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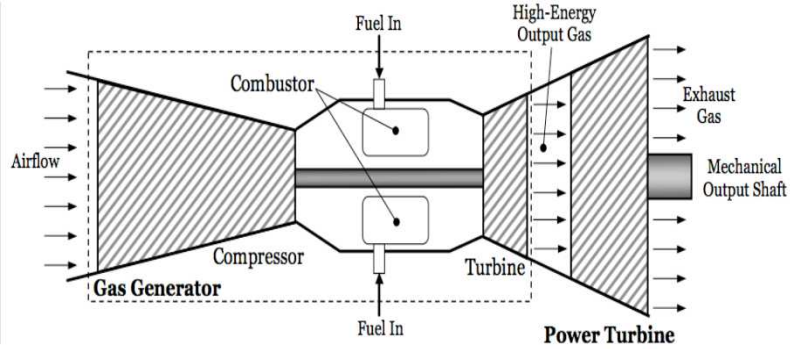

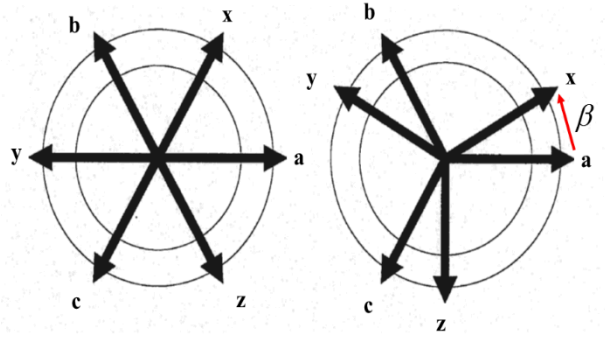

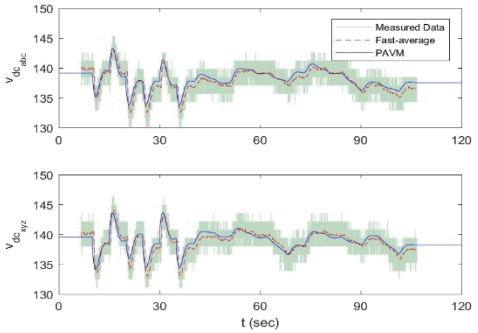

Dynamic Considerations of Power System Coupling through Dual-Wound Generators

L. J. Rashkin, J. C. Neely, S. F. Glover, T. J. McCoy, S. D. Pekarek

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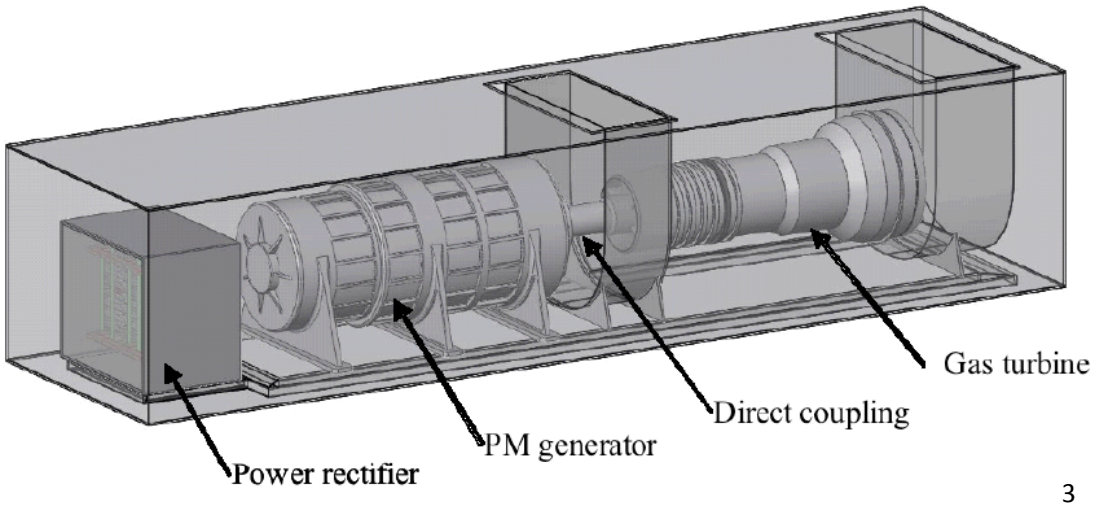
Outline

- Motivation and operational considerations
- Test System Model
  - Gas Turbine
  - Dual Wound Generator
  - Passive Rectifier
- Hardware and Validation of simulation model
- Simulation Results for Extreme Events
- Conclusions

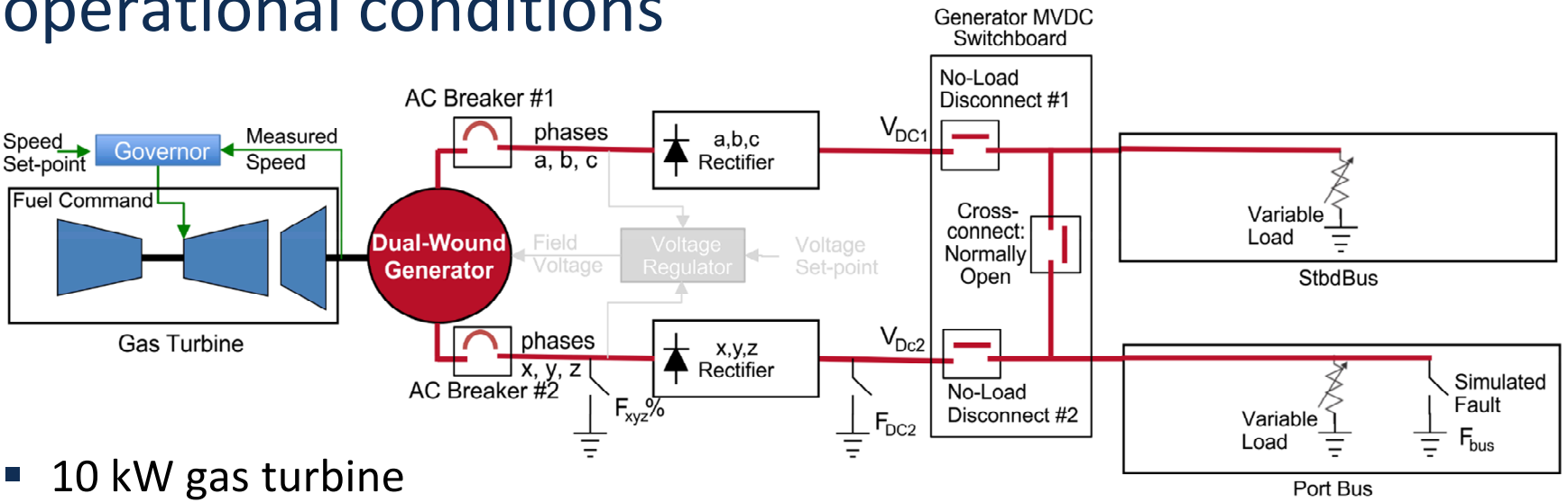
Dual wound generator implementation is motivated by needs of Navy Electric Ship

- Medium Voltage DC grid (MVDC)
- Less time spent under light load conditions
- Flexibility in power dispatch
- Enables a range of odd numbered generator deployments

- Tightly coupled systems
  - Galvanic Coupling
  - Mechanical Coupling

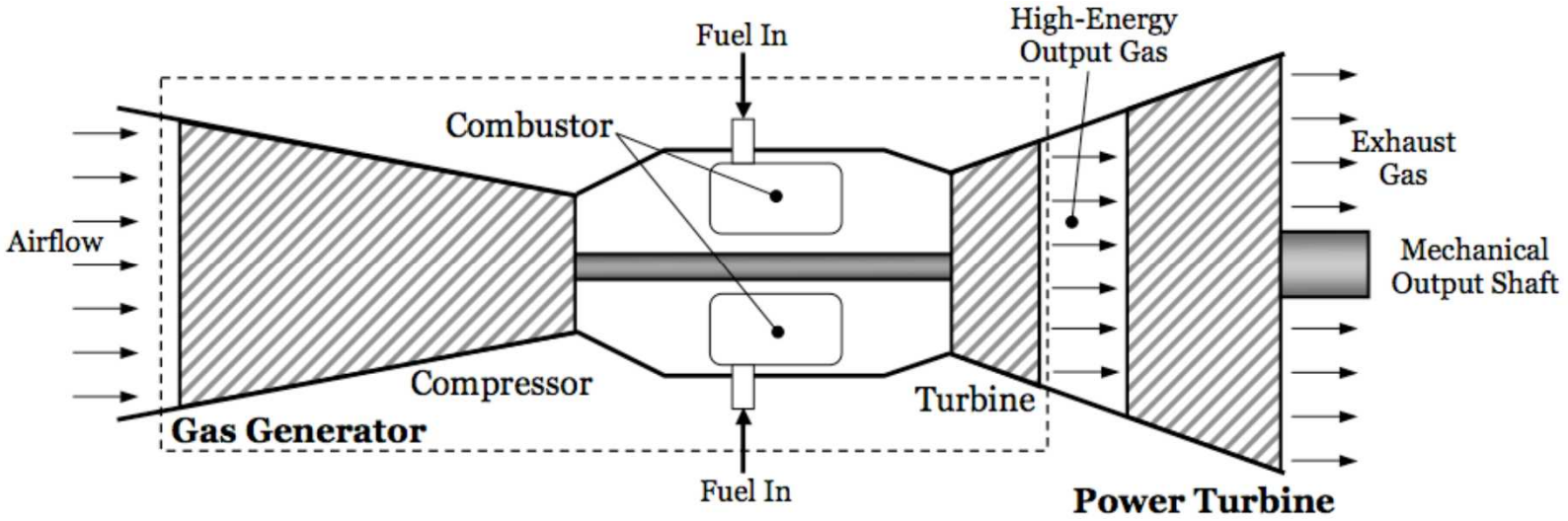


The test system considers multiple setups and operational conditions



- 10 kW gas turbine
  - Speed governor
- Dual wound permanent magnet synchronous generator
  - 60^{o} and 30^{o} offsets between phases
  - Exciter in full system
- Two passive rectifiers with LC output filters
  - Active Rectifiers in full system
- Variable resistance DC loads
- Various Faulting conditions

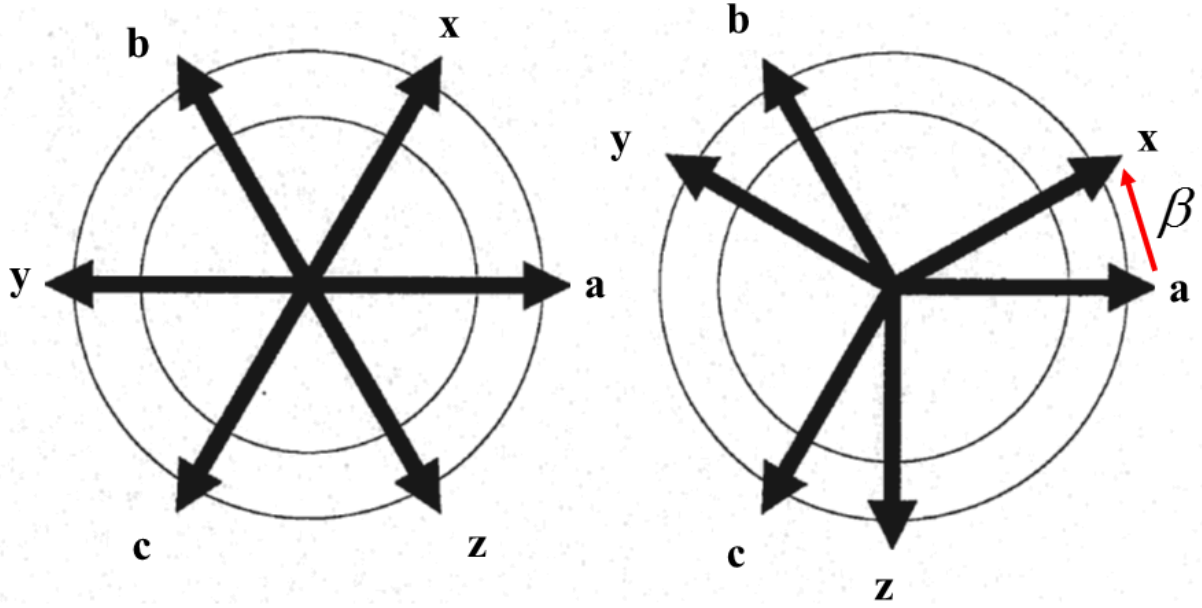
Gas Turbine model is based on power flow



- Empirical model based on turbine power flow[1]
  - Fits to various machine properties, max and min fuel power vs. speed, and output power vs steady state fuel power and turbine speed
  - Net turbine power and speed used to find turbine torque, which can be used in mechanical system model
- Simple PI control based governor was used

[1] Christopher J. Doktorcik, "Modeling and Simulation of a Hybrid Ship Power System" Master's thesis, Purdue University, 2011.

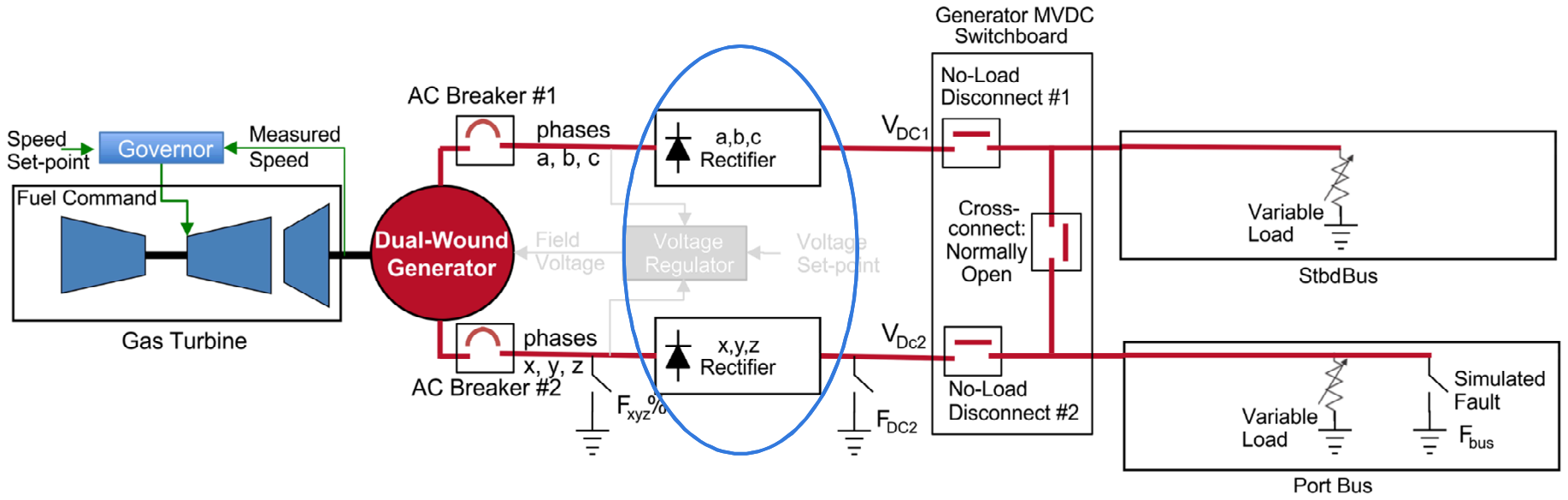
Dual-wound generators have 2 different potential configurations



- Focused on 2 basic options for a dual wound configuration based on offset β[2]:
  - Symmetric Machine – 60° offset between the *abc*- and *xyz*-phase sets
  - Asymmetric Machine – 30° offset between the *abc*- and *xyz*-phase sets
- Benefits and disadvantages to each option

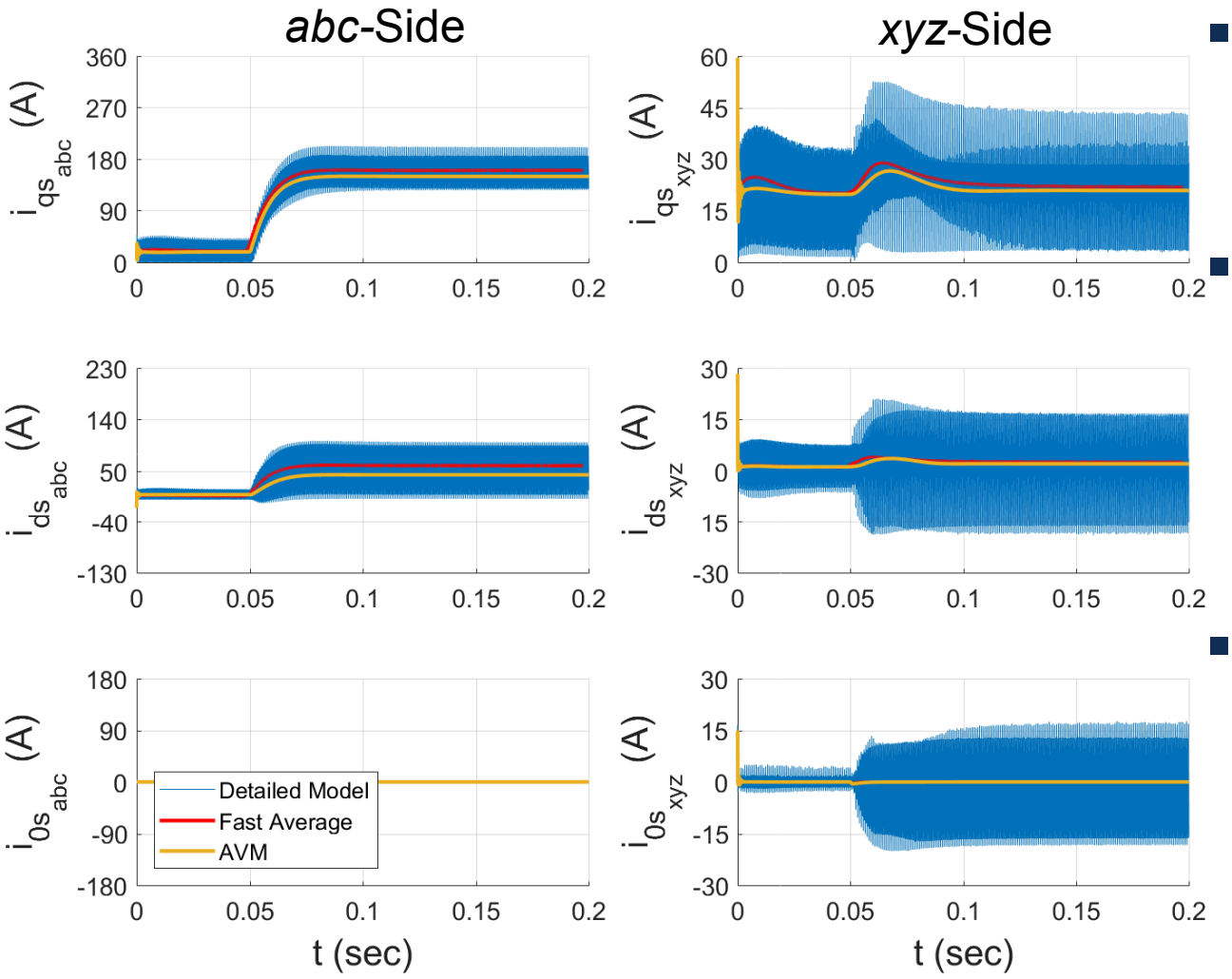
[2] N. Doerry and J. Amy Jr., "The Road to MVDC," presented at ASNE Intelligent Ships Symposium 2015, Philadelphia, PA, May 20-21, 2015.

Passive Rectifiers require a parametric average-value model (PAVM)



- Parameters are a function of loading on each inverter, z_{abc} and z_{xyz}
- Parameters relate inputs, *qd*-currents and DC side voltages, to outputs, DC side currents and *qd*-voltages
- Parameters are modeled as linearized look-up tables obtained from load sweeps

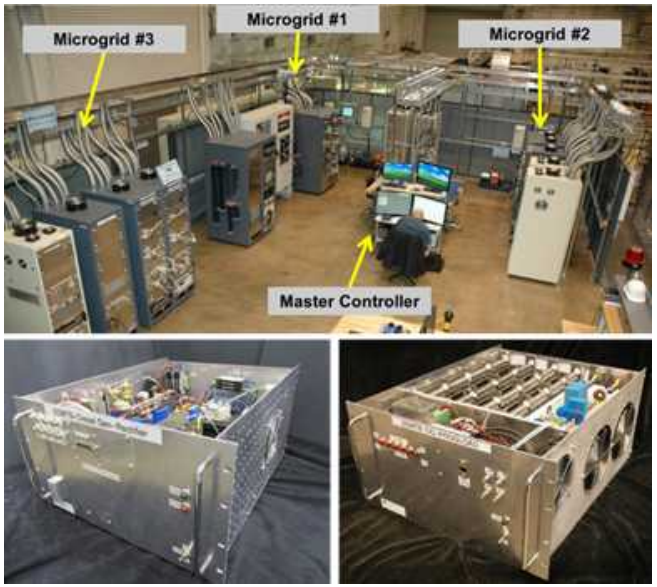
Average-value rectifier model is used to reduce computational load



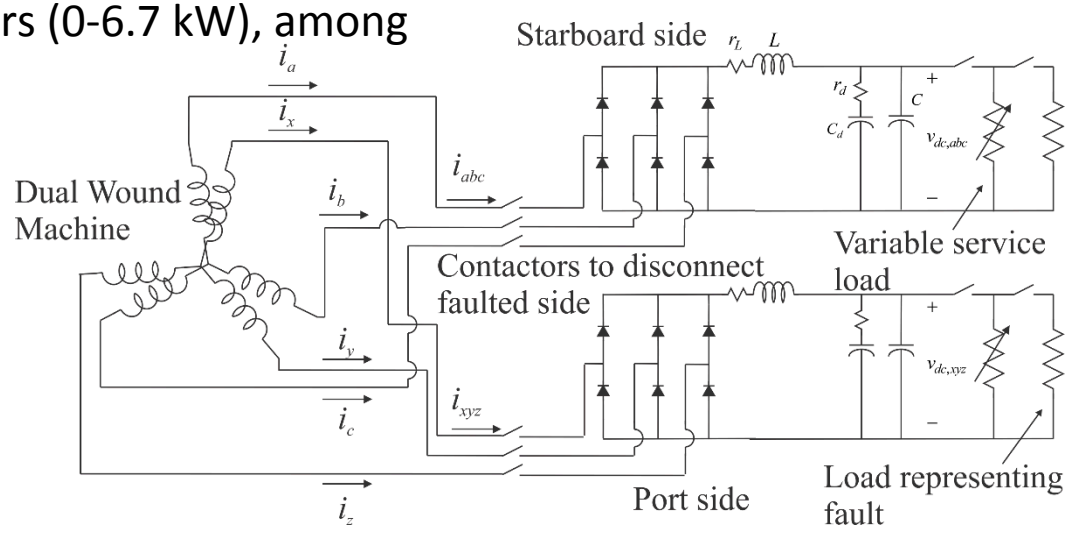
- Start with load of 15.6 Ω on both sides of system
- Apply low impedance fault of 1 Ω to the *abc*-side of system at 0.05 seconds
- While there are some discrepancies, the PAVM holds closely to the fast-average

Sandia's Secure Scalable Microgrid Testbed (SSMTB) was used for Hardware Validation

- The SSMTB was configured to represent an all-electric ship power system with multiple busses (or zones)
- The testbed includes
  1. Several PMSM generators (6.5-10.0 kW)
  2. Several 5 kW rated energy storage emulators
  3. Commercial motor drives with custom controls to emulate different rotational generators
  4. High-power digital resistors (0-6.7 kW), among other components.

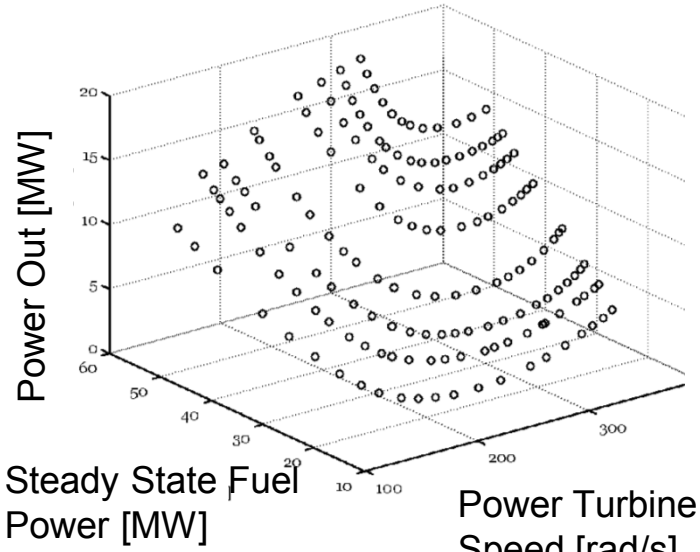


Schematic Layout used for Experiment

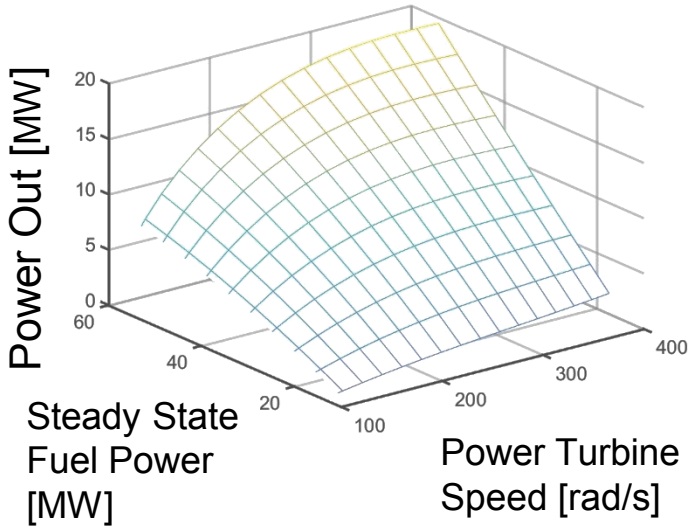


The Gas Turbine was Emulated in Hardware using a Rotational Generator Emulator

Data set used for fitting in [1]

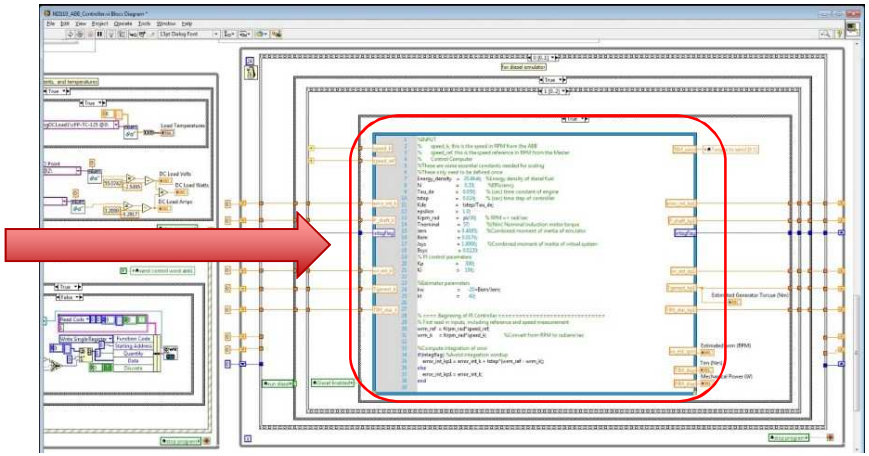


Fitted data using model



Custom dual-wound machine

Similar Matlab code used in Simulation and embedded in LabView controller



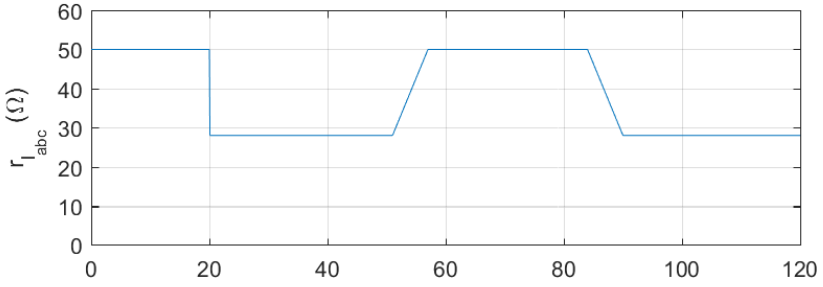
[1] Christopher J. Doktorcik, "Modeling and Simulation of a Hybrid Ship Power System" Master's thesis, Purdue University, 2011.

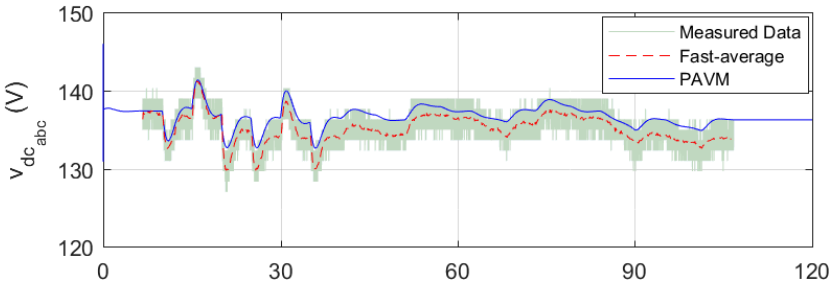
System simulation results match testbed measured response

Load profile

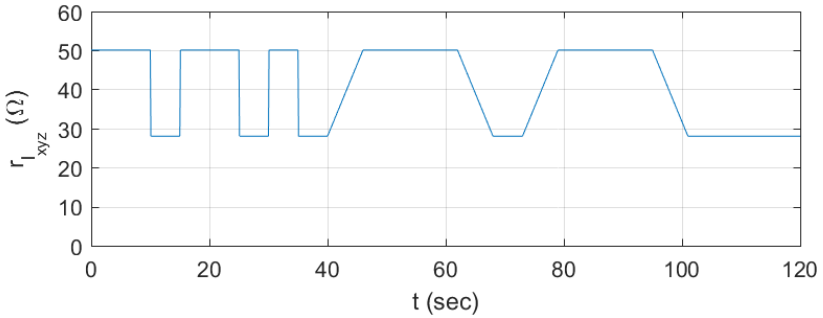
DC voltage response

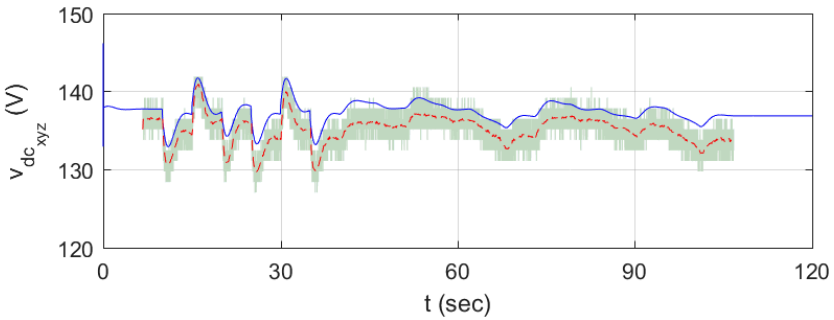
abc-side





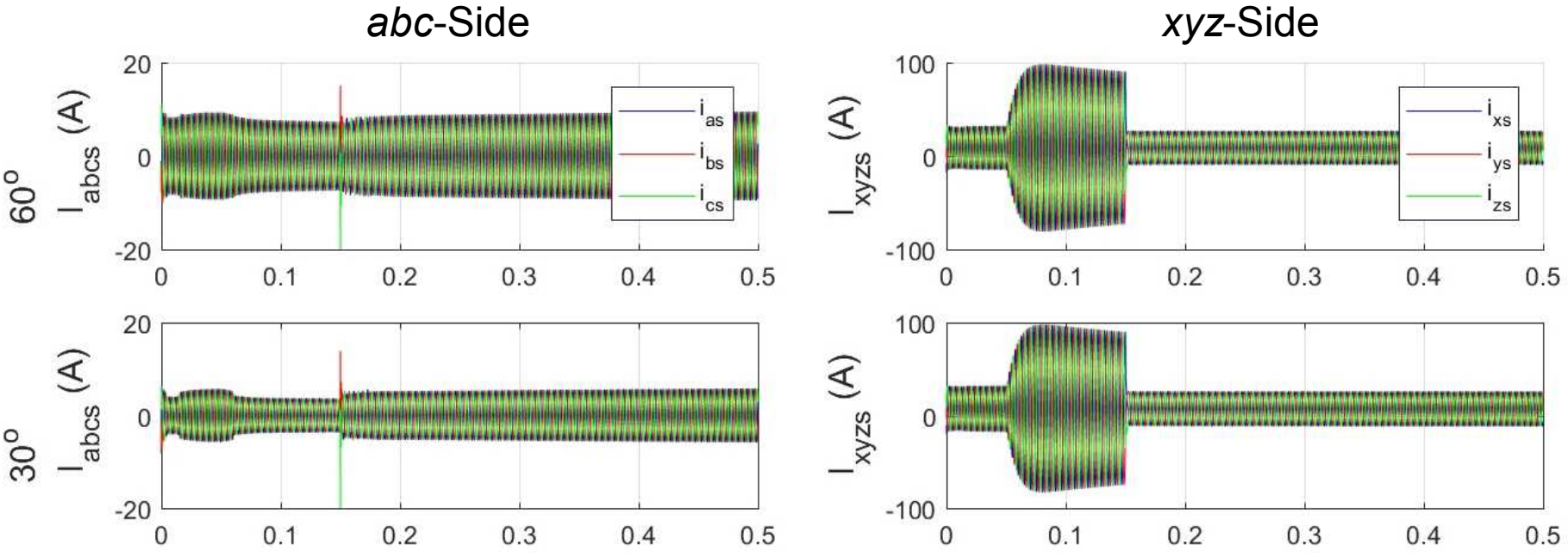
xyz-side





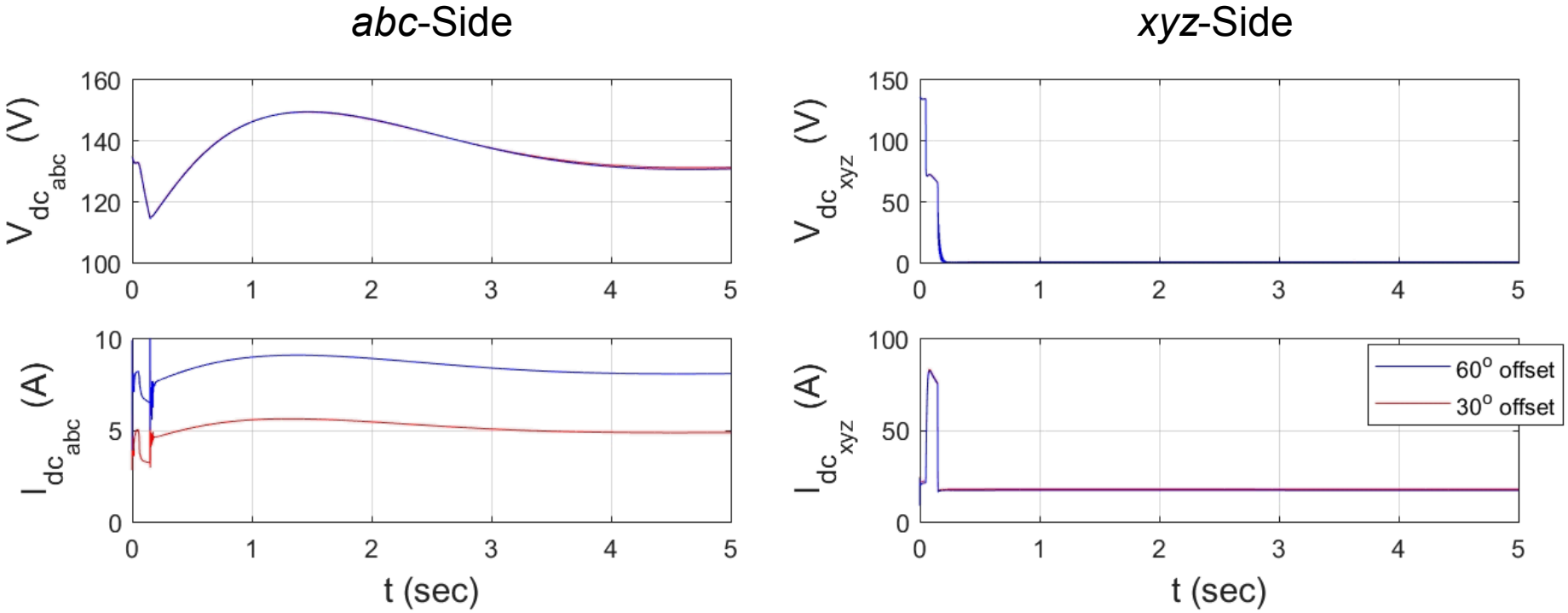
- Model was compared to hardware response to the load profile on the left that consists of multiple steps and ramps between 50 Ω and 28 Ω of both DC loads
- The results show an RMS error of 0.96 V_{RMS} for the *abc*-side and 1.43 V_{RMS} on the *xyz*-side

Simulation shows galvanic coupling effects a short time scales



- Low impedance fault of 1 Ω occurs at 0.05 seconds on *xyz*-side DC bus
- Breaker opens on AC side of *xyz*-rectifier at 0.15 seconds

Simulation shows mechanical coupling effects at long time scales



- Low impedance fault of 1 Ω occurs at 0.05 seconds on *xyz*-side DC bus
- Breaker opens on AC side of *xyz*-rectifier at 0.15 seconds

Summary and Conclusions

- Dual-wound synchronous machines provide several benefits as a part of a gas turbine genset
  - MVDC networks
  - Flexibility
  - Lifespan
- A simulation model was constructed of a dual-wound gas turbine generator system with two loads to investigate the impact of one phase set on the output of the other phase set
  - Empirical gas turbine model
  - Dual-wound synchronous machine
  - Parameterized average-value rectifier model
- Simulation model was shown to correlate to hardware results

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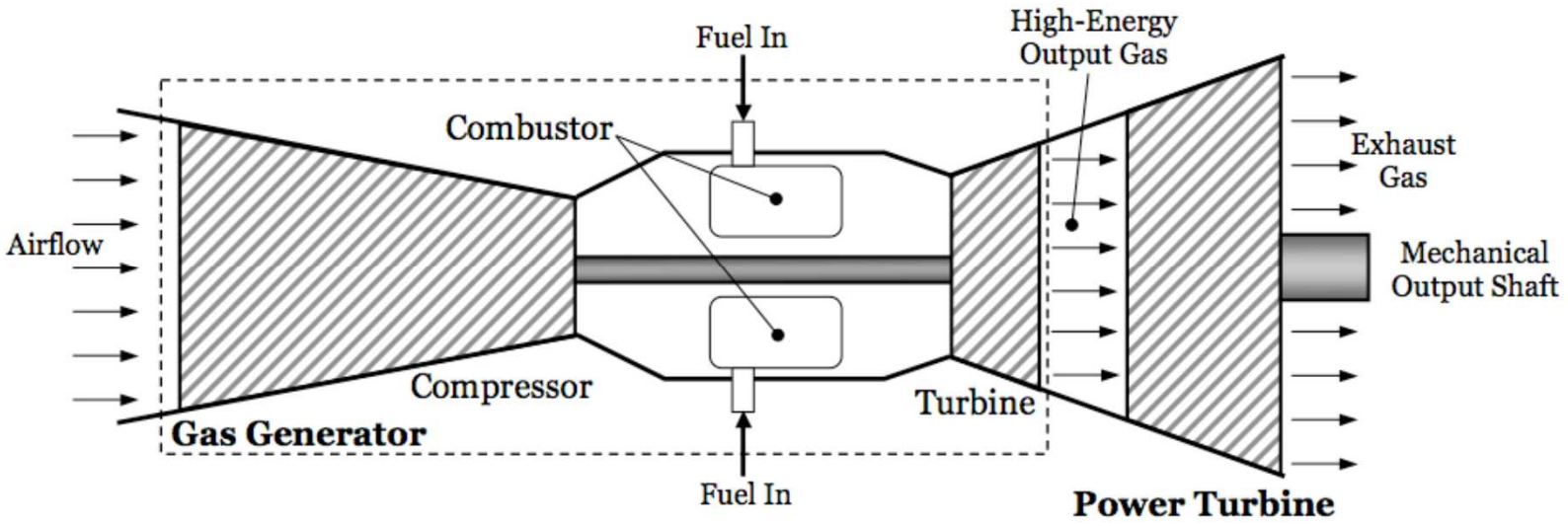
BACK-UP SLIDES

Gas turbine equations used to model mechanical system



$$P_{fuel}^{*} = (c_6 + c_7\omega_{rm} + c_8\omega_{rm}^2 + c_9\omega_{rm}^3)u_{fuel} + (c_{10} + c_{11}\omega_{rm} + c_{12}\omega_{rm}^2 + c_{13}\omega_{rm}^3)(1 - u_{fuel})$$

$$\frac{dP_{fuel}}{dt} = m_{rate}\tanh\left(\frac{P_{fuel}^{*} - P_{fuel}}{\tau_{fuel}m_{rate}}\right)$$

$$\frac{dP_{comp}}{dt} = k_5P_{comp} + k_6P_{fuel}$$

$$P_{wf3} = \eta_{comb}P_{fuel} + P_{comp}$$

$$P_{turb} = \left(c_1 + k_1P_{wf3} + k_2P_{wf3}^2\right)\omega_{rm} + \left(k_3P_{wf3} + k_4P_{wf3}^2\right)\omega_{rm}^2$$

$$T_{turb} = \frac{P_{turb}}{\omega_{rm}}$$

[1] Christopher J. Doktorcik, “Modeling and Simulation of a Hybrid Ship Power System” Master’s thesis, Purdue University, 2011.

PAVM Equations

$$z_{abc} = \frac{\bar{v}_{c_{abc}}}{\left\|\bar{\imath}_{qds_{abc}}\right\|}$$

$$z_{xyz} = \frac{\bar{v}_{c_{xyz}}}{\left\|\bar{\imath}_{qds_{xyz}}\right\|}$$

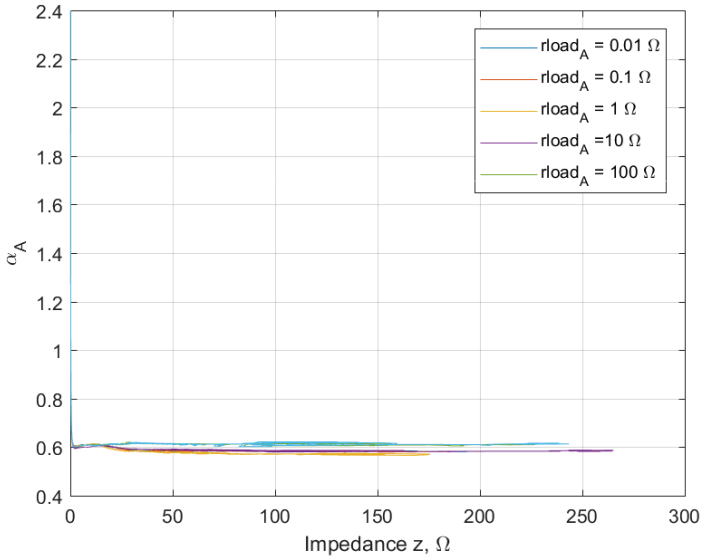
$$\delta_{r_{abc}} = \arctan\left(\frac{\bar{\imath}^{r}_{ds_{abc}}}{\bar{\imath}^{r}_{qs_{abc}}}\right) - \phi_{abc}\left(z_{abc}, z_{xyz}\right) \qquad \delta_{r_{xyz}} = \arctan\left(\frac{\bar{\imath}^{r}_{ds_{xyz}}}{\bar{\imath}^{r}_{qs_{xyz}}}\right) - \phi_{xyz}\left(z_{abc}, z_{xyz}\right)$$

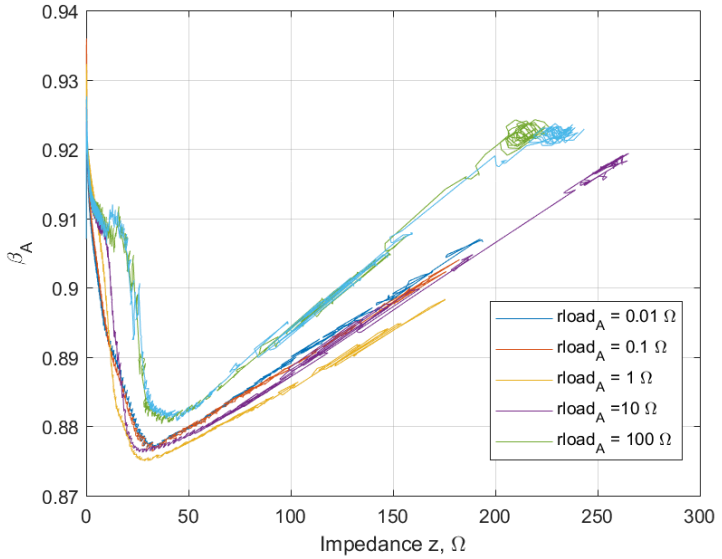
$$\bar{v}^{r}_{qs_{abc}} = \alpha_{abc}\left(z_{abc}, z_{xyz}\right)\bar{v}_{dc_{abc}}\cos\left(\delta_{r_{abc}}\right) \qquad \bar{v}^{r}_{qs_{xyz}} = \alpha_{xyz}\left(z_{abc}, z_{xyz}\right)\bar{v}_{dc_{xyz}}\cos\left(\delta_{r_{xyz}}\right)$$

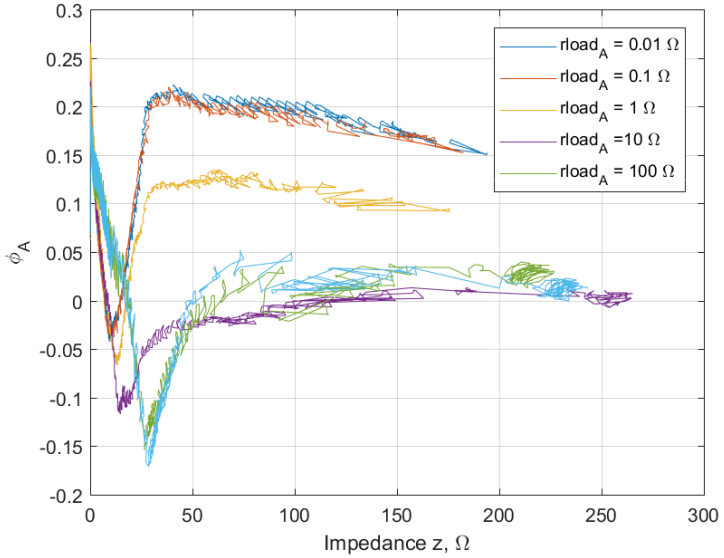
$$\bar{v}^{r}_{ds_{abc}} = \alpha_{abc}\left(z_{abc}, z_{xyz}\right)\bar{v}_{dc_{abc}}\sin\left(\delta_{r_{abc}}\right) \qquad \bar{v}^{r}_{ds_{xyz}} = \alpha_{xyz}\left(z_{abc}, z_{xyz}\right)\bar{v}_{dc_{xyz}}\sin\left(\delta_{r_{xyz}}\right)$$

$$\bar{\imath}_{dc_{abc}} = \beta_{abc}\left(z_{abc}, z_{xyz}\right)\left\|\bar{\imath}_{qds_{abc}}\right\| \qquad \bar{\imath}_{dc_{xyz}} = \beta_{abc}\left(z_{abc}, z_{xyz}\right)\left\|\bar{\imath}_{qds_{xyz}}\right\|$$

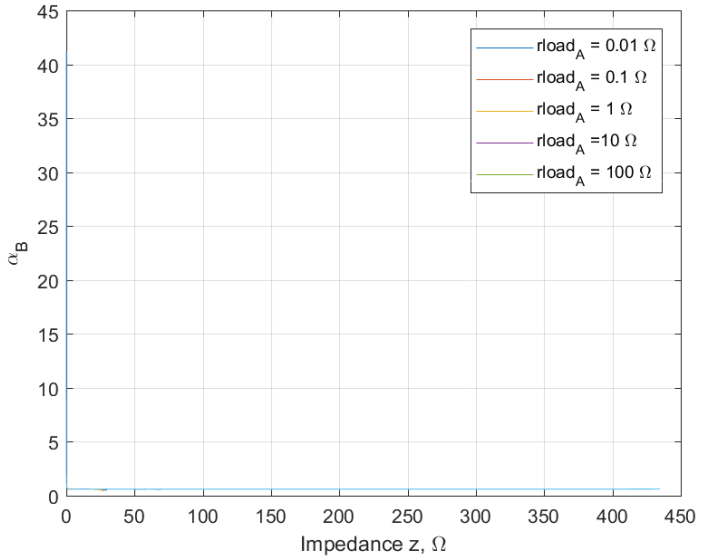
PAVM parameters, *abc*-side, 60° offset

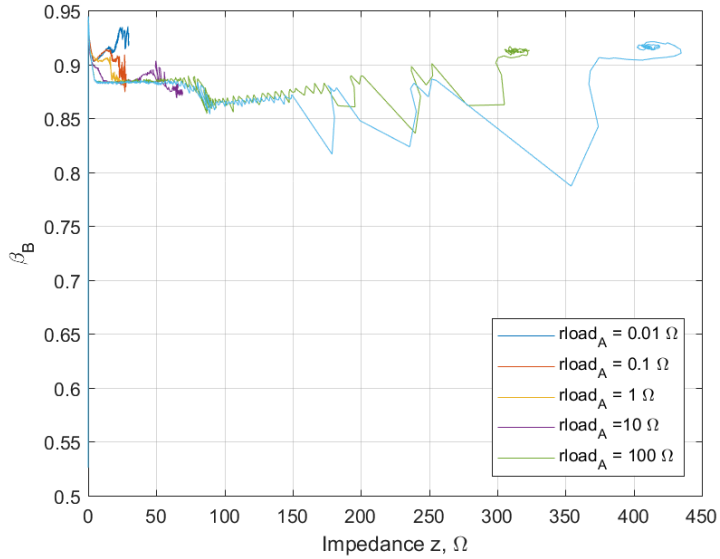


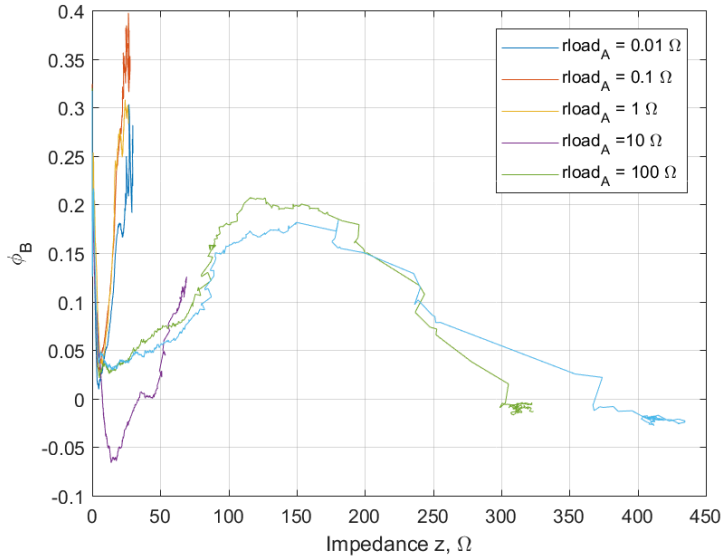




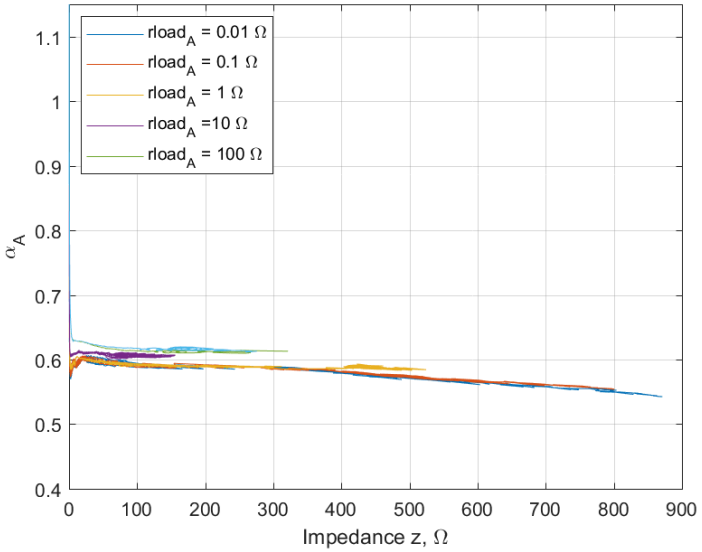
PAVM parameters, *xyz*-side, 60° offset

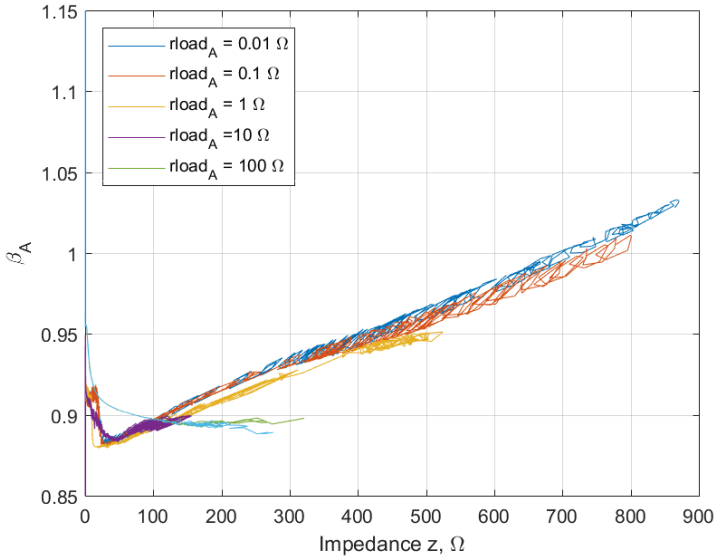


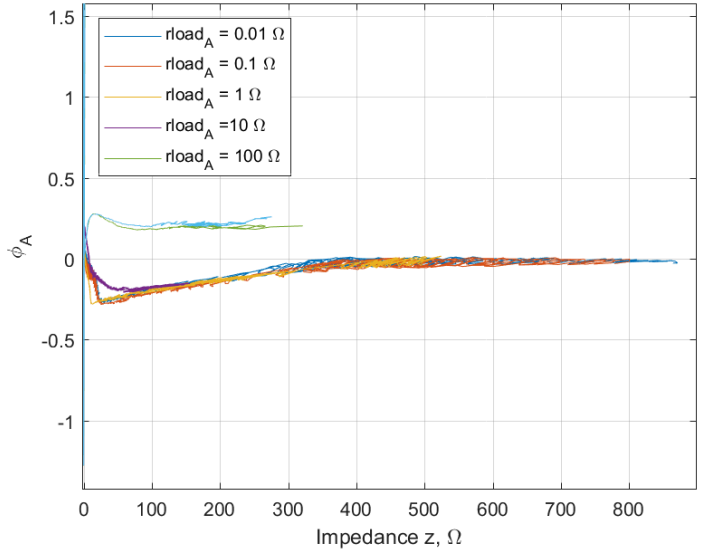




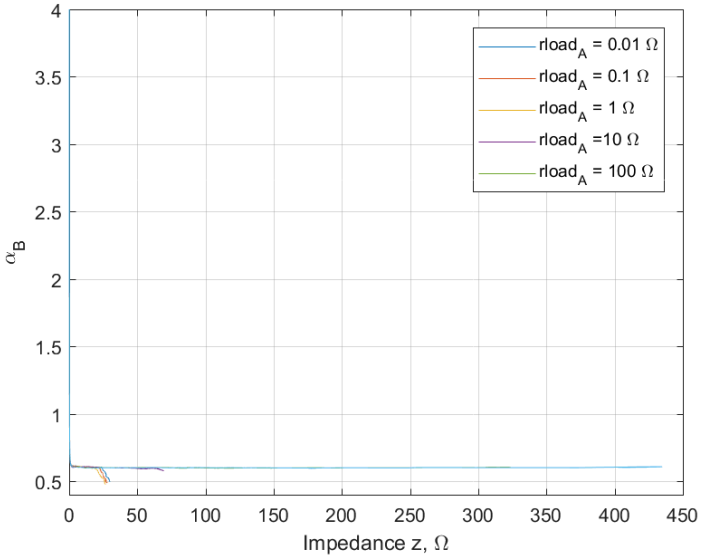
PAVM parameters, *abc*-side, 30° offset

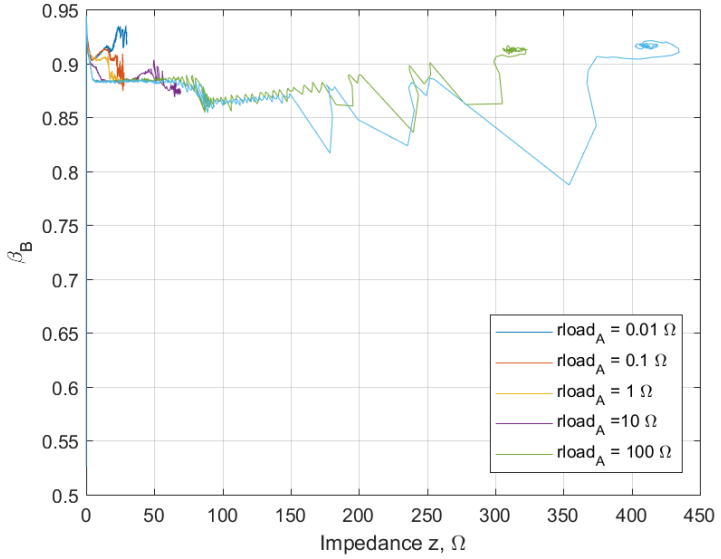


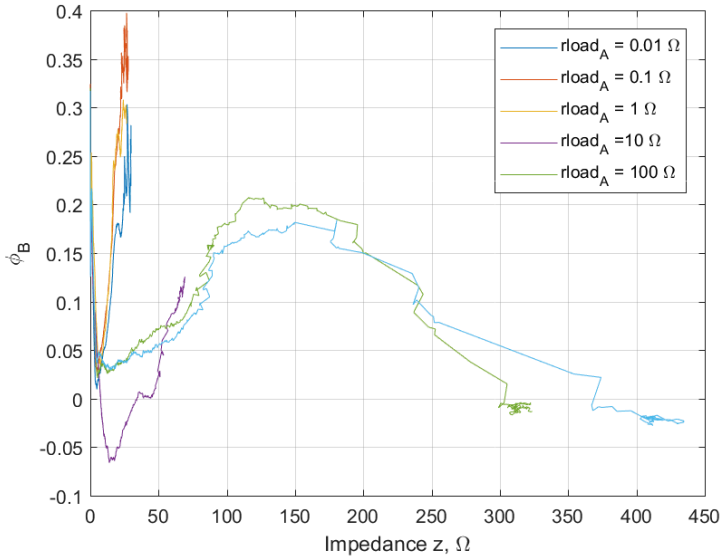




PAVM parameters, *xyz*-side, 30° offset







30° offset behavior