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Network Reduction for Power Hardware-in-the-Loop (PHIL) Simulation

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MIDAS Solar Project

- **3 YEARS**
- **7 PARTNERS**
- **DOE SOLAR ENERGY TECHNOLGOGY OFFICE (SETO) Funded**

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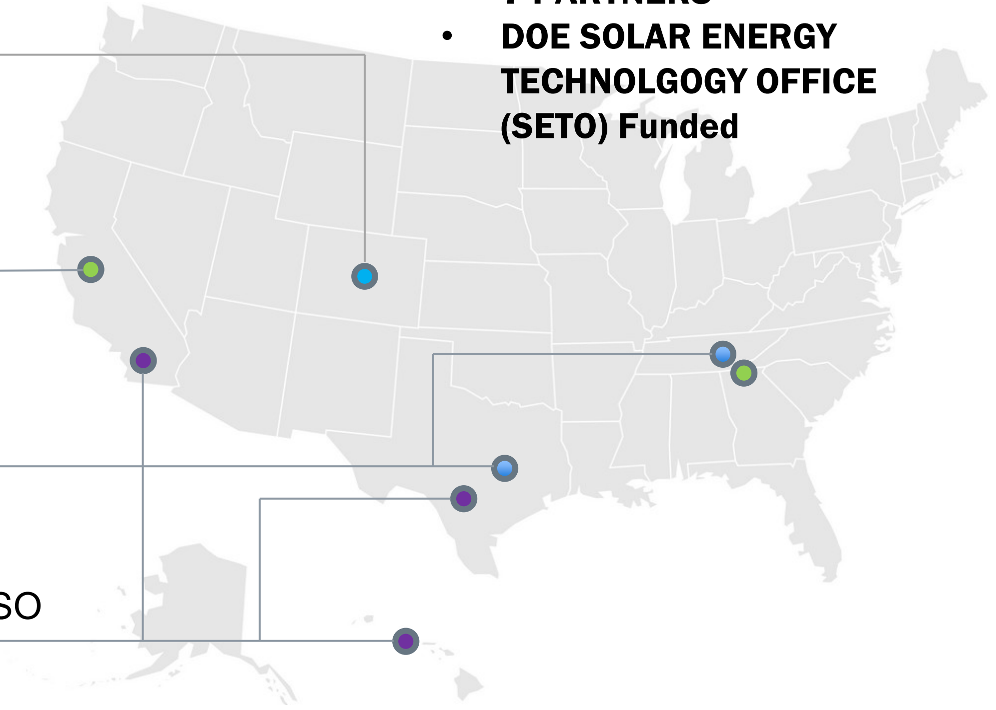
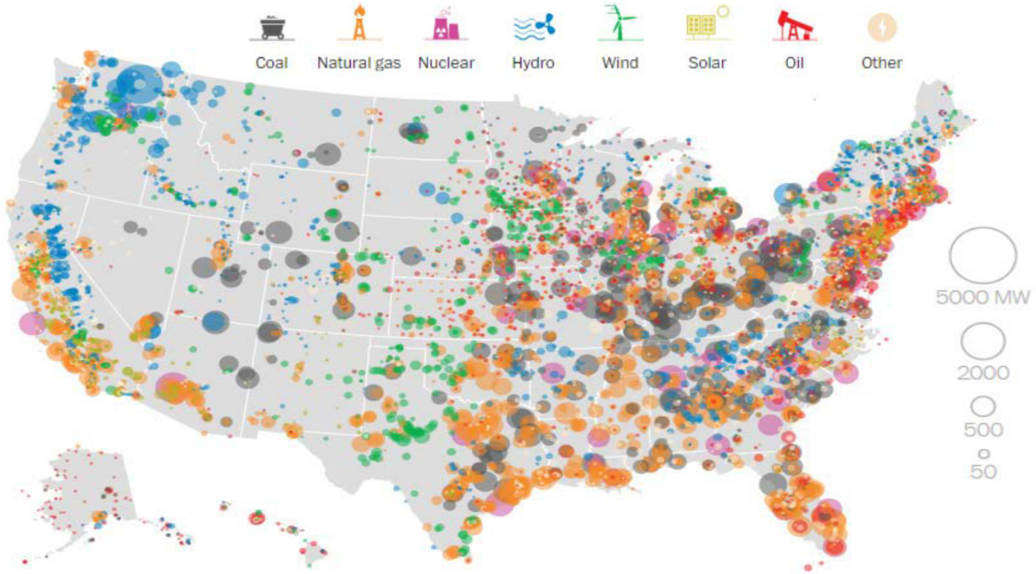


Content

Why PHIL?

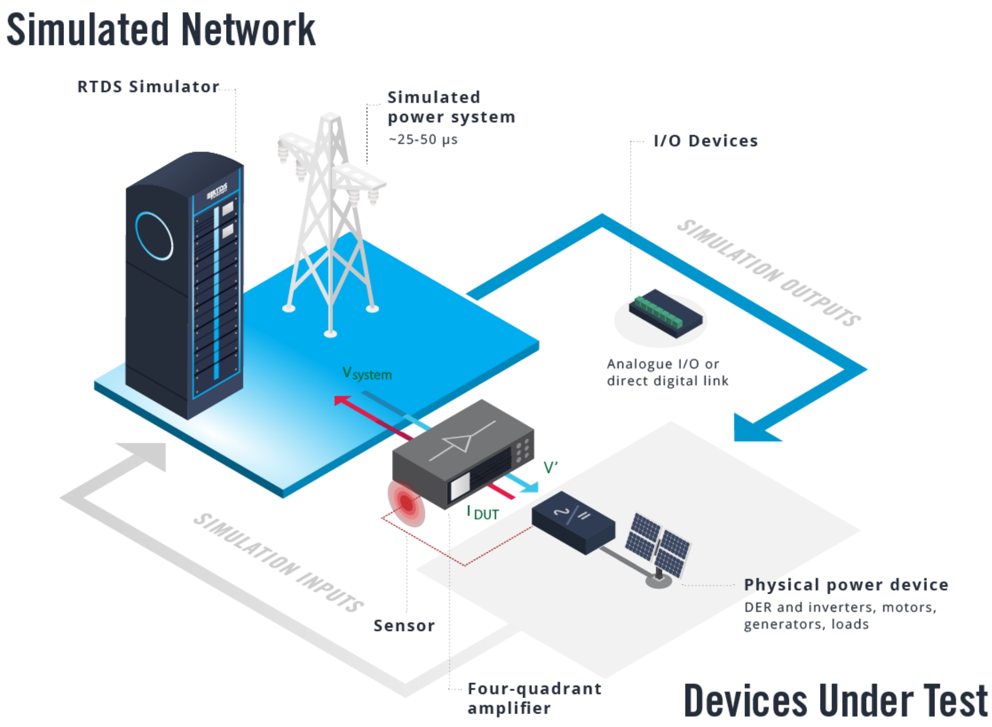
- **More challenging** stability assessment and control evaluation for power systems with a high share of IBRs, due to
  - ➢ **Unknown, unavailable or inaccurate dynamic models**
  - ➢ Problem size



https://www.lowtechmagazine.com/2017/09/how-to-run-modern-society-on-solar-and-wind-powe.html

Why Network Reduction for PHIL?

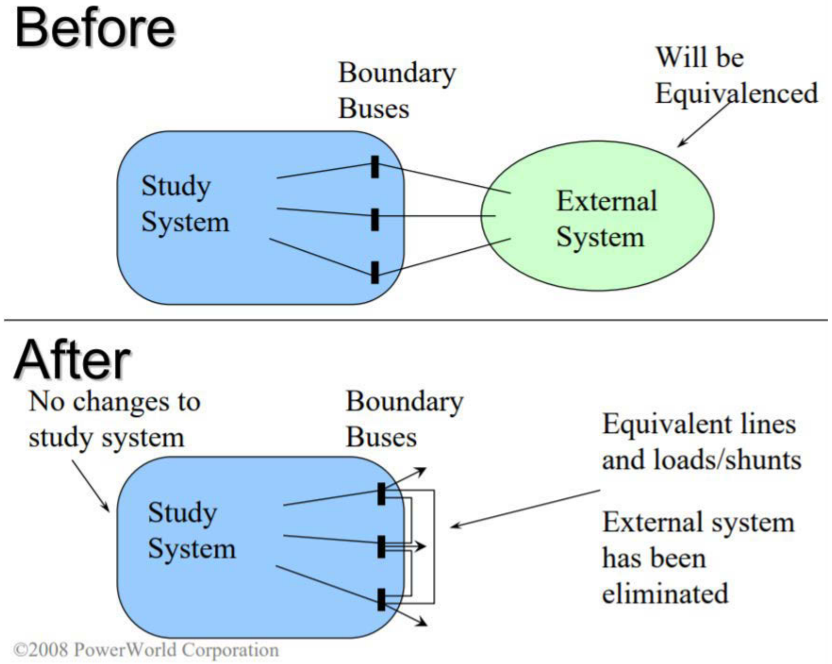
- **PHIL can help** investigate potential detrimental behaviors, and de-risk their deployment within a laboratory.
- **Real-time simulation tools required by PHIL** always only have limited capability and cannot handle a too large system.
- Therefore, a model reduction is usually required for PHIL sims of large systems.



https://www.rtds.com/applications/power-hardware-in-the-loop/

Why a New Network Reduction Approach?

- Traditional approaches, e.g. Ward equivalent and DYNRED, usually only focus on a local portion of the system.
  - Internal system (or study system)
  - Boundary
  - External system
  - Works fine if only a local portion of the system is of interest
- Need a new approach (**to be open sourced**) to reduce meshed networks, where dynamic elements of interest could spread all over the networks, for PHIL testing of distributed generations at different locations.



https://www.powerworld.com/files/TrainingI14Equivalents.pdf

Proposed single-port equivalent

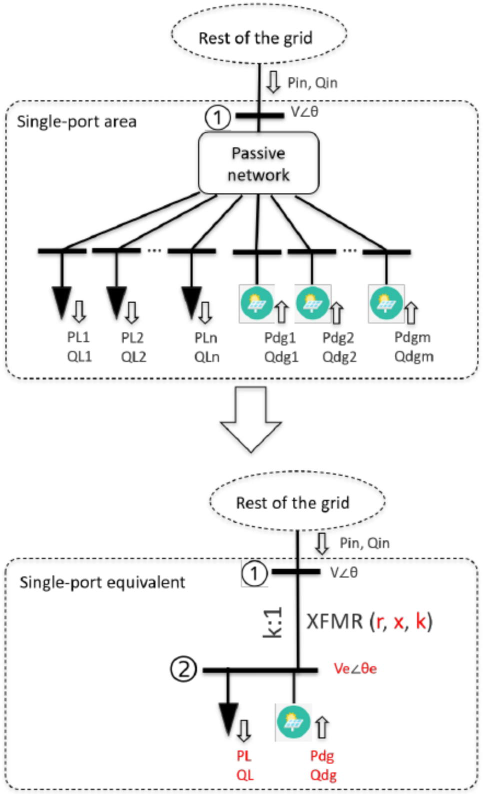


Fig. 1. Single-port equivalent.

- **9 real-valued unknowns**
- **9 equations**:
  - 4 real-valued eqs. by KCL at buses 1 and 2 (1)-(2)
  - 4 eqs. by conservation of total load and generation (3)-(6)
  - 1 more equation on Ve (7)
- **Solution** in (8)-(11)

$$\left(\frac{P_{\text{in}}+jQ_{\text{in}}}{V\angle\theta}\right)^* = \frac{V\angle\theta}{r+jx} - \frac{V_e\angle\theta_e}{k(r+jx)} \tag{1}$$

$$\frac{-V\angle\theta}{k(r+jx)} + \frac{V_e\angle\theta_e}{k^2(r+jx)} = \left(\frac{P_{\text{dg}}-P_L+j(Q_{\text{dg}}-Q_L)}{V_e\angle\theta_e}\right)^* \tag{2}$$

$$P_L = \sum_{i=1}^{n} P_{Li} \tag{3}$$

$$Q_L = \sum_{i=1}^{n} Q_{Li} \tag{4}$$

$$P_{\text{dg}} = \sum_{i=1}^{m} P_{\text{dg}i} \tag{5}$$

$$Q_{\text{dg}} = \sum_{i=1}^{m} Q_{\text{dg}i} \tag{6}$$

$$V_e = \frac{1}{n+m}\left(\sum_{i=1}^{n} V_{Li} + \sum_{i=1}^{m} V_{\text{dg}i}\right) \tag{7}$$

$$k = \frac{V_e}{V} \cdot \frac{\sqrt{P_{\text{in}}^2 + Q_{\text{in}}^2}}{\sqrt{(P_L - P_{\text{dg}})^2 + (Q_L - Q_{\text{dg}})^2}} \tag{8}$$

$$\alpha = V_e \frac{P_{\text{in}} + jQ_{\text{in}}}{V\angle\theta} \tag{9}$$

$$\theta_e = \sin^{-1}\frac{k(Q_L - Q_{\text{dg}})}{\sqrt{\text{Re}(\alpha)^2 + \text{Im}(\alpha)^2}} - \tan^{-1}\frac{\text{Im}(\alpha)}{\text{Re}(\alpha)} \tag{10}$$

$$r + jx = \frac{V\angle\theta - \frac{V_e}{k}}{\left(\frac{P_{\text{in}}+jQ_{\text{in}}}{V\angle\theta}\right)^*} \tag{11}$$

Proposed two-port equivalent

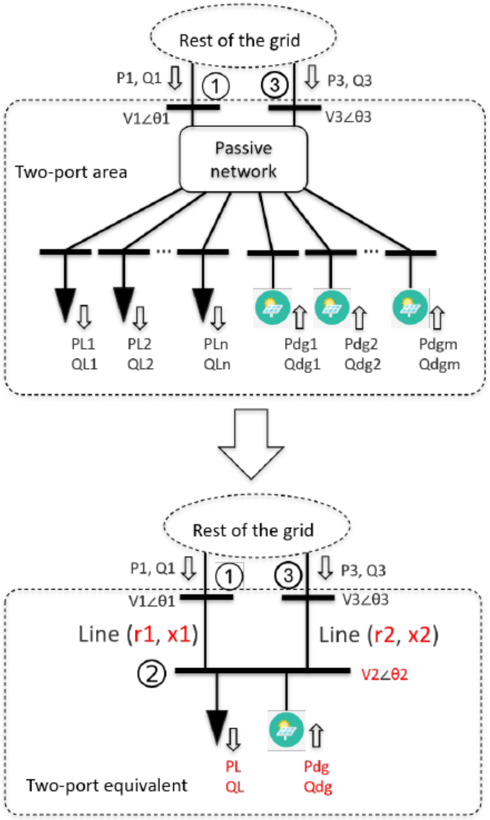


Fig. 2. Two-port equivalent.

- **10 real-valued unknowns**
- **10 equations**:
  - 6 real-valued eqs. by KCL at buses 1, 2 and 3 (12)-(14)
  - 4 eqs. by conservation of total load and generation (3)-(6)
- **Solution** in (15)-(17)

$$\left(\frac{P_1+jQ_1}{V_1\angle\theta_1}\right)^* = \frac{V_1\angle\theta_1 - V_2\angle\theta_2}{r_1+jx_1} \quad (12)$$

$$\left(\frac{P_{\mathrm{dg}}-P_{\mathrm{L}}+j(Q_{\mathrm{dg}}-Q_{\mathrm{L}})}{V_2\angle\theta_2}\right)^* = \frac{V_1\angle\theta_1 - V_2\angle\theta_2}{r_1+jx_1} + \frac{V_3\angle\theta_3 - V_2\angle\theta_2}{r_2+jx_2} \quad (13)$$

$$\left(\frac{P_3+jQ_3}{V_3\angle\theta_3}\right)^* = \frac{V_3\angle\theta_3 - V_2\angle\theta_2}{r_2+jx_2} \quad (14)$$

$$P_{\mathrm{L}} = \sum_{i=1}^{n} P_{\mathrm{L}i} \quad (3)$$

$$Q_{\mathrm{L}} = \sum_{i=1}^{n} Q_{\mathrm{L}i} \quad (4)$$

$$P_{\mathrm{dg}} = \sum_{i=1}^{m} P_{\mathrm{dg}i} \quad (5)$$

$$Q_{\mathrm{dg}} = \sum_{i=1}^{m} Q_{\mathrm{dg}i} \quad (6)$$

$$V_2\angle\theta_2 = \frac{P_{\mathrm{dg}}-P_{\mathrm{L}}+j(Q_{\mathrm{dg}}-Q_{\mathrm{L}})}{\frac{P_1+jQ_1}{V_1\angle\theta_1}+\frac{P_3+jQ_3}{V_3\angle\theta_3}} \quad (15)$$

$$r_1+jx_1 = \frac{V_1\angle\theta_1 - V_2\angle\theta_2}{\left(\frac{P_1+jQ_1}{V_1\angle\theta_1}\right)^*} \quad (16)$$

$$r_2+jx_2 = \frac{V_3\angle\theta_3 - V_2\angle\theta_2}{\left(\frac{P_3+jQ_3}{V_3\angle\theta_3}\right)^*} \quad (17)$$

Remarks

- Single-port and two-port equivalents can guarantee:
  - Conservation of total load and total generation within the area
  - Equivalence of steady-state terminal quantities, including P/Q injections and voltage magnitude and angle
  - Power flow of rest of the system unchanged
- Two assumptions implicitly adopted s.t. all loads and generations can be respectively combined:
  - All loads and generations share the same voltage level
  - All loads and generations respectively share the common dynamic models

- A slight modification to relax the two assumptions:
  - Elements with a different voltage level or dynamic model can be then connected to bus 2 through a zero-impedance transformer.

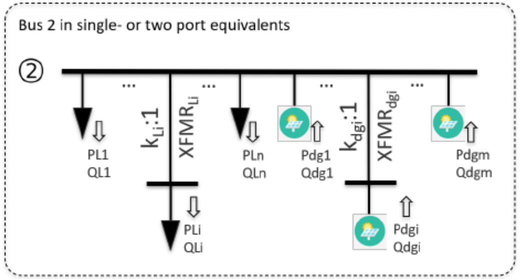


Fig. 3. Connection to bus 2 through zero-impedance transformer.

- Dynamic behavior of the entire system may be altered over the reduction, to some extent.
- Should not apply reduction to areas where generation of critical interest for dynamic studies is connected.

Maui Grid

- As the 2nd largest island in Hawaii, Maui has ~190 MW renewable, including >100 MW DG and 72 MW wind, plus >75 MW HPPs under development [1].
- A PSS/E case representing the daytime min load in the year 2022 provided by HECO.
- Instantaneous renewable power penetration level = 82.9%.

TABLE I
BASIC INFORMATION ABOUT HECO DAY MINIMUM CASE

Total load	162.0 MW	Distributed PV	67.0 MW
Total generation	164.0 MW	Utility-scale PV	5.4 MW
Total renewable	136.0 MW	Wind	63.6 MW
Total inertia	225.3 MVA·s	Min voltage level	0.48 kV
Renewable penetration	82.9%	Max voltage level	69 kV

Fig. 4. Maui island and the one-line diagram of its 69kV transmission system.

[1] Hawaii Electric Company, Inc., “Power facts,” 2020.

Network Reduction of Maui Grid

- 10 single-port areas
- 6 two-port areas

TABLE II
SUMMARY OF MAUI GRID NETWORK REDUCTION

Elements	# in full model	# in reduced model
Synchronous generator	9	6
Bus	212	45
Line	106	31
Transformer	108	13
Load	89	13
Distributed PV	171	36
Utility-scale PV	2	2
Wind	4	4
Battery	1	1

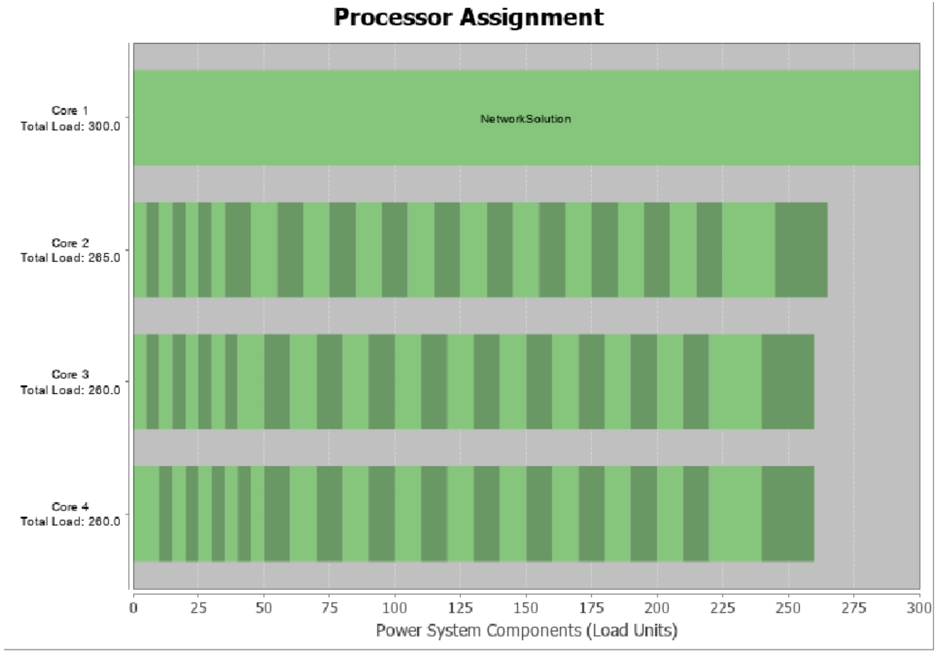
- **Small hydro units**: 4 small BTM hydro units, rating from 1.35-1.67 MW, were combined into one equivalent hydro unit.
- **Thermal units**: Remaining five thermal units were unchanged to preserve individual dynamics.
- **Distributed PVs**: The resulting 36 PVs are connected to 12 buses in the reduced system, where each bus has three PVs of different types.
- **Loads**: Loads from different voltage levels were directly combined in terms of MW, Mvar and settings of UFLS.

Network Reduction for RTDS Simulation

- **Full Maui grid** would require 2090 load units (even before adding detailed DPV, wind and BESS models).
- Available resources:
  - NREL's Flatirons campus has 8 NovaCor cores on two racks.
  - Each core can handle 300 load units.
  - Only 4 cores can currently be used for this project, i.e. **1200 load units**.
- **Reduced Maui grid** only requires 920 load units, well within the capability of 1200 from the 4 available cores.

Network Reduction for RTDS Simulation

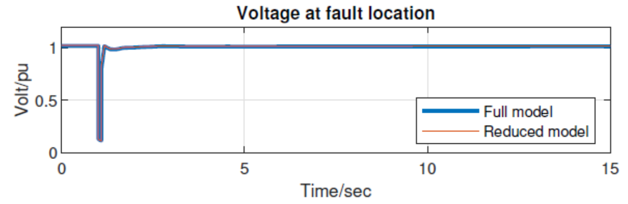
- Added to reduced model:
  - UPV, AGC and HPP models
  - Implemented half precision float-point representation-based communication for 179 channels
- Reduced model only requires 1085 load units.
- More to be added…
  - Detailed Wind
  - Detailed DPV
  - Detailed BESS

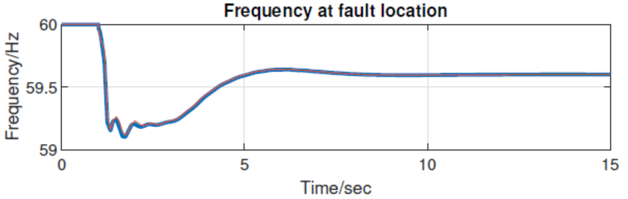


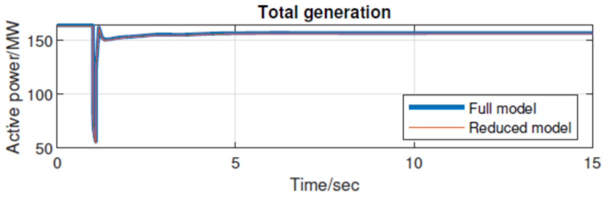
1085 load units in total (out of 1200 available from 4 cores) required to simulate in RSCAD

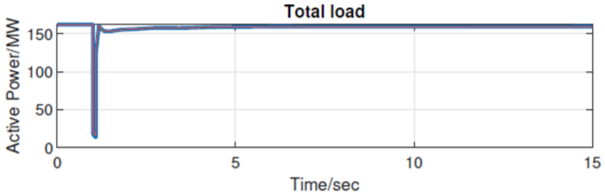
Validation of Reduced Maui Grid

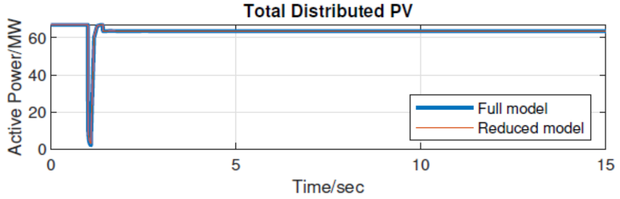
- Full Maui grid model and reduced model are simulated and compared over a large disturbance (generation trip):
  - Three-phase fault (fault R = 1.5 Ohm) added on a 69 kV bus at t = 1s
  - Fault cleared in 5 cycles
  - Thermal unit M16 tripped upon the fault clearance
  - Simulation lasts for 15 seconds

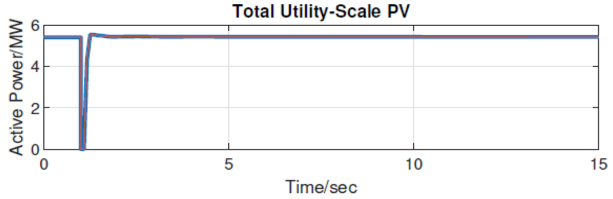












Conclusions

- Proposed two network reduction techniques based on KCL, i.e. single-port and two-port equivalents.
- Parameters in reduced system are uniquely and explicitly determined, (i) preserving the voltage and power at the port and (ii) keep the power flow pattern in the rest of the system unchanged.
- Accuracy and effectiveness have been demonstrated on the Maui transmission network.
- **Python code to reduce PSSE models using proposed techniques has been posted on GitHub**: https://github.com/NREL/PSSE_Network_Reduction

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Thank you!

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