Advanced PHIL Interface for Multi-MW Scale Inverter Testing

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Overview

- Controllable Grid Interface (CGI) at the National Wind Technology Site
- CGI recent upgrades
- Communication links
- RTDS-CGI power-hardware-in-the-loop (PHIL) interface
- Delay compensation techniques
- PHIL test results
    - Fault testing (L-L , L-G)
    - Generator trip test and frequency response support from wind turbine
    - Capacitor bank switching

NWTC 7-MVA Controllable Grid Interface

Image from NREL

CGI Main Technical Characteristics

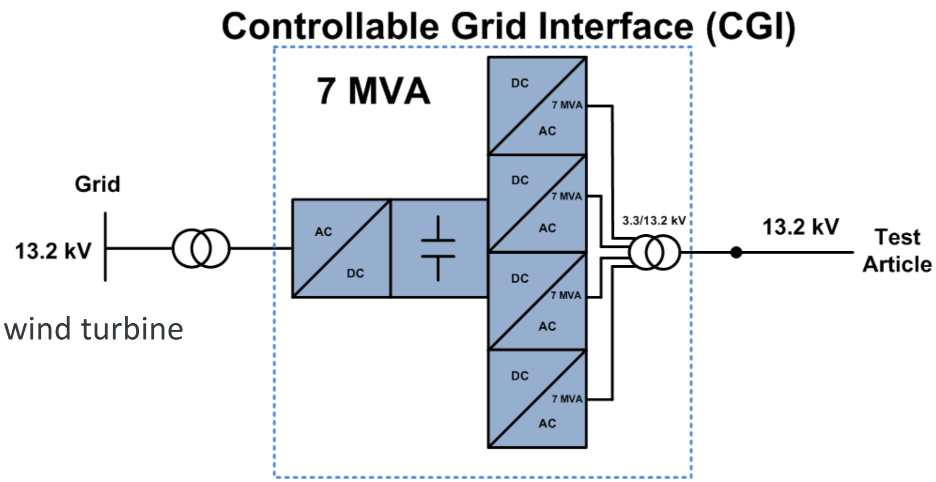
Power rating
- 7-MW continuous
- 39-MVA short circuit capacity (for 2 sec)
- 4-wire, 13.2-kV

Possible test articles
- Types 1, 2, 3 and 4 wind turbines
- Capable of fault testing of world's largest 6.15-MW Type 3 wind turbine
- Photovoltaic (PV) inverters, energy storage systems
- Conventional generators
- Combinations of technologies

Voltage control (no load THD <3%)
- Balanced and unbalanced voltage fault conditions (ZVRT and 130% HVRT) – independent voltage control for each phase on 13.2-kV terminals
- Response time – 1 ms (from full voltage to zero, or from zero back to full voltage)
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0-10 Hz) – SSR conditions
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)

Frequency control
- Fast output frequency control (3 Hz/sec) within 45-65-Hz range
- 50/60-Hz operation
- Can simulate frequency conditions for any type of power system

- **RTDS – PHIL capability**



Capabilities
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing (over and under voltage and frequency limits)
- Islanding operation
- Sub-synchronous resonance conditions
- 50 Hz tests

Recent upgrades in CGI

CGI 2.0 – commissioned in January 2016

- **Faster dynamic response**
- Various transformer saturation protection algorithms to allow ride-through of any reference command

Coming soon:

- High frequency LR filter to improve power quality with minor impact on dynamics
- Decreasing processing delays

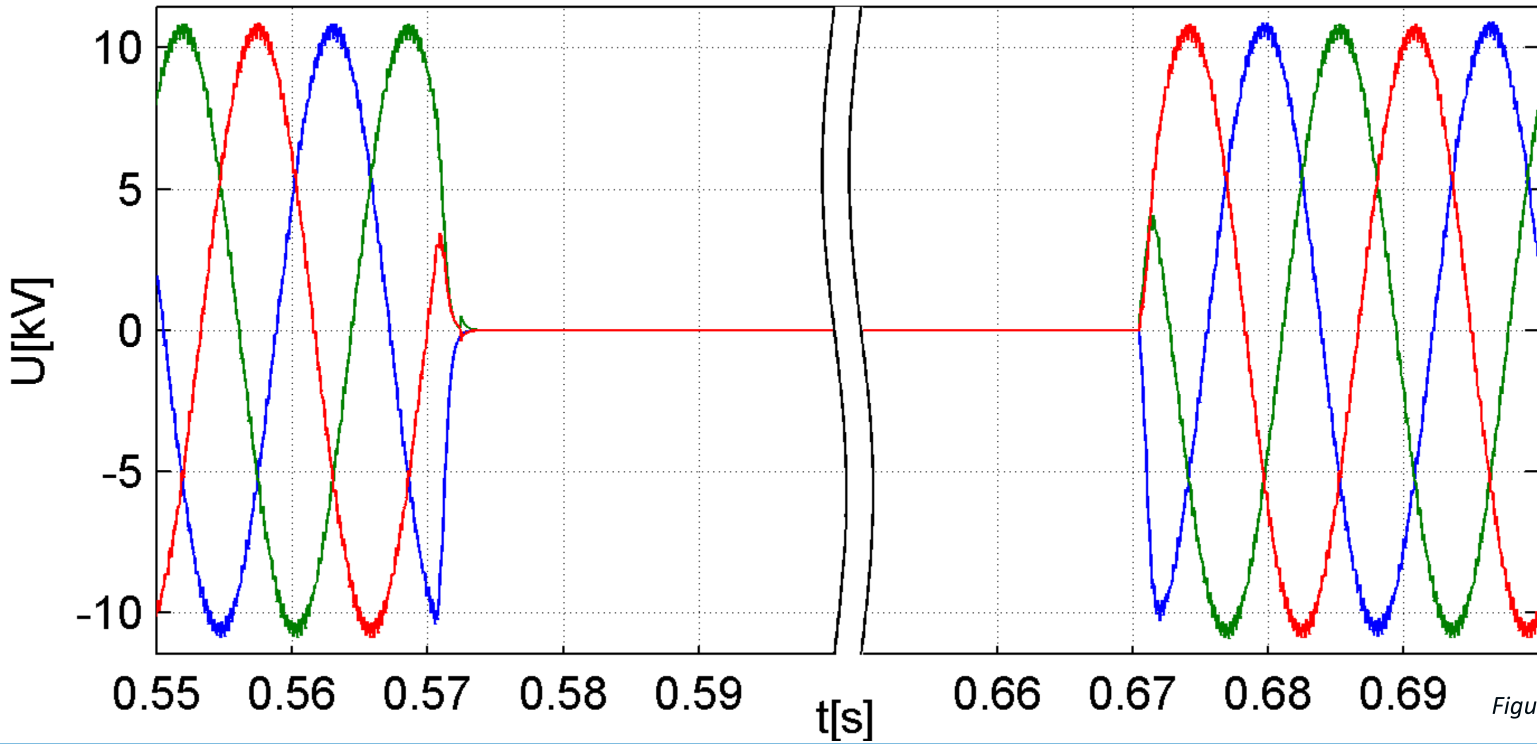
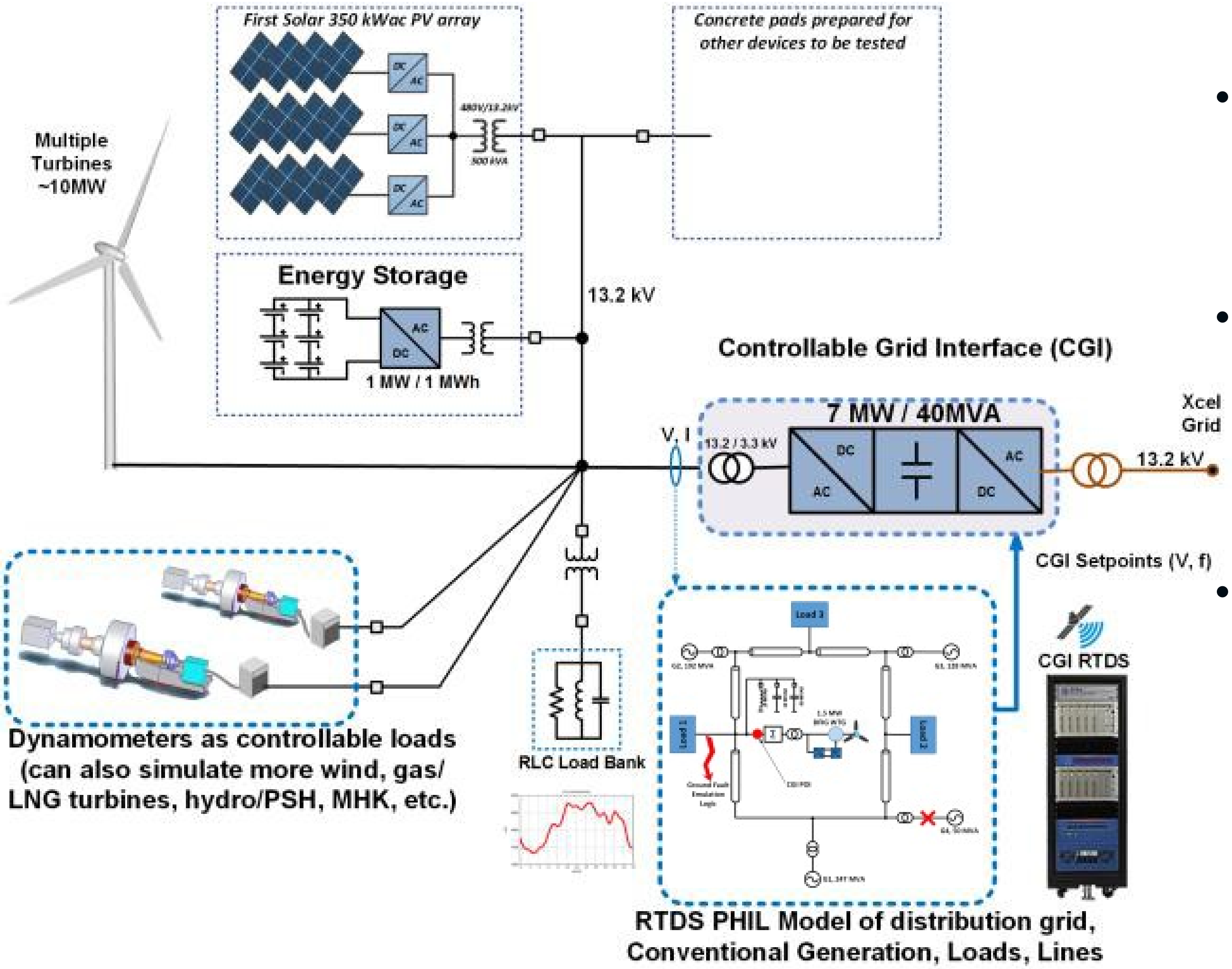


Figure from ABB

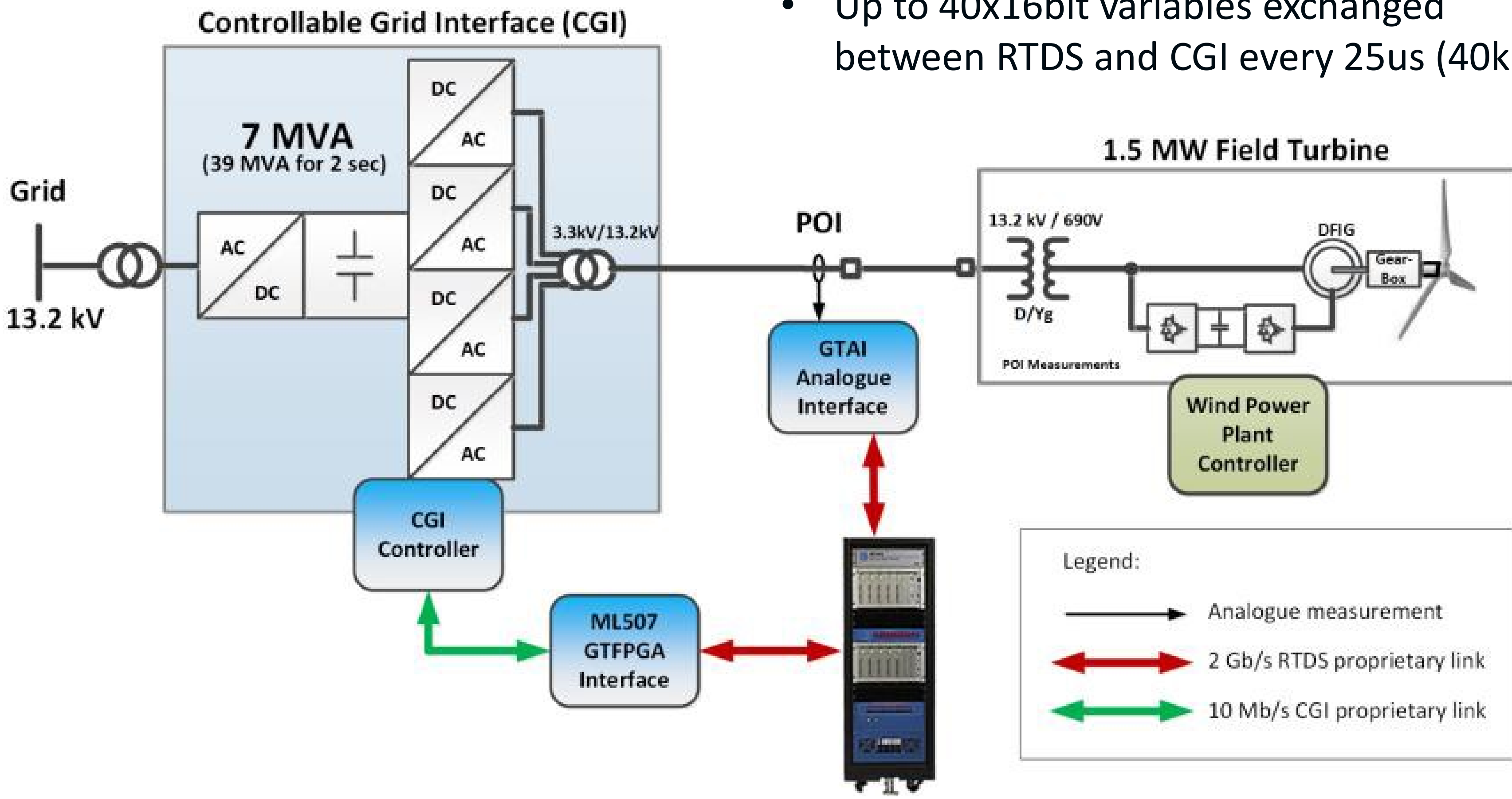
Site Overview



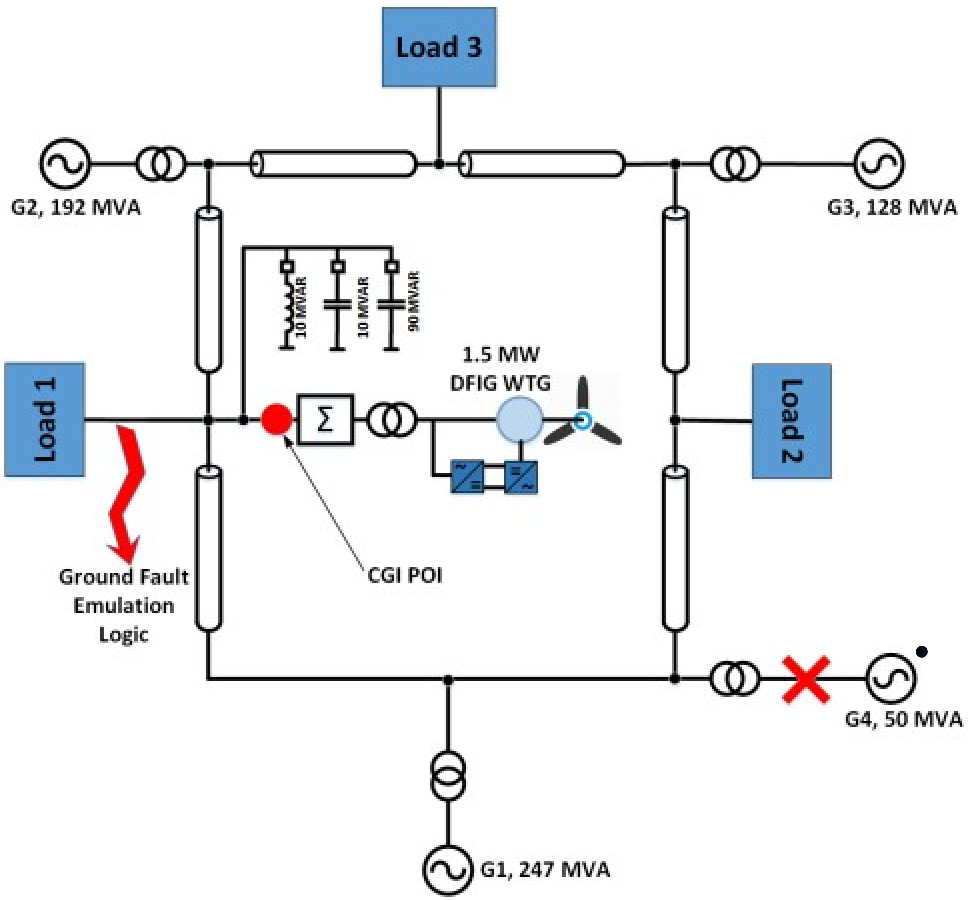
- Unique infrastructure for multi-MW grid integration testing
- Typically devices are tested against arbitrary voltage and frequency patterns in open loop
- PHIL for testing of device operation in relatively weak grids where distributed energy resources (DERs) also impact the grid

Communication Architecture

- Distances between RTDS-point of connection (POI) and CGI ca. 300ft
- Preferred digital optical communication
- 2Gb/s RTDS optical link – glass optical fiber
- 10Mb/s CGI-ABB proprietary link – plastic optical fiber
- Up to 40x16bit variables exchanged between RTDS and CGI every 25us (40kHz)



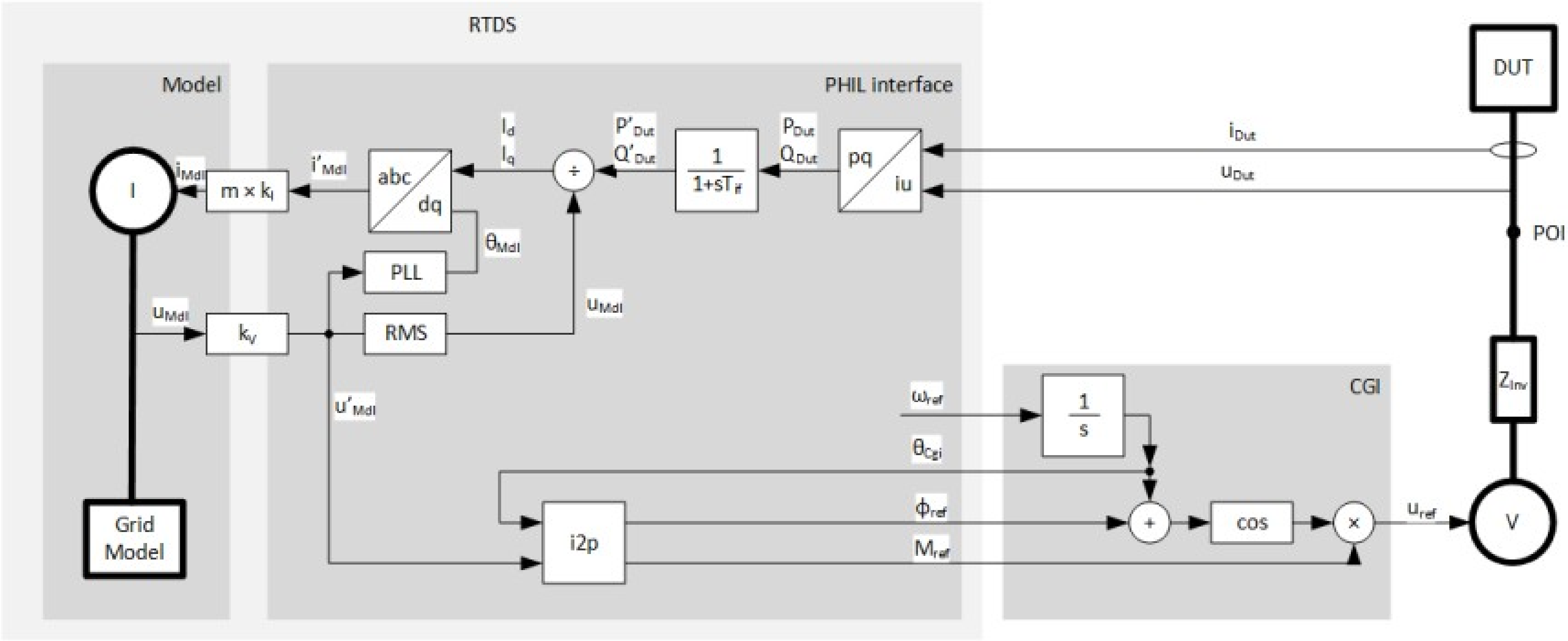
RTDS Grid Model



- RTDS 9-bus model
  - 130-kV transmission
  - 4x synchronous generators with total capacity of 617 MW
  - AGC implemented
  - Loads during test at 400 MW
  - Various test scenarios
    - Dropping of G4 – 12.5% generation
    - Line to ground (LG) & line to line (LL) faults emulation
    - Cap bank switching
- PHIL Point of Interconnection (POI)
  - Configurable multiplier - "*m*" – allows for multiplying the impact of real devices connected to CGI to simulated grid

CGI-RTDS PHIL Interface

- Instantaneous voltage measured in model and commanded to CGI
  - Very fast tracking achieved thanks to instantaneous to phasor (I2P) algorithm
  - Controllable phase delay
- Active and reactive power measured at CGI terminals is fed back to model
  - Active (P) and reactive (Q) power is filtered to avoid PHIL experiment instability
  - Current is injected back to model and synchronized using PLL



RTDS -> CGI Voltage Tracking Capabilities

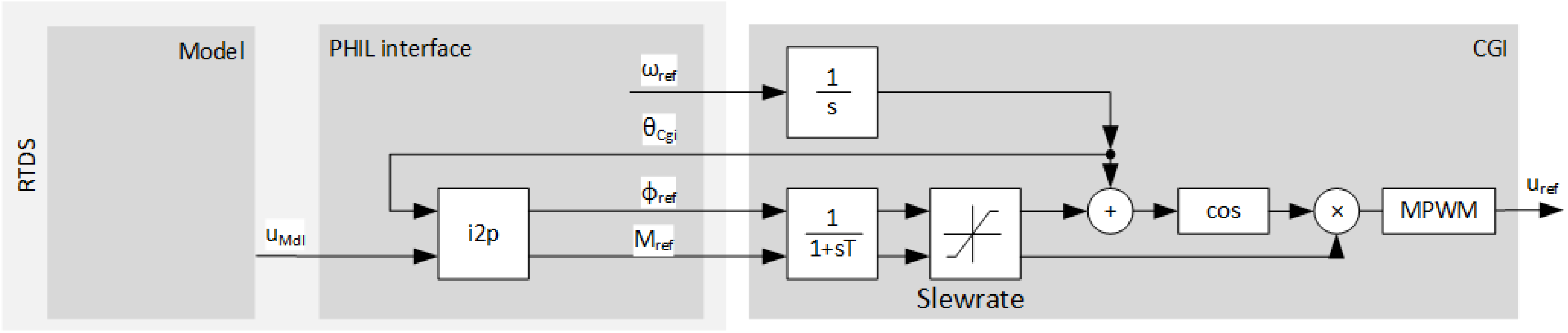
Output from RTDS simulation is 3x instantaneous voltages u_{Mdl}

CGI voltage is controlled by:

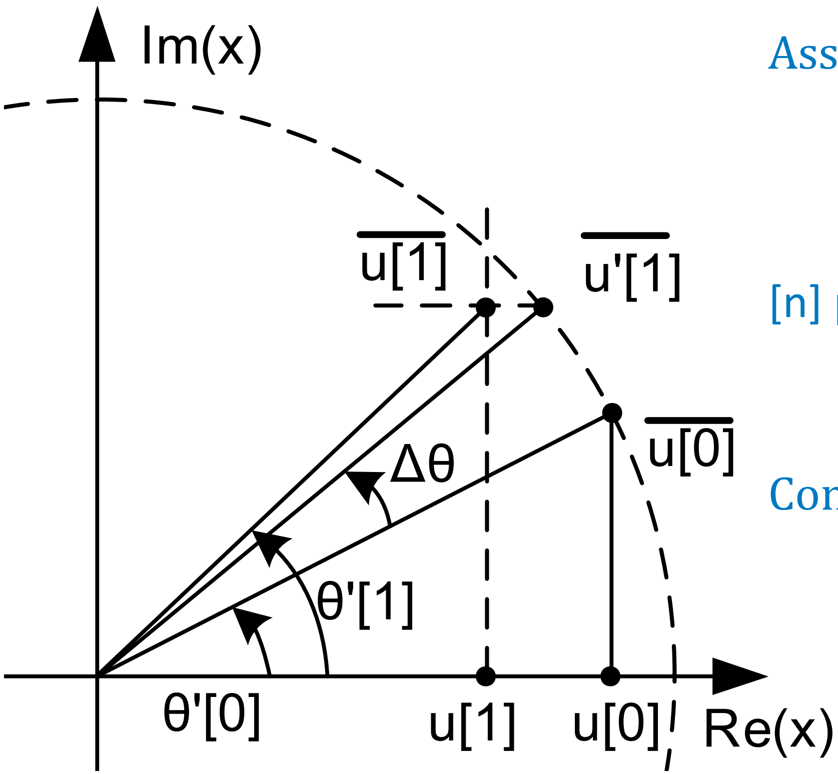
1) Frequency setpoint – ω_{ref}
2) 3xPhasor magnitude – M_{ref}
3) 3xPhasor angle – Φ_{ref}
4) CGI precise integrator (<0.001Hz accuracy) - actual angle (θ_{Cgi}) is sent back to RTDS for synchronization

Real time algorithm I2P (Instantaneous to phasor) developed to allow:

1) Instantaneous synchronization of u_{ref} & u_{Mdl}
2) Smooth phasor (M_{ref}/ϕ_{ref}) reconstruction – to avoid dynamic limitations in CGI
3) Allow asymmetrical voltages (zero, pos, neg sequence)
4) Minimize delay for PHIL operation
5) Allow constant group delay – don't distort waveform
6) Don't depend on phase locked loop (PLL) for frequency control (transients, etc.)



I2P – next step calculation + diagram



Assumption for lossless instantaneous conversion

$$u[n] = Re\{M[n]e^{i(\Phi[n]+\theta[n])}\}$$

$$\overline{u[n]} = M[n]e^{i(\Phi[n]+\theta[n])}$$

$$u[n] = Re\{\overline{u[n]}\}$$

[n] point approximation based on [n-1] filtered phasor

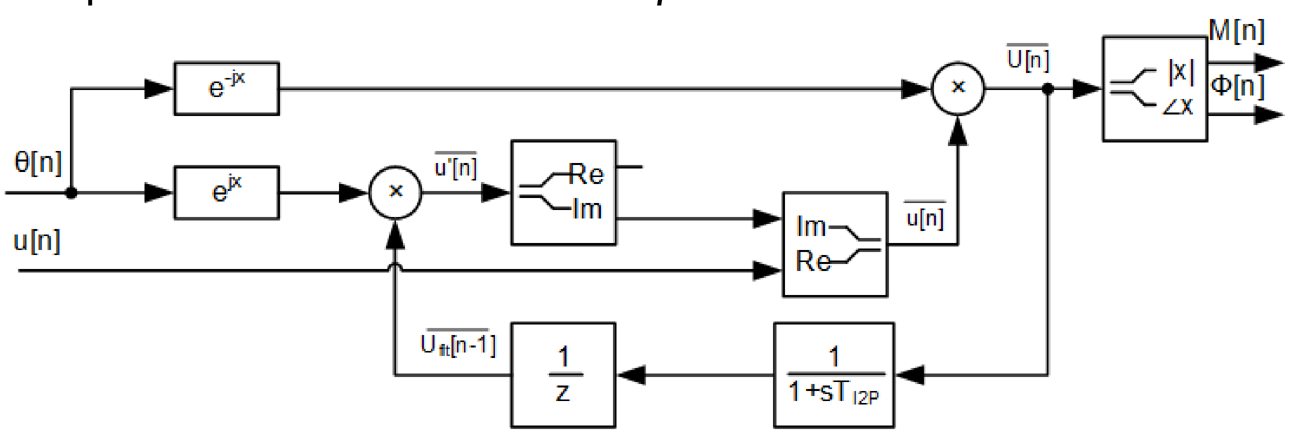
$$\overline{u'[n]} = \overline{U_{flt}[n-1]}e^{i\theta[n]}$$

$$\overline{u[n]} = u[n] + i\ Im\{\overline{u'[n]}\}$$

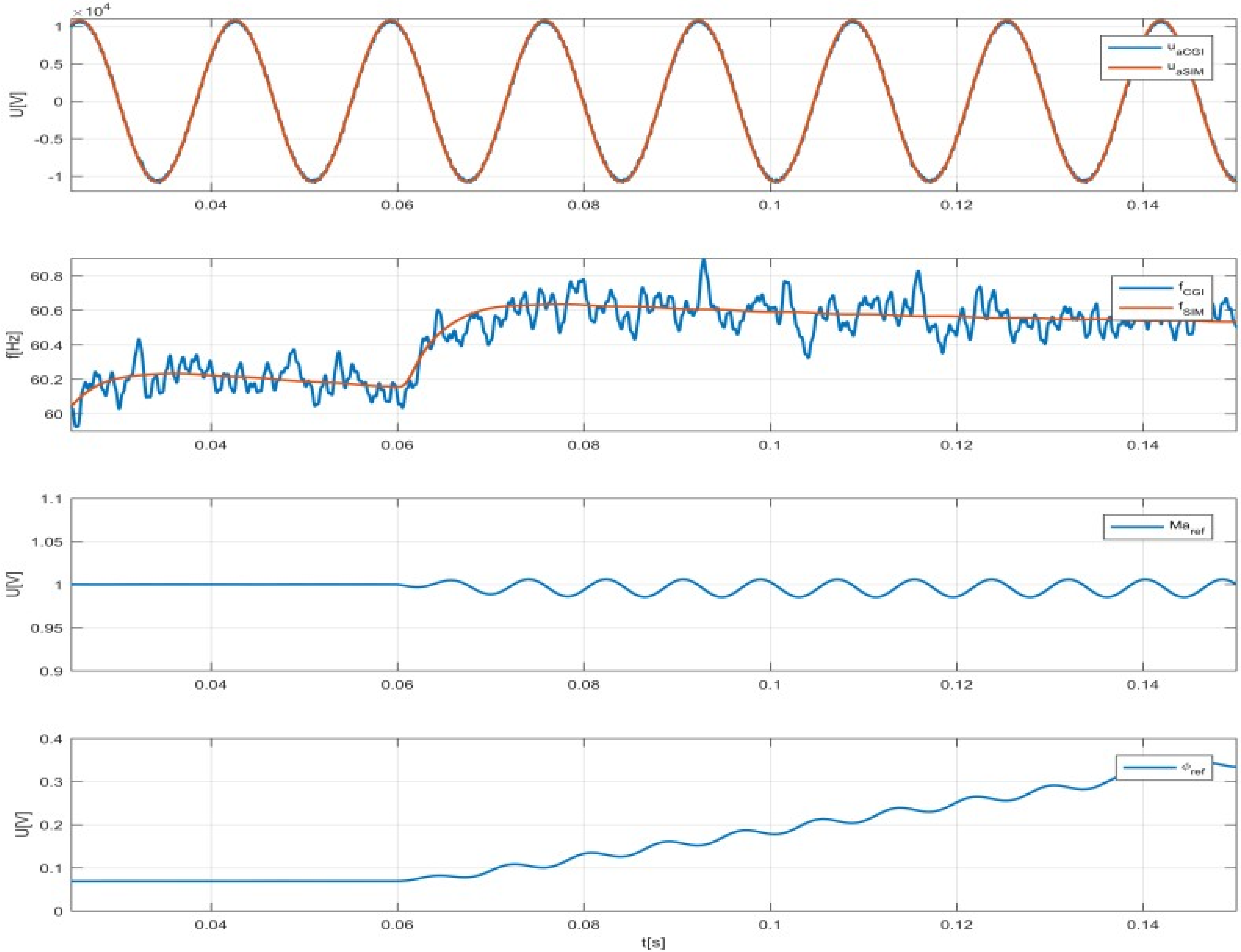
Convert back to stationary frame – phasor reference

$$\overline{U[n]} = \overline{u[n]}e^{-i\theta[n]}$$

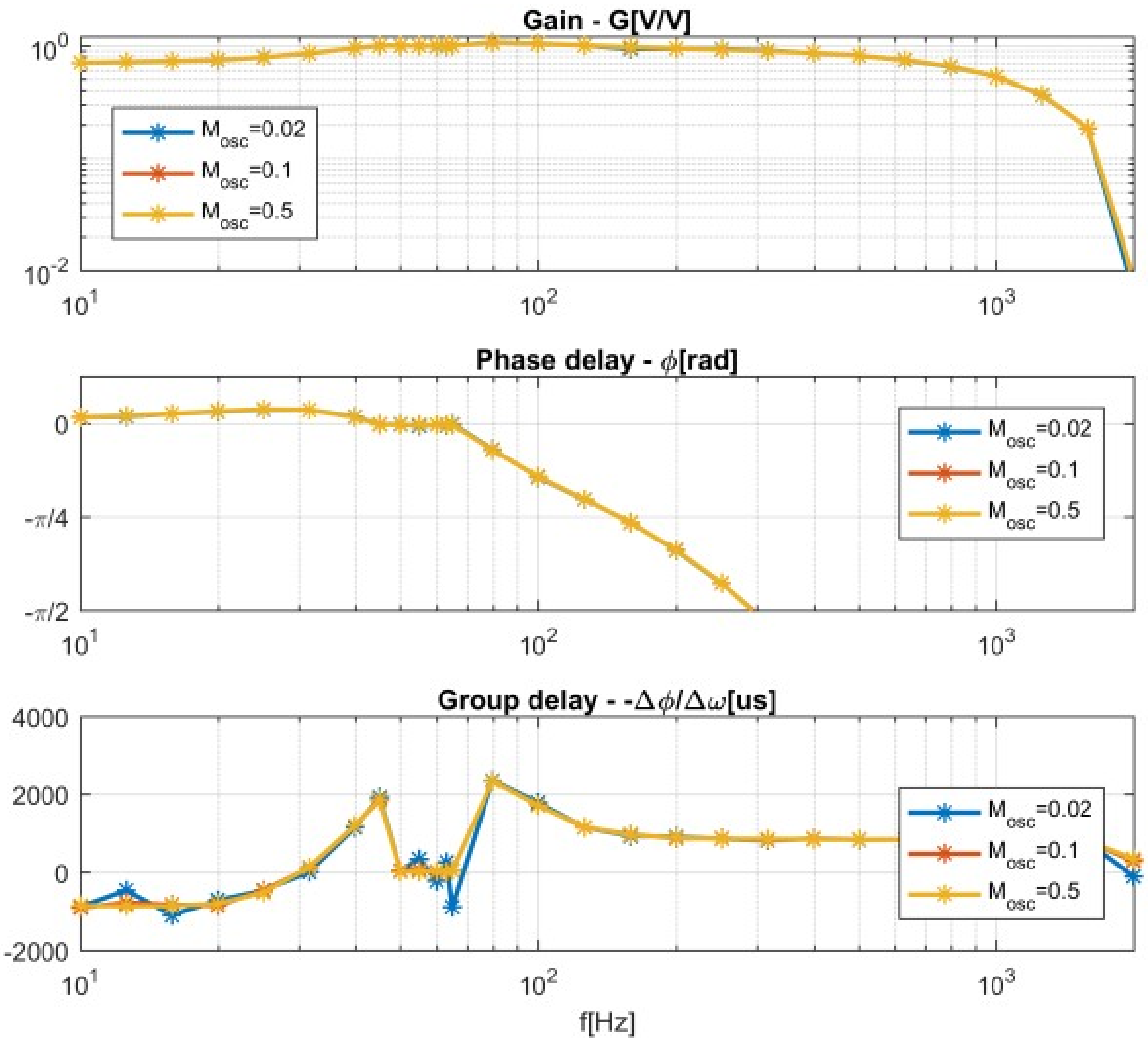
$$\theta'^{[n]} = \Phi[n] + \theta[n]$$



Frequency Step Test – CGI Voltage Tracking



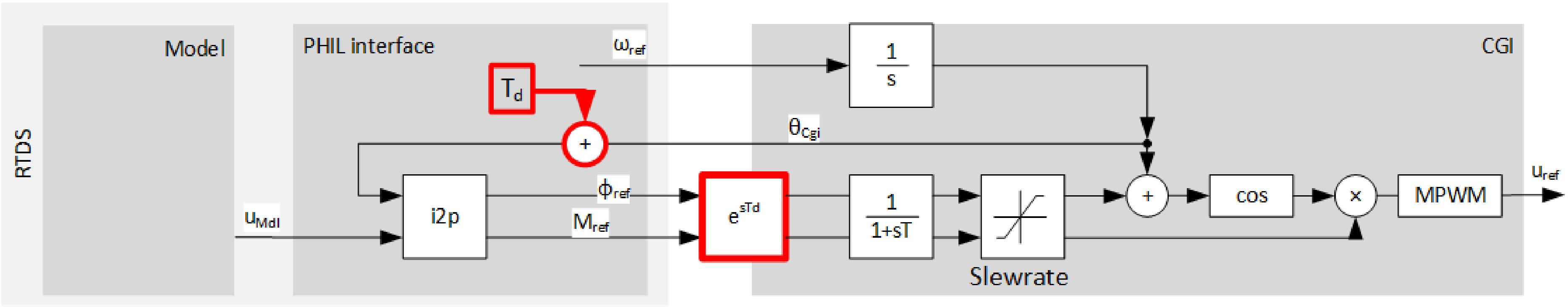
Bode Plot



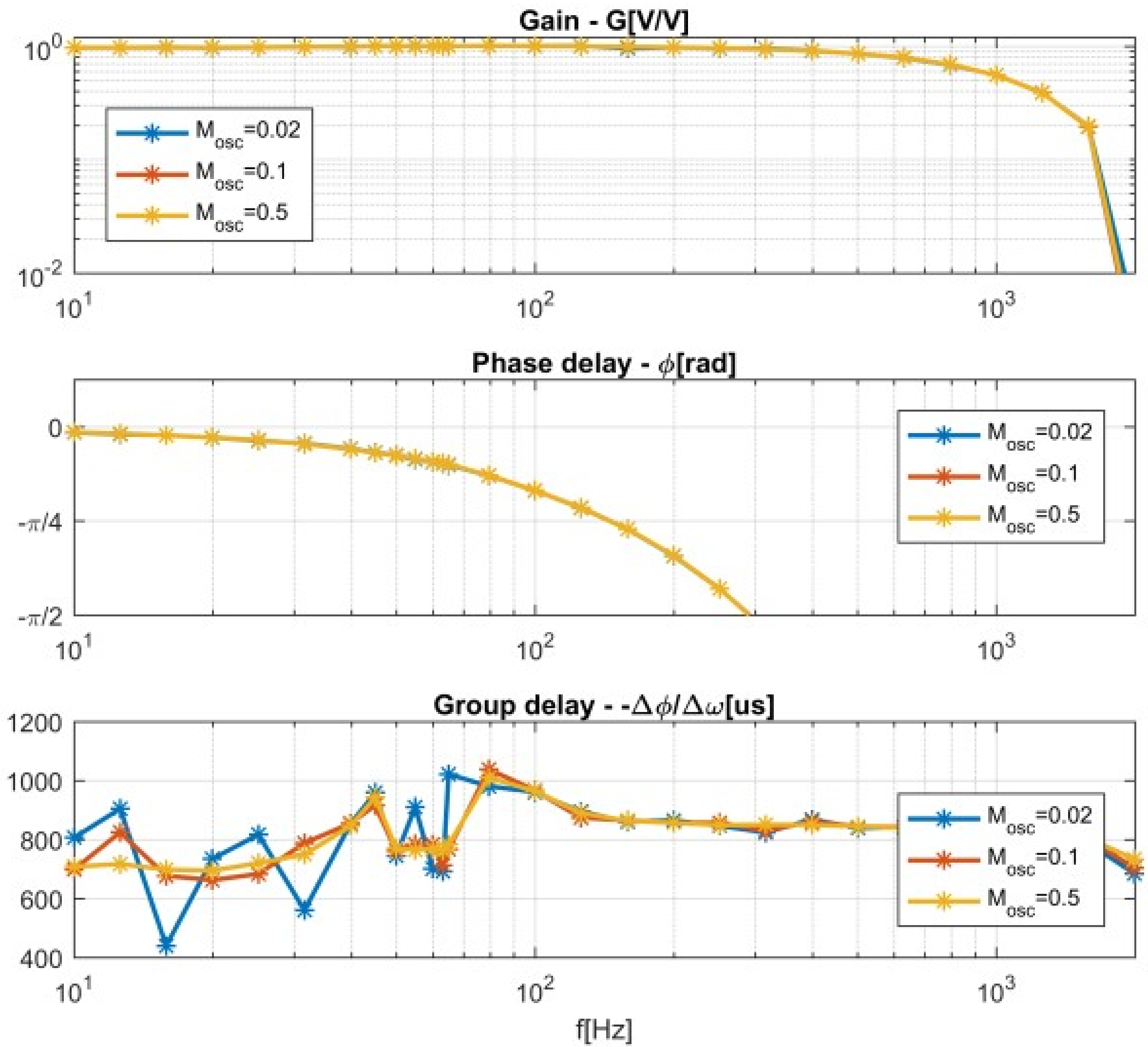
- Algorithm optimized for very low delay at nominal converter frequency: 45-65 Hz
- Leading phase delay at low frequencies/lagging at higher frequencies – causes distortion to wide spectrum voltages (e.g. transients)

Delay Compensation Technique

- Delay can be compensated to allow distortion less transfer function
- Group delay must be constant
- Comm delays ~ 25us
- Actual CGI delay mostly due to processing – Td



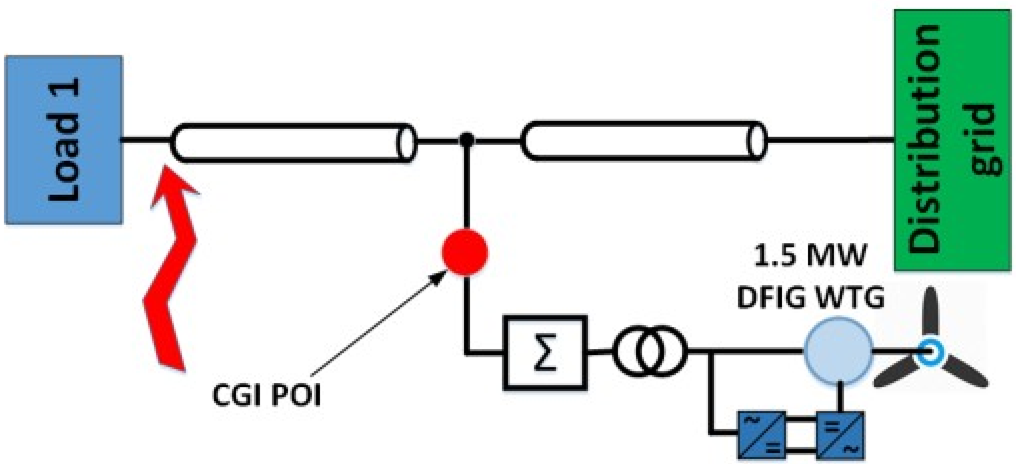
Delay Compensation: Bode Plot

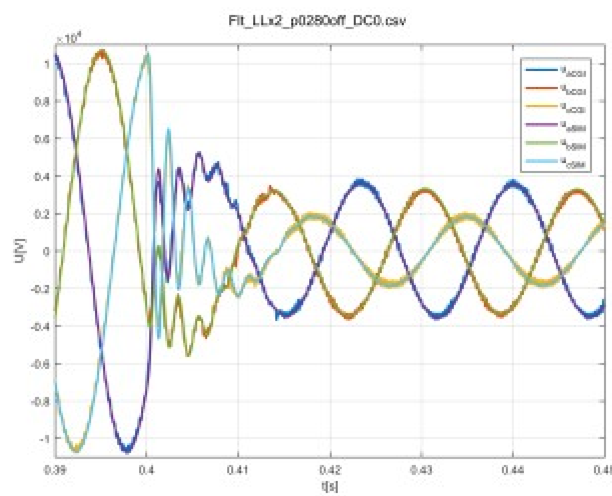


- Transfer function optimized towards distortion less voltage transfer
- Group delay is close to constant

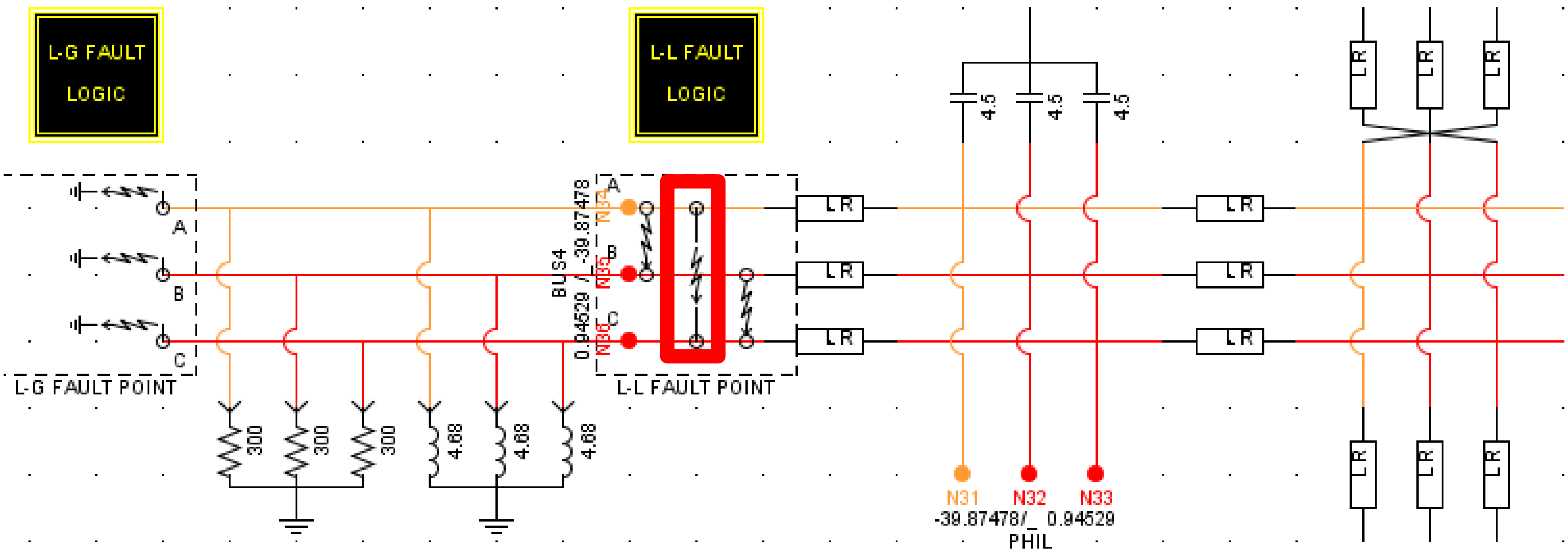
Line Fault Testing

- More real life example
- Line to line and line to ground faults simulated in RTDS – within certain electrical distance from POI
- Transient with rich harmonic content
- Zero, positive and negative sequence
- Highly asymmetrical events

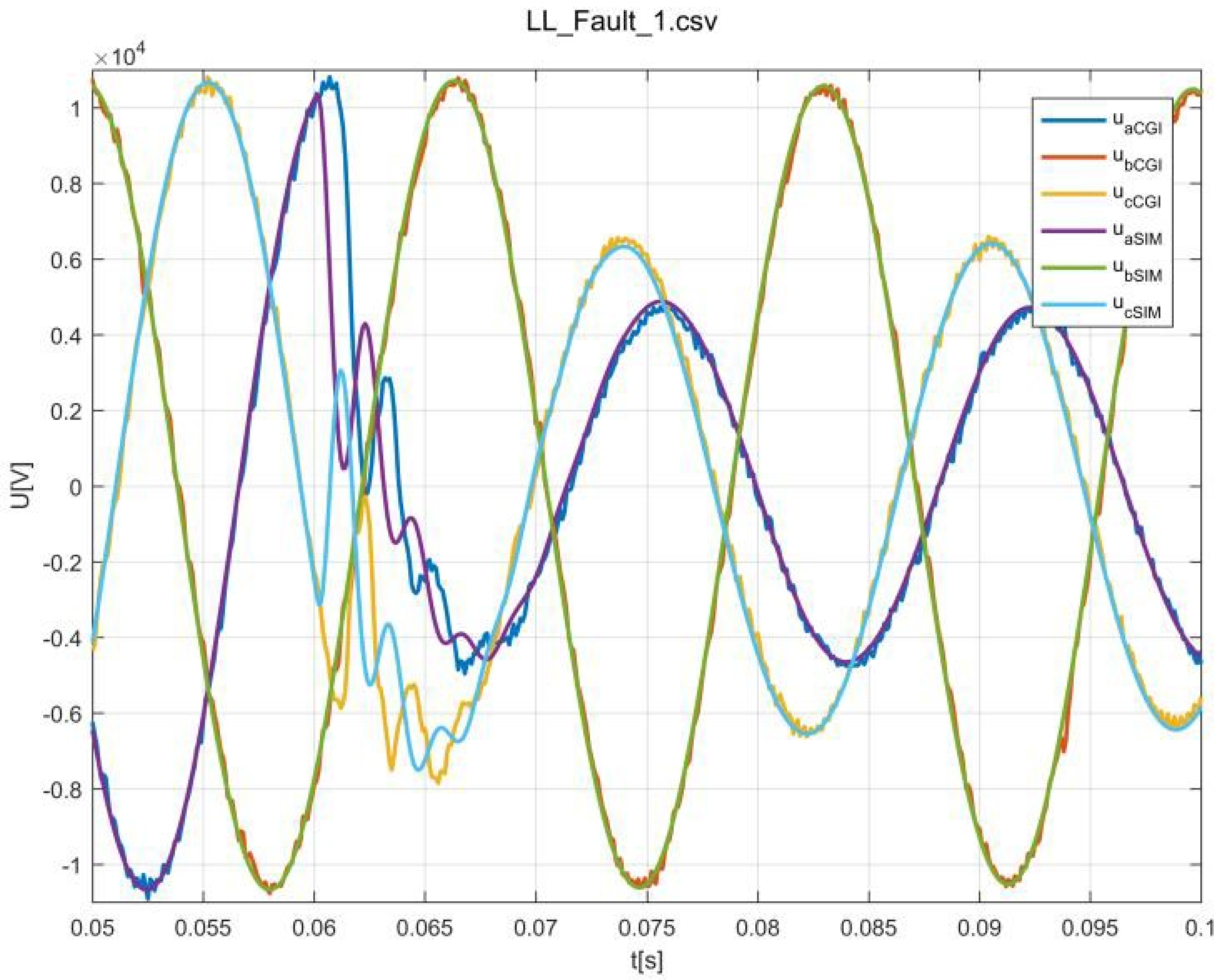




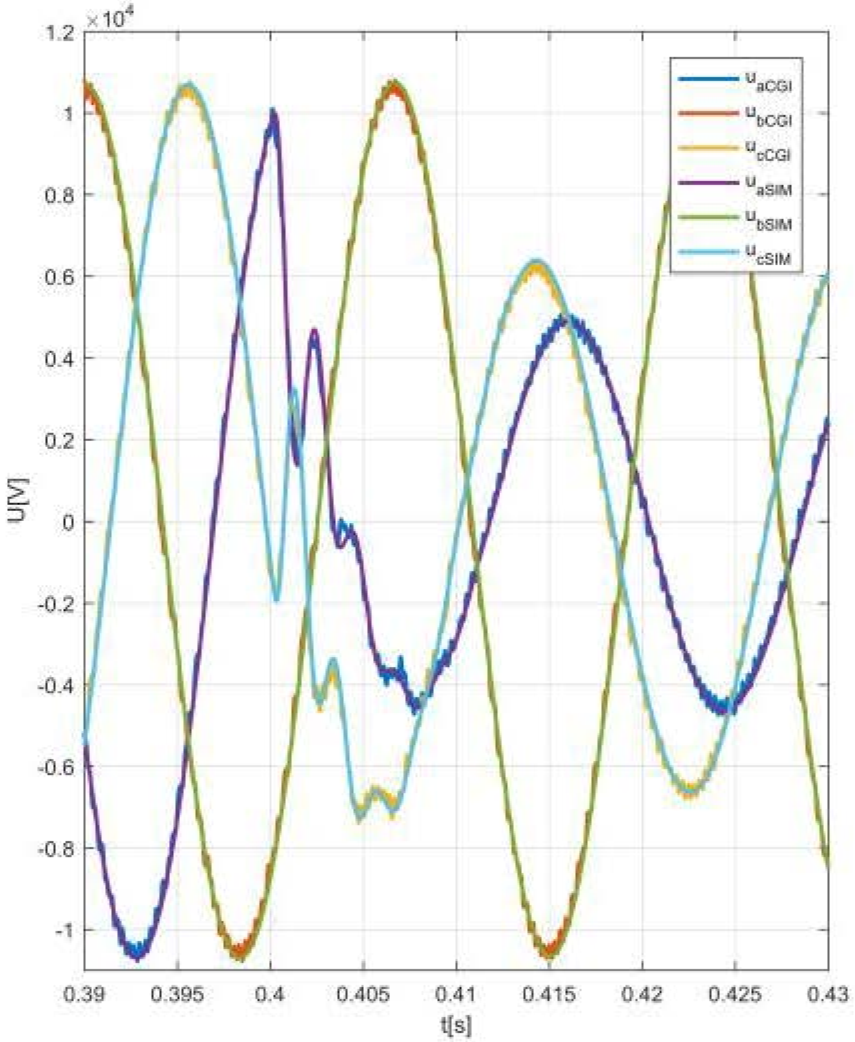
1 Phase Line to Line Fault

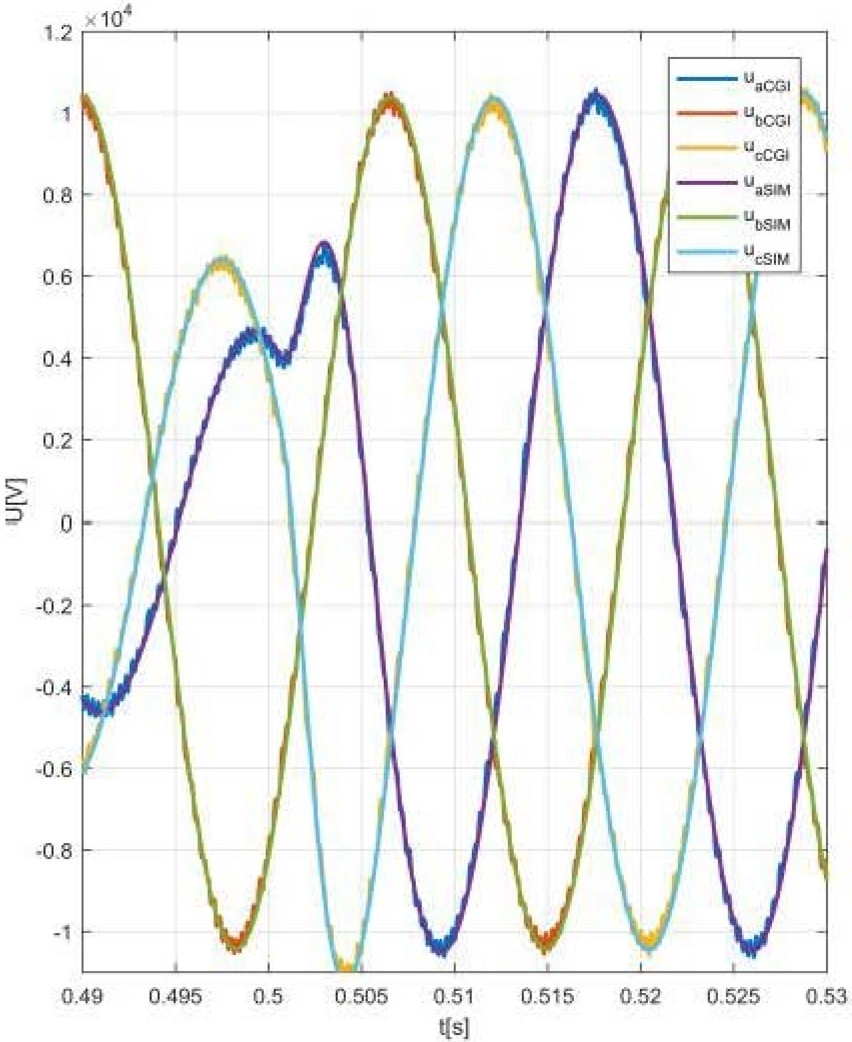


1 Phase Line to Line Fault: No Delay Compensation



1 Phase Line to Line: With Delay Compensation





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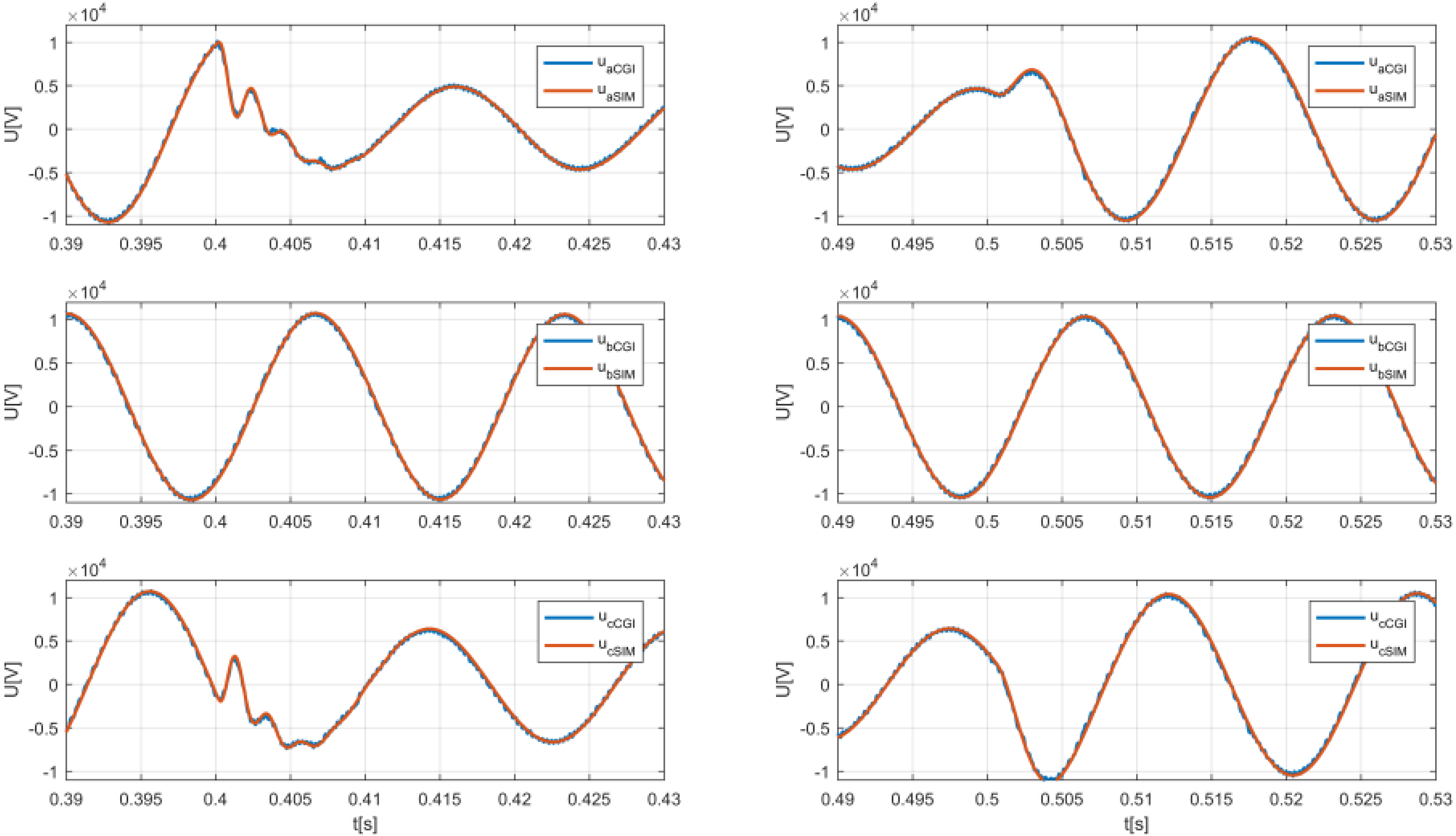

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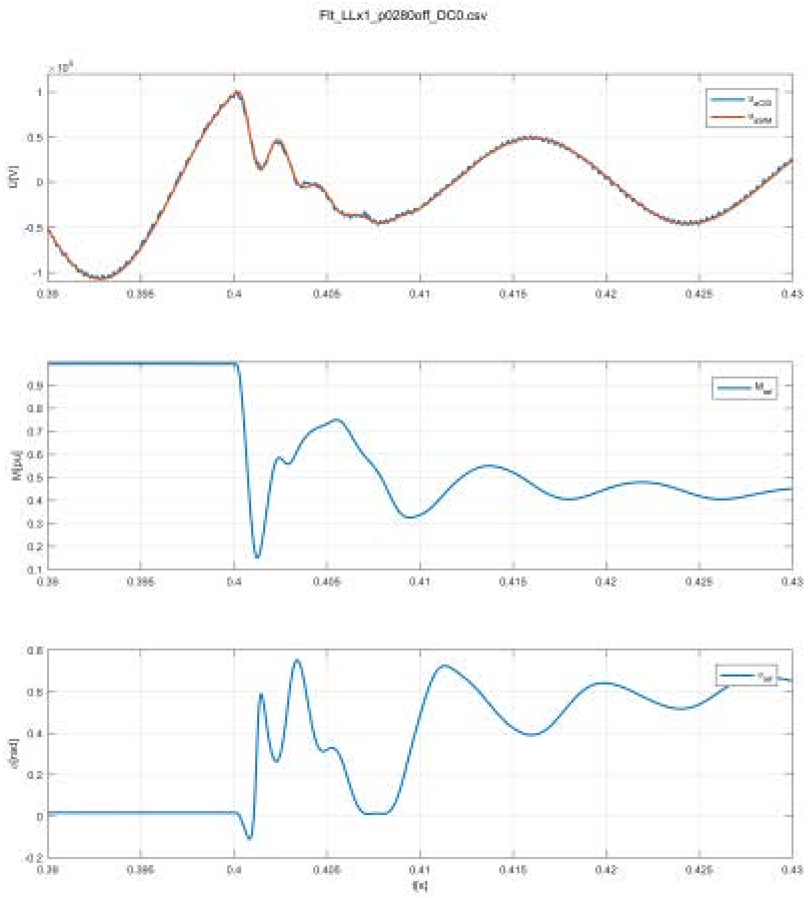
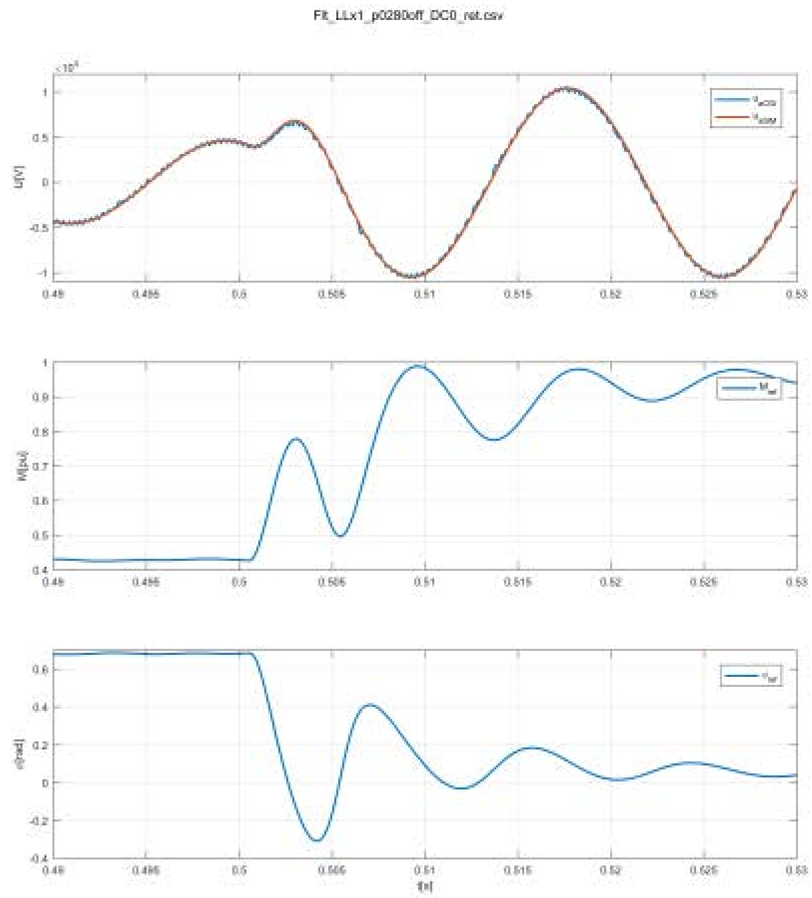
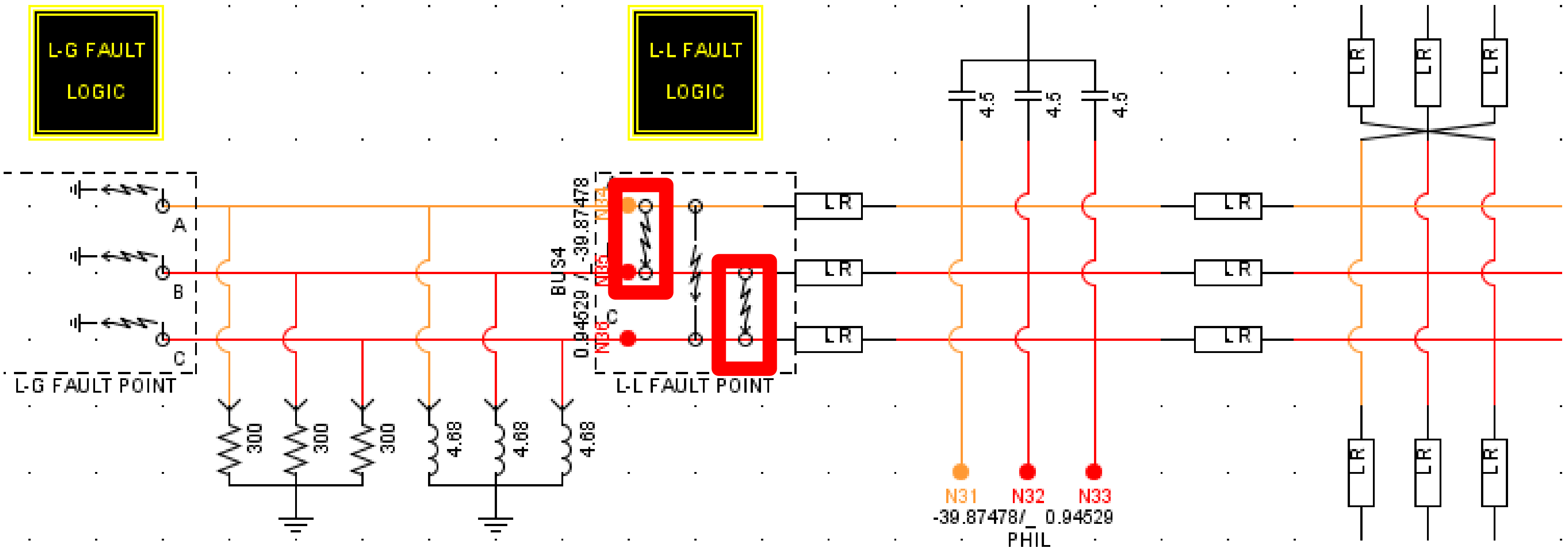




2 Phase Line to Line Fault



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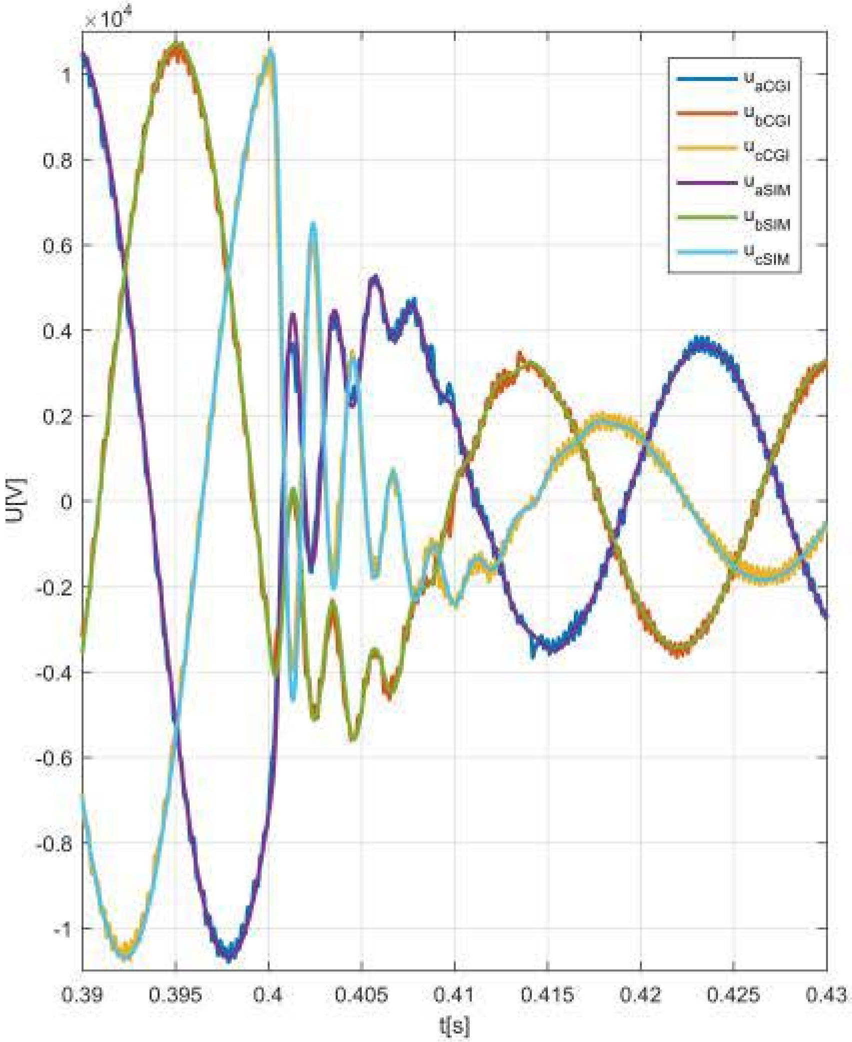
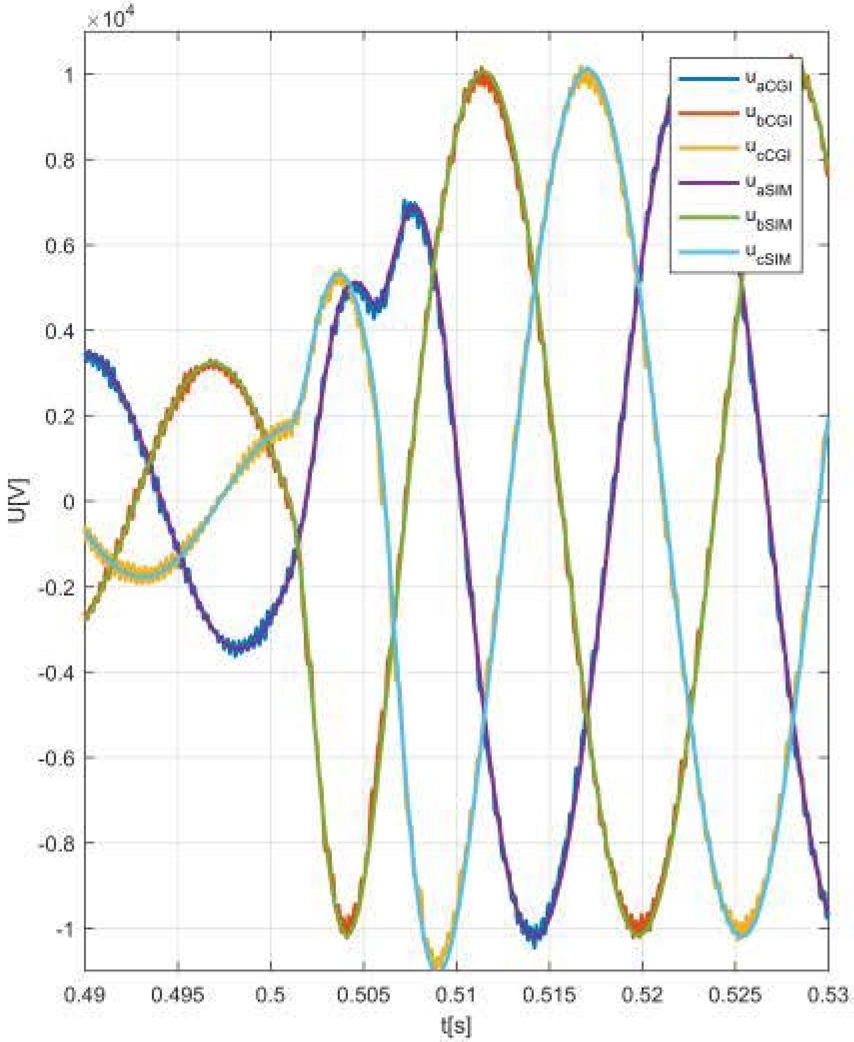
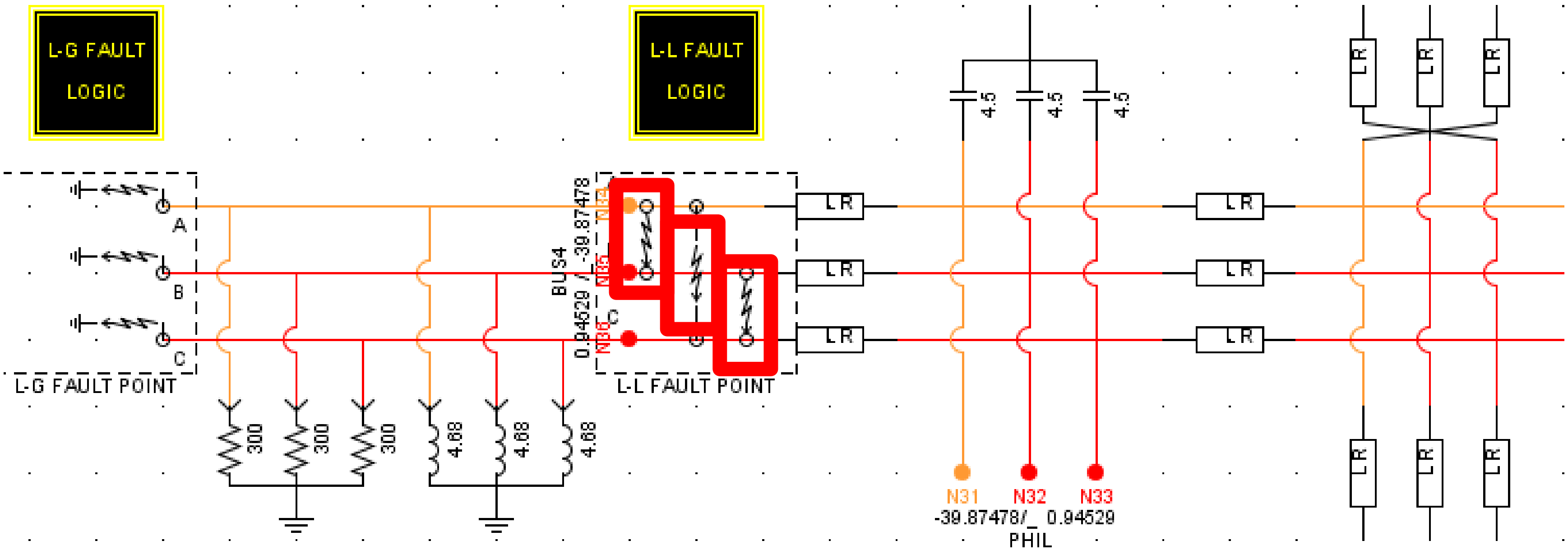
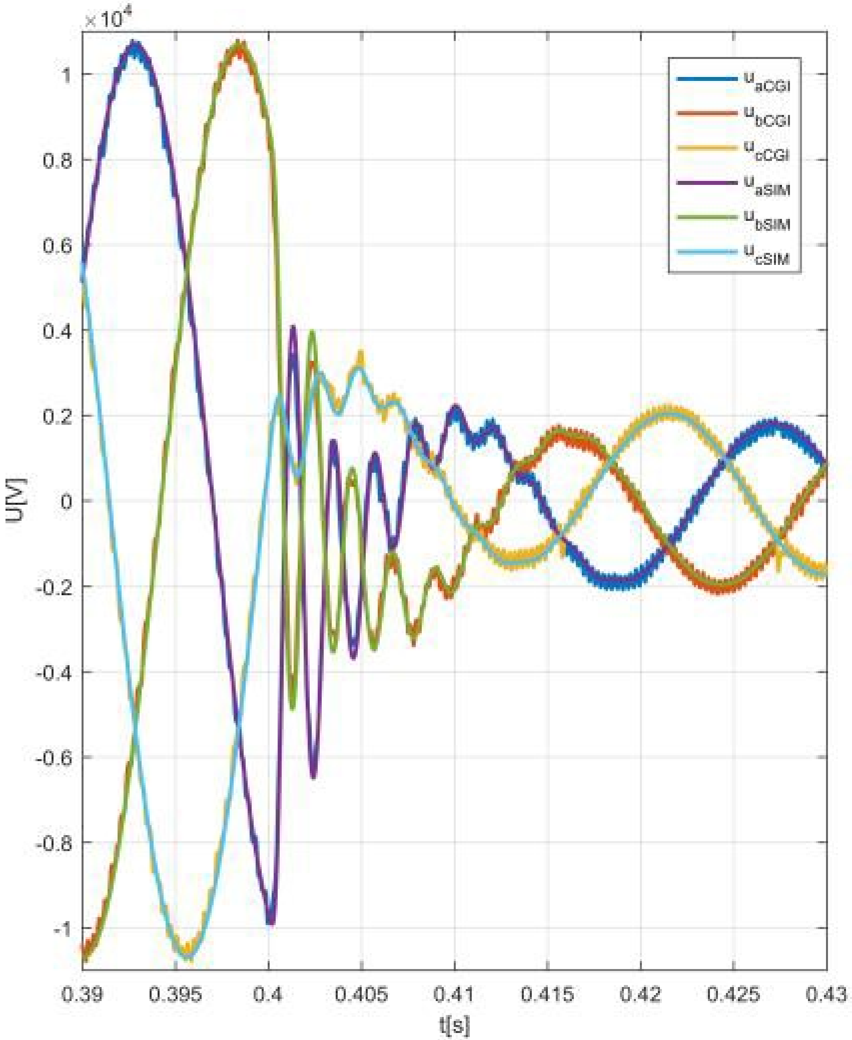


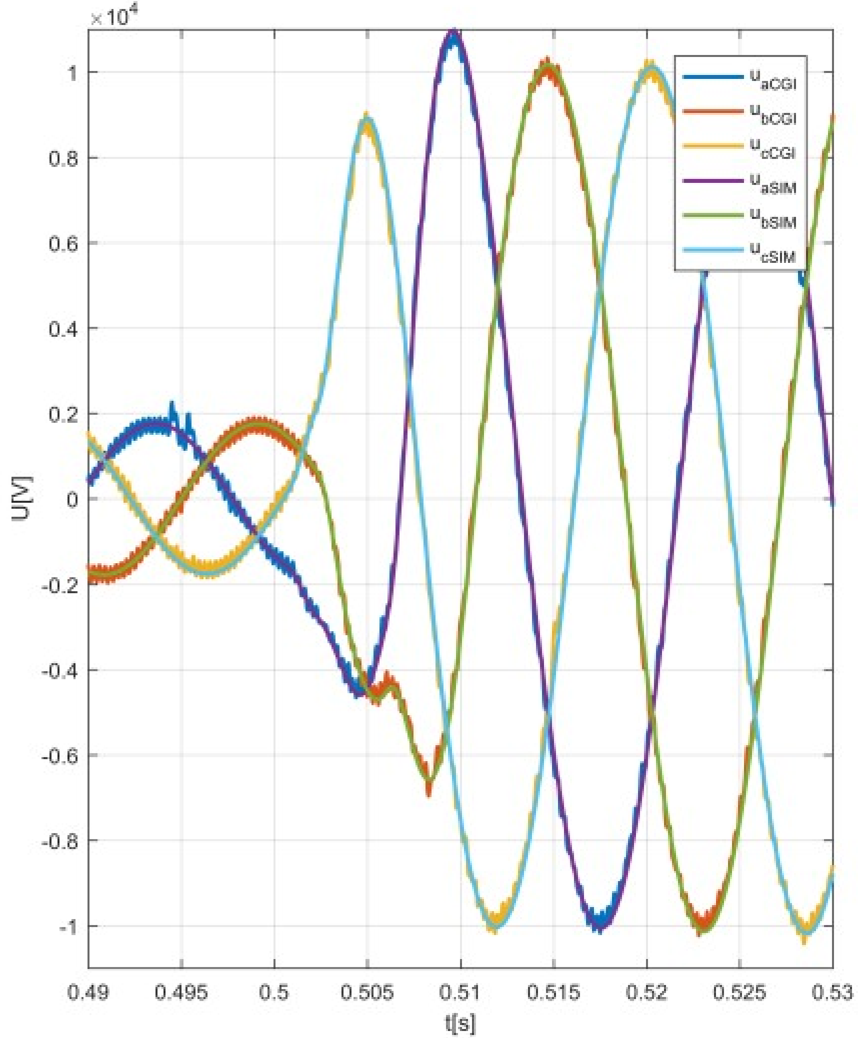


3 Phase Line to Line Fault

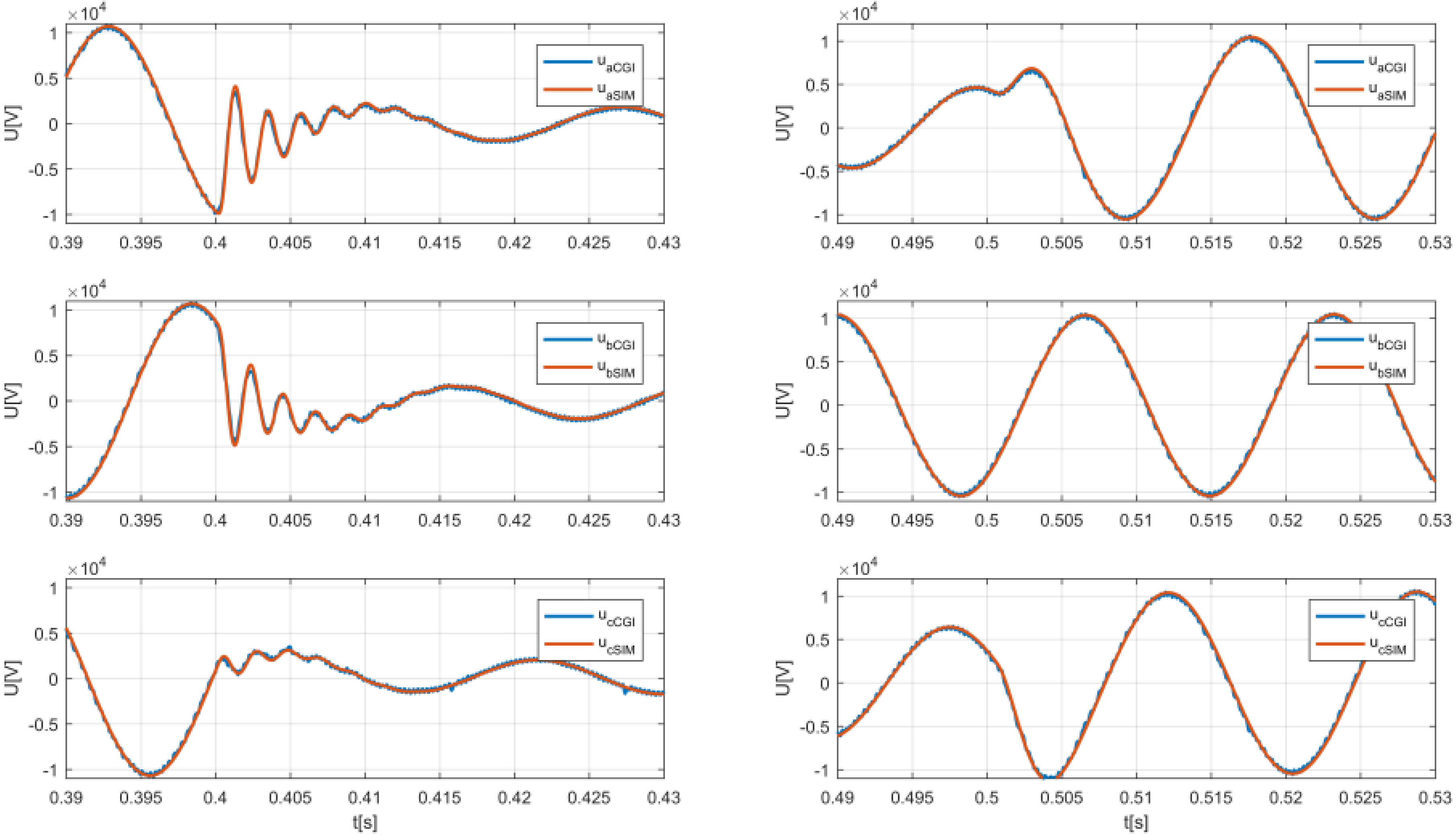


3 Phase Line to Line





3 Phase Line to Line



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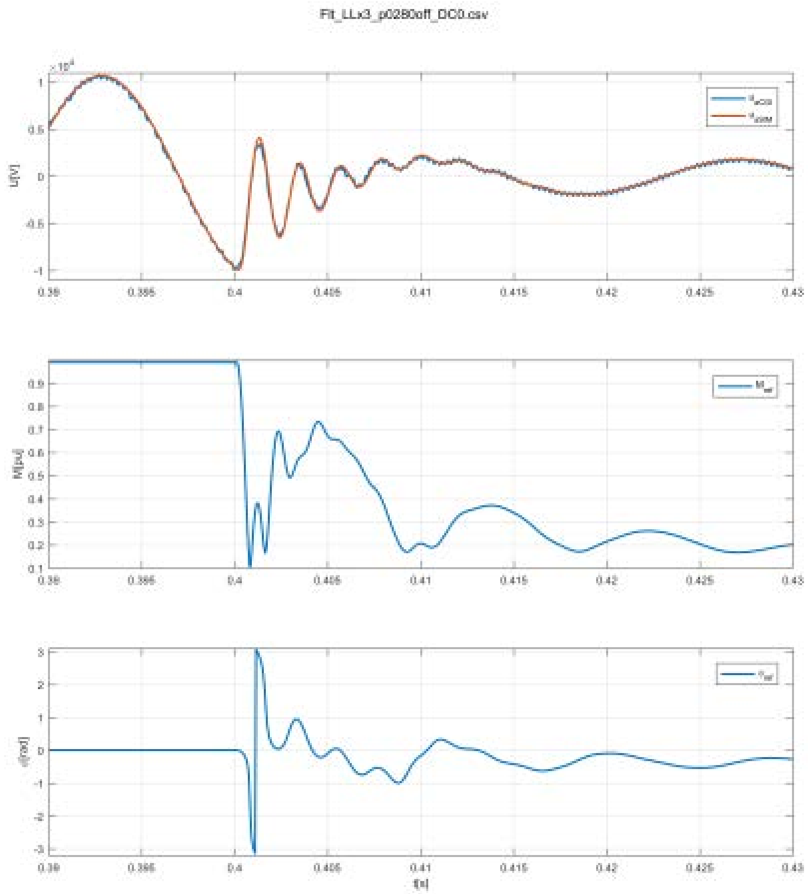
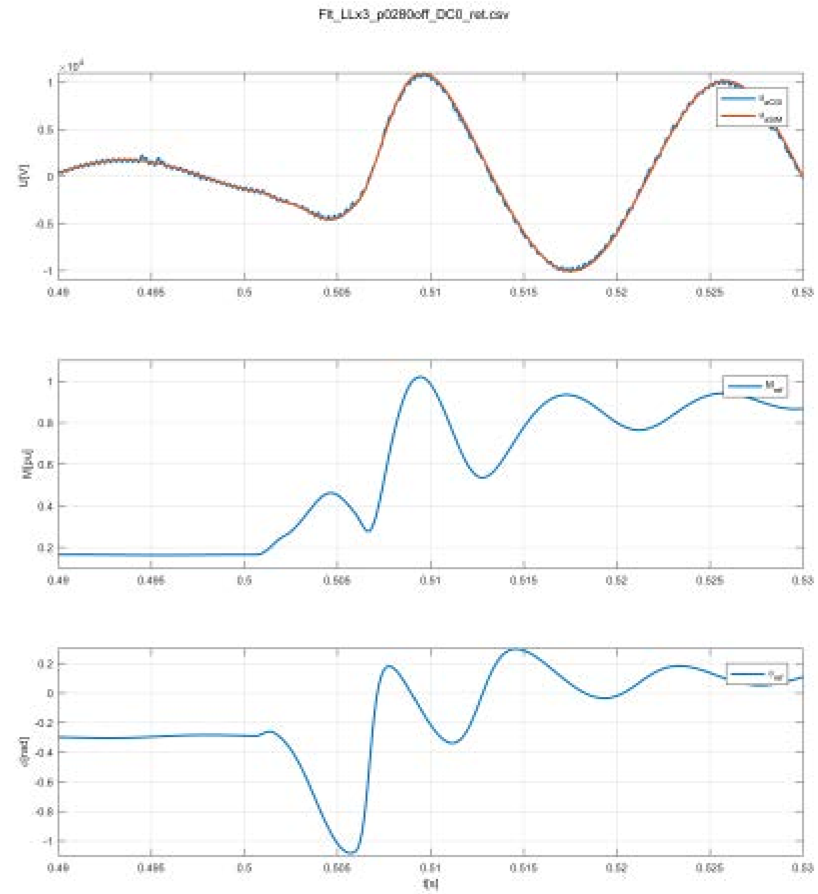
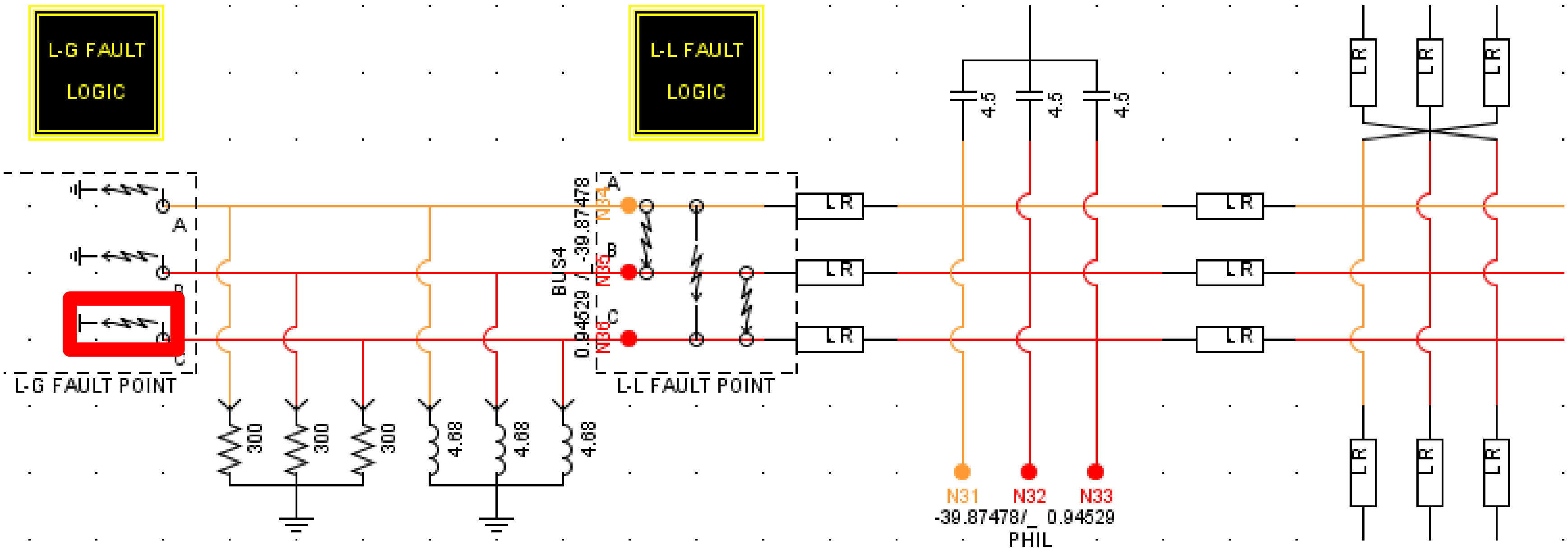




1 Phase Line to Ground Fault



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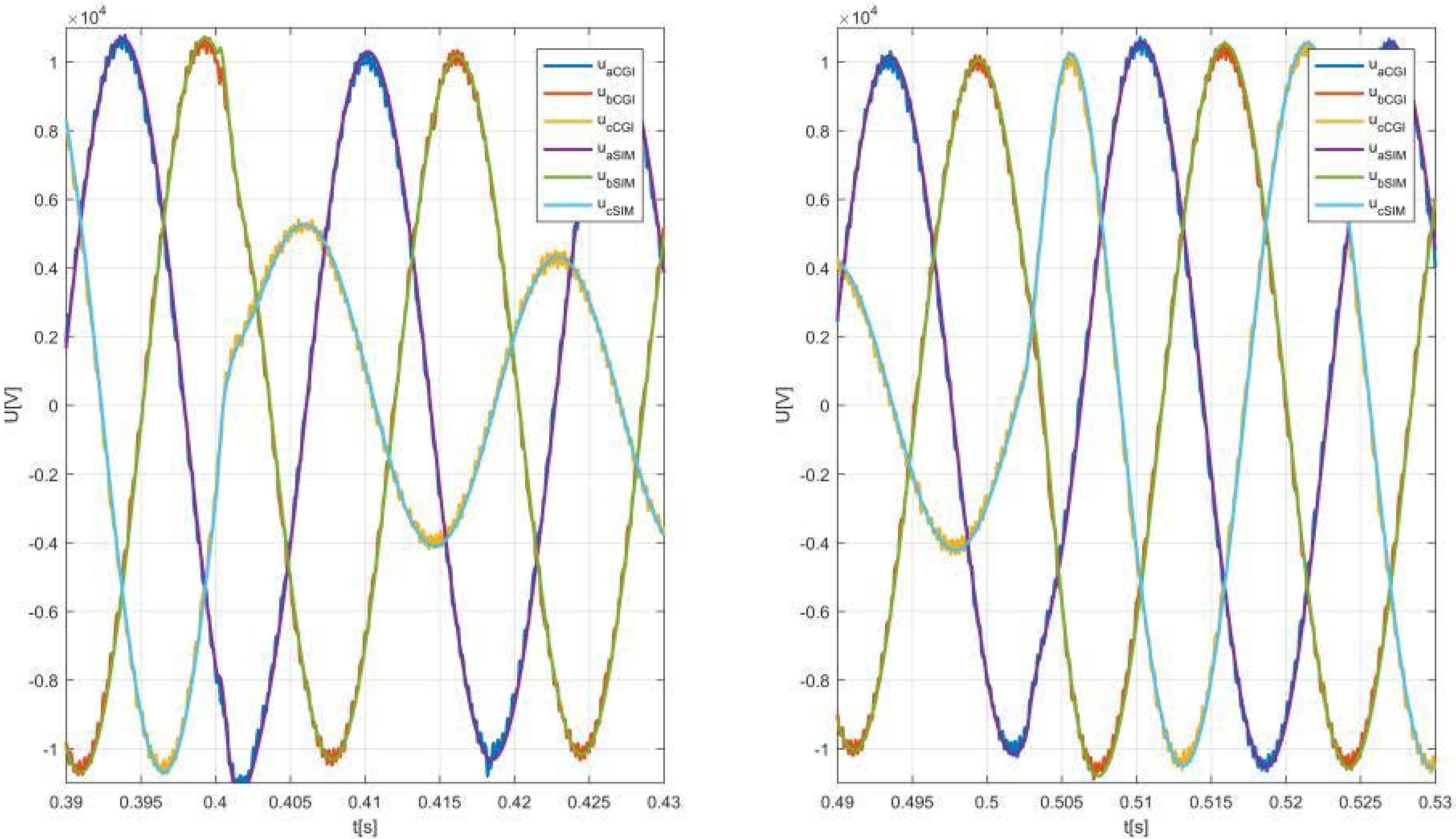

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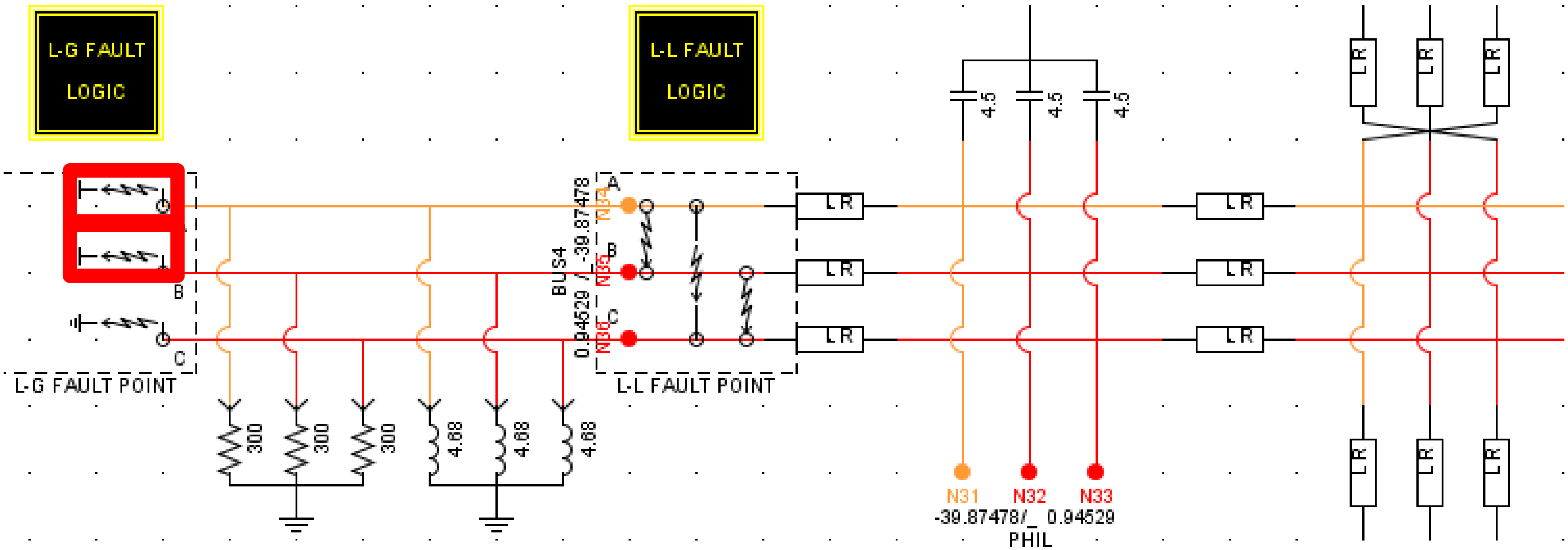

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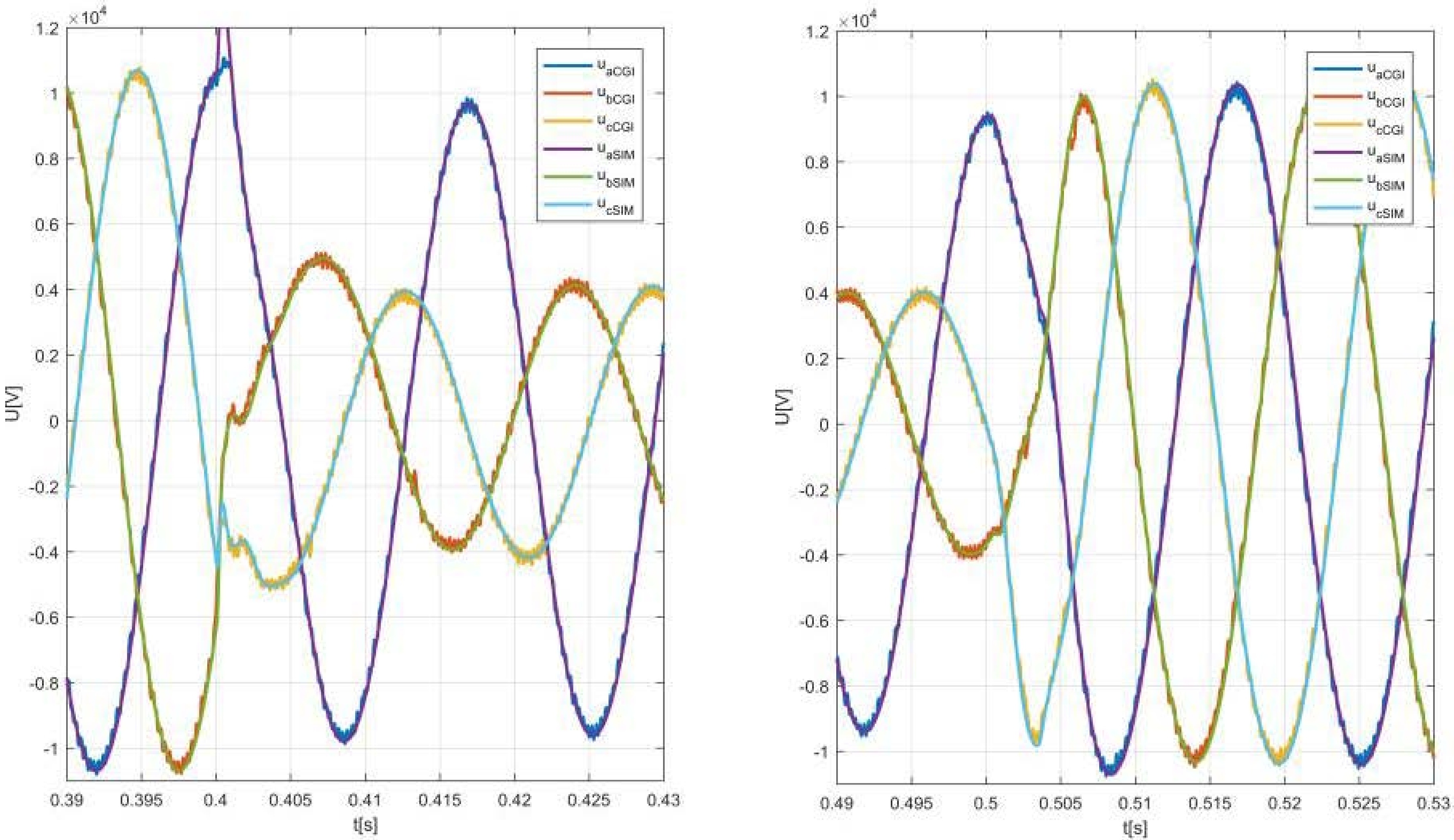
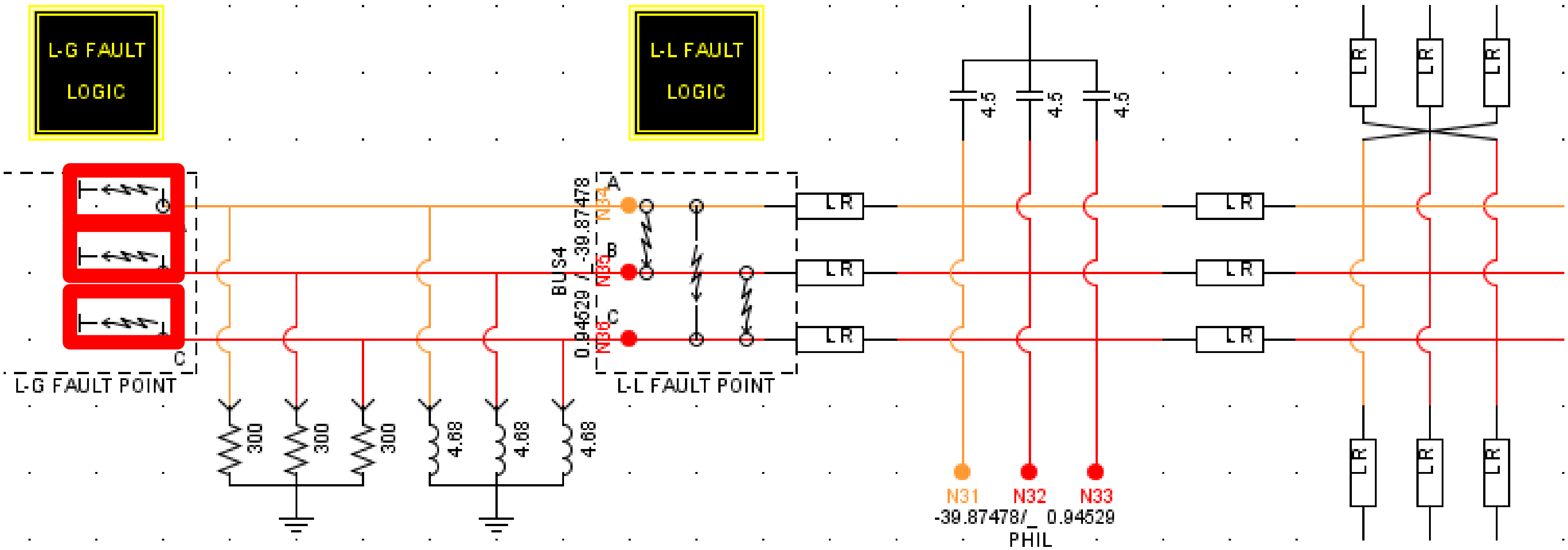
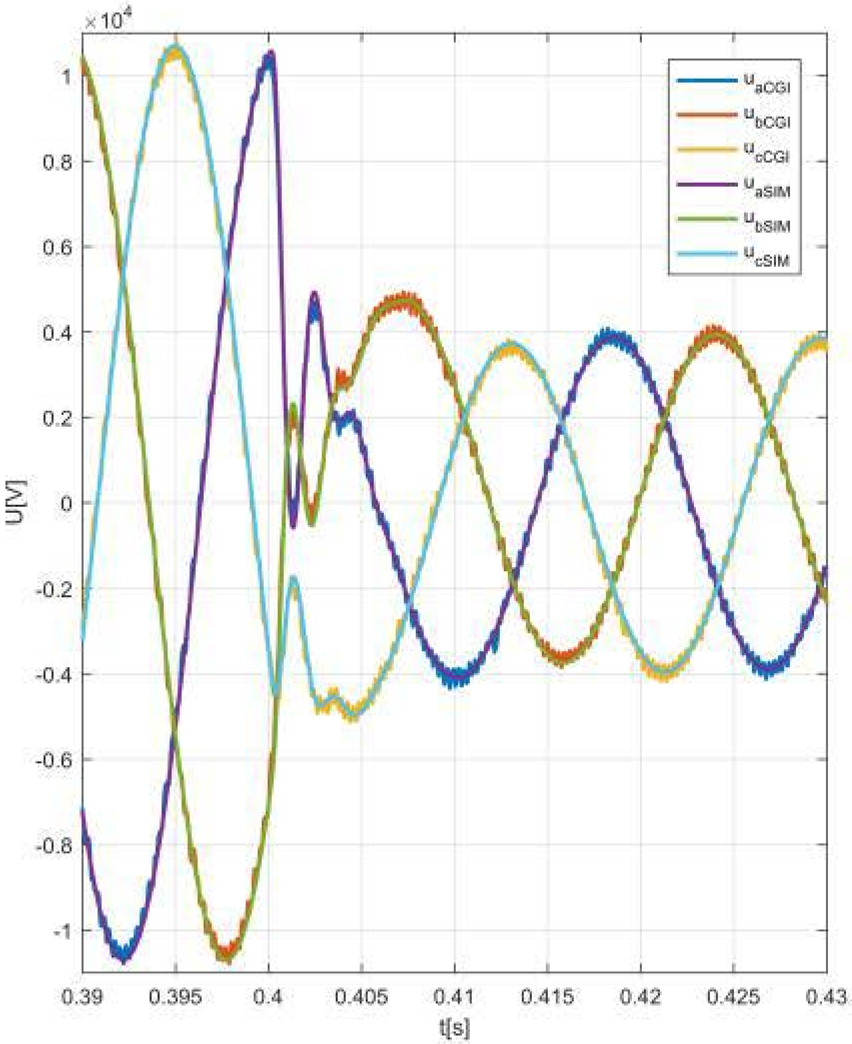
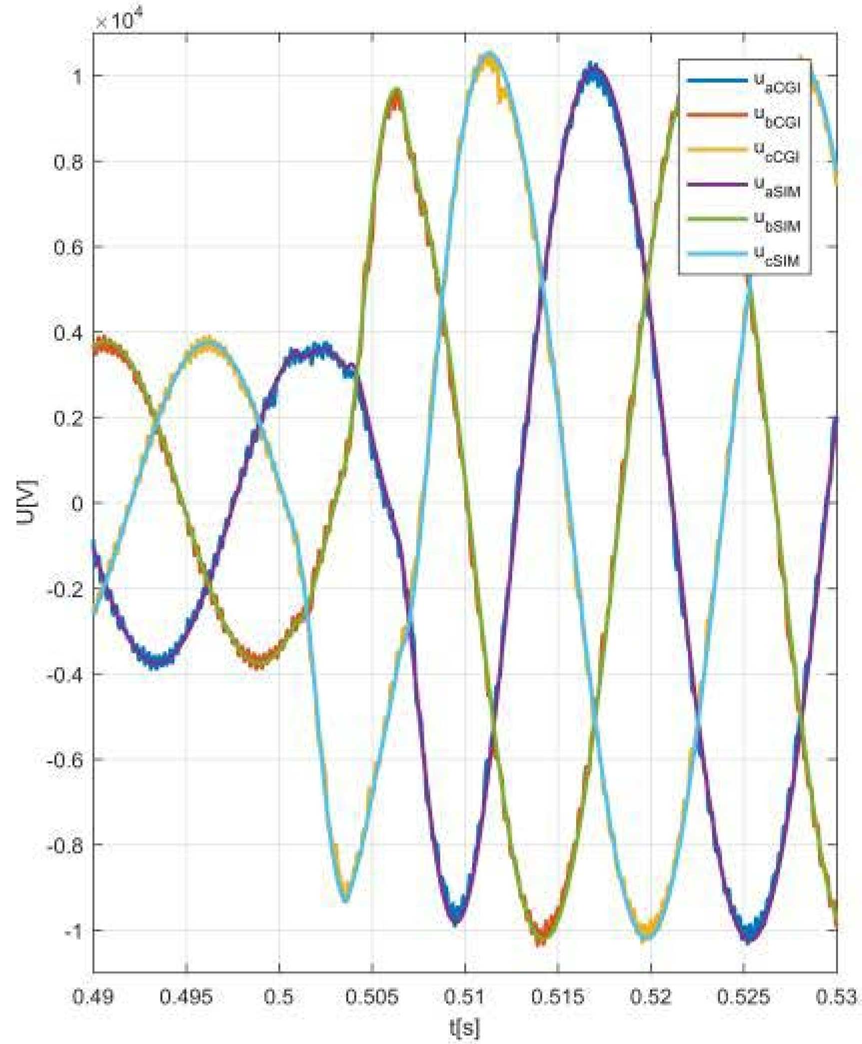




L-G FAULT LOGIC
L-L FAULT LOGIC
L-G FAULT POINT
L-L FAULT POINT
BUS4
0.94529 /_-39.87478
N34
N35
N36
A
B
C
300
300
300
4.68
4.68
4.68
4.5
4.5
4.5
L R
N31
N32
N33
-39.87478/_ 0.94529
PHIL

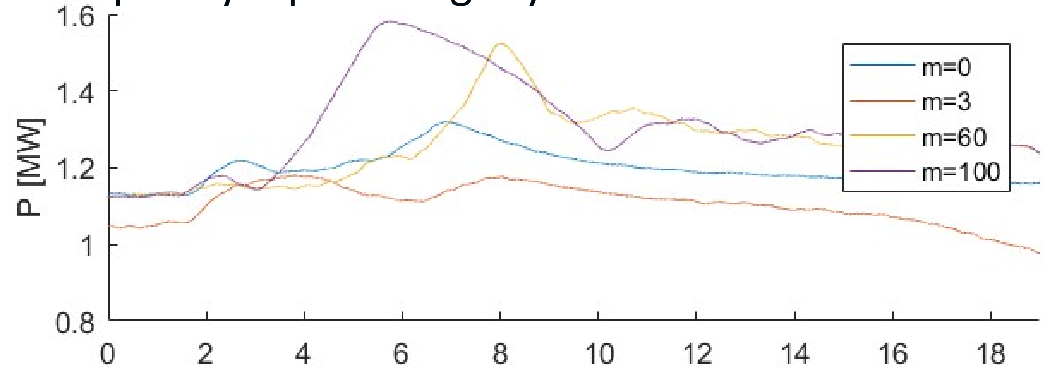
3 Phase Line to Ground Fault

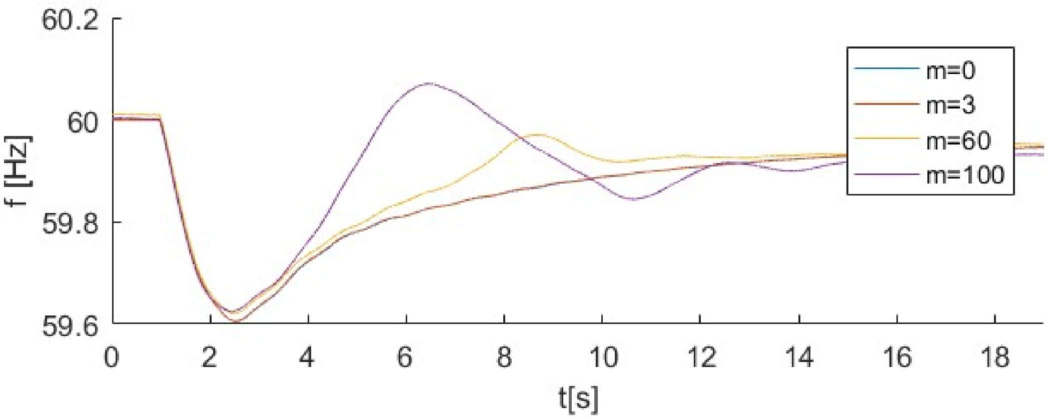


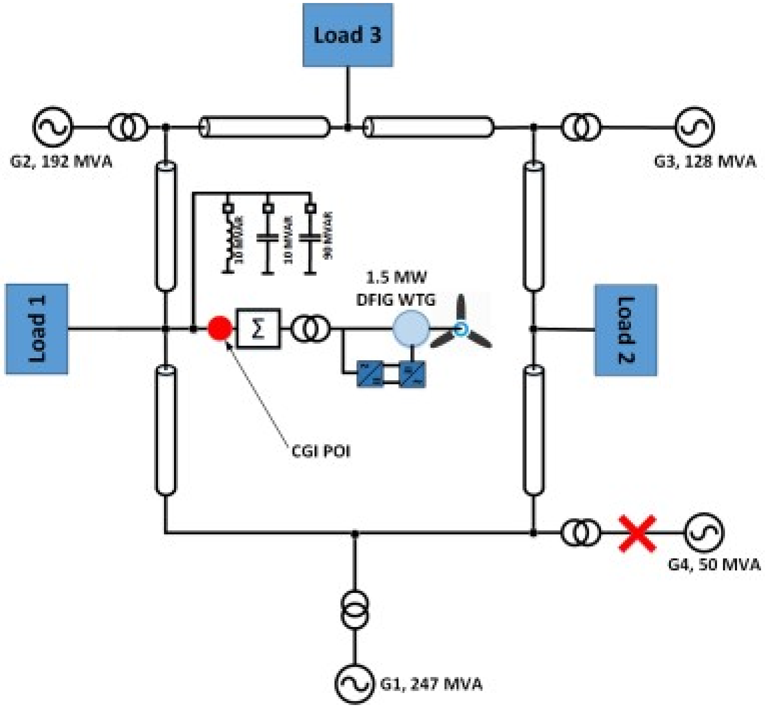


PHIL Tests – GE 1.5 MW - 12% Generation Drop Case

- G4 generating 50 MW before the event
- G4 CB opens
- GE 1.5-MW wind energy controller (WEC) reacts with inertial response & droop
- Frequency recovers faster with higher *m*
- Frequency dip was sligthly limited



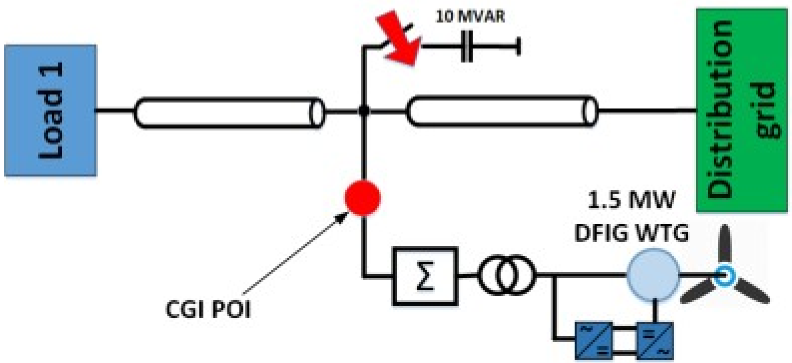


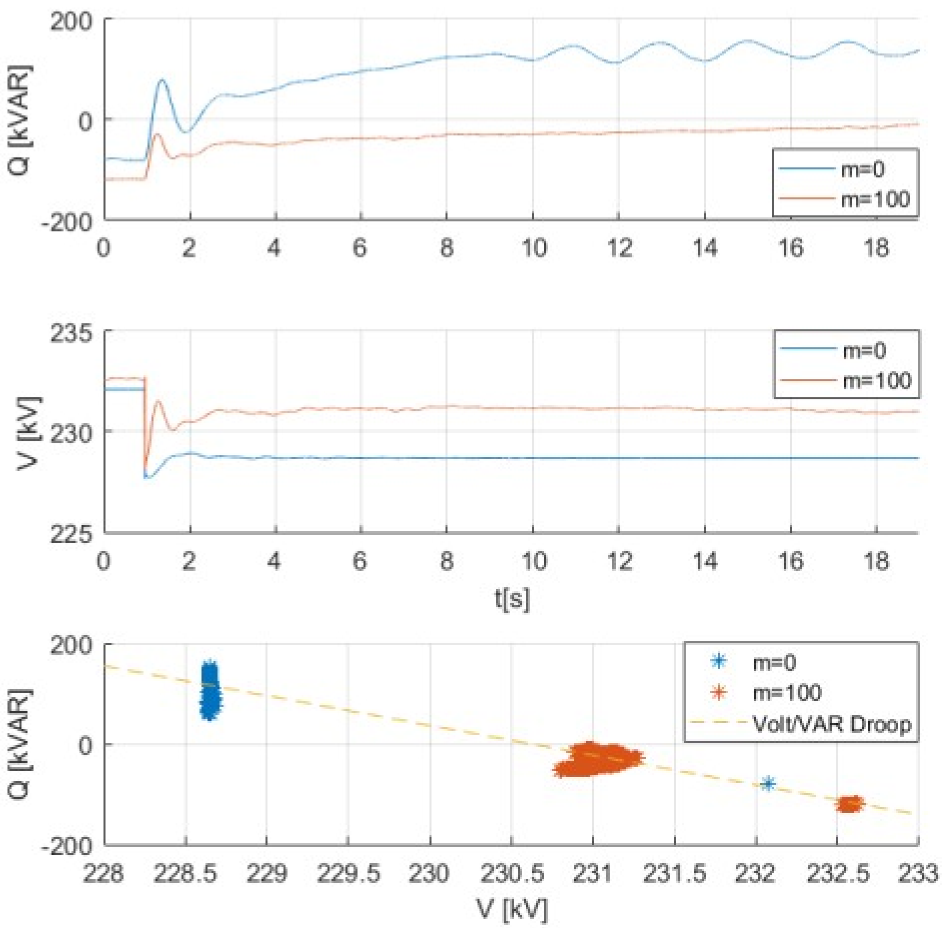


m	f_{min}[Hz]
0	59.606
3	59.608
69	59.621
100	59.625

PHIL Test – GE 1.5 MW – Capacitor Bank Enabling

- Wind Plant Controller (WPC) is configured to control voltage at POI with Volt/VAR droop
- Cap bank is disabled at t=0.9s





- With m=0 there is no impact of reactive power on POI voltage
- With m=100 voltage is being controlled by WPC
- PHIL helps in testing droop/load sharing techniques

Publications

- P. Koralewicz: „Power Electronic Grid Simulator: Platform of Drives and Power Quality Products for Power Electronics Testing", 3rd International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains, Florida State University, Tallahasee, USA, November 2015.
- P. Koralewicz, V. Gevorgian, R. Wallen, W. van der Merwe, P. Jörg, "Advanced Grid Simulator for Multi-Megawatt Power Converter Testing and Certification", IEEE Transactions on Energy Conversion, ECCE, June 2016 conference.
- V. Gevorgian, P. Koralewicz, R. Wallen, E. Muljadi, X. Wang, "Controllable Grid Interface for Testing Ancillary Service Controls and Fault Performance of Utility-Scale Wind Power Generation", 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power.
- P. Koralewicz, V. Gevorgian, R. Wallen, "Multi-Megawatt-Scale Power-Hardware-in-the-Loop Interface for Testing Ancillary Grid Services by Converter-Coupled Generation", IEEE COMPEL 2017 conference, July 2017.

Thank you!

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