setup with eHS simulation



Physical Setup

Device under test

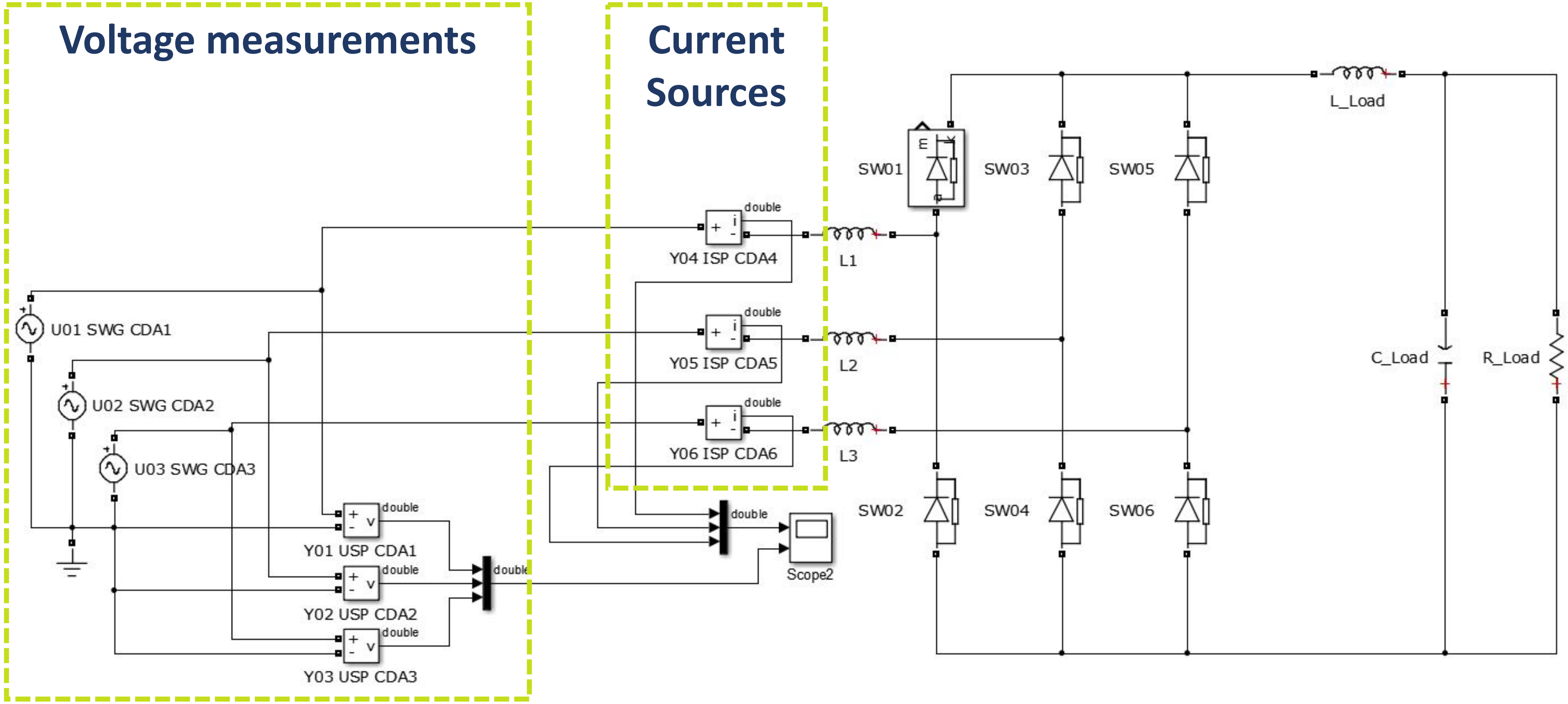
EGSTON
COMPISO Digital Amplifier



SFP
5 Gbps

OPAL-RT
Real-time processor

eHS model of non-linear load



eHS model of non-linear load

Operation modes:

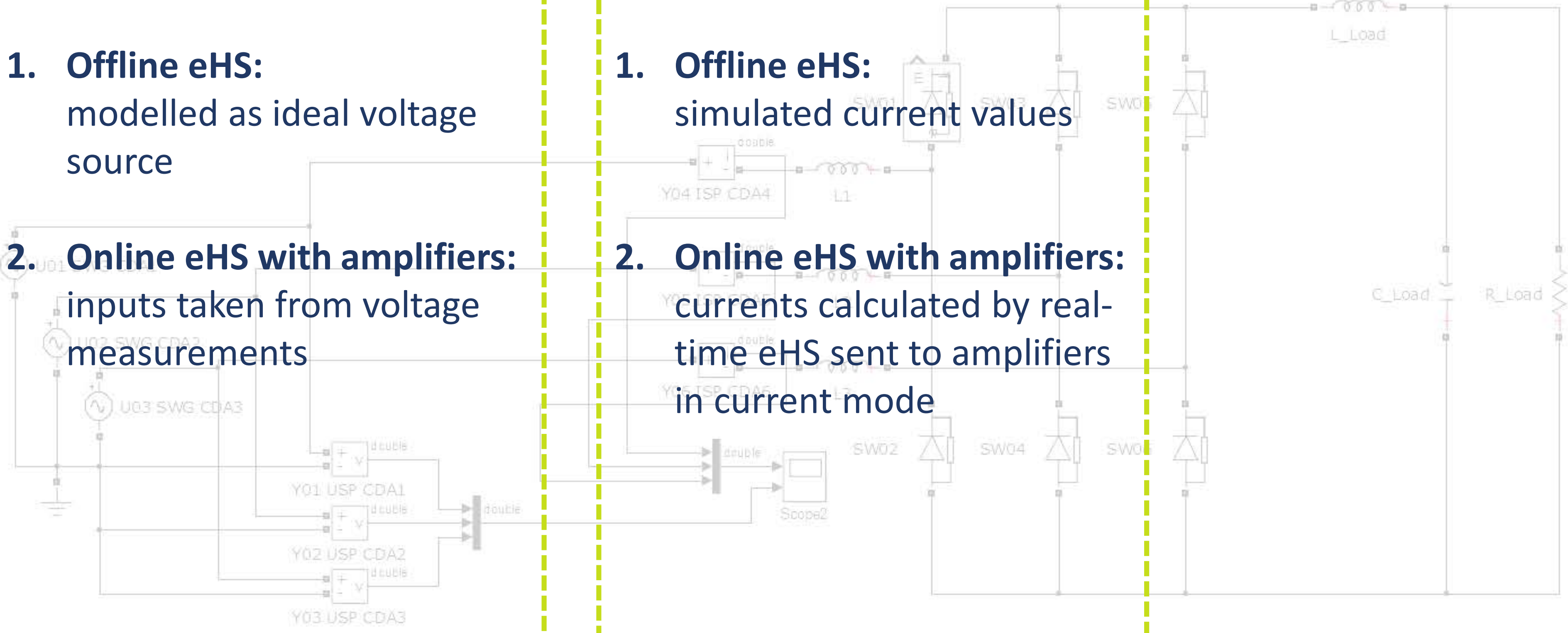
1. **Offline eHS:**
   modelled as ideal voltage source

2. **Online eHS with amplifiers:**
   inputs taken from voltage measurements

Operation modes:

1. **Offline eHS:**
   simulated current values

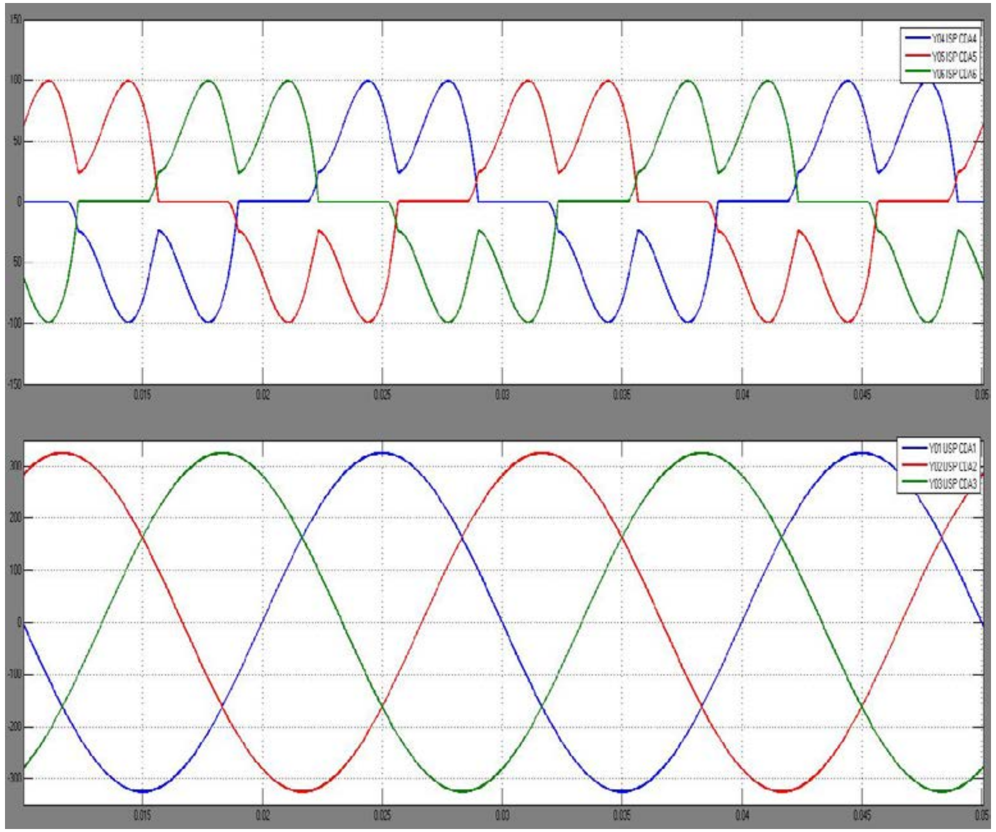
2. **Online eHS with amplifiers:**
   currents calculated by real-time eHS sent to amplifiers in current mode

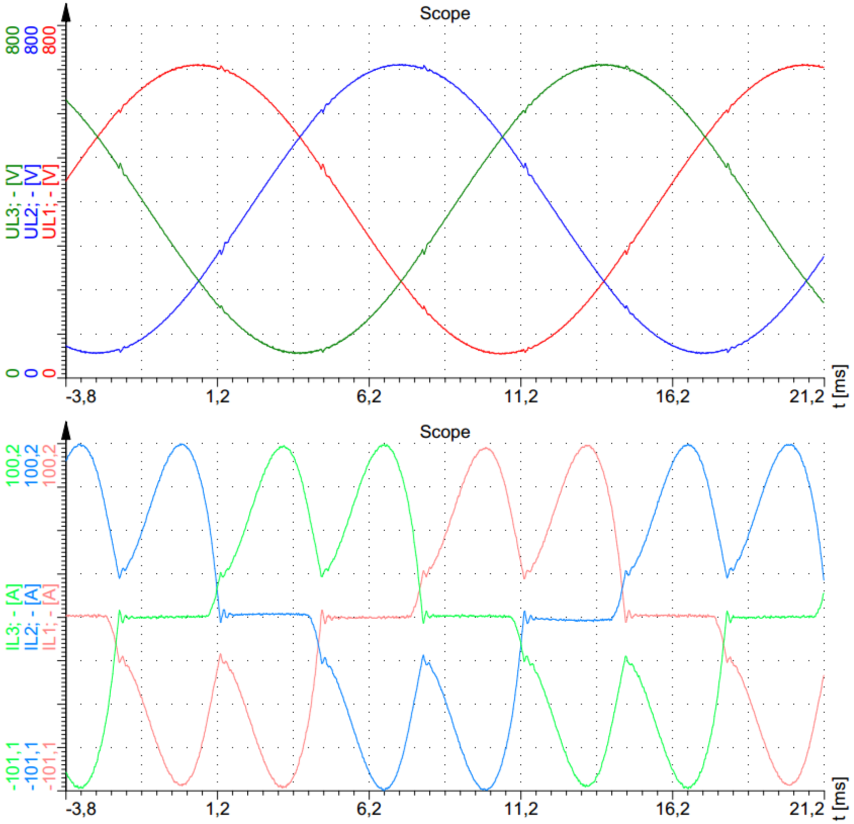


50 Hz - eHS simulation VS real setup results

Component values: L1 = L2 = L3 = 0.4mH f = 50Hz

R_{Load} = 8Ω L_{Load} = 2µH C_{Load} = 2mF

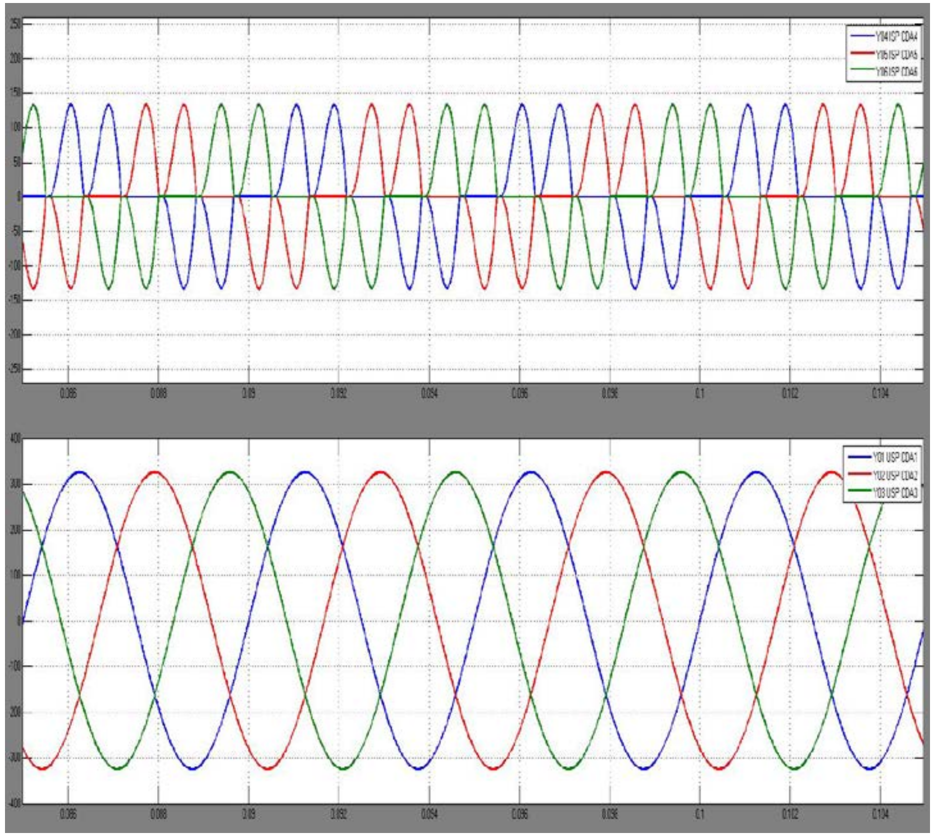


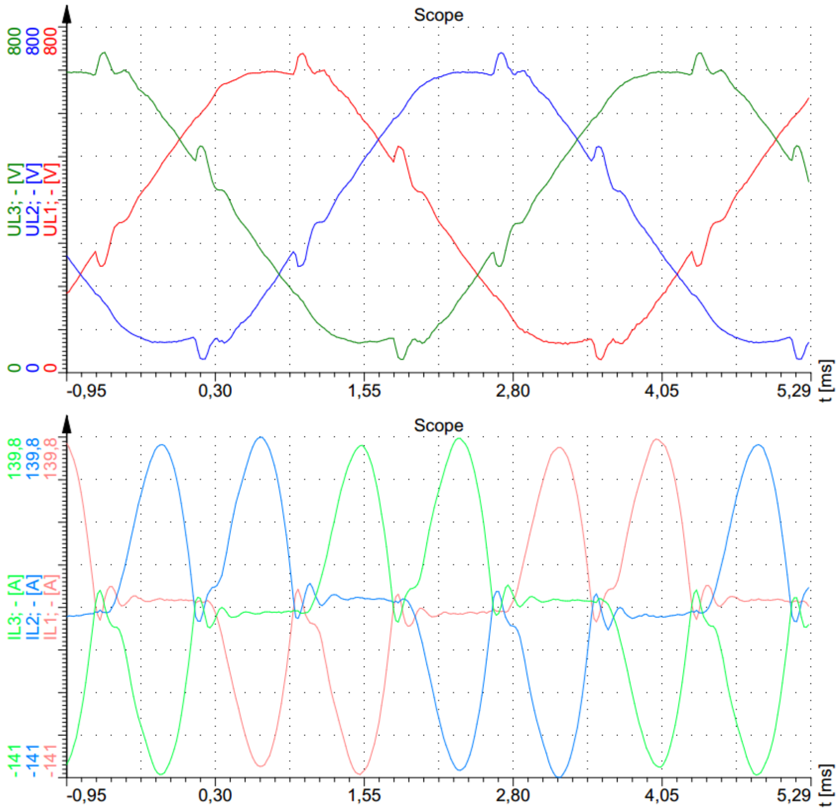


200 Hz - eHS simulation VS real setup results

Component values: L1 = L2 = L3 = 50µH f = 200Hz

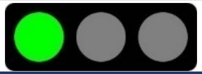
R_{Load} = 8Ω L_{Load} = 2µH C_{Load} = 500µF





Conclusions (Part 2)

- **System:** S = 100kVA, I_{MAX} = ±100A_{peak}
- **Qualitative analysis:**
  - At 50 Hz operating point, simulation matches measured results, also when varying the R,L,C on the load side
  - At 100 Hz operating point, there are visible mismatches, and THD can be observed in the voltage spectrum
  - At 200 Hz operating point, the mismatches are significant, and THD is much more pronounced in the voltage spectrum
  - At 400 Hz operating point, the deviation between simulation and measured results is very high, the voltage spectrum contains lots of harmonic distortions

			
f_{GRID}	**100Hz**	**200Hz**	**400Hz**