Systematic Characterization of Power Hardware-in-the-Loop Evaluation Platform Stability

Jing Wang, Blake Lundstrom, Ismael Mendoza, and Annabelle Pratt

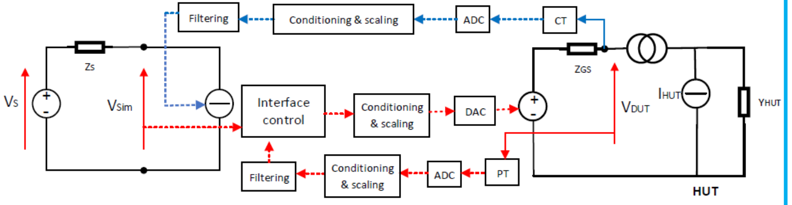
National Renewable Energy Laboratory, Golden, CO 80401, USA

Abstract

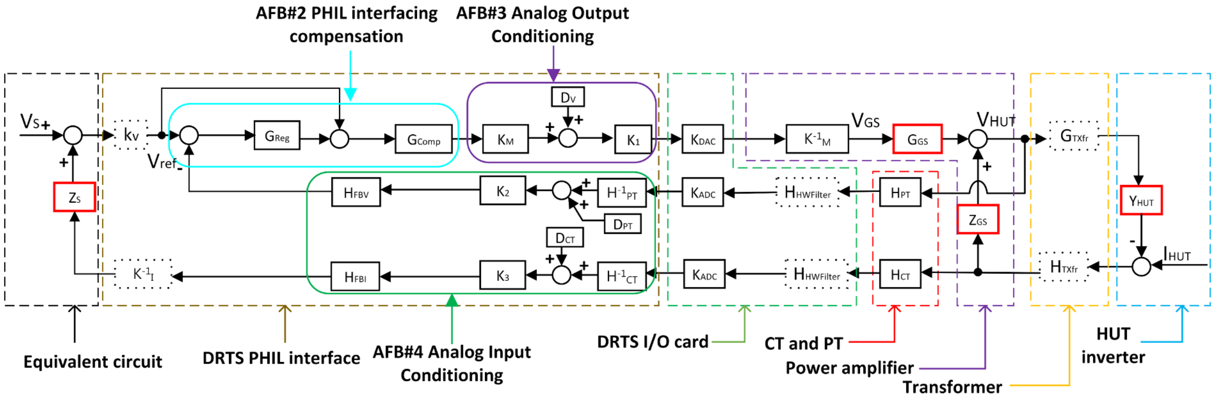
This paper presents a systematic approach to characterize the stability of a power-hardware-in-the-loop (PHIL) platform, an important step in PHIL tests. Many existing works focus the stability assessments on the PHIL interface algorithm; however, this work considers all software and hardware subsystems that form the closed loop of the PHIL experiment and develops a complete closed-loop stability assessment. This assessment is developed in the context of a common framework that can be readily applied to other PHIL platforms. This paper presents methods for characterizing key PHIL subsystems toward obtaining transfer functions to be used for analysis. The systematic stability assessment approach is demonstrated for a case study involving PHIL testing of a solar inverter and validated using experimental data.

PHIL Platform Configuration

- Equivalent circuit of the simulated electrical power system (Thevenin circuit)
- PHIL system software interface (signal conditioning, interface algorithms, and system controllers)
- PHIL system hardware interface (analog/digital converters, power amplifier, transformer, and sensors)
- Hardware under test (HUT)

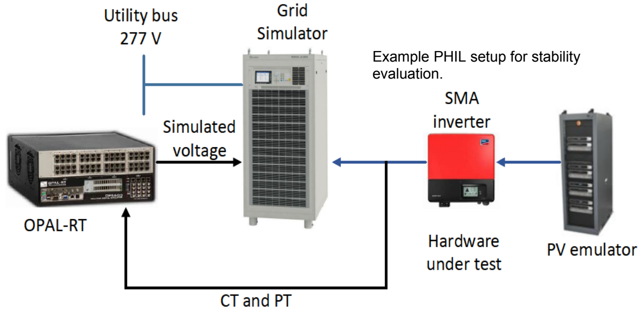


Generalized electrical diagram of a PHIL experimental setup



Transfer function block diagram of the PHIL experimental setup including all the elements in the closed loop

Experimental Results



Example PHIL setup for stability evaluation.

Table I. List of Experimental Results of Evaluation of PHIL Platform Stability

Power Amplifier Measured Power		DRTS Injected Power		Accuracy
Active power (kW)	Reactive power (kVar)	Active power (kW)	Reactive power (kVar)	Error in active power (%)
2.36	0.1	2.315	-0.173	-1.91
3.9	0.07	3.812	-0.175	-2.26
5.97	0.32	5.851	-0.186	-1.99
8.04	0.34	7.868	-0.192	-2.14
10.102	0.34	9.869	-0.195	-2.31
11.85	0.34	11.6	-0.207	-2.11

Characterizing the PHIL Platform

- Virtual system equivalent grid impedance Z_S: applying the frequency scan approach in the selected electric grid, the output impedance we obtain is $Z_s=0.055+j0.12$, with $R_s=0.055\ \Omega$ and $L_s=100.2\ \mu H$.
- Power amplifier G_{GS} and Z_{GS}:

$$G_{GS}(s)=\frac{V_{out}(s)}{V_{in}(s)}=\frac{G}{s+P_0}e^{-sT_{delay}}=\frac{4.6427e3}{s+4.6814e3}e^{-s0.00003}$$

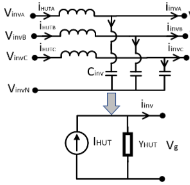
→ Frequency swap from fundamental to 49th
V_{in}, voltage reference from OPAL-RT
V_{out}, output voltage from power amplifier

$$Z_{GS}(s)=7.4e^{-3}s+\frac{1}{197_e{}^{-6}17.5_e{}^{-6}s^2+1}$$

→ Perform experiments to determine the output impedance of the power amplifier.

- HUT inverter Y_{HUT}: modeled as a Norton equivalent comprising a controlled-current source with a parallel-connected admittance.

$$Y_{HUT}=C_{inv}\begin{bmatrix}\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3}\\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3}\\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3}\end{bmatrix}=\frac{2}{3}sC_{inv}$$

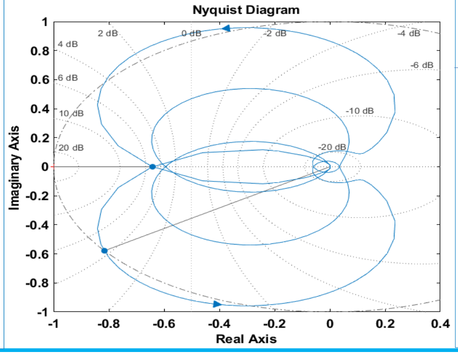


- Interfacing components: G_{Reg}, G_{Comp}, H_{FBV}, and H_{FBI} are designed by the user; K_M, D_v, K_1, K_{DAC}, G_{TXfr}, H_{TXfr}, H_{PT}, H_{CT}, K_{ADC}, K_2, K_3, D_{PT}, D_{CT}, K_v, and K_I can be derived from element specifications/data sheet.

System Stability Evaluation

- Open-loop transfer function

$$G_{OL}(s)=Y_{HUT}H_{IF}Z_SG_1=\frac{Y_{HUT}H_{IF}Z_S(1+G_{Reg})G_{Comp}K_{DAC}G_{GS}}{1+H_{VF}G_{Reg}G_{Comp}K_{DAC}G_{GS}+Z_{GS}Y_{HUT}}$$



Conclusion

This paper presents the stability evaluation of a PHIL platform prior to normal lab test and study. First, a diagram of the PHIL platform including all the associated elements is presented to give a high-level view of the system. Then, characterization is performed to get the mathematical representation of each element with special focus on four elements: amplifier gain and output impedance of the power amplifier, equivalent voltage source impedance, and equivalent HUT admittance. Next, the stability is evaluated analytically by checking the open-loop transfer function by the Nyquist criteria and poles of the closed-loop system. Finally, experimental tests are performed to demonstrate the stability of the PHIL system. This work provides a highly efficient tool to predict the stability of a PHIL simulation with accurate models of the components in the loop.

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Electricity, Advanced Grid Research & Development. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

2019 IEEE ECCE
Baltimore, MD
Sep. 29–Oct. 3, 2019
NREL/PO-5D00-74970