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Transforming ENERGY

De-Risking Field Deployment of Power System Innovations Using Hardware-in-the-Loop Experiments

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Photo by Werner Slocum, NREL 68547

Energy Systems Integration Facility

The Energy Systems Integration Facility (ESIF) is a national user facility located in Golden, Colorado, on the campus of the National Renewable Energy Laboratory (NREL).

http://www.nrel.gov/esif

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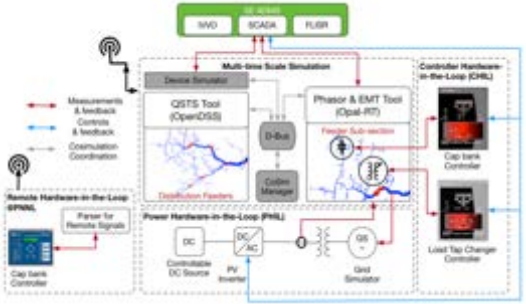
Controller- and Power-Hardware-in-the-Loop

NREL's megawatt-scale controller- and power-hardware-in-the-loop (CHIL/PHIL) capabilities allow researchers and manufacturers to test energy technologies at full power in real-time grid simulations to safely evaluate performance and reliability.

Microgrids



Cosimulation

Power system studies

Photos by NREL

Technology Readiness Levels (TRLs)

- Metric system developed to support the assessment of the maturity of a technology
- Allows for consistent comparisons of maturity among different types of technologies
- Used in the space industry
- Nine levels of maturity are identified in the original paper (Mankins 1995).

Technology Readiness Level	
TRL 1	Very low cost, idea
TRL 2	Low cost, idea
TRL 3	Moderate cost, idea to proof
TRL 4	Moderate cost, proof of concept
TRL 5	Moderate cost, proof of concept
TRL 6	Increased cost, validation
TRL 7	Increased cost, validation
TRL 8	High cost, deployment
TRL 9	Ideally market price, production stage

Source: Mankins 1995

Technology Readiness Levels

Technology Readiness Level	
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Source: Mankins 1995

Borrowing Technology Readiness Levels for Power Systems

- What is a proof of concept?
- What is a breadboard validation in a laboratory environment?
- What is a relevant environment?
- What is a demonstration?

Source: Mankins 1995

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- Boundaries of physics
- Electromagnetic transient (EMT) simulation
- Dynamic simulation
- Steady-state simulation
- Hardware experiments
- Software experiments
- Hardware-in-the-loop experiments
- Field deployment.

Source: Mankins 1995

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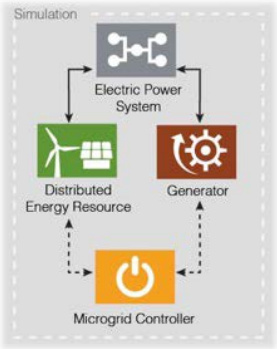
It depends

Source: Mankins 1995

Evaluation Approaches Used in the Industry

A) Pure simulation



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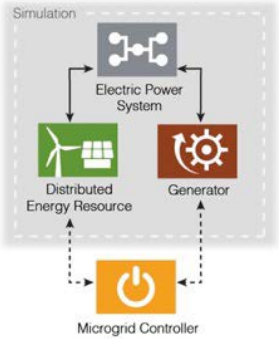
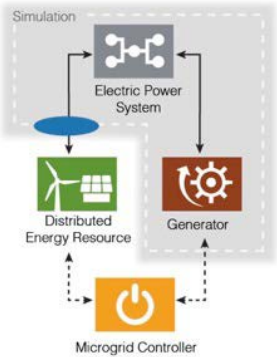


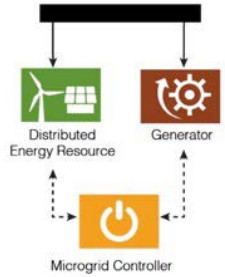
B) CHIL

B) Controller-hardware-in-the-loop

C) Controller-hardware-in-the-loop and power-hardware-in-the-loop



C) CHIL & PHIL



D) Hardware only

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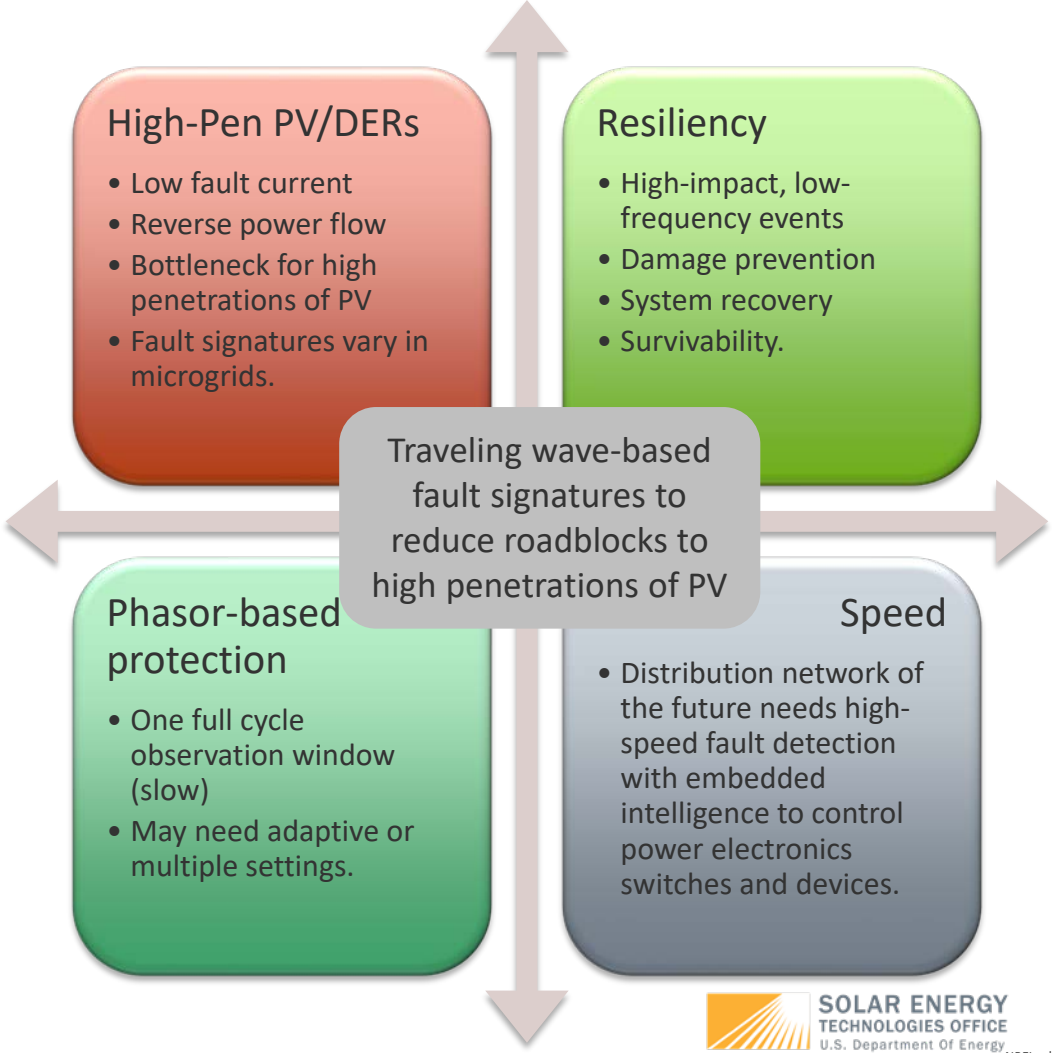
Source: Maitra 2007

The Challenge



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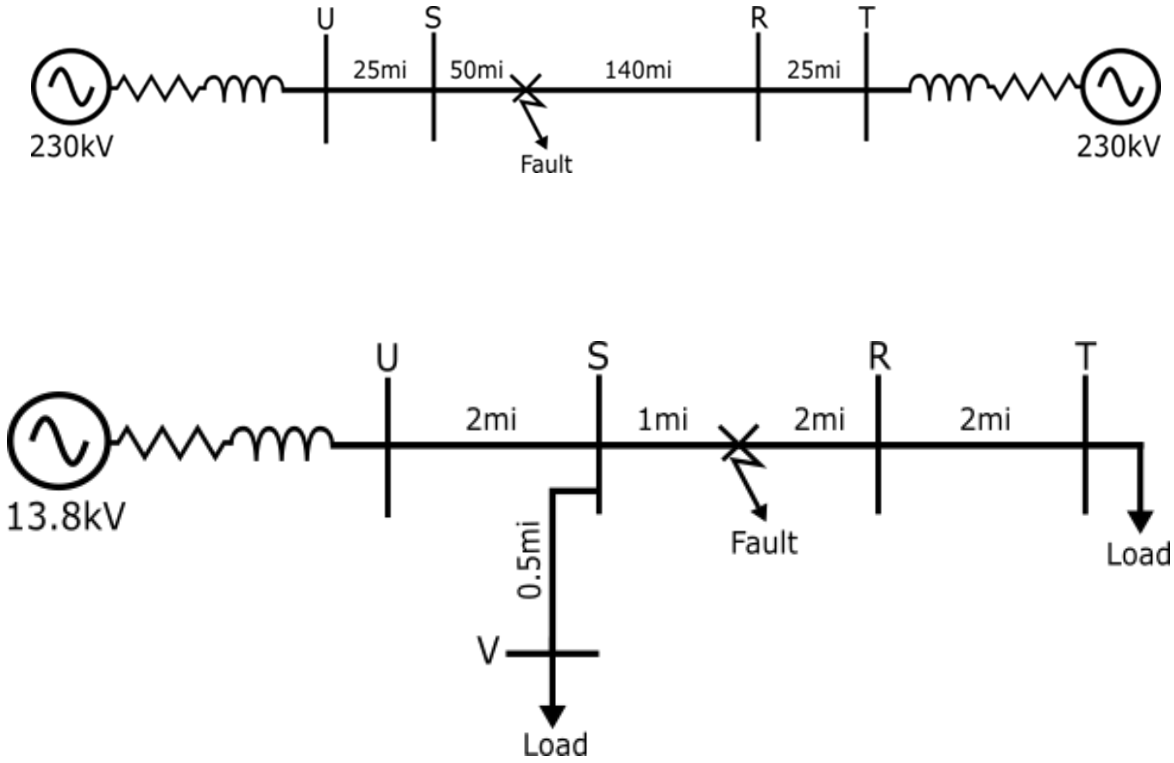
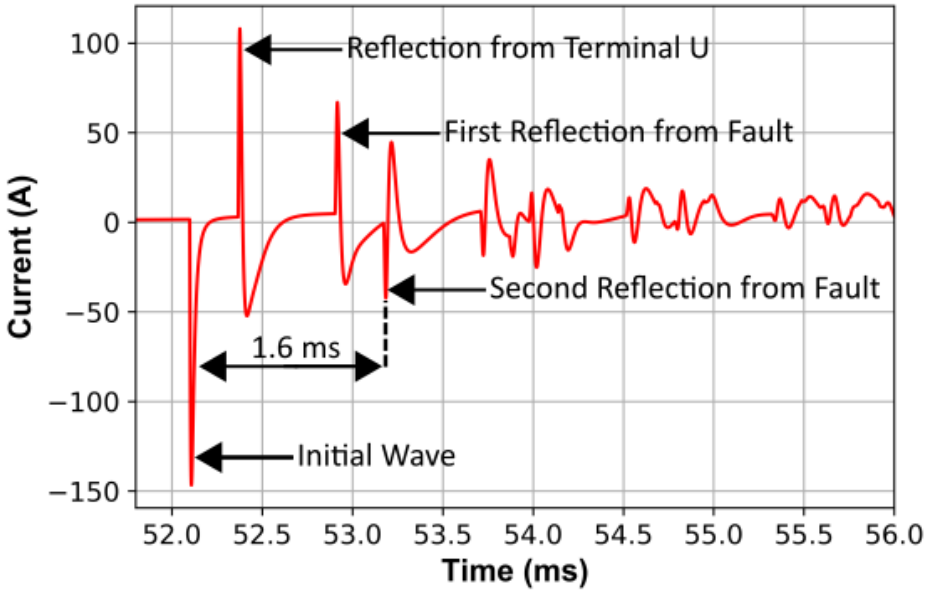
Software Simulation: Traveling Waves in Transmission and Distribution

- Transmission and distribution are modeled at 230 kV and 13.8 kV, respectively, with source impedance.
- Second-order band-pass filter from EMTP-RV is tuned at 20 kHz in transmission.
- Low TRL.

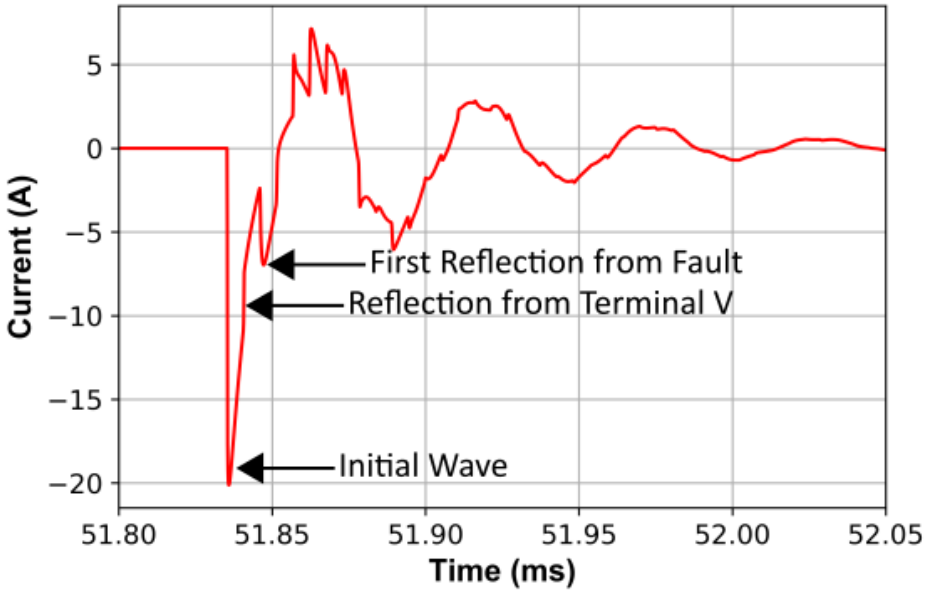


Source: Prabakar et al. 2021

Results: Traveling Waves in Transmission and Distribution



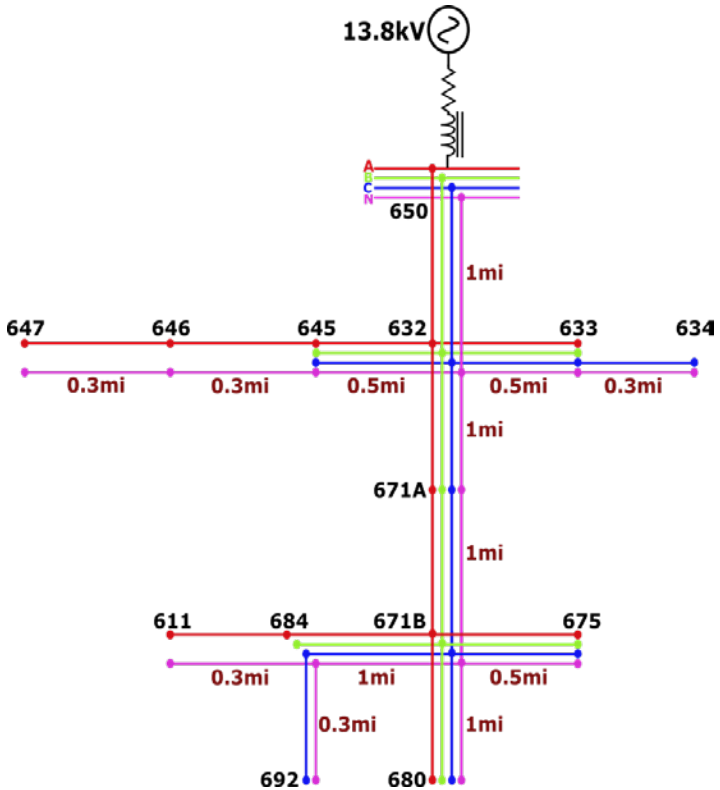
Filtered data at terminal S in transmission system

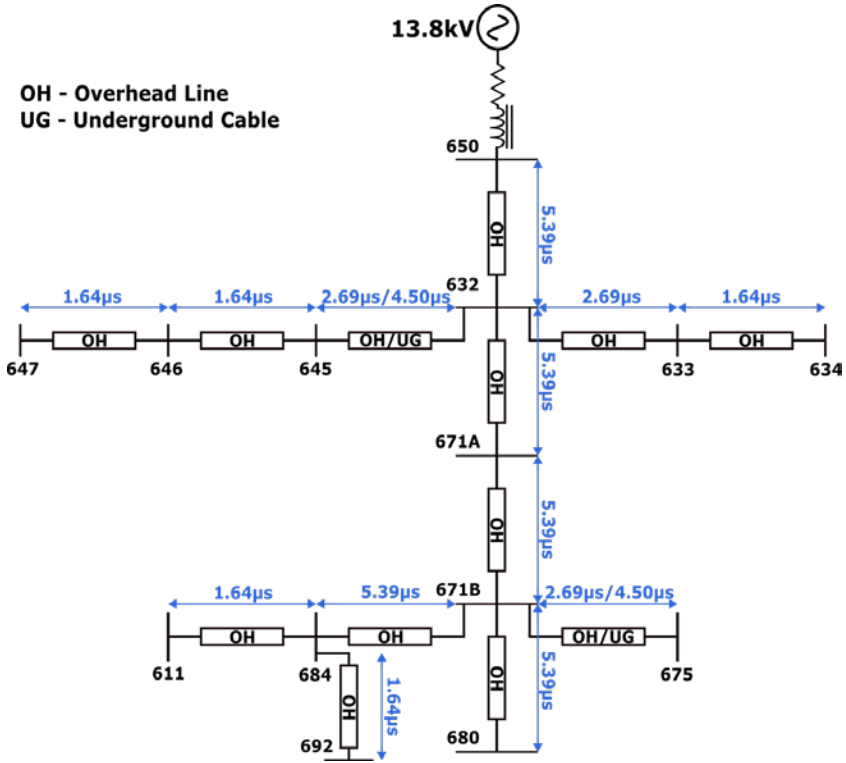


Filtered data at terminal S in distribution system

Source: Prabakar et al. 2021

Modified IEEE 13-Bus System

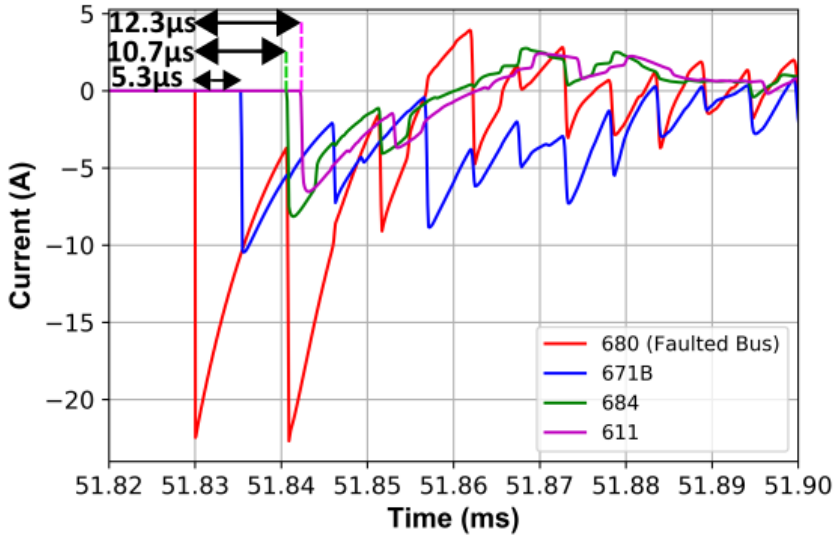


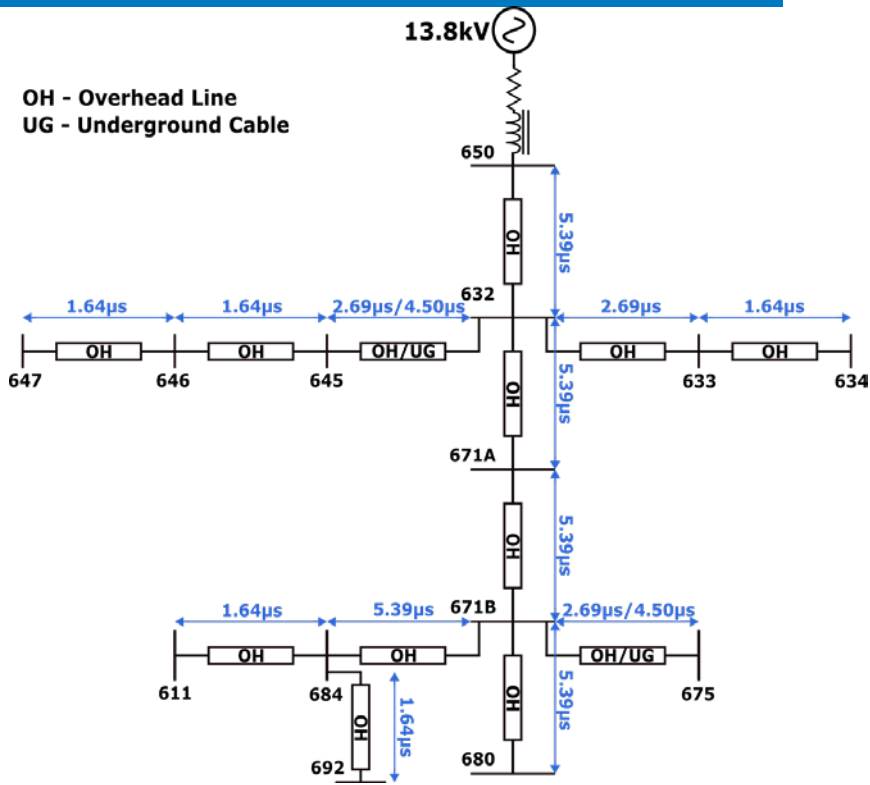


Source: Prabakar et al. 2021

Overhead Lines with Fault on Bus 680

- Initial wave times estimated at 671B, 684, and 611 are 5.39µs, 10.78µs, and 12.42µs, respectively.
- Low TRL.





Source: Prabakar et al. 2021

Challenges in Digital Real-Time Simulation of Traveling Waves

- Analyzing traveling waves in digital real-time simulators (DRTS)
- Fidelity and scalability of the models
- Transmission products released in 2018
- No DRTS modeling approach is available for short transmission lines.
- We must skip CHIL and PHIL and move to power hardware experiments.

Goals of the Experiments

- Use real-world overhead and underground lines (no digital or analog emulation).
- Use real faults .
- Use off-the shelf, available, inexpensive CTs.
- Capture wide frequency data (up to ~100 MHz).
- Show traveling wave in a field experiment.
- Show capability to differentiate between noise and high-frequency waves in real time.
- Mid to high TRL.

Source: Prabakar et al. 2021

Experimental Setup

Photos by Ismael Mendoza and Colin Tombari, NREL

Source: Prabakar et al. 2021

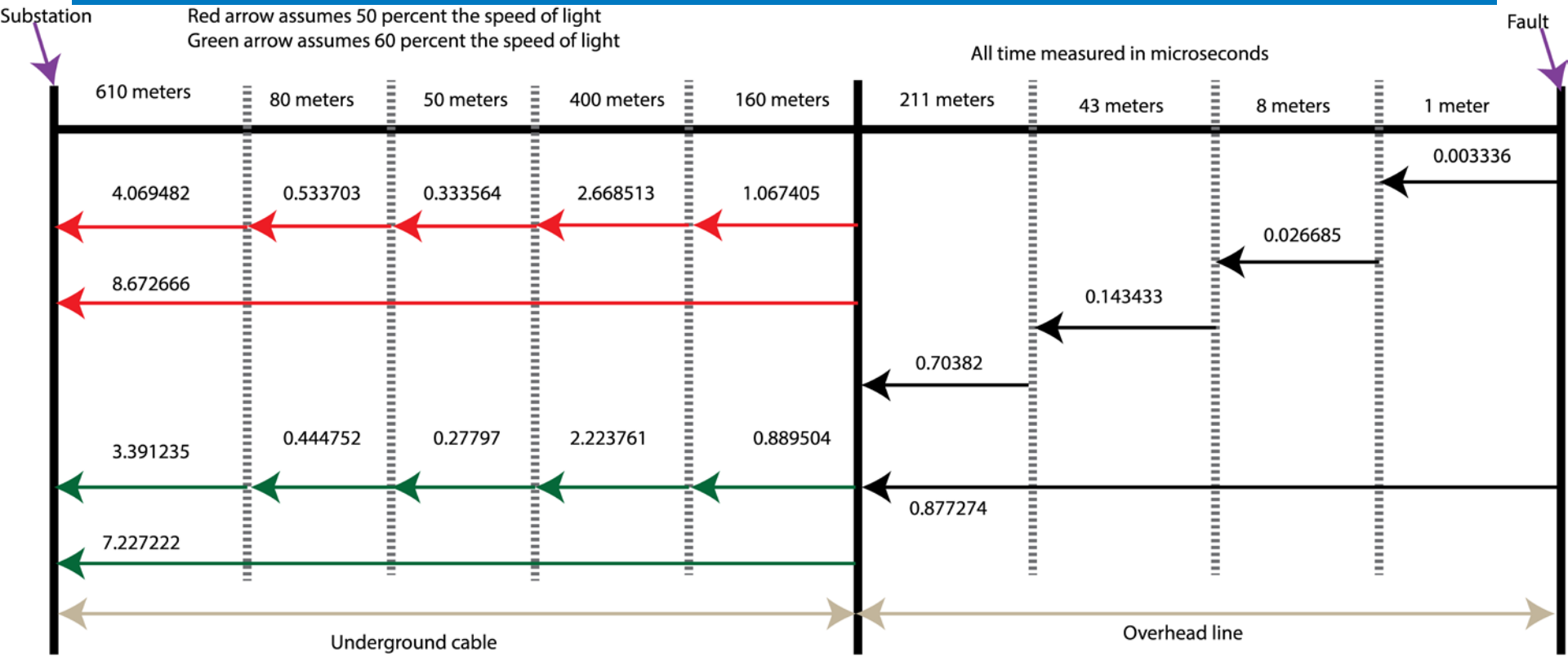
Field Experiments

Photos by Ismael Mendoza and Colin Tombari, NREL

Setup for Single-Phase Faults

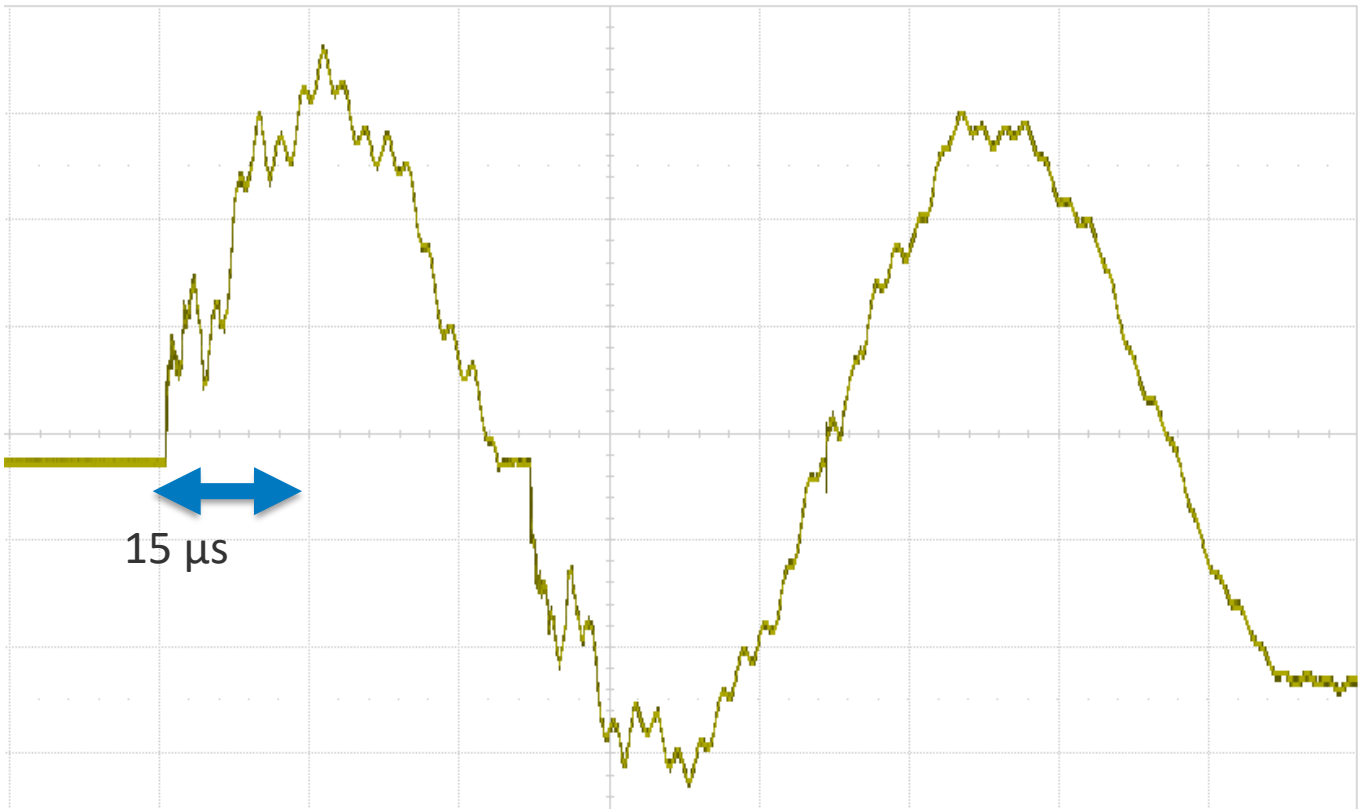
Source: Prabakar et al. 2021

Length of the Lines and Theoretical Traveling Time



Source: Prabakar et al. 2021

Results

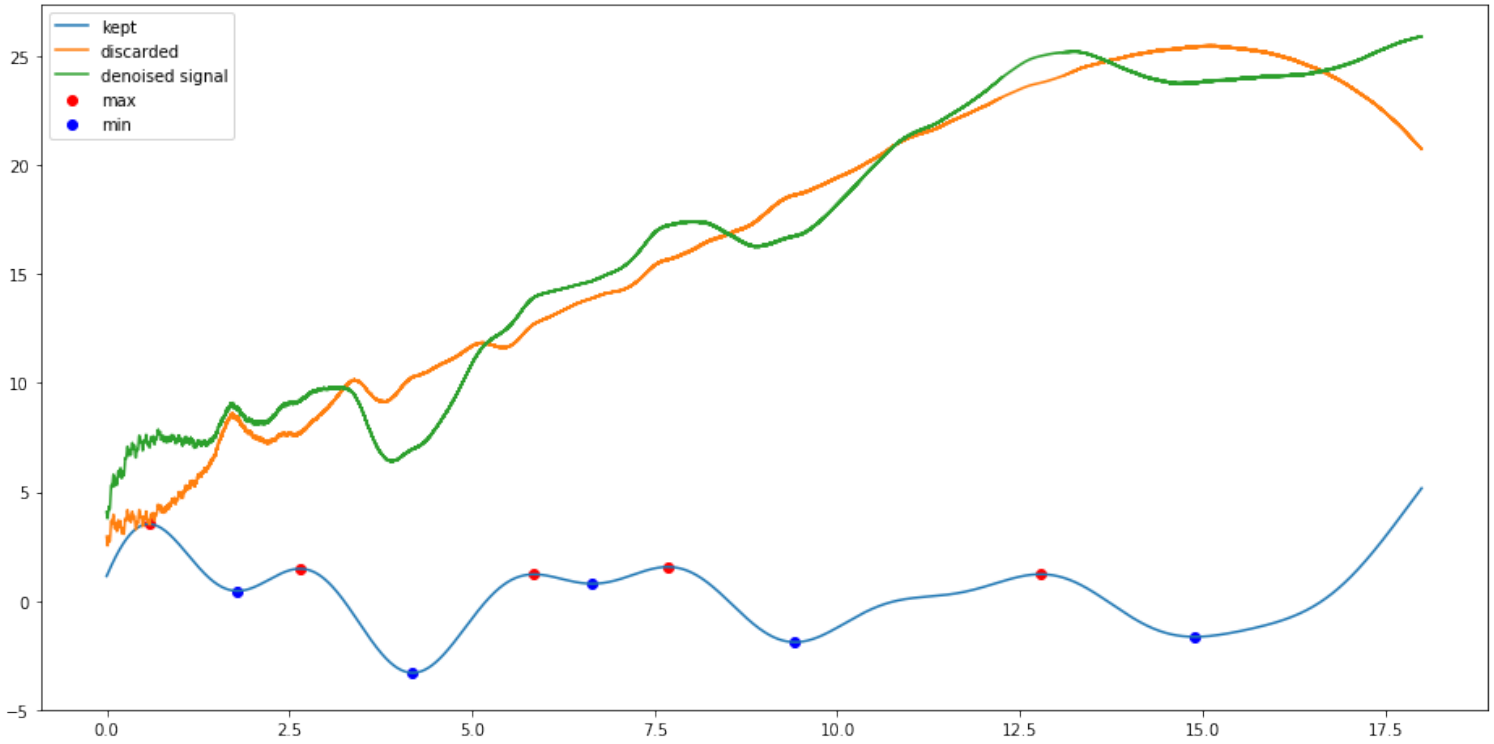


Trace Properties

Appearance	
Trace Color	adaa00
Scale	
Horizontal/Div	14.8 µs
Vertical/Div	6.7 V
Frame	
Horizontal Start	-95.450000 µs
Horizontal Stop	52.550000 µs
Vertical Start	-24.98 V
Vertical Stop	26.80 V
Misc	
Points	185.002 kS
Hor. Center	21.3 µs
Ver. Center	-1.819 V

Source: Prabakar et al. 2021

Advanced Mathematics-Based Signal Processing Result



Source: Prabakar et al. 2021

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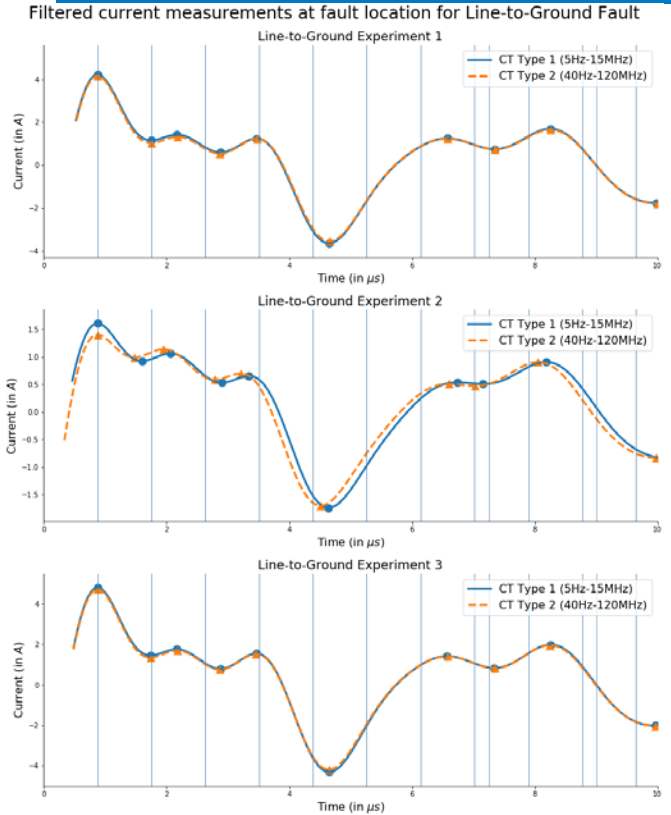
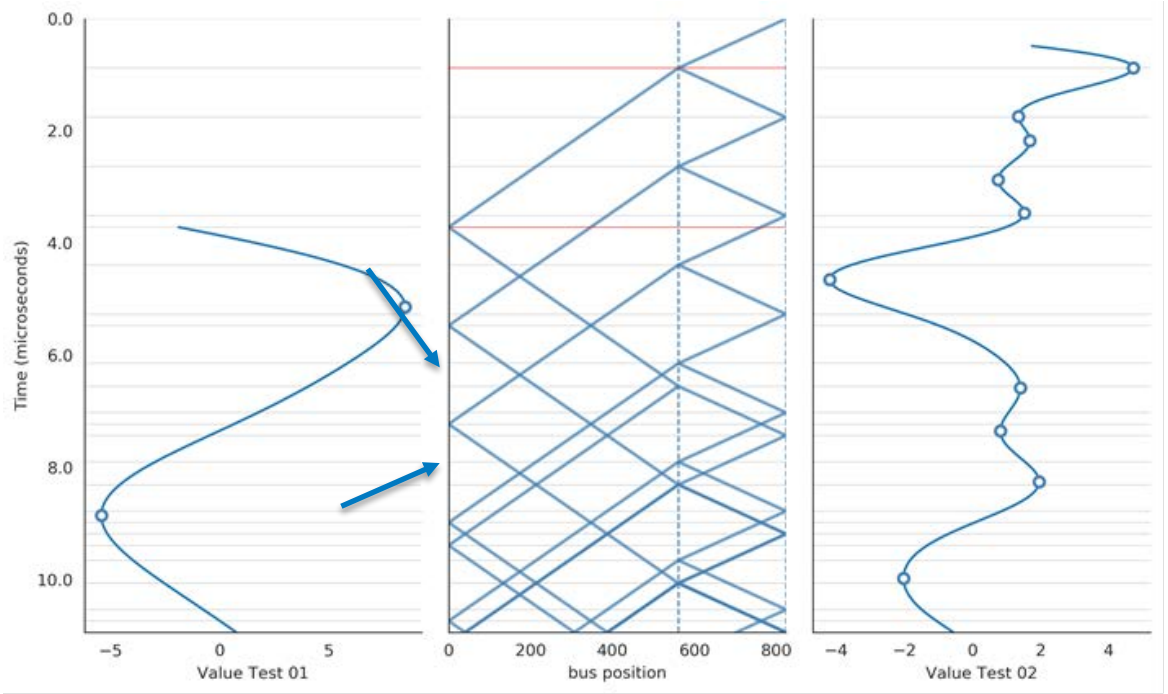
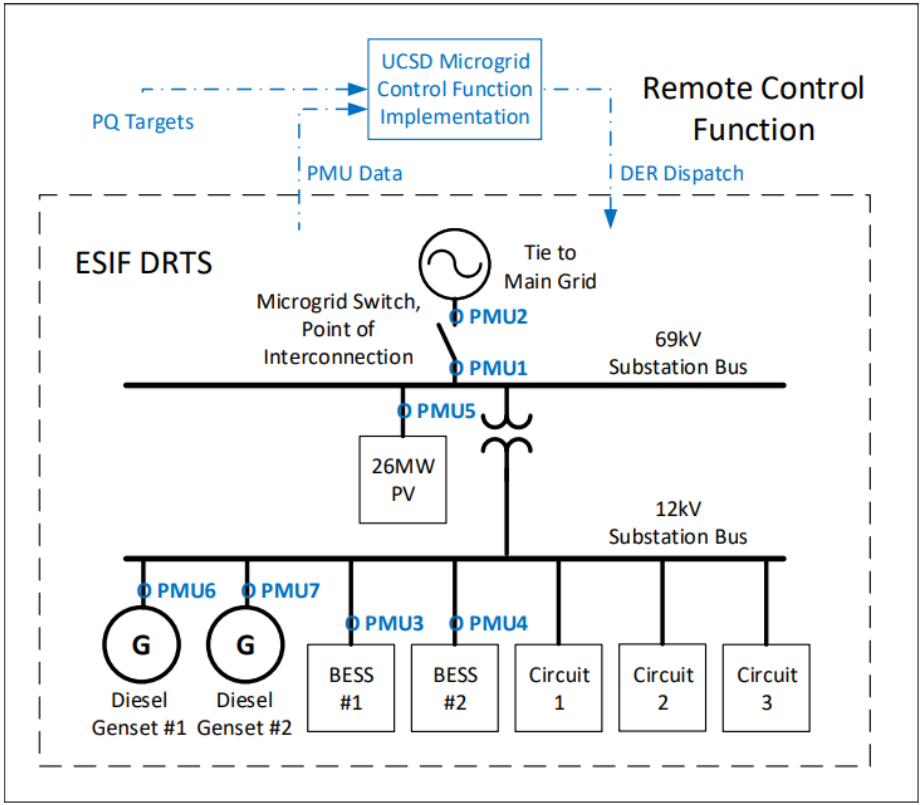
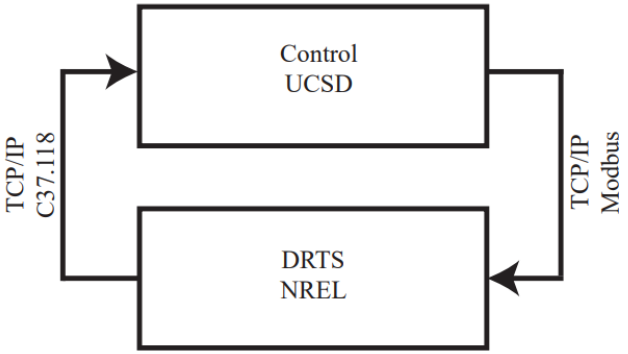


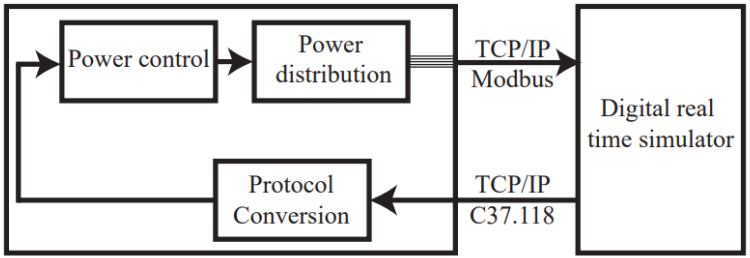


Source: Prabakar et al. 2021

Controller-Hardware-in-the-Loop Evaluation







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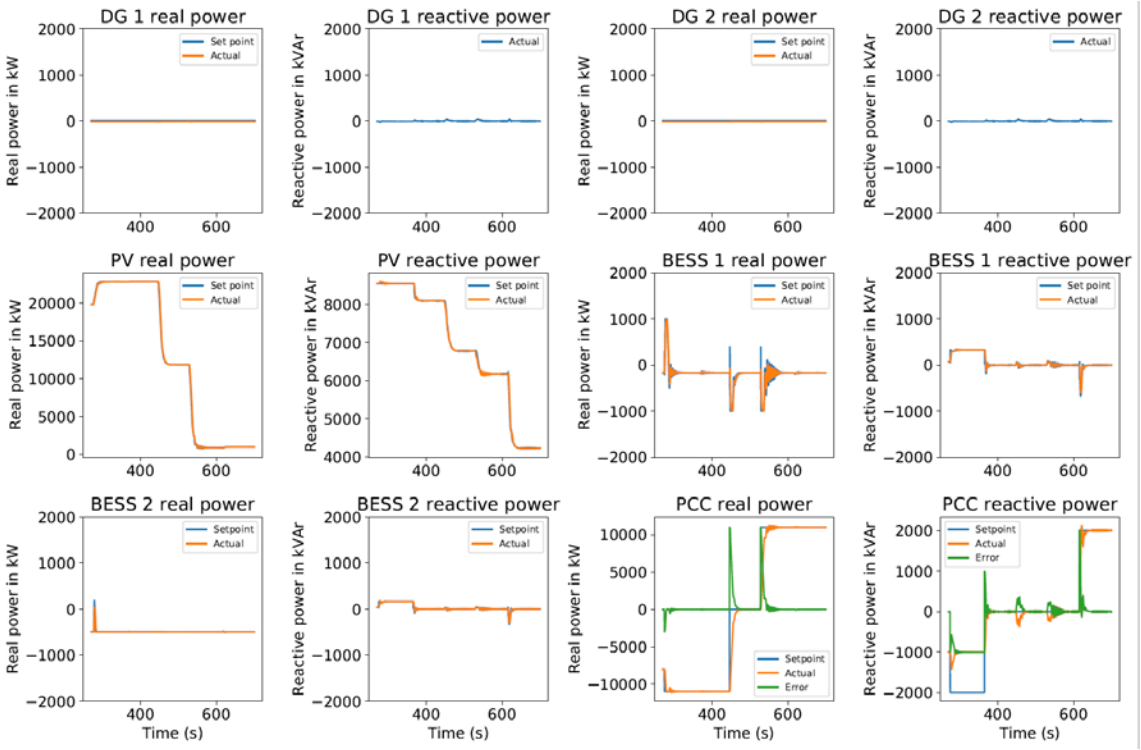
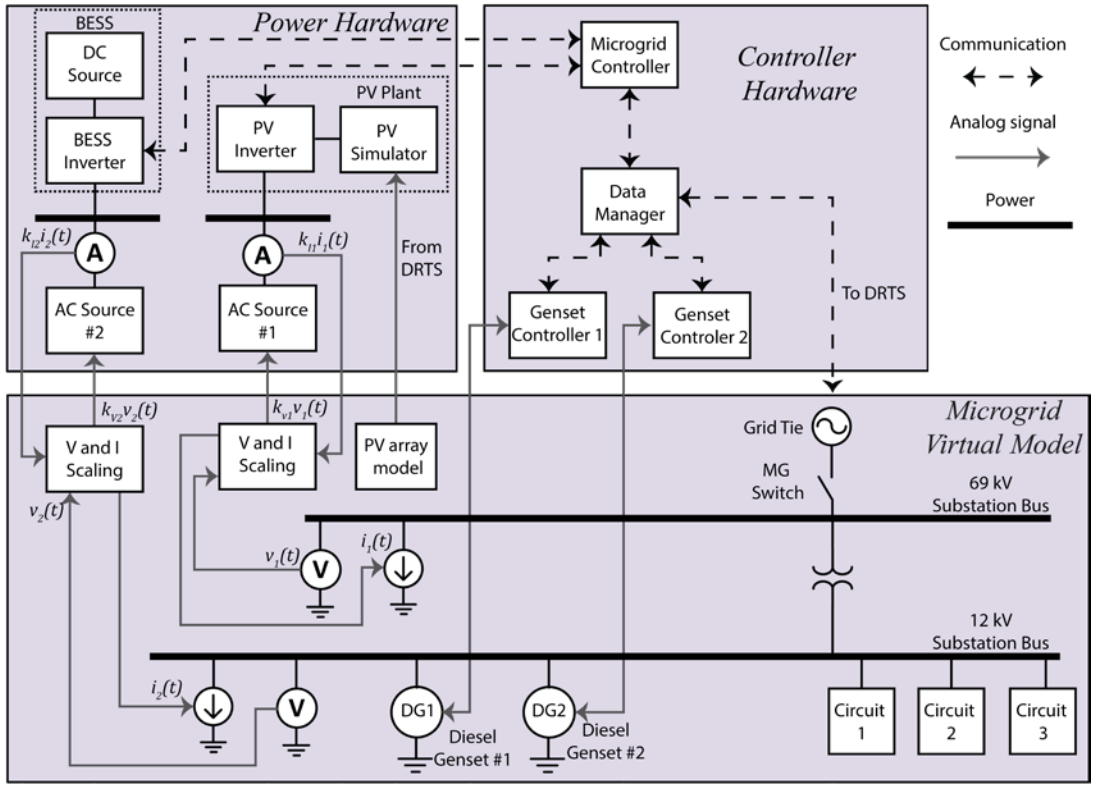


Source: Prabakar et al. 2020

Controller-/Power-Hardware-in-the-Loop Evaluation



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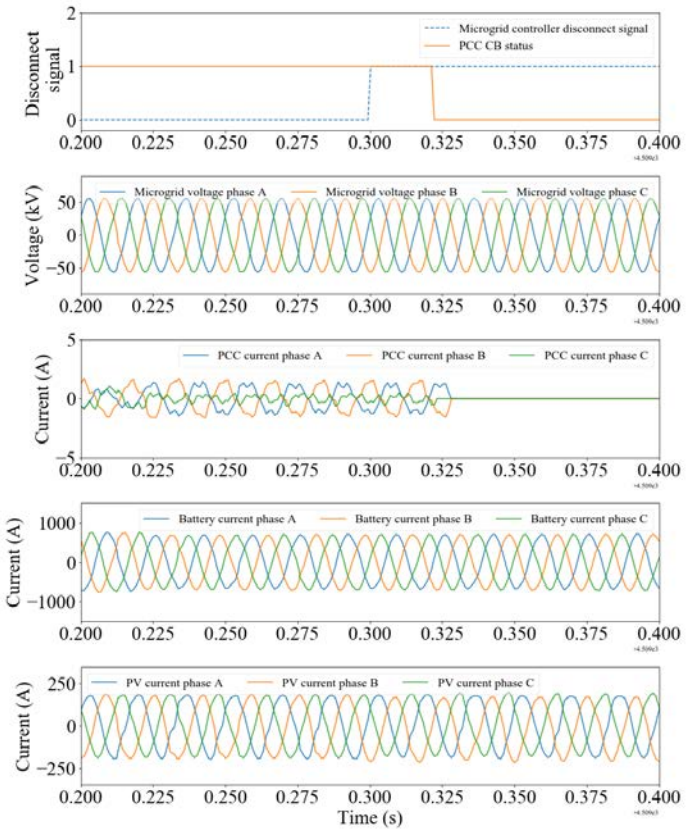
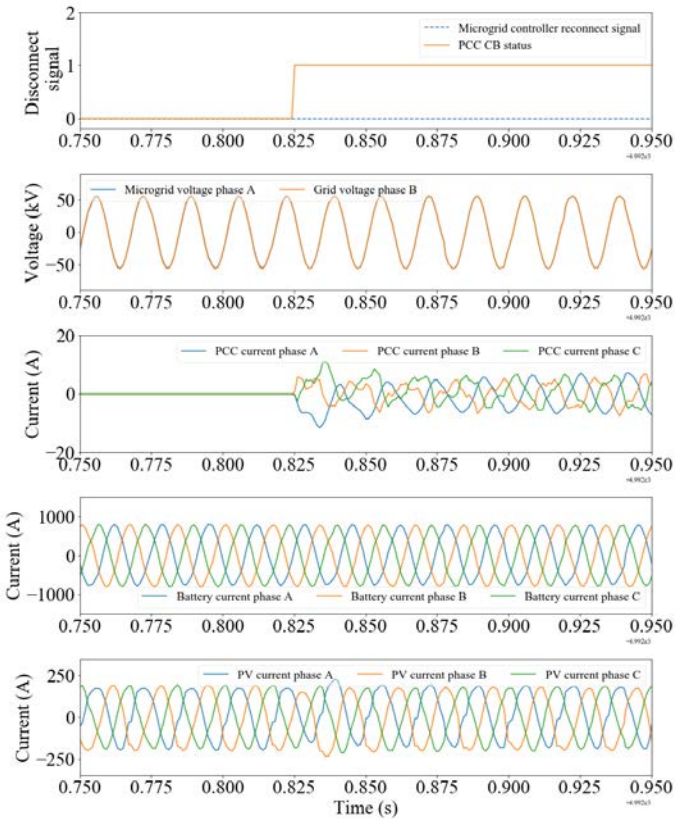
Controller-/Power-Hardware-in-the-Loop Evaluation





Source: Prabakar et al. 2019

Summary

- Presented background on technology readiness levels
- Critical to understand the maturity level and for comparisons between technologies
- Presented background on software simulation, power hardware experiments, controller-hardware-in-the-loop experiments, and power-hardware-in-the-loop experiments
- Appropriate use of evaluation technologies can reduce the risk.

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