# Improving Power Hardware-in-the-loop Interfaces via Optimal Control

Jonathan Eid, Ashley Meagher

McGill University, Department of Mechanical Engineering

McGill

DECAR

OPAL-RT TECHNOLOGIES

Hydro Québec

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# The Power Hardware-in-the-loop Interfacing Problem

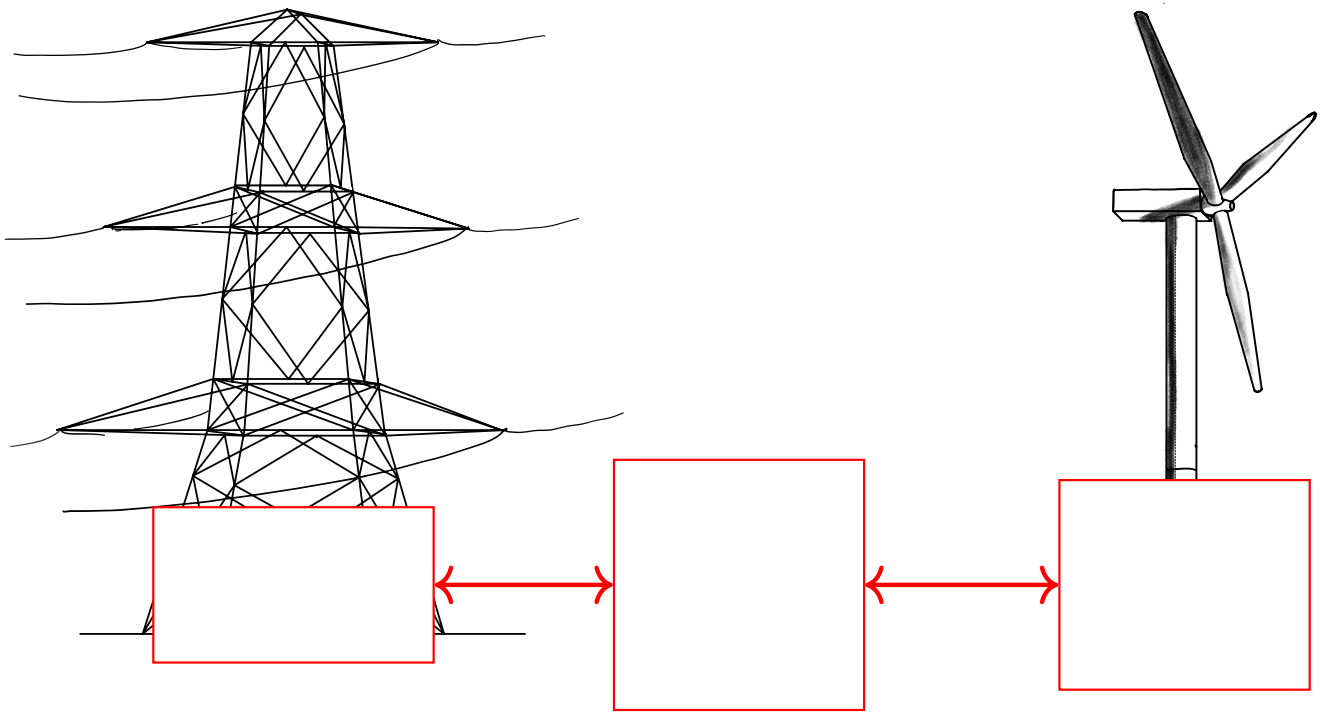

Figure 1: Power hardware-in-the-loop (PHIL) simulation.

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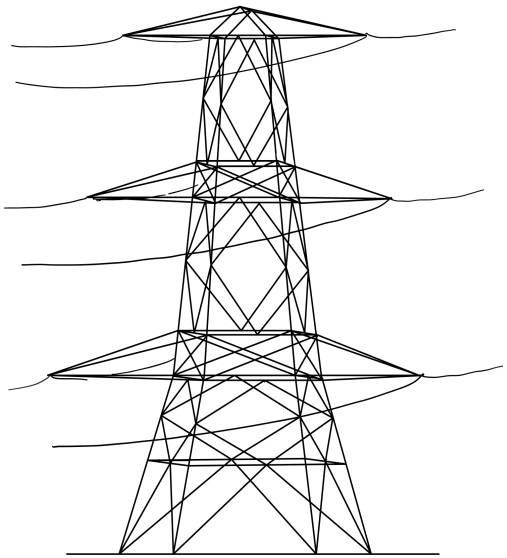
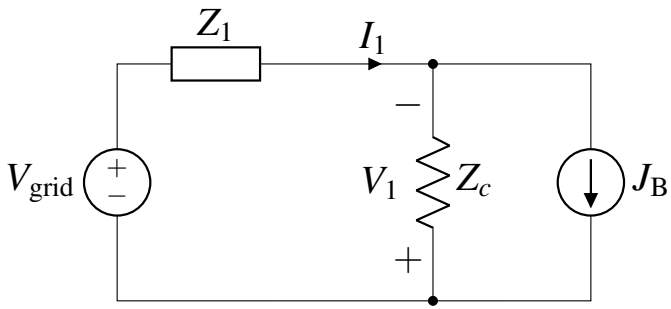


(a) Illustration of the simulated grid.




(b) Circuit model of the simulated grid.

Figure 2: The simulated grid.

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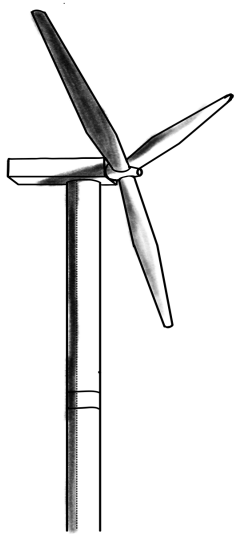
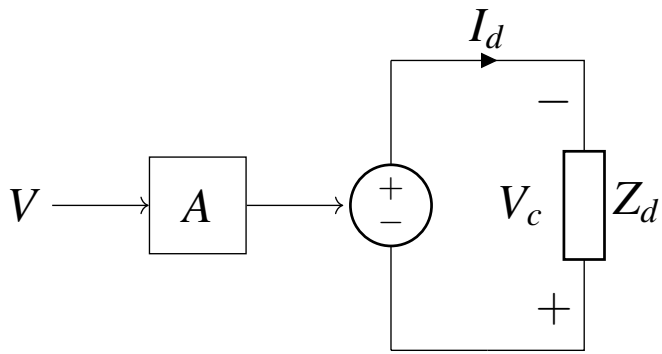


(a) Illustration of the device.




(b) Circuit model of the amplifier and device.

Figure 3: The amplifier and device under test.

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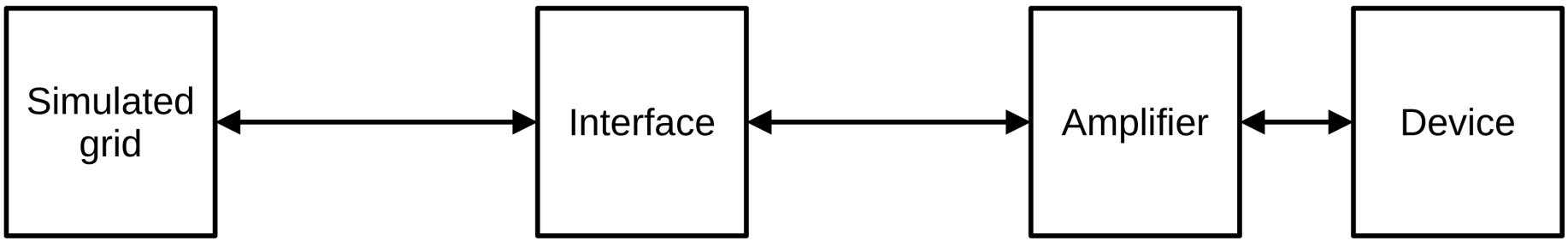


Figure 4: Illustration of a PHIL experimental setup.

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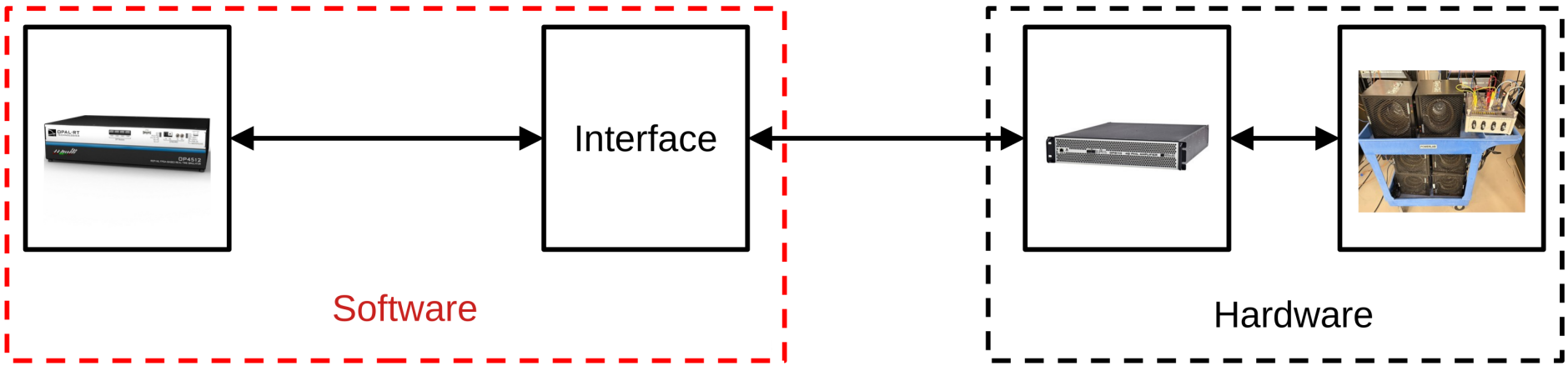


Figure 5: Illustration of a PHIL experimental setup.

[1] Images retrieved from https://tmesystems.net/RT-LAB, https://www.opal-rt.com/hardware/simulators/real-time-simulators/op4512/, and https://opal-rt.atlassian.net/wiki/spaces/PSSDD/pages/144647230/OP8110+4Q+Power+Amplifier.

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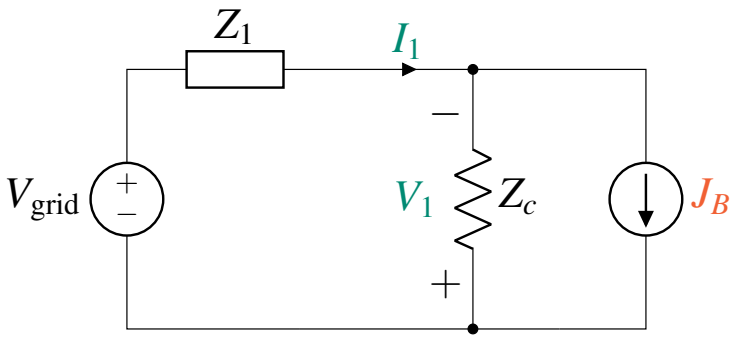


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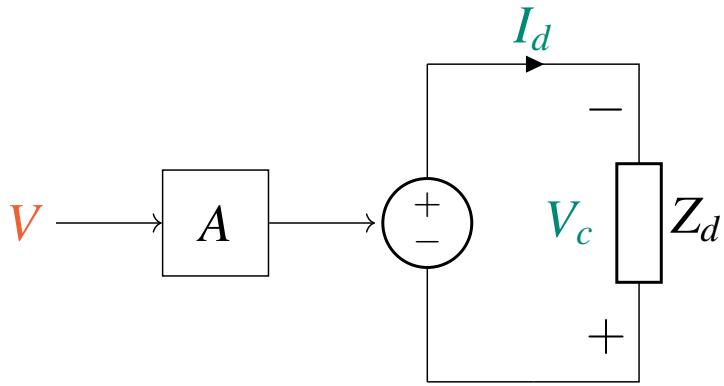


(b) Circuit model of the amplifier and device.

**Stable interface:** the measurement signals, $V_1$, $I_1$, $V_c$, and $I_d$, and actuation signals, $V$ and $J_B$, do not diverge.

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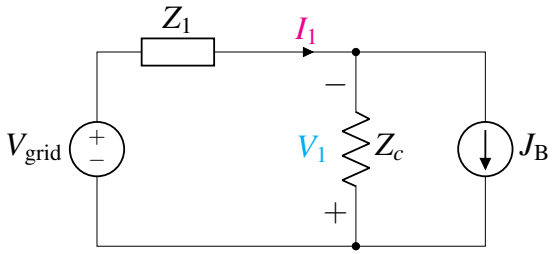


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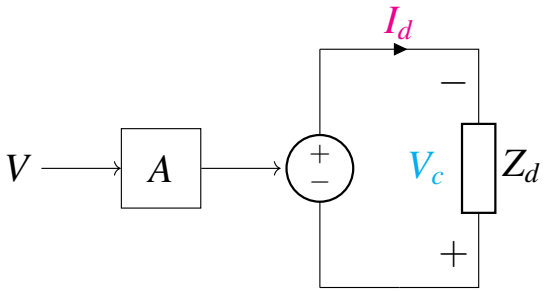


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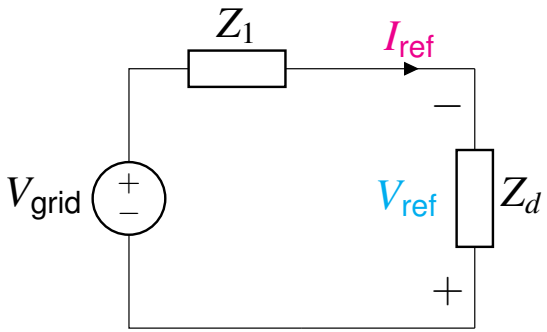


(c) Circuit model of the idealized interconnection.

Two notions of **precision:** accuracy and transparency.

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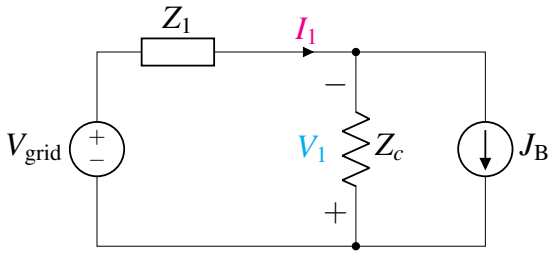


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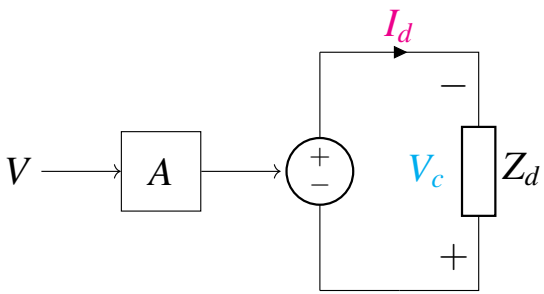


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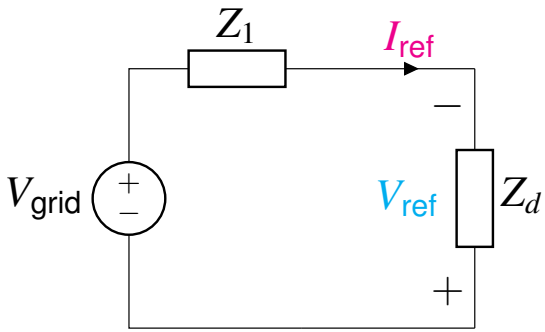


(c) Circuit model of the idealized interconnection.

Two notions of **precision:** accuracy and transparency.

**Accurate interface:** the signals $V_1 - V_c$ and $I_1 - I_d$ converge to zero.

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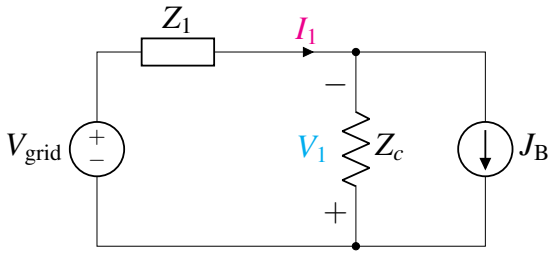


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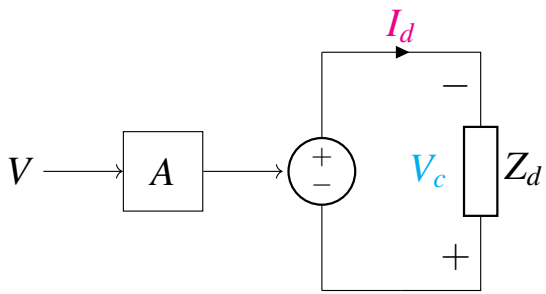


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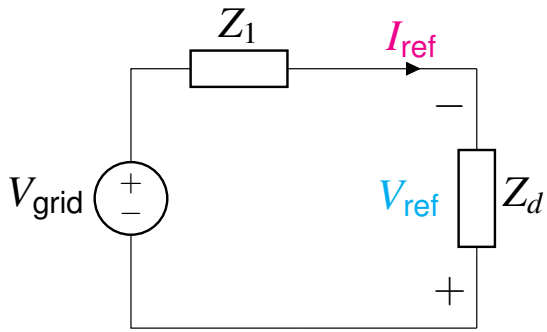


(c) Circuit model of the idealized interconnection.

Two notions of **precision:** accuracy and transparency.

**Accurate interface:** the signals $V_1 - V_c$ and $I_1 - I_d$ converge to zero.

**Transparent interface:** the signals $V_1 - V_{\text{ref}}$, $V_c - V_{\text{ref}}$, $I_1 - I_{\text{ref}}$, and $I_d - I_{\text{ref}}$ converge to zero.

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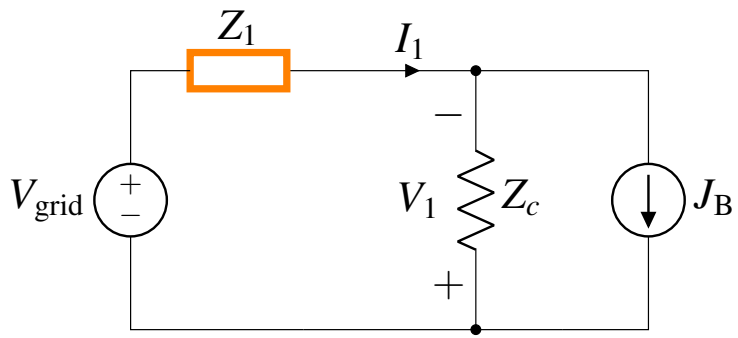
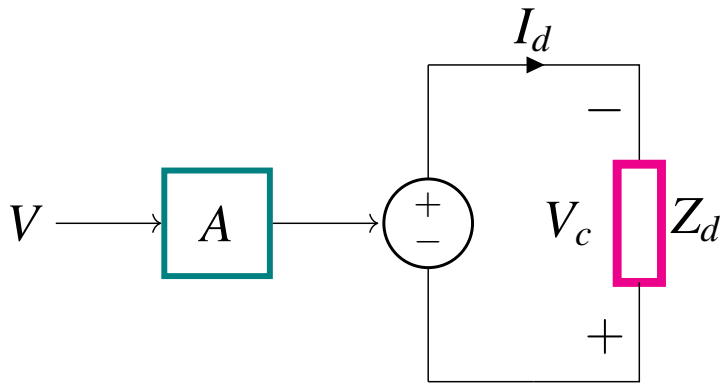



(a) Off-nominal circuit model of the simulated grid.




(b) Off-nominal circuit model of the amplifier and device.

Practical PHIL experiments involve

- communication **delays**,

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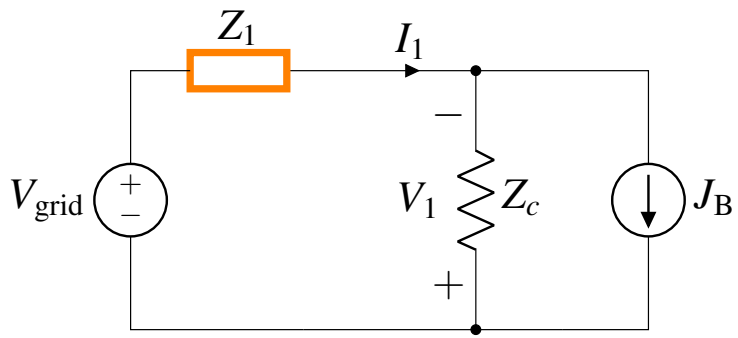
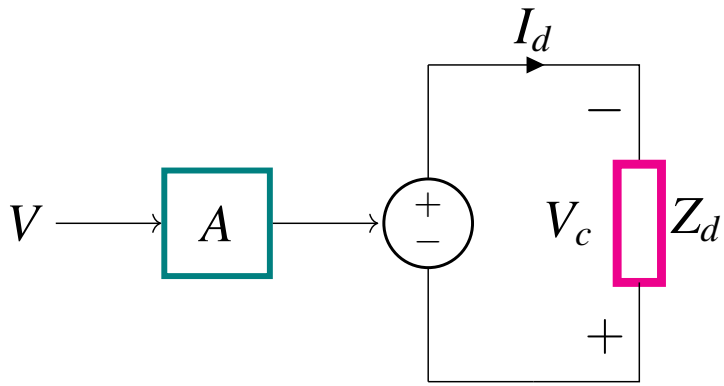



(a) Off-nominal circuit model of the simulated grid.




(b) Off-nominal circuit model of the amplifier and device.

Practical PHIL experiments involve

- communication **delays**,
- intentional **variation** of the grid load,

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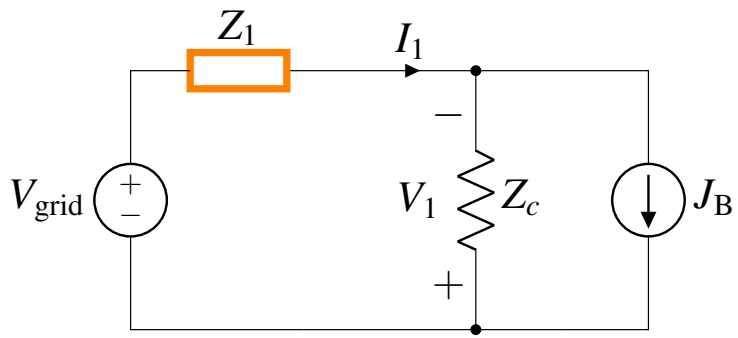


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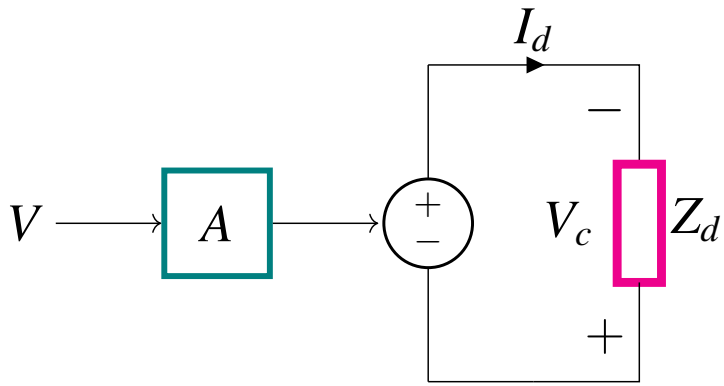


(b) Off-nominal circuit model of the amplifier and device.

Practical PHIL experiments involve

- communication **delays**,
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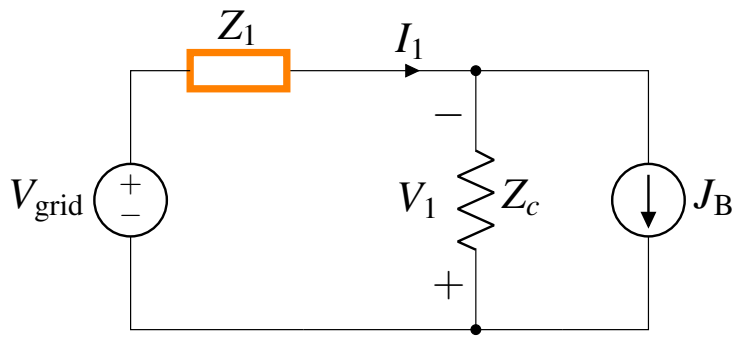


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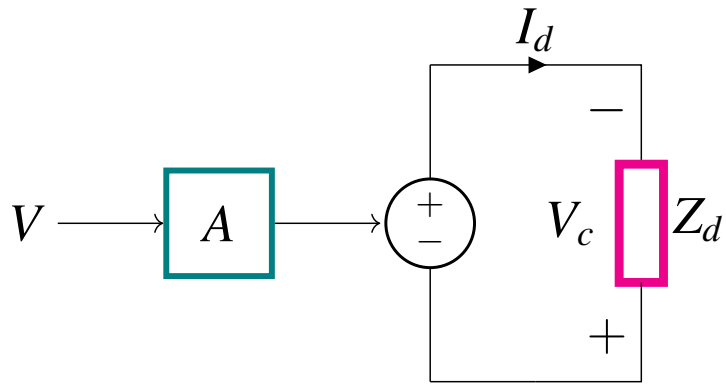


(b) Off-nominal circuit model of the amplifier and device.

Practical PHIL experiments involve

- communication **delays**,
- intentional **variation** of the grid load,
- **uncertainties** in amplifier model due to system identification, and
- **uncertainties** in and **various operating conditions** of device load due to linear model approximating complex hardware.

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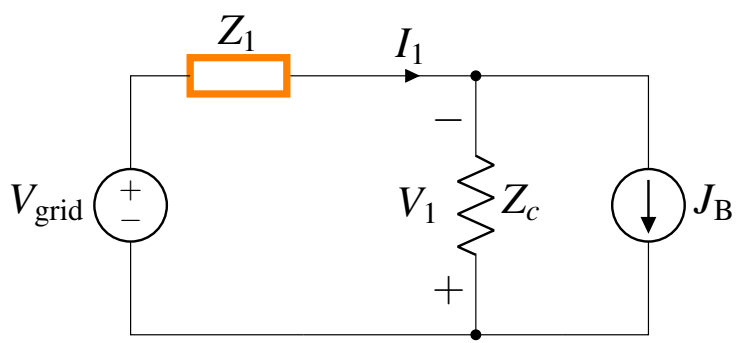


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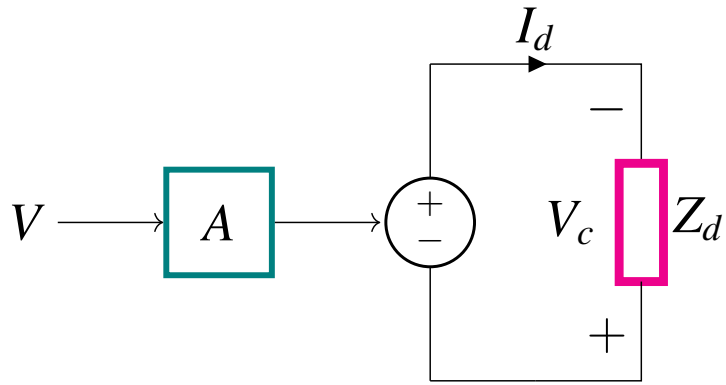
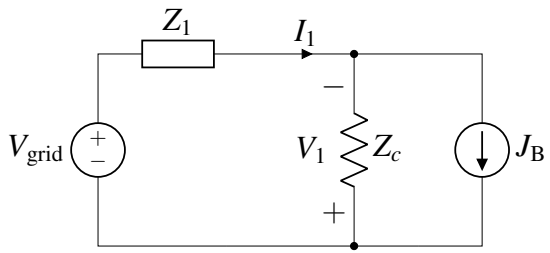



(b) Off-nominal circuit model of the amplifier and device.

**Robust interface:** stability is ensured even under uncertainties and various operating conditions.

# Approach to Precision: Model Matching




(a) ROS model.

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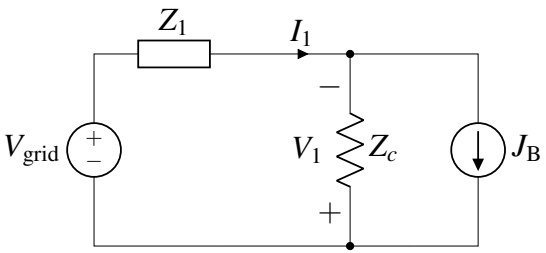


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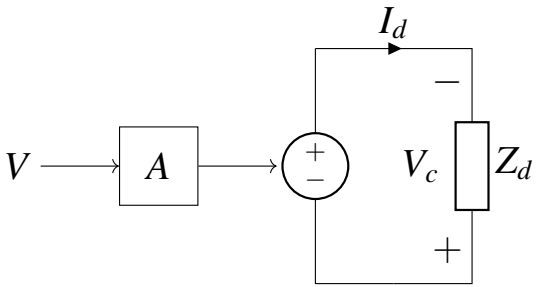


(b) DUT and amplifier models.

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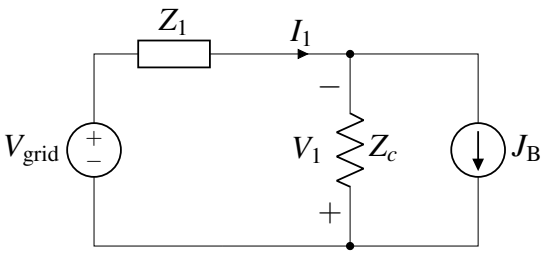


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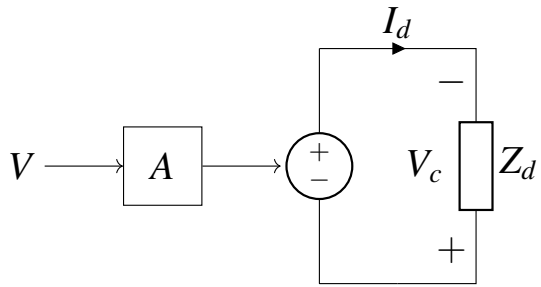


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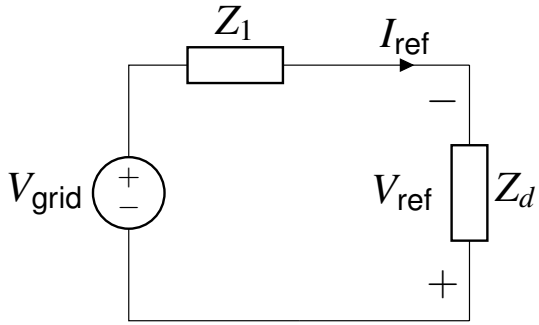


(c) Idealized, reference interconnection.

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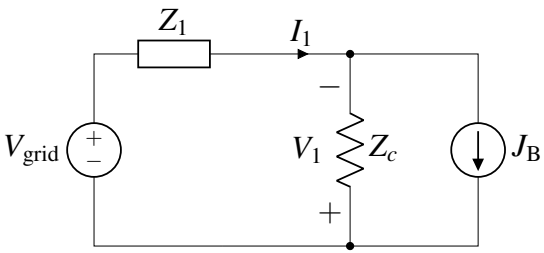


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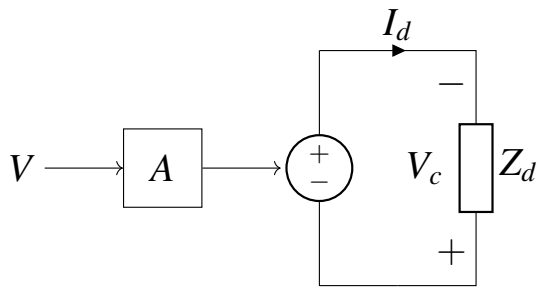


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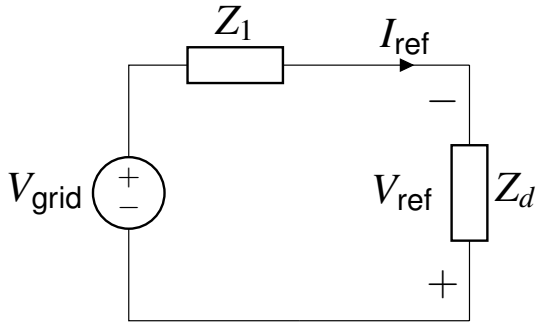


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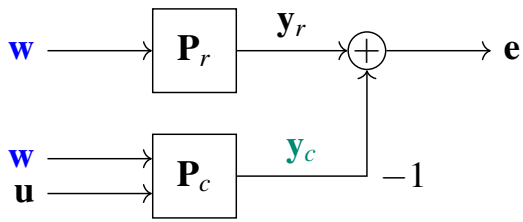


(d) Model matching architecture, where $\mathbf{z} = [\mathbf{e}^{\mathsf{T}}\ \mathbf{u}^{\mathsf{T}}]^{\mathsf{T}}$ and $\mathbf{y} = \mathbf{y}_c$.

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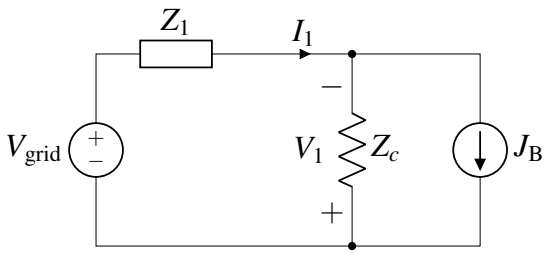


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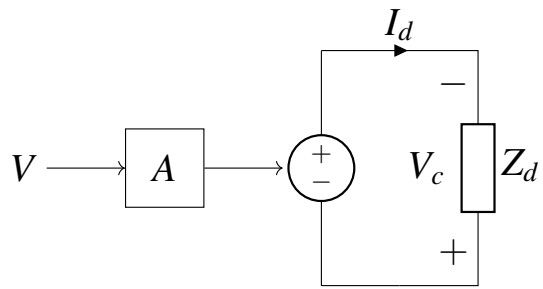


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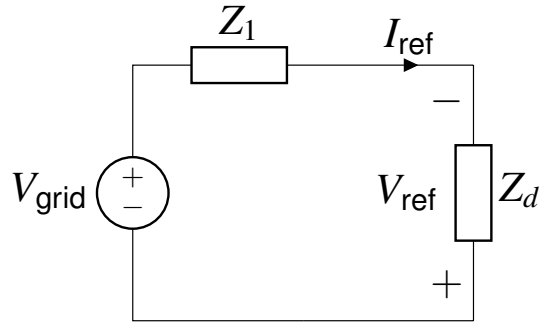


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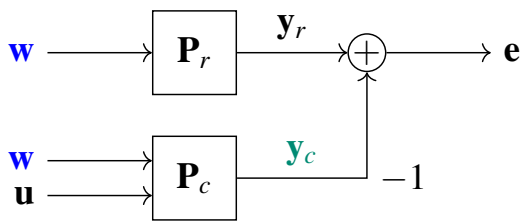


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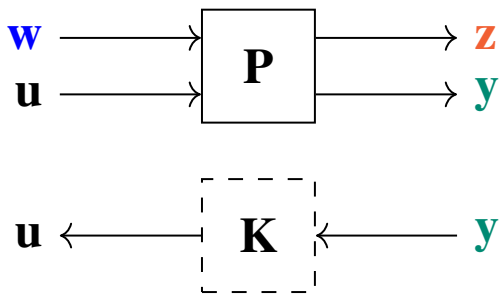
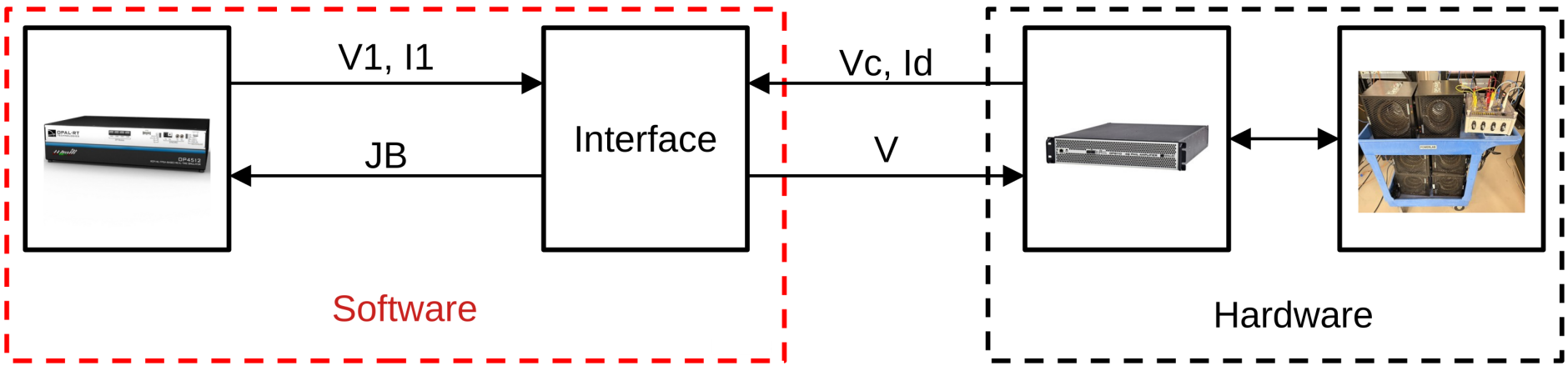



(e) Generalized control problem.

# Experimental Validation

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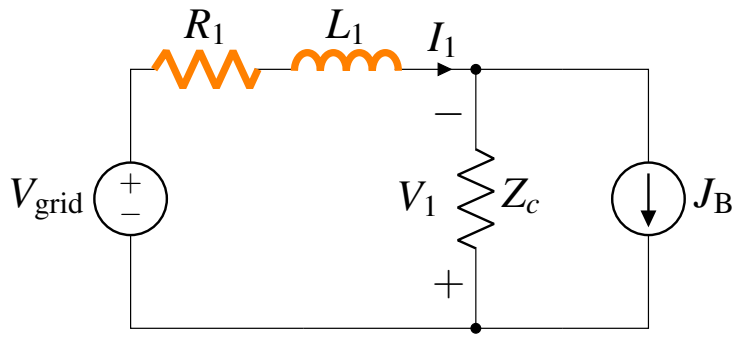
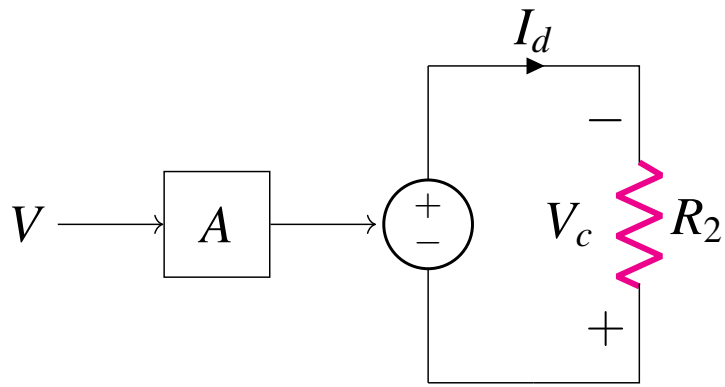



(a) Experiment-specific model of the simulated grid.




(b) Experiment-specific model of the device.

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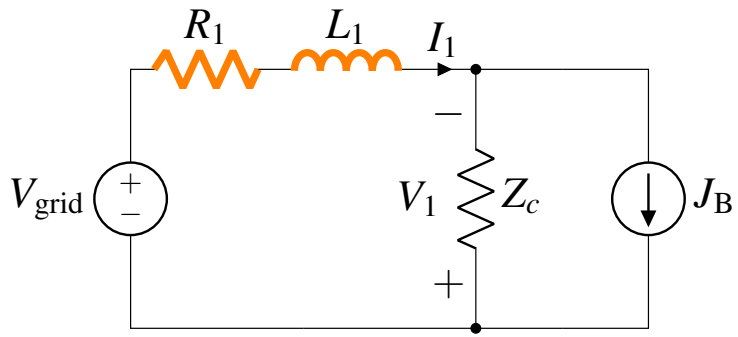


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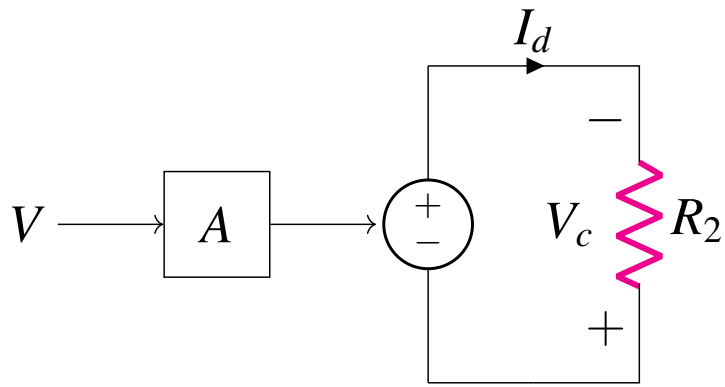


(b) Experiment-specific model of the device.

The device is modeled as a resistor.

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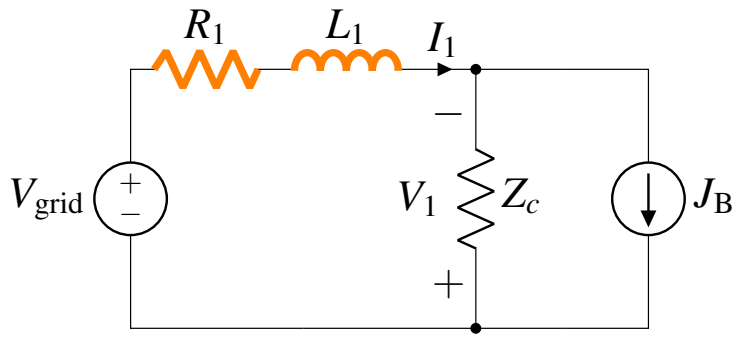


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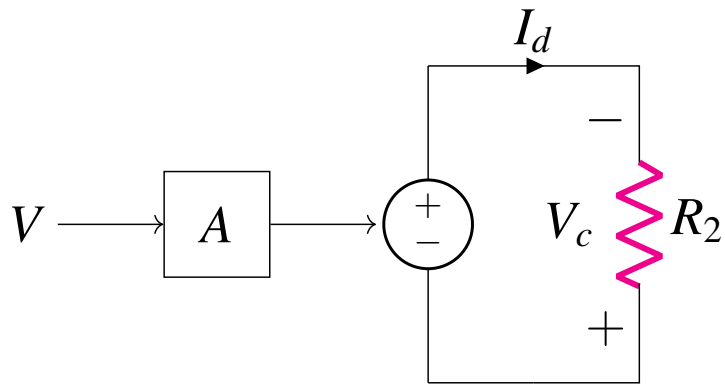



(b) Experiment-specific model of the device.

The device is modeled as a resistor.

The grid load is modeled as a resistor and inductor inversely proportional to the grid's *short-circuit ratio* $S$.

# Experimental Validation

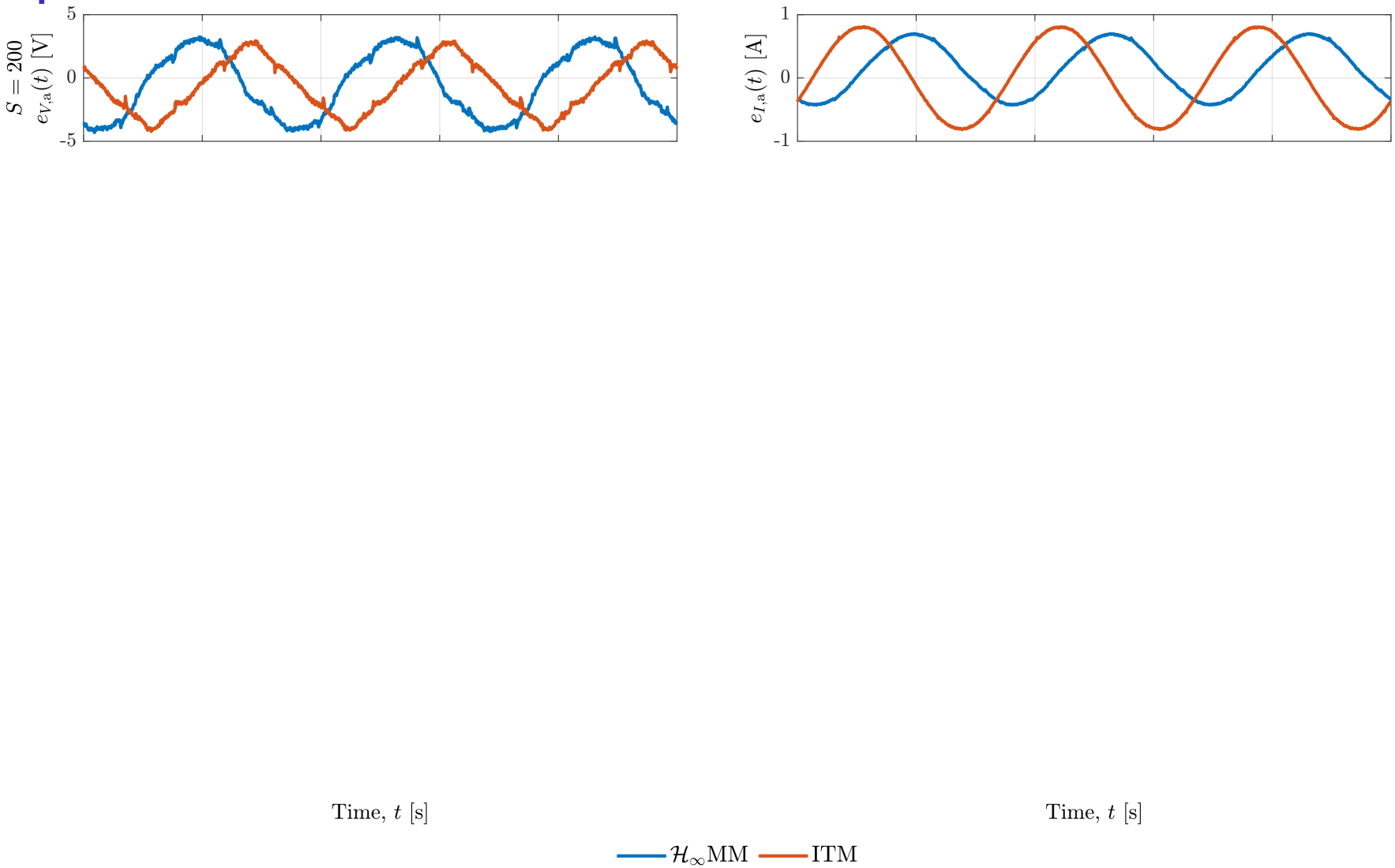



Figure 13: Time-domain response comparison of an $\mathcal{H}_\infty$ model matching-based and ITM-based interface under various operating conditions.

# Experimental Validation

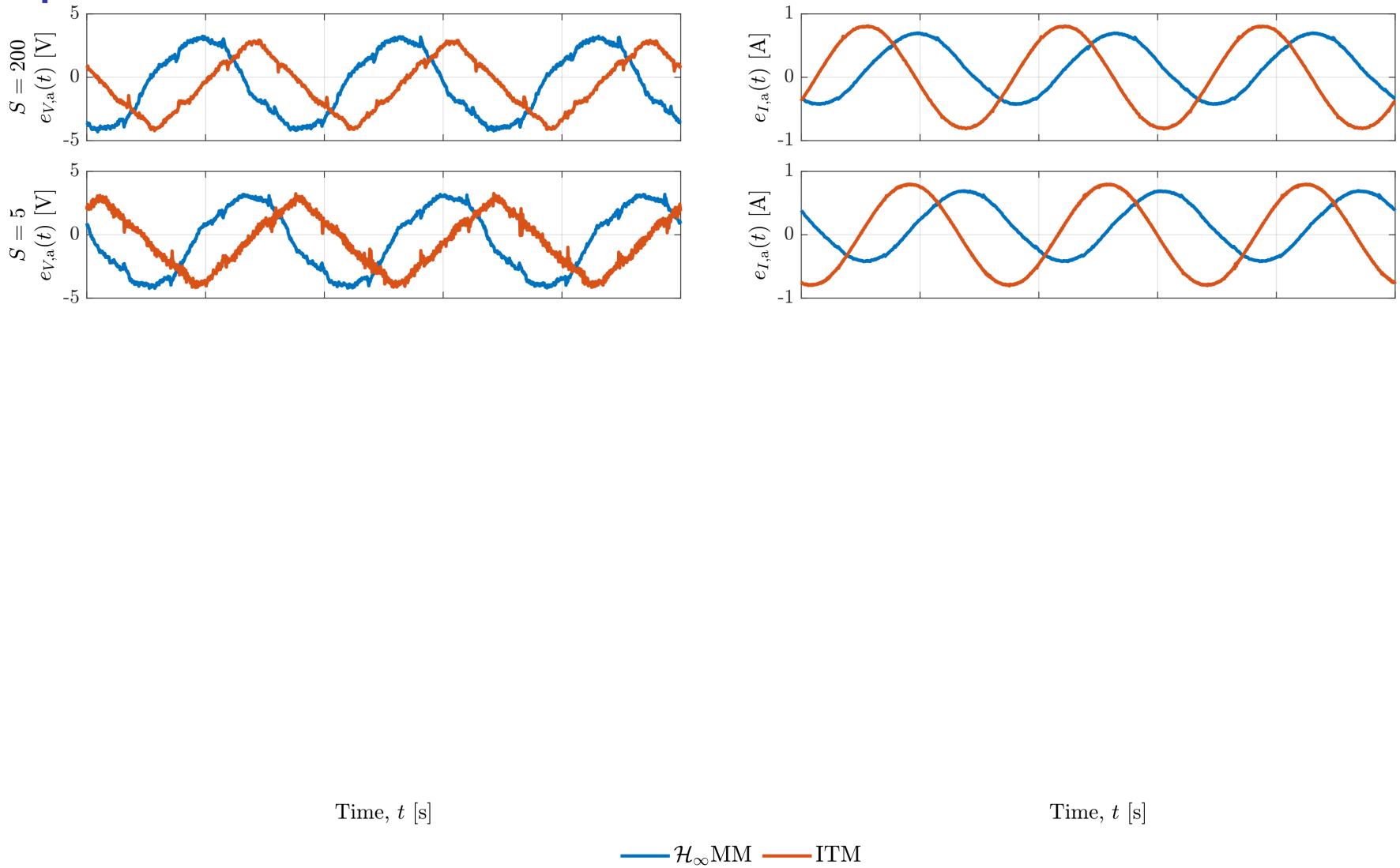



Figure 14: Time-domain response comparison of an $\mathcal{H}_\infty$ model matching-based and ITM-based interface under various operating conditions.

# Experimental Validation

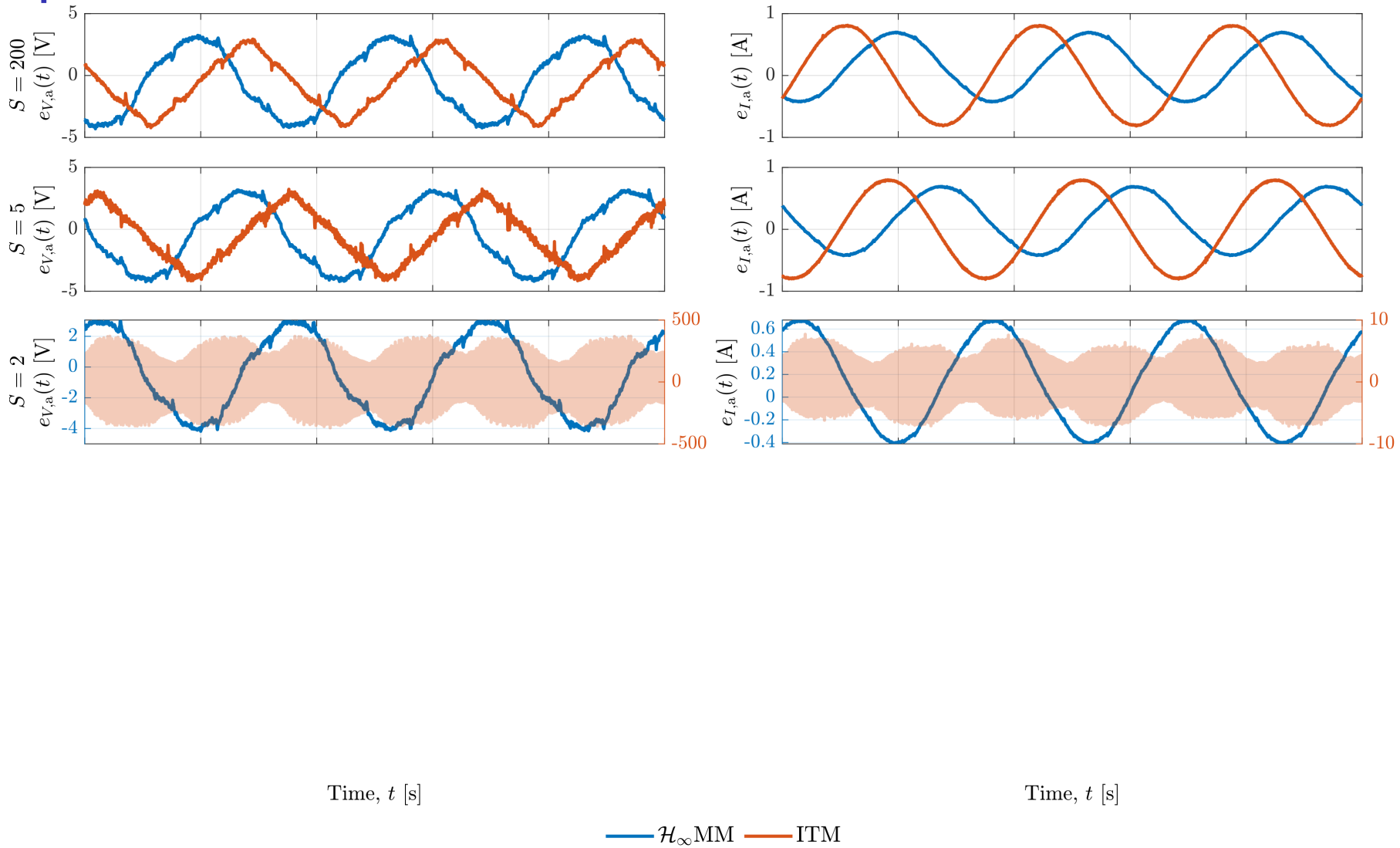



Figure 15: Time-domain response comparison of an $\mathcal{H}_\infty$ model matching-based and ITM-based interface under various operating conditions.

# Experimental Validation

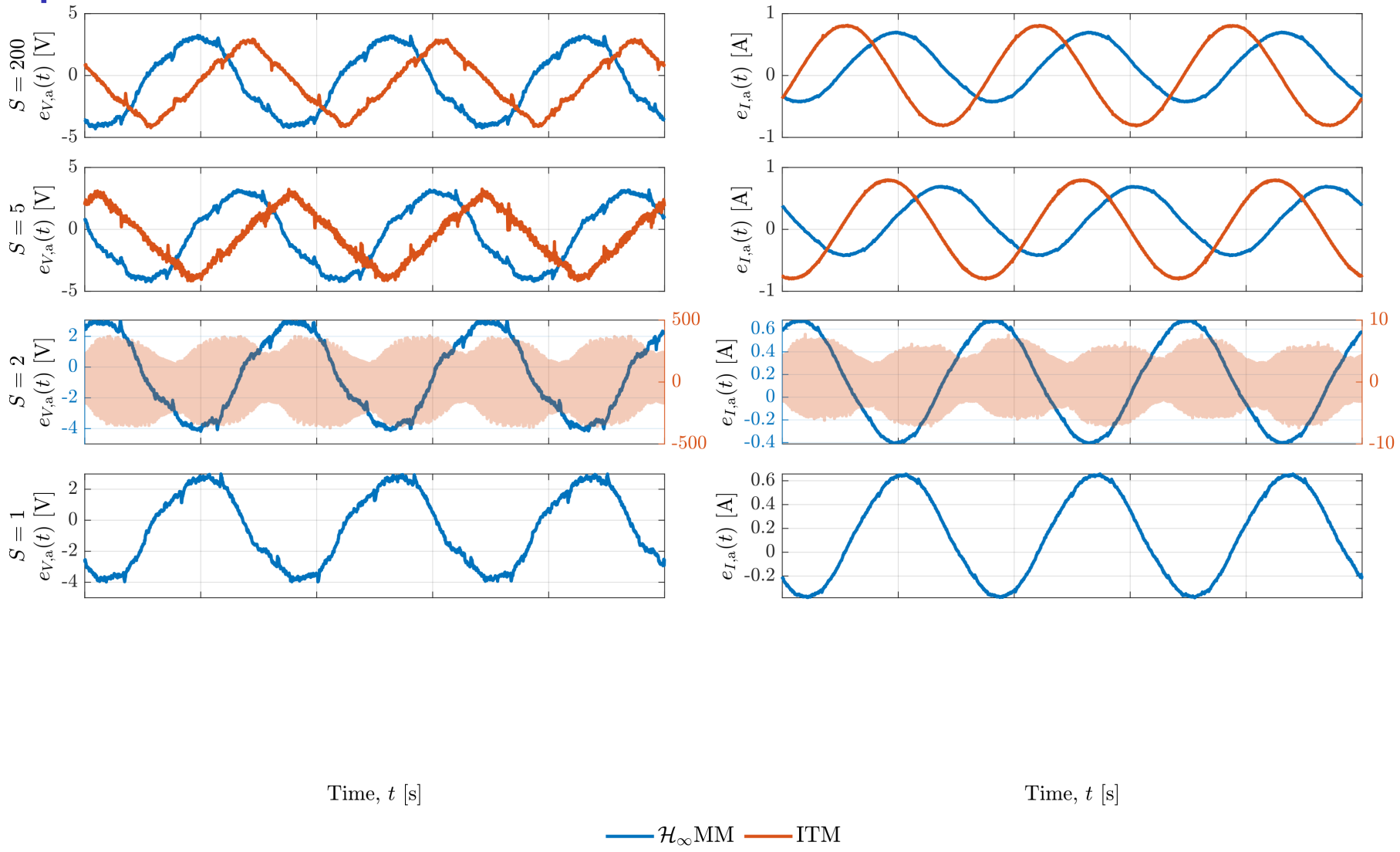



Figure 16: Time-domain response comparison of an $\mathcal{H}_\infty$ model matching-based and ITM-based interface under various operating conditions.

# Experimental Validation

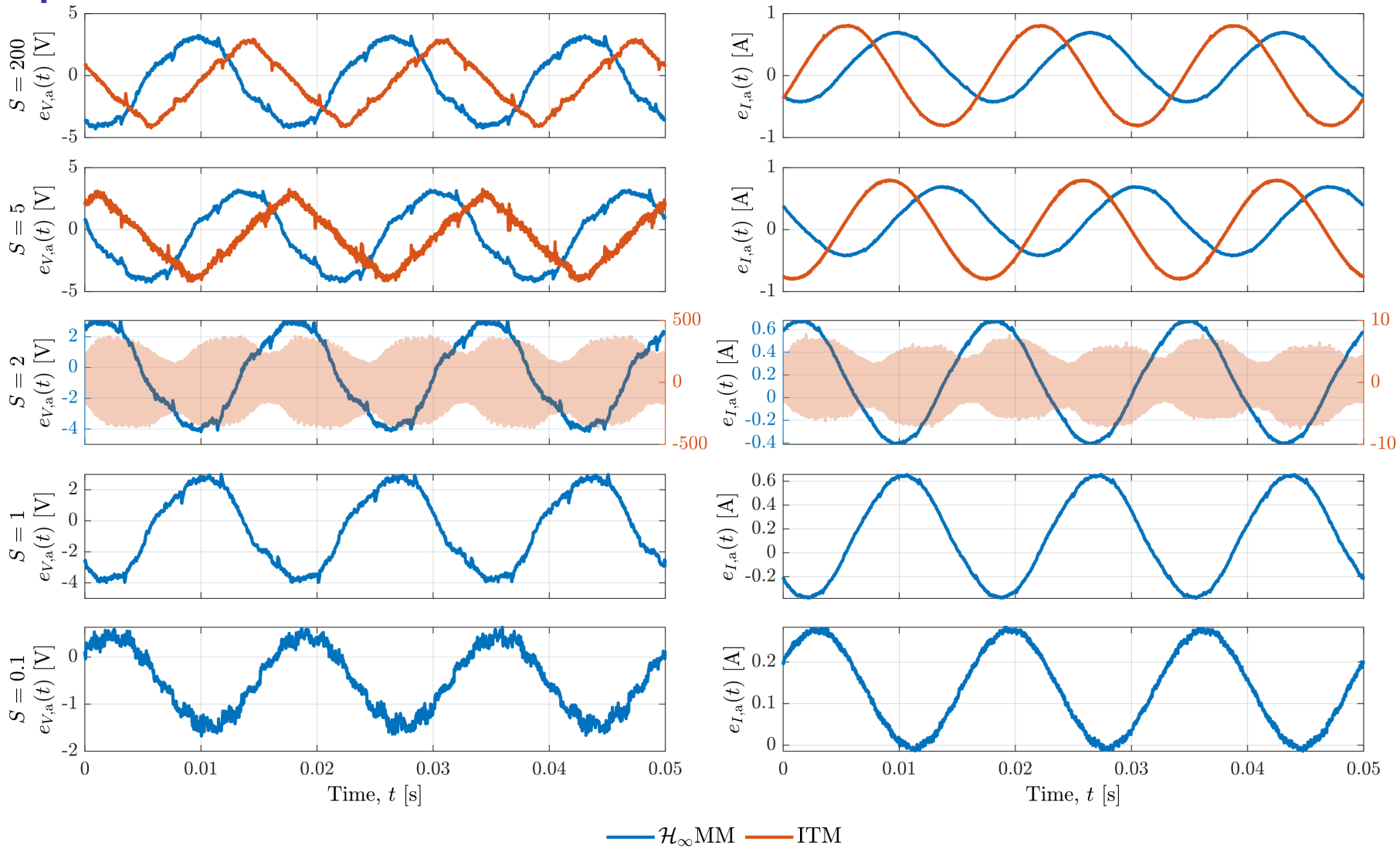
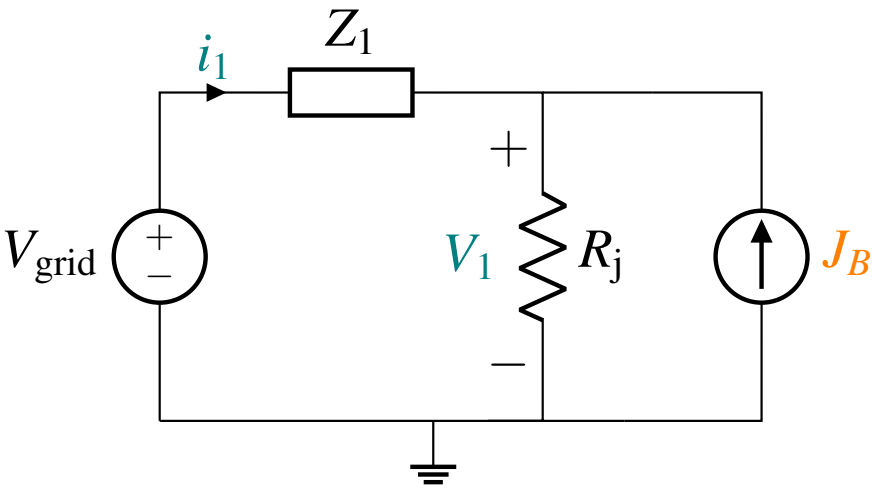
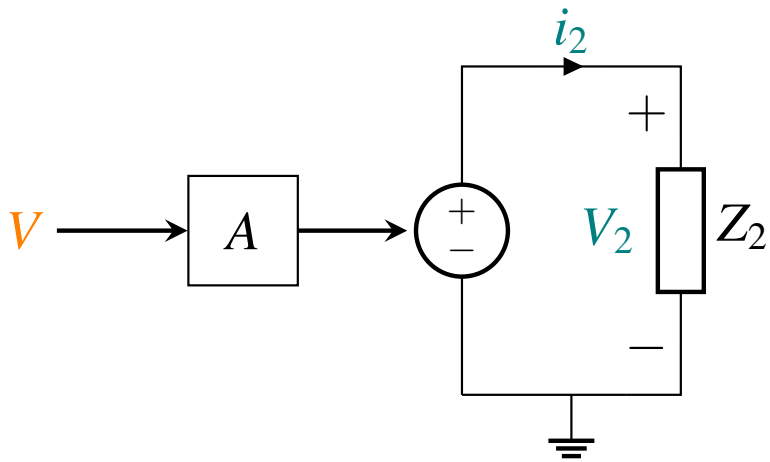



Figure 17: Time-domain response comparison of an $\mathcal{H}_\infty$ model matching-based and ITM-based interface under various operating conditions.

# PHIL Model




(a) Circuit model of the simulated grid




(b) Circuit model of the amplifier and device

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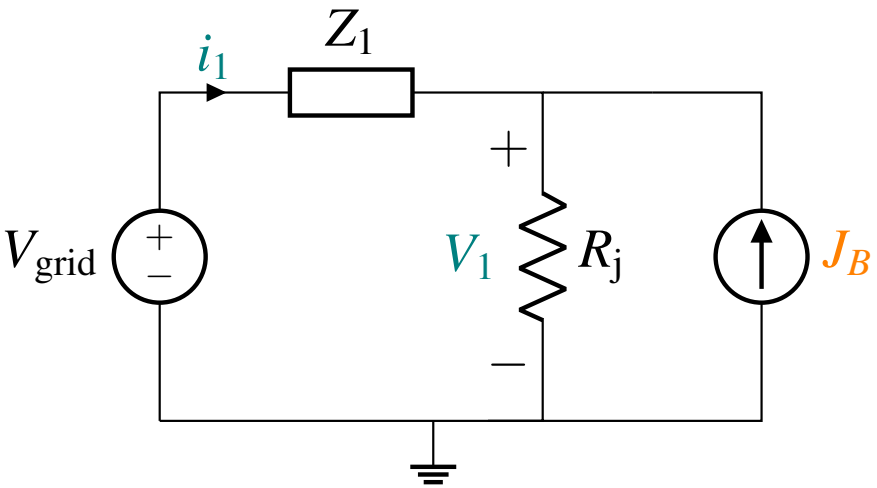


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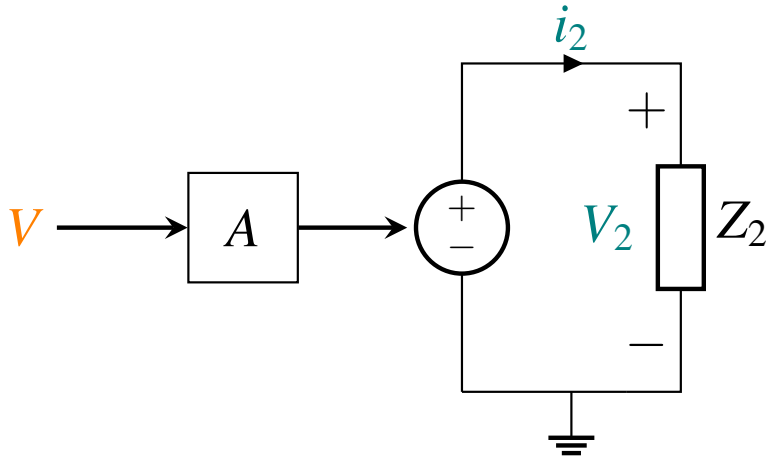


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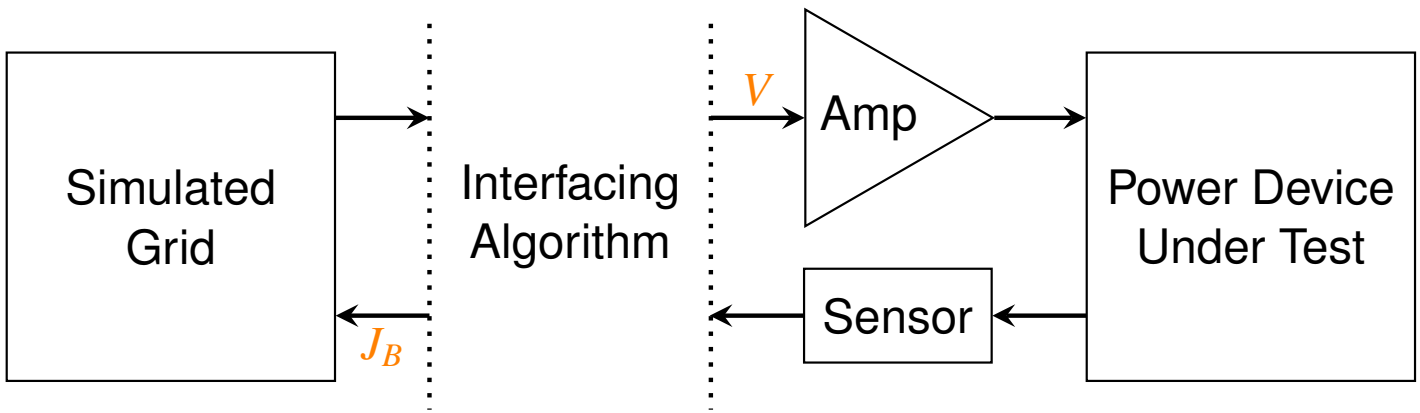
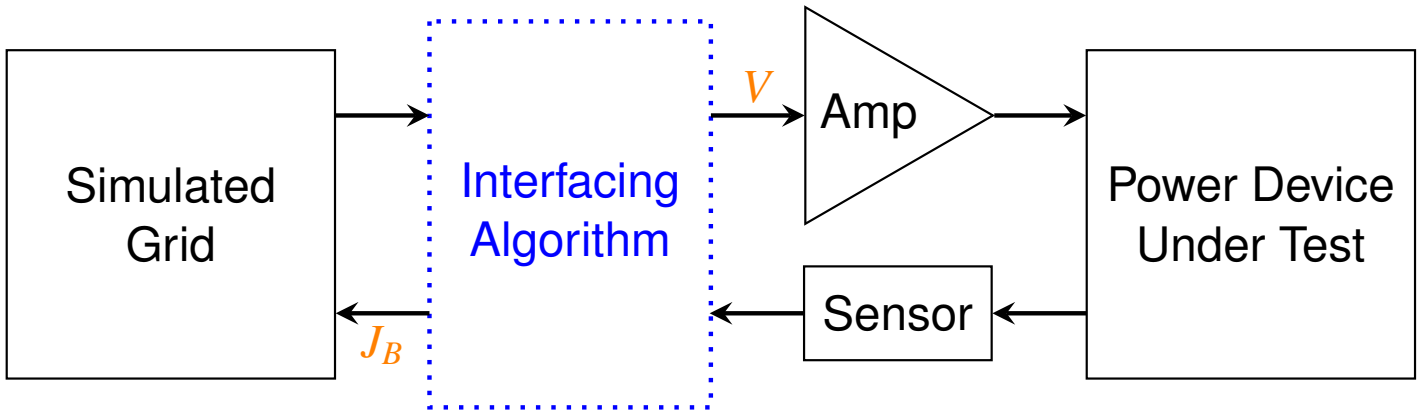
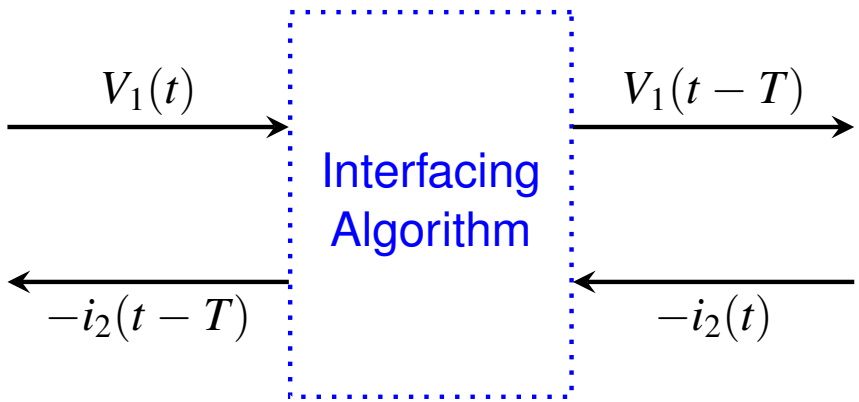
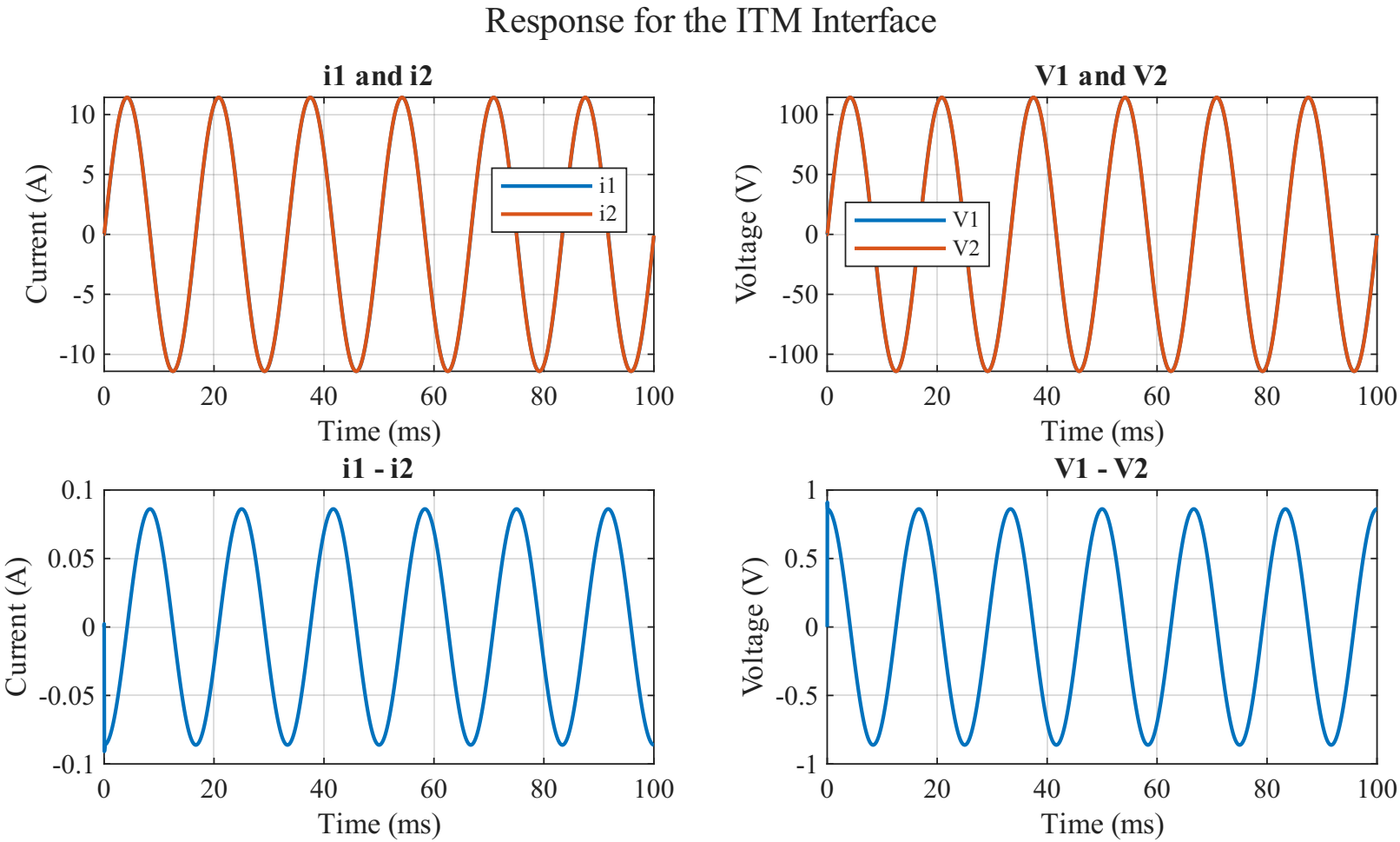


# Ideal Transformer Method (ITM)

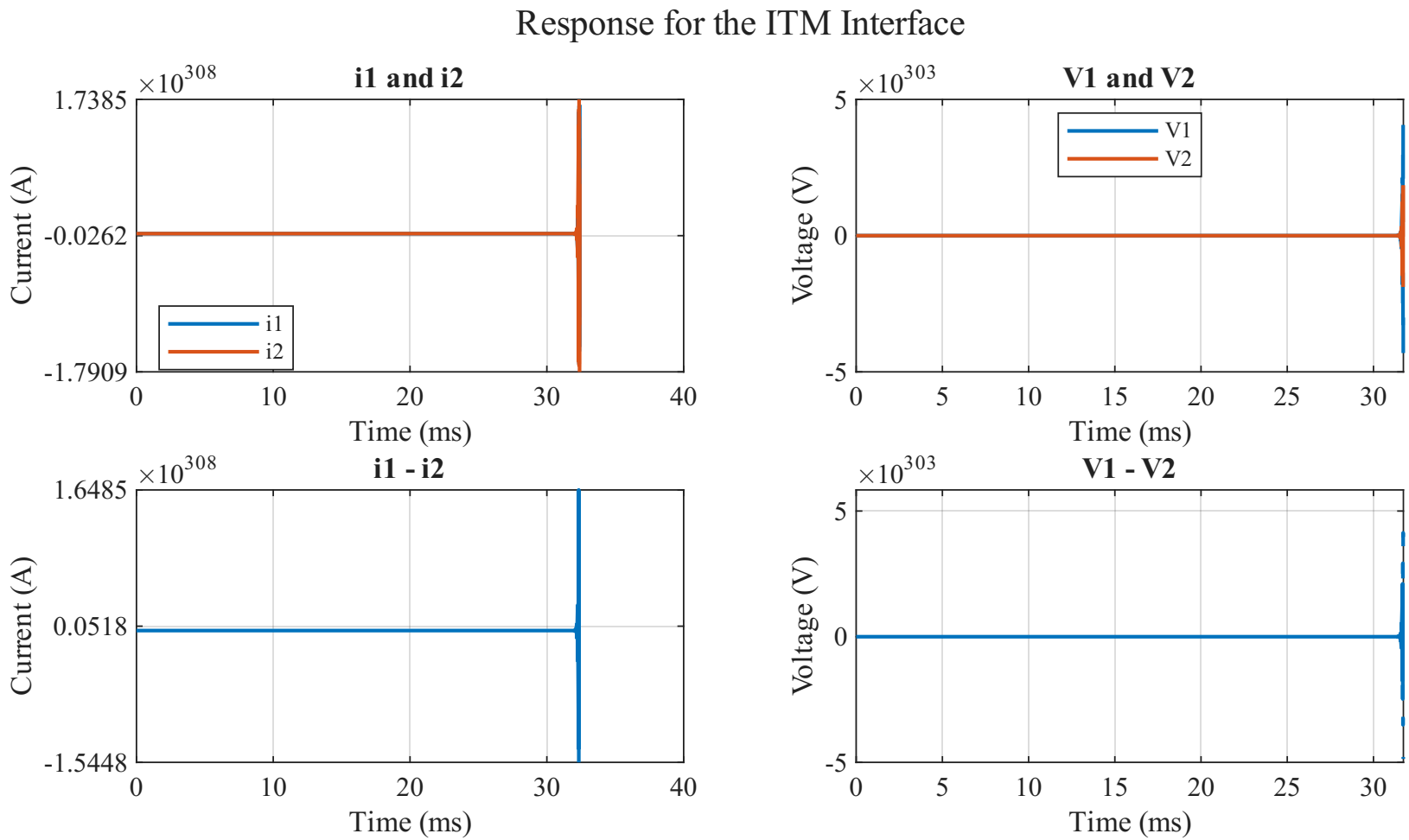


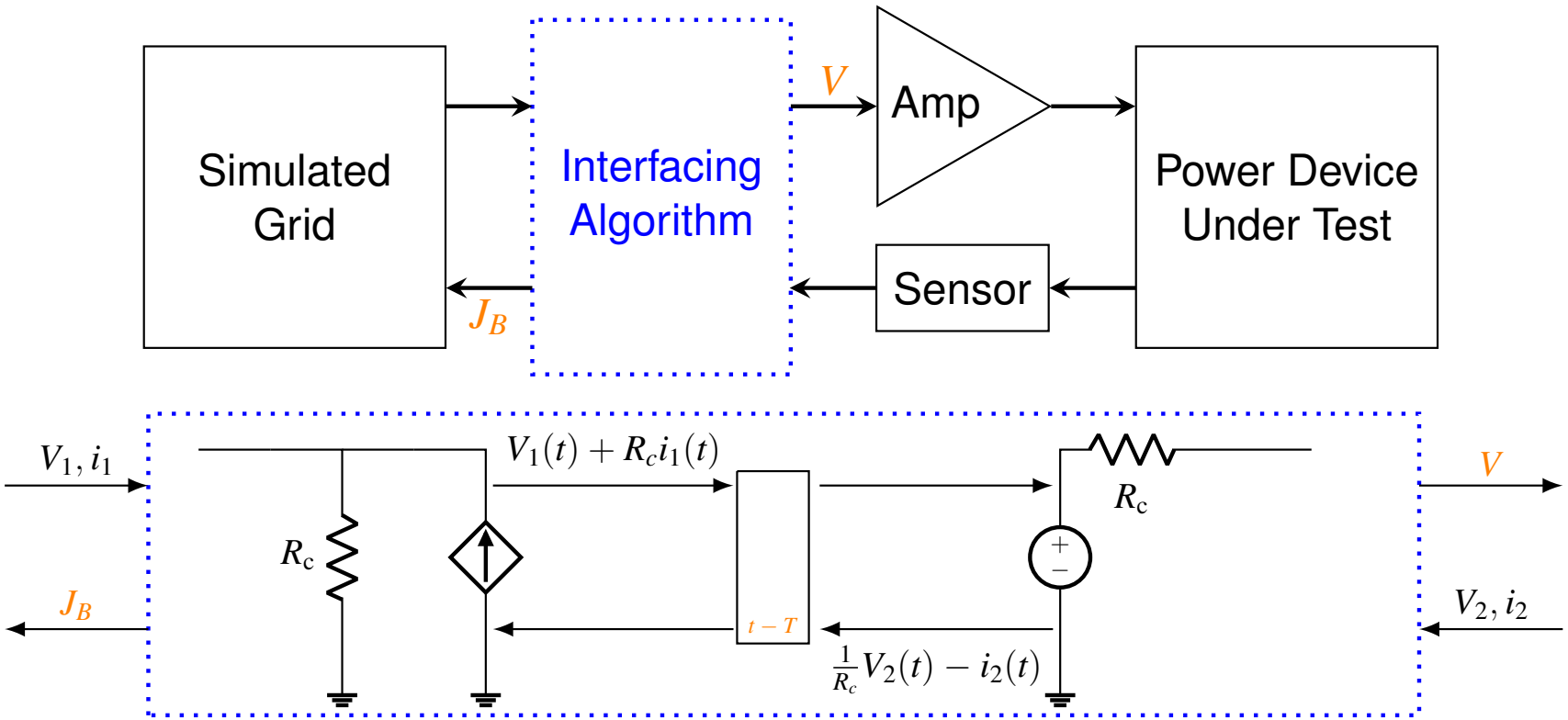
# Nominal ITM Response



# Off-Nominal ITM Response



# Transmission Line Method (TLM)



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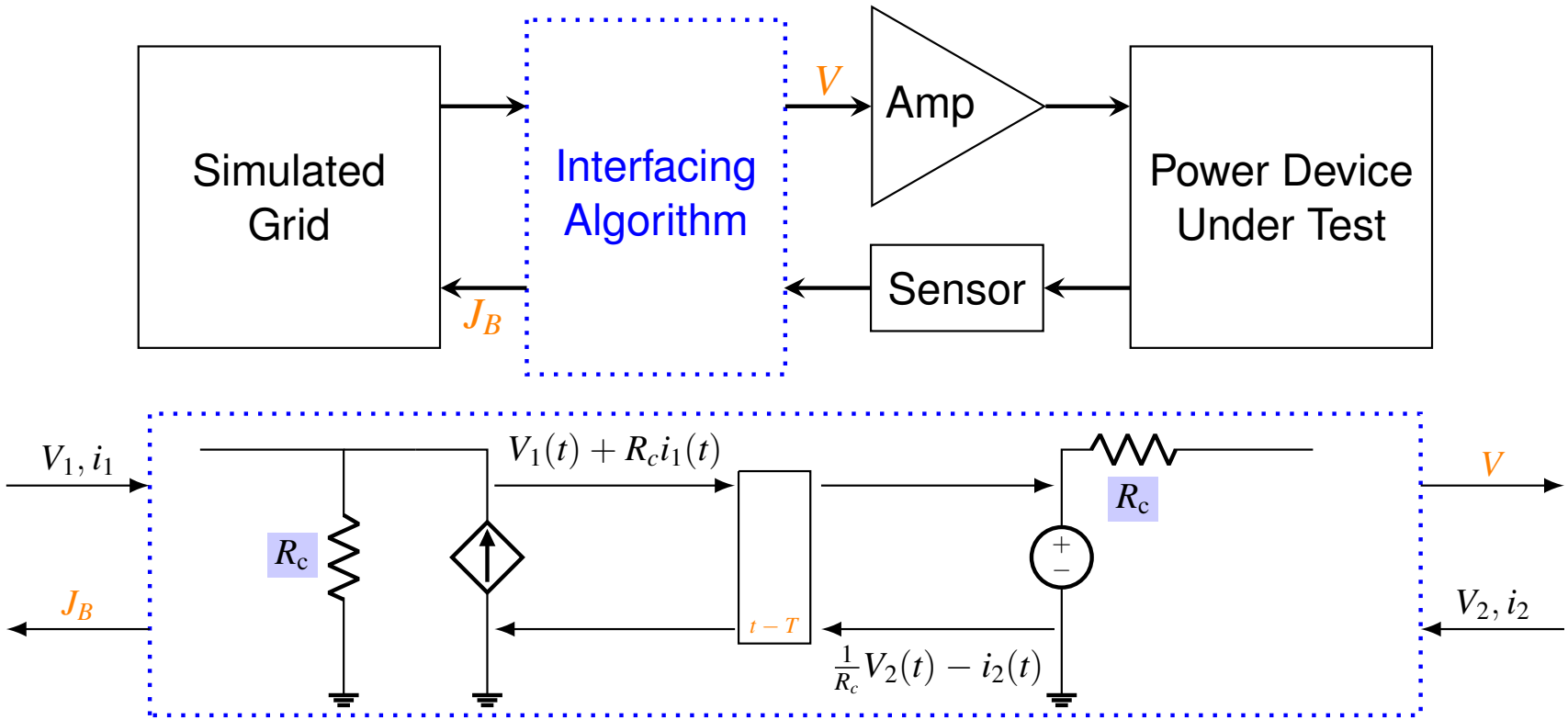
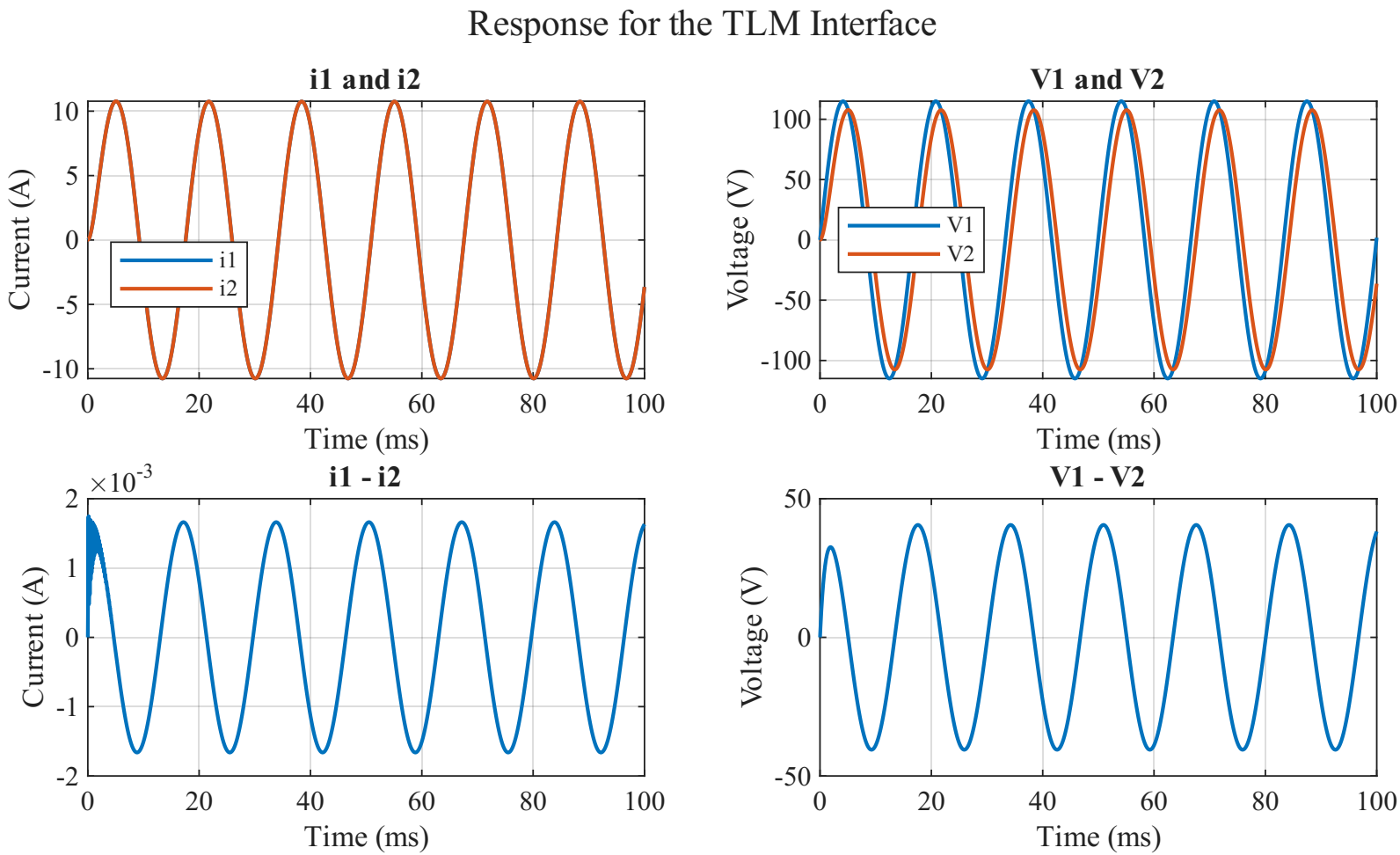


# Nominal TLM Response with $R_c = 500\Omega$



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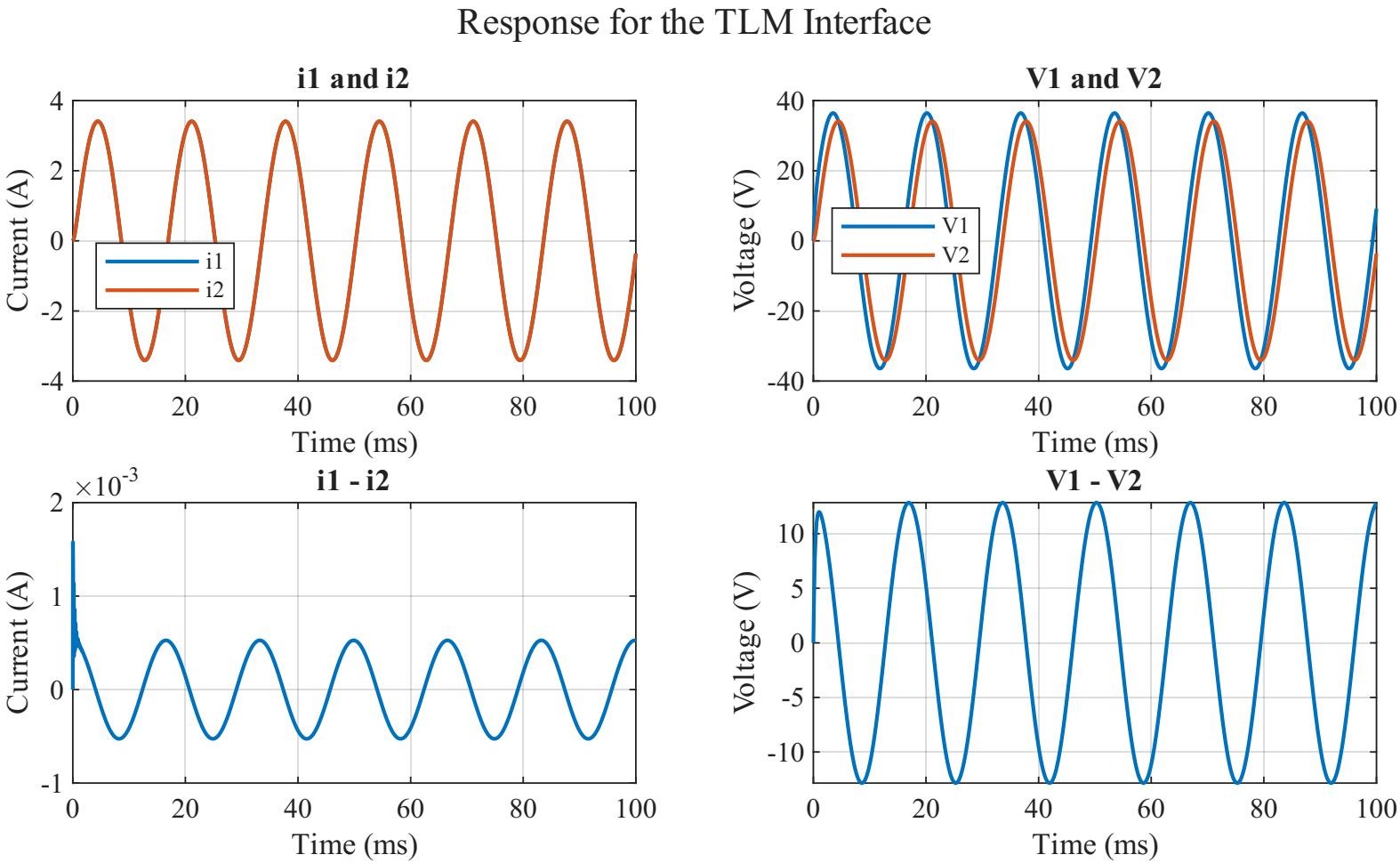
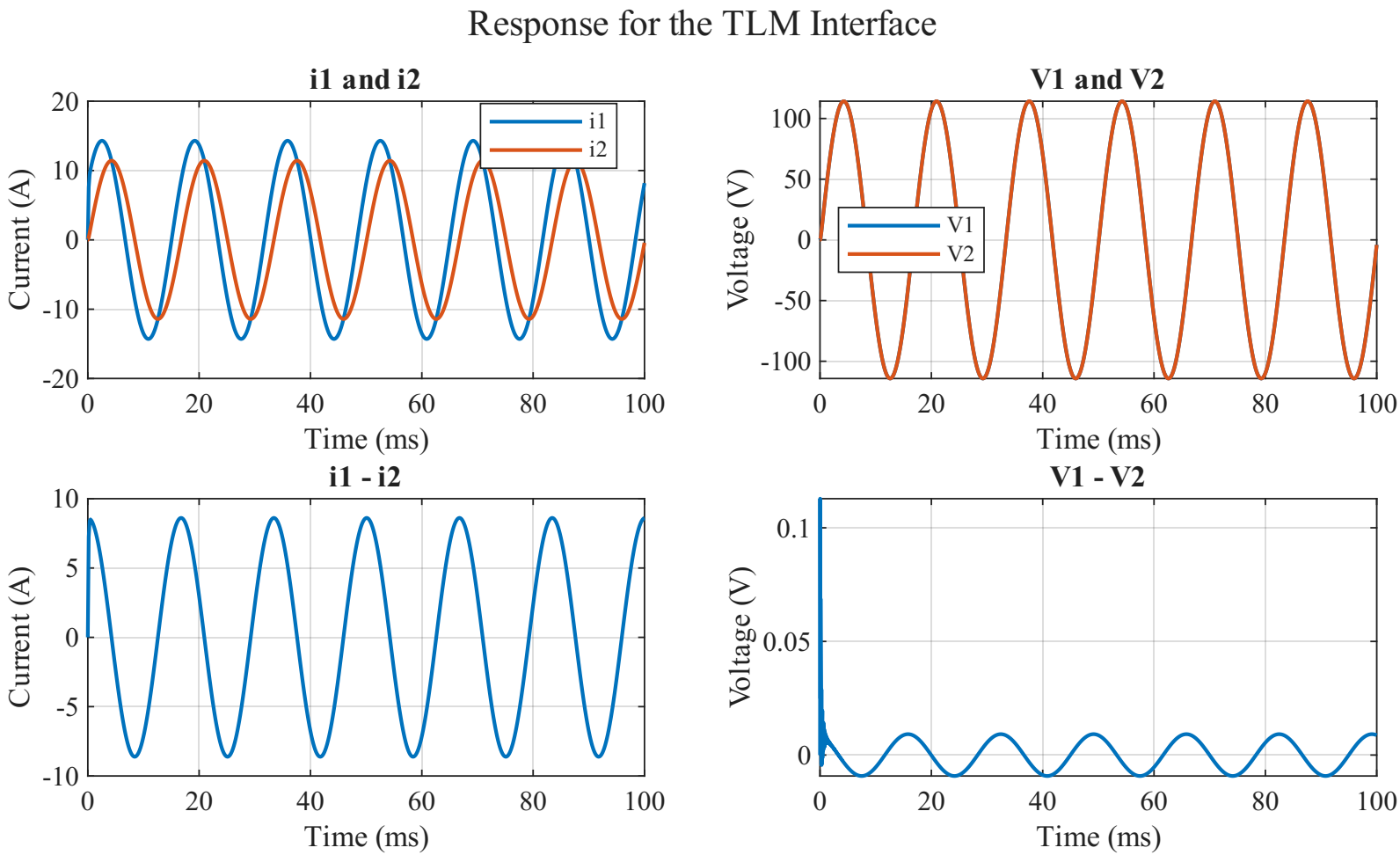


# Nominal TLM Response with $R_c = 0.1\Omega$



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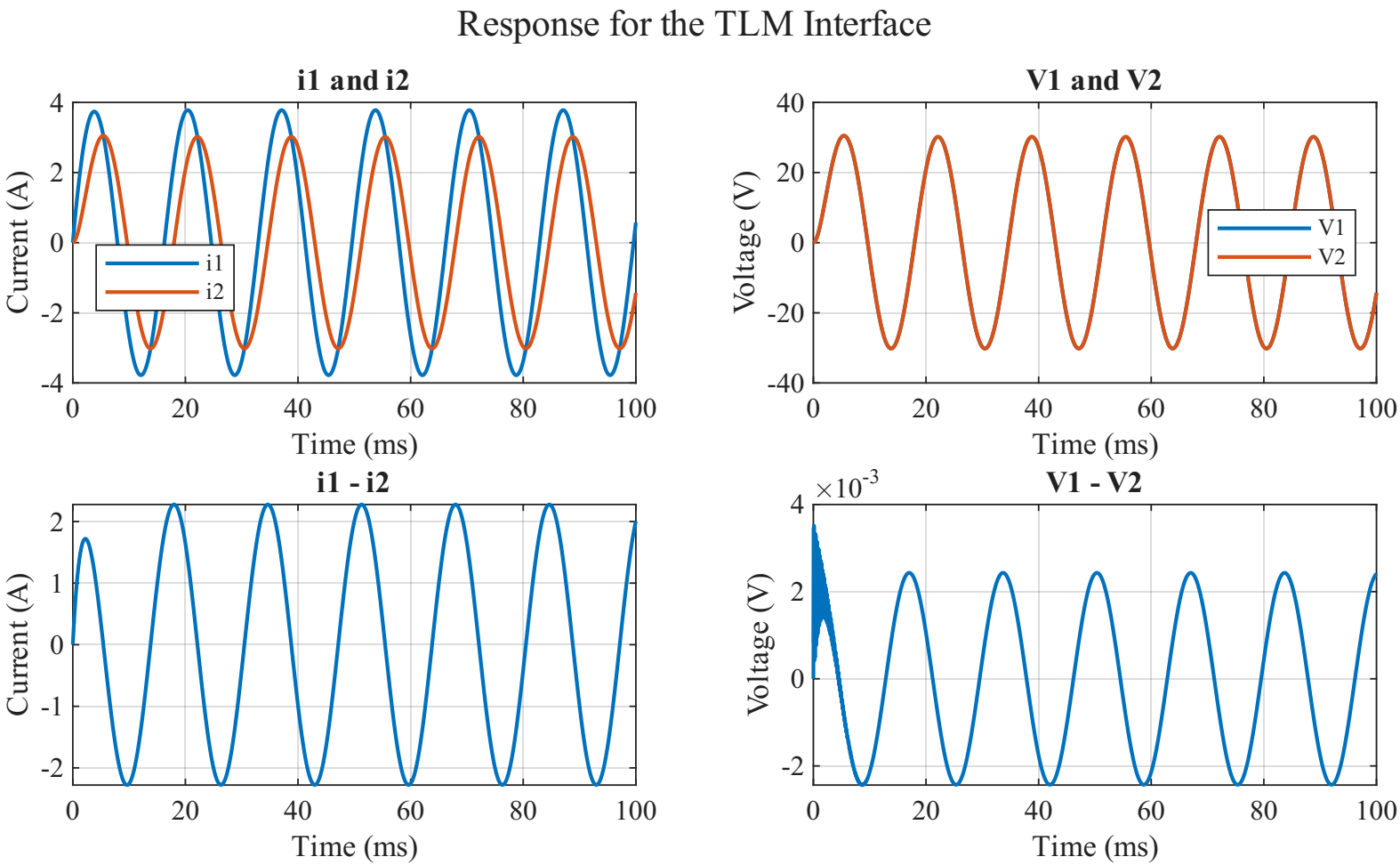

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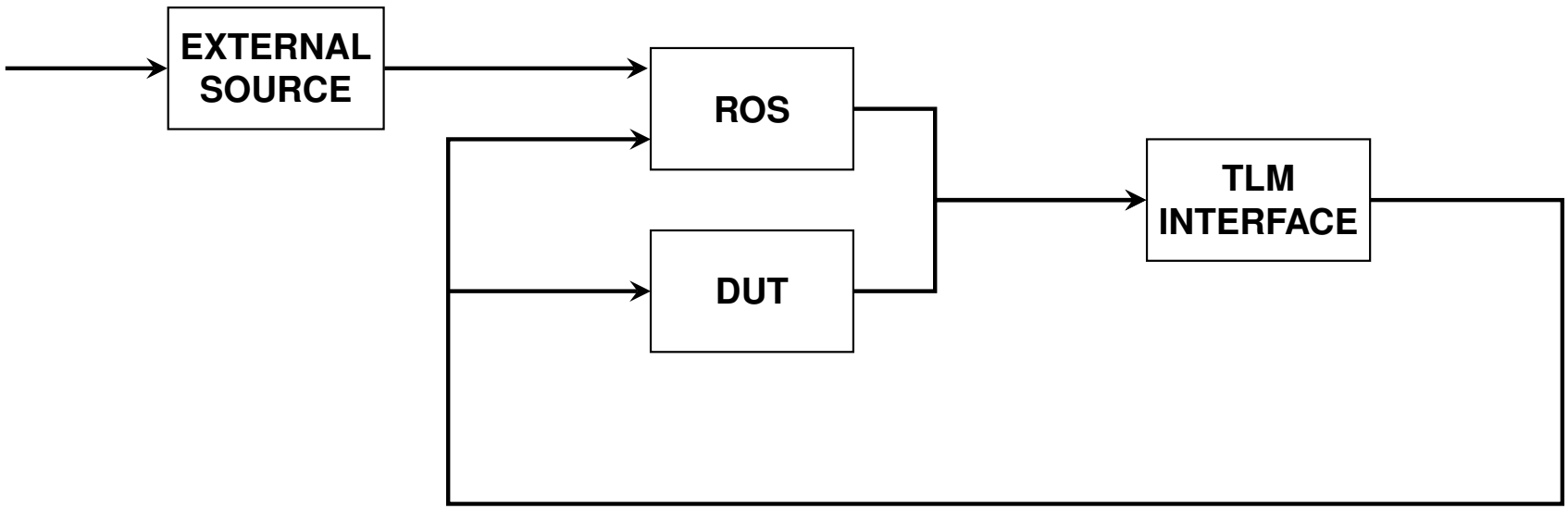
- A passive system is one that does not generate energy on its own, but only stores or dissipates energy.
- Passive system = stable system.
- But how can we select $R_c$ to improve performance?
- New approach: fix the value of $R_c$ and design a feeback controller while perserving passivity.

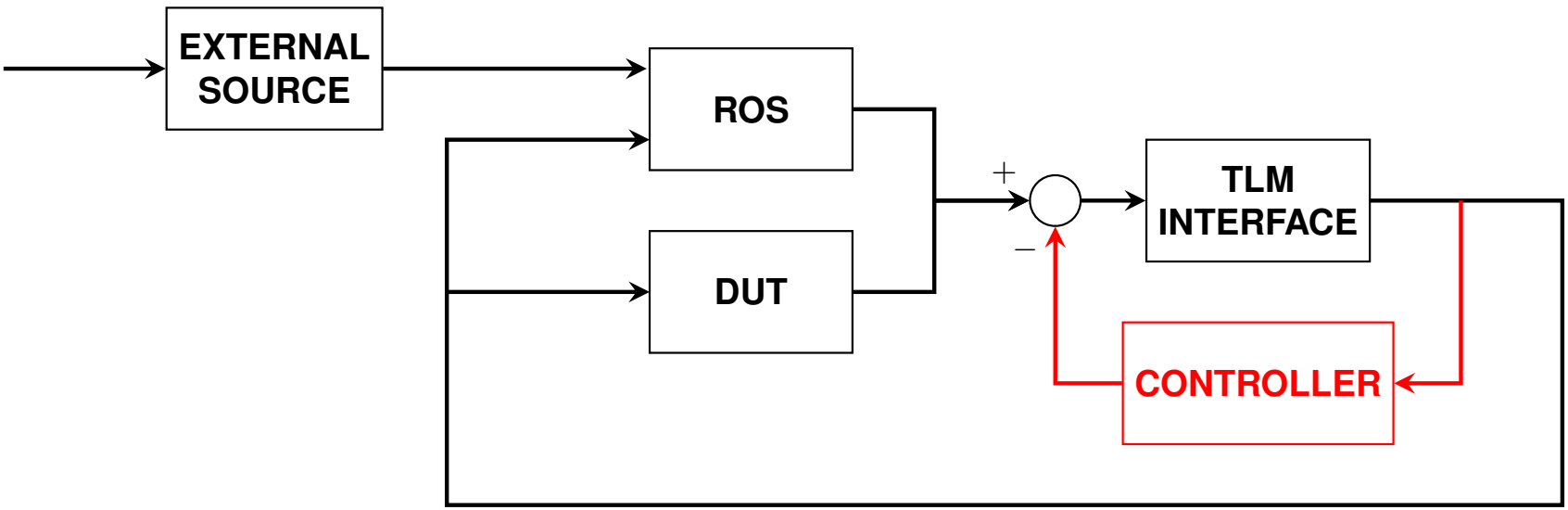
# Interconnection of PHIL

- The PHIL problem can be looked at as a block diagram.



# Interconnection of PHIL

- Add a controller in feedback.



# Controller Synthesis

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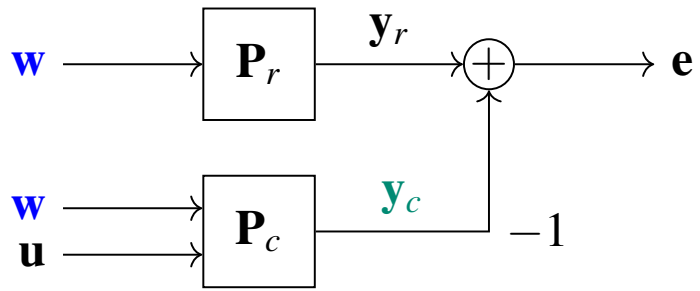
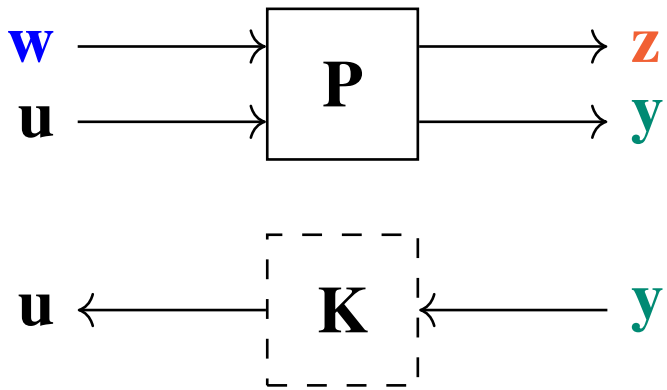



(a) Model matching architecture, where $\mathbf{z} = [\mathbf{e}^\mathsf{T}\ \mathbf{u}^\mathsf{T}]^\mathsf{T}$ and $\mathbf{y} = \mathbf{y}_c$.




(b) Generalized control problem.

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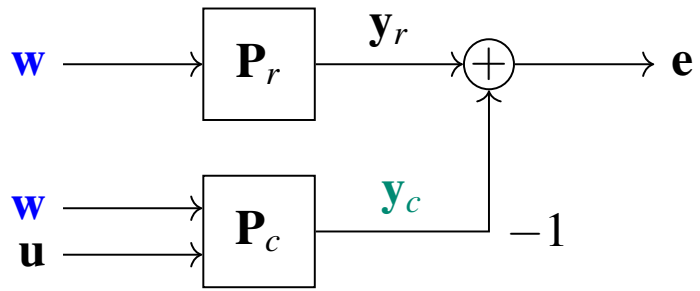


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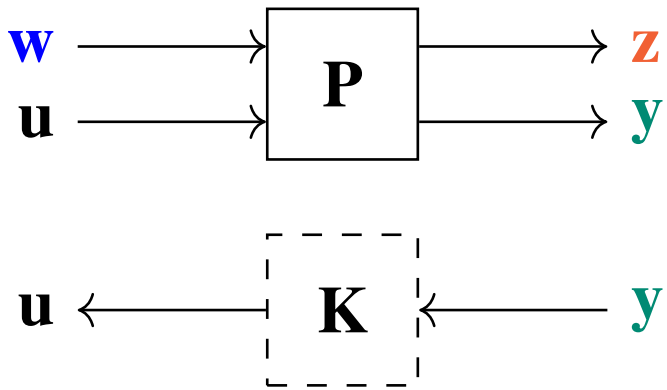
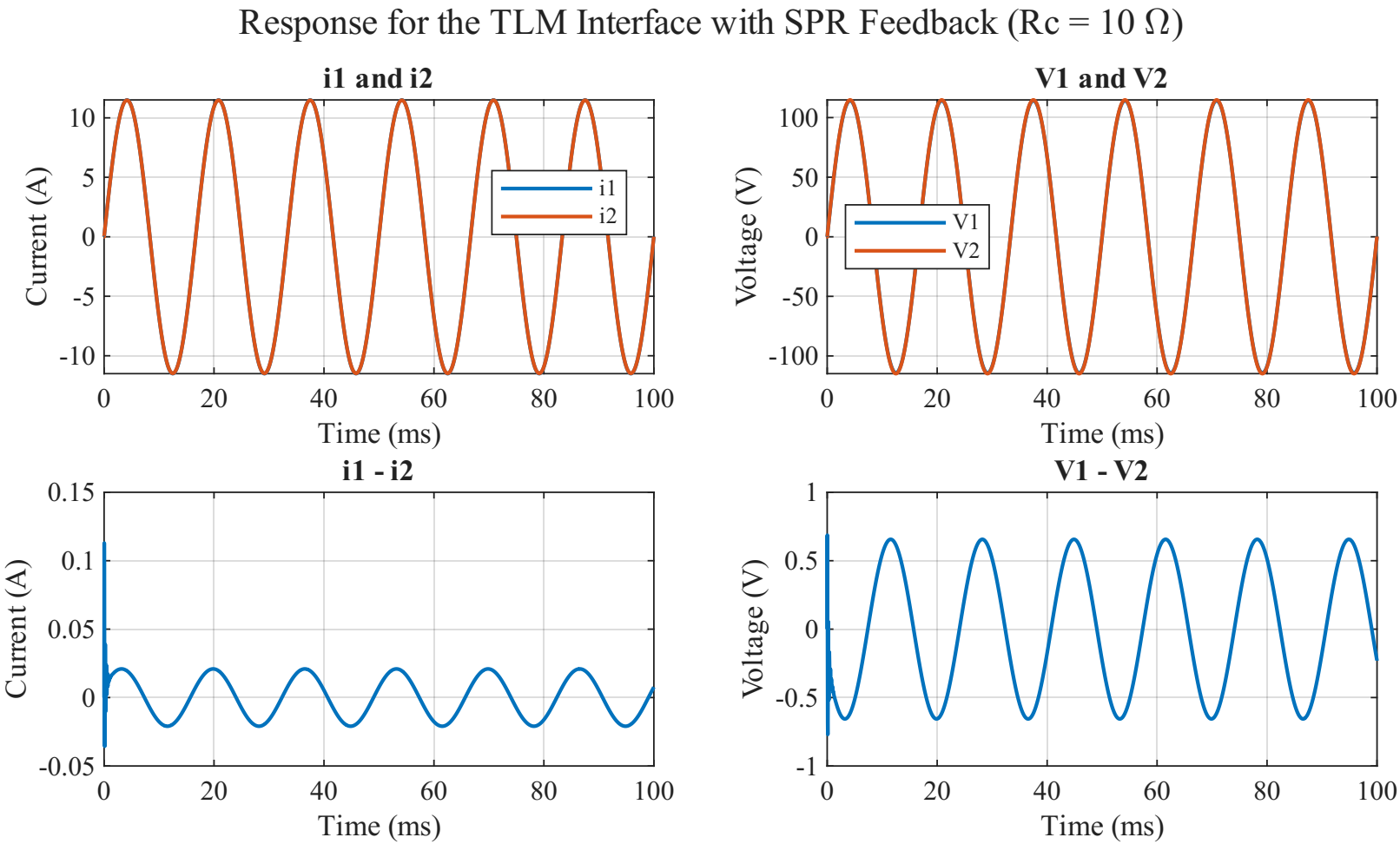


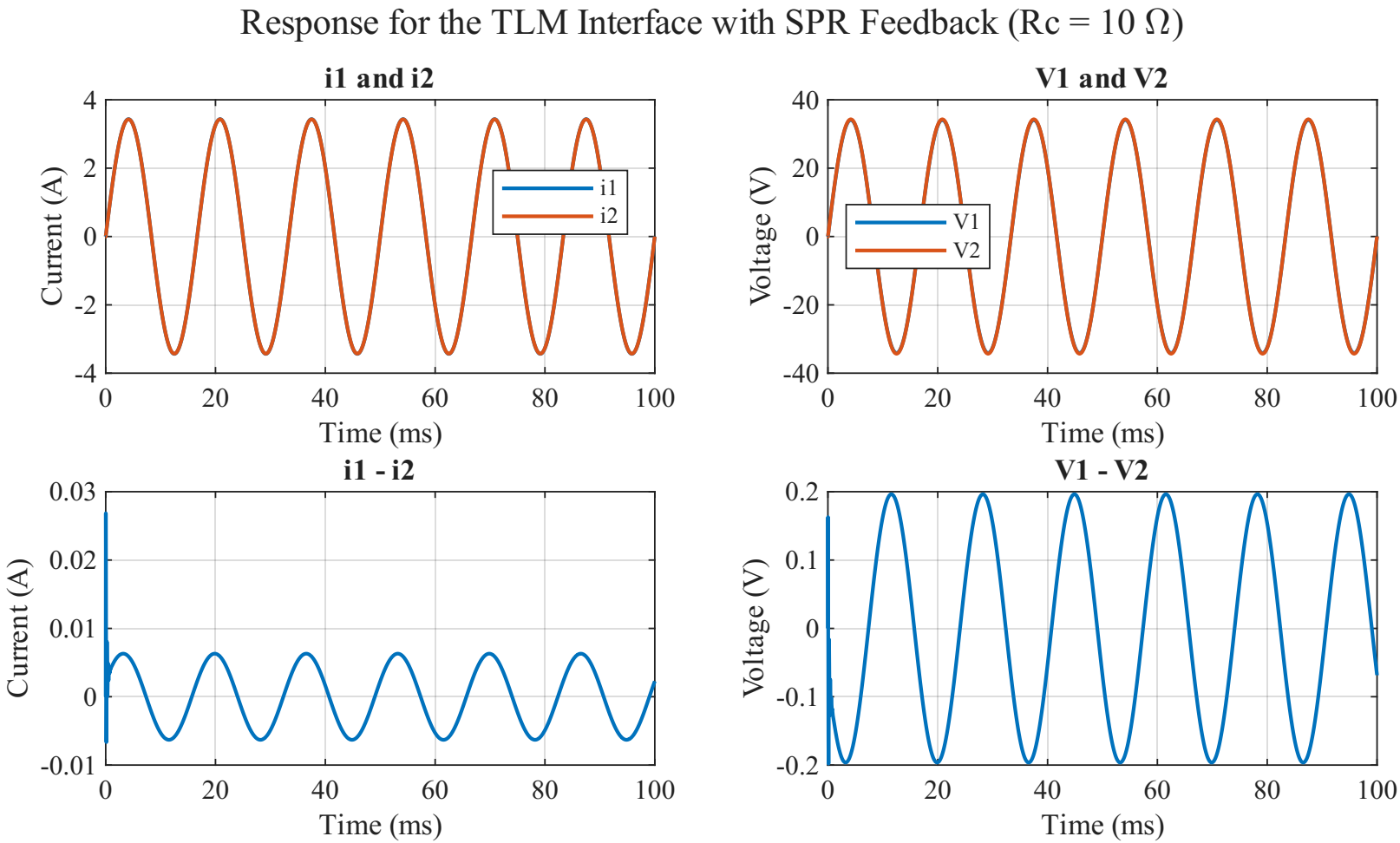

(b) Generalized control problem.

- Design a controller using $\mathcal{H}_2$ or $\mathcal{H}_\infty$ synthesis.
- Add an additional passivity constraint to the controller.

# Nominal Response with Passive Feedback



# Off-Nominal Response with Passive Feedback



# Conclusion

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- Closed-loop synthesis and testing is a useful approach to PHIL interfacing.
- Model matching and optimal control tools offer a systematic approach to precision.
- Optimal passivity-based control improves upon the TLM and the model matching method, offering a systematic approach to both precision and robustness.

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