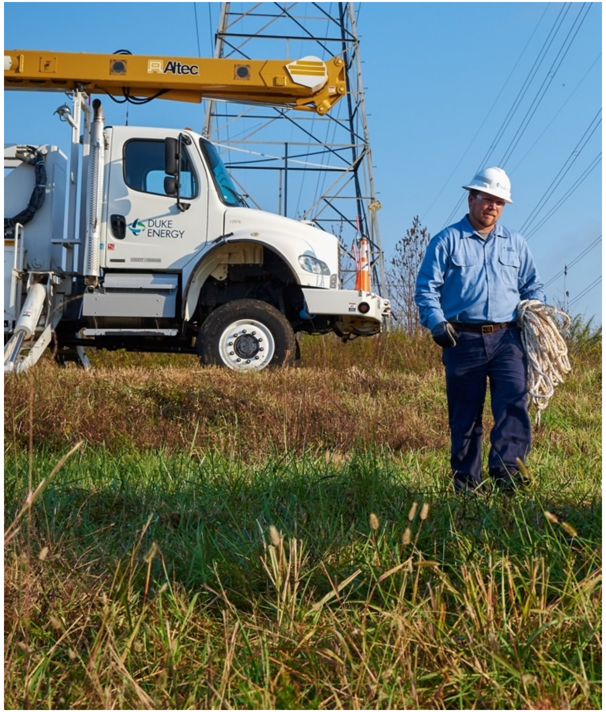
Enhanced Algorithms for Real-time Stability Tracking

An Overview of Duke Energy and NCSU PSSE Simulation Based PMU Research

Kat Sico, Tim Gubitz, and Dr. Aranya Chakrabortty



DUKE ENERGY

Presentation Overview

- Duke Energy PMU Deployment
- Review what Lyapunov Exponents (LEs) Are
- Review Application of LEs to DEC PSSE System Model
    - Stability of Stable Systems using LEs
    - Improvement in LE Prediction Using Filters
    - Application of LEs to System Results

Duke Energy Phasor Deployment

Carolinas West

- 128 PMUs installed at 60 substations (covers all 500kV & 230kV substations, tie lines, and other select substations)
- PMU capable DFR for generators: 18 @ 5 plants, Plans for 10 additional @ 3 plants
- Current Tools: Visualization Software / Post Event Analysis; EMS integration of phasors in State Estimation
- PMUs installed at one distribution (solar) facility

Carolinas East

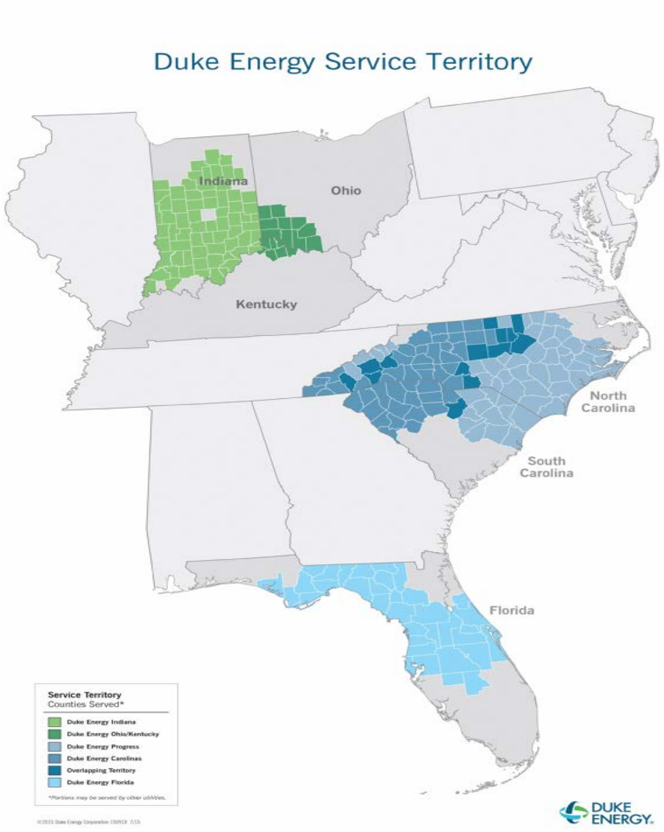
- 9 PMUs installed; Plans for 39 by end of 2018
- PMU capable DFR for generators: 4 @ 2 plants

Duke Energy Midwest

- Originally 32 PMUs installed as part of MISO program at select 345 & 230kV substations
- Plan to add 6 PMUs in 2016 as part of relay upgrade projects

Duke Energy Florida

- Plans for 20 PMUs over the next few years



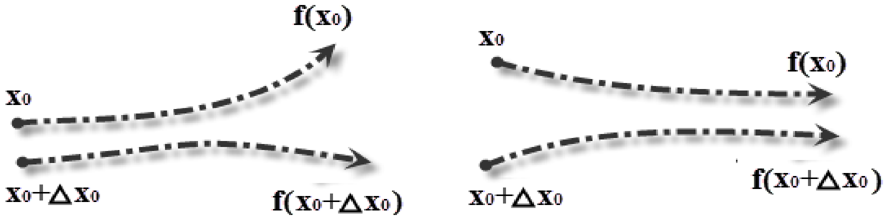
Research Effort

- Research Team
  - Duke Energy
  - SAS Institute
  - North Carolina State University
- Goal: develop tools that provide useful information for real-time operations.
- Short-Term Voltage Stability Assessment
  - Lyapunov Exponent
- Learning loop system
  - Use PSS/E simulation software to generate cases for voltage stability
  - Use Lyapunov Exponent to identify vulnerable situations
  - Apply to PMU data in real time

Lyapunov Exponent

- Characterizes the rate of convergence or divergence of non-linear dynamical systems.
- For unstable/stable systems the Lyapunov Exponent will be positive/negative

+λ Unstable



-λ Stable

- General Equation

$$d(f^n(x_0), f^n(x_0 + \Delta x_0)) = e^{\lambda n} d(x_0, x_0 + \Delta x_0)$$

$$\lambda = \frac{1}{n} ln\left[\frac{d(f^n(x_0), f^n(x_0 + \Delta x_0))}{\Delta x_0}\right]$$

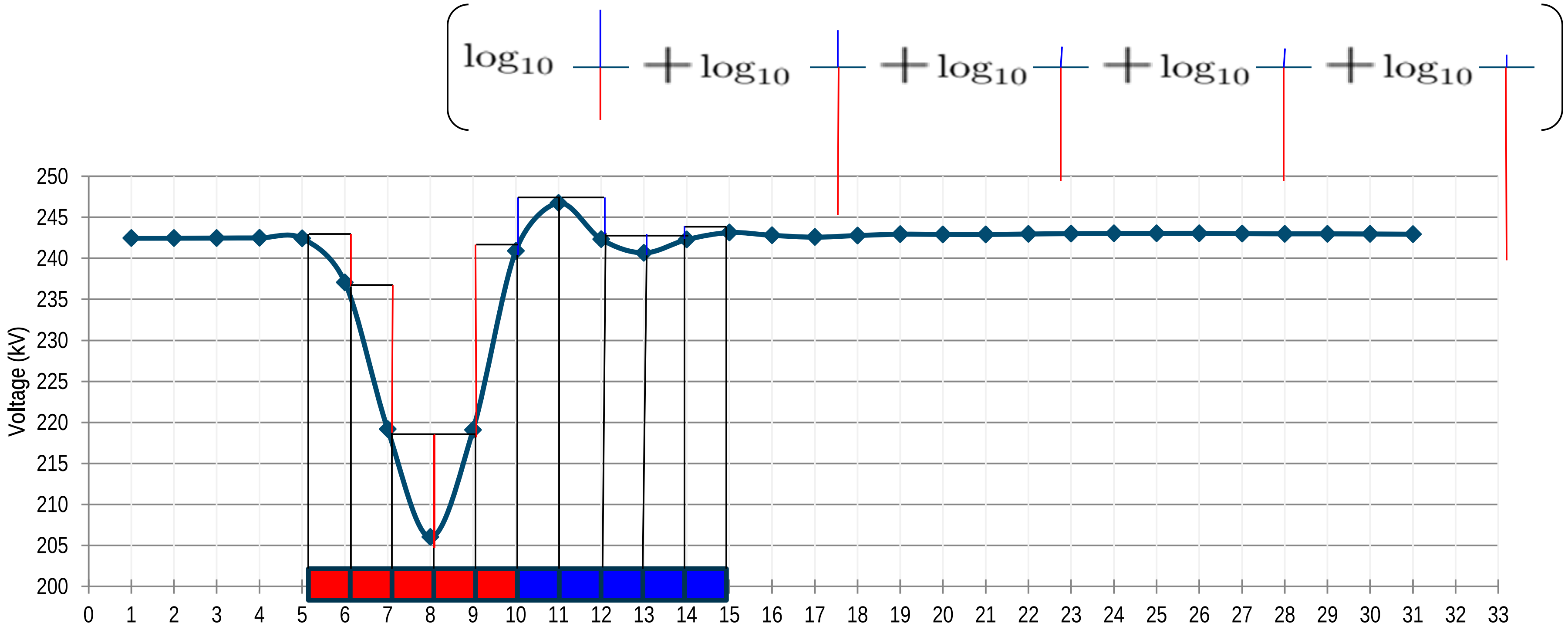
[Reference 1]

- Time Series Calculation

$$\lambda = \frac{1}{Nk\Delta t} \times \sum_{m=1}^{N} \log_{10} \frac{|v^i_{(k+m)\Delta t} - v^i_{(k+m-1)\Delta t}|}{|v^i_{m\Delta t} - v^i_{(m-1)\Delta t}|}, k > N$$

[Reference 2]

Lyapunov Exponent Time Series

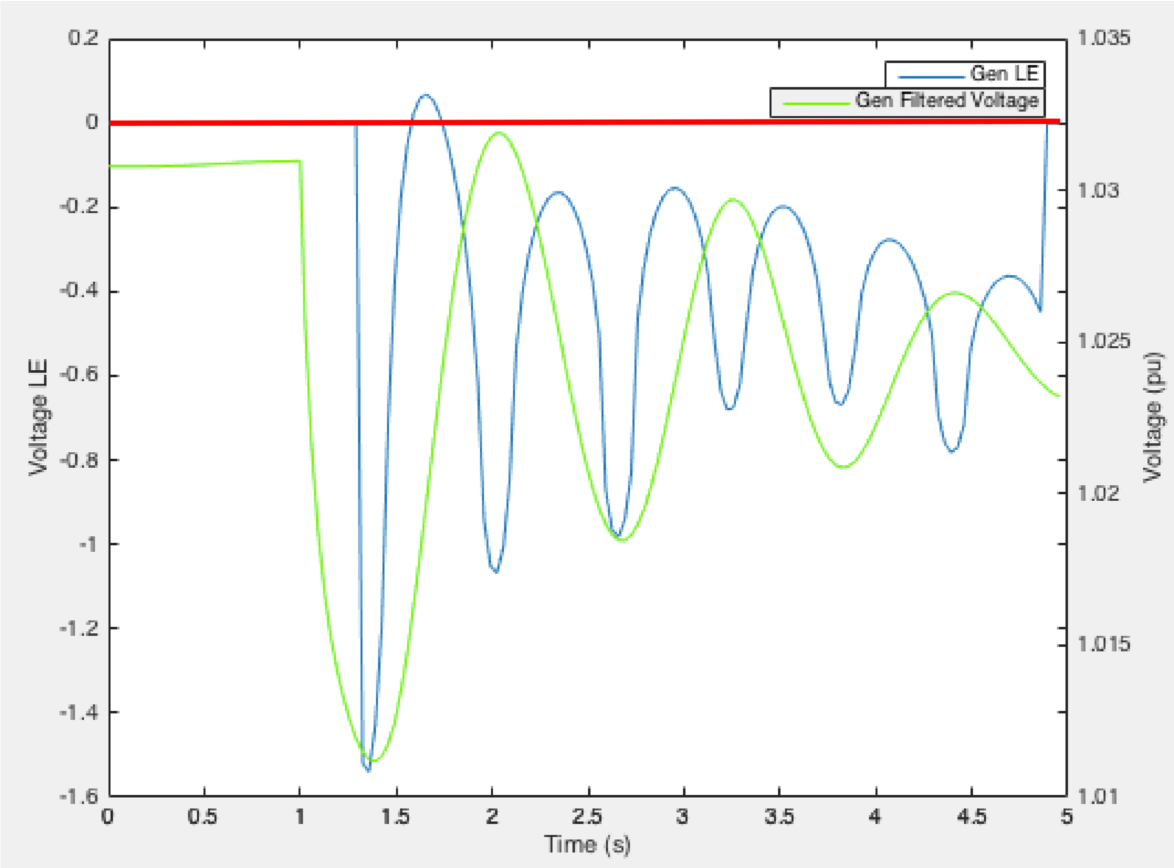


Equation for single bus contribution

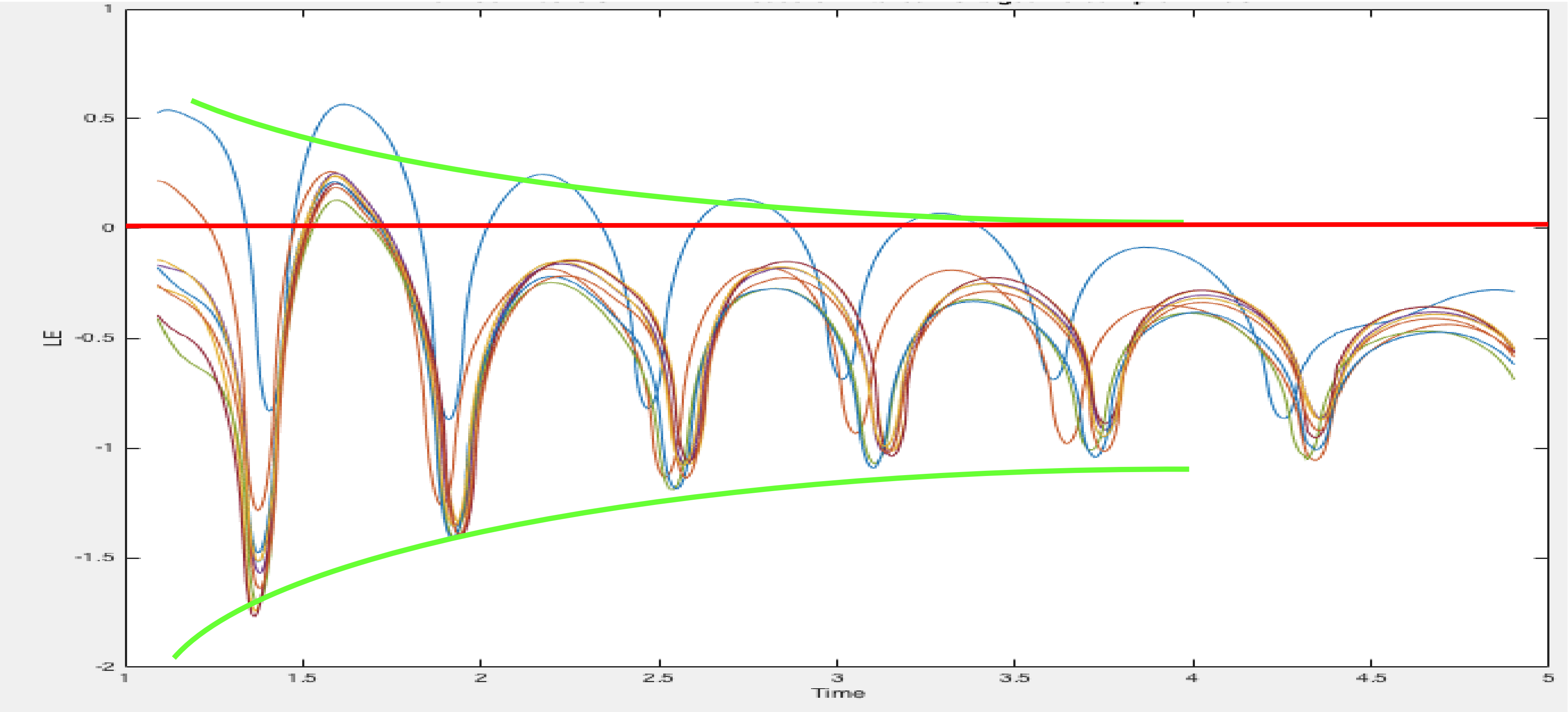
$$\frac{1}{Nk\Delta t} \times \sum_{m=1}^{N} \log_{10} \frac{\left|v^i_{(k+m)\Delta t} - v^i_{(k+m-1)\Delta t}\right|}{\left|v^i_{m\Delta t} - v^i_{(m-1)\Delta t}\right|}, k > N$$

[reference 2]

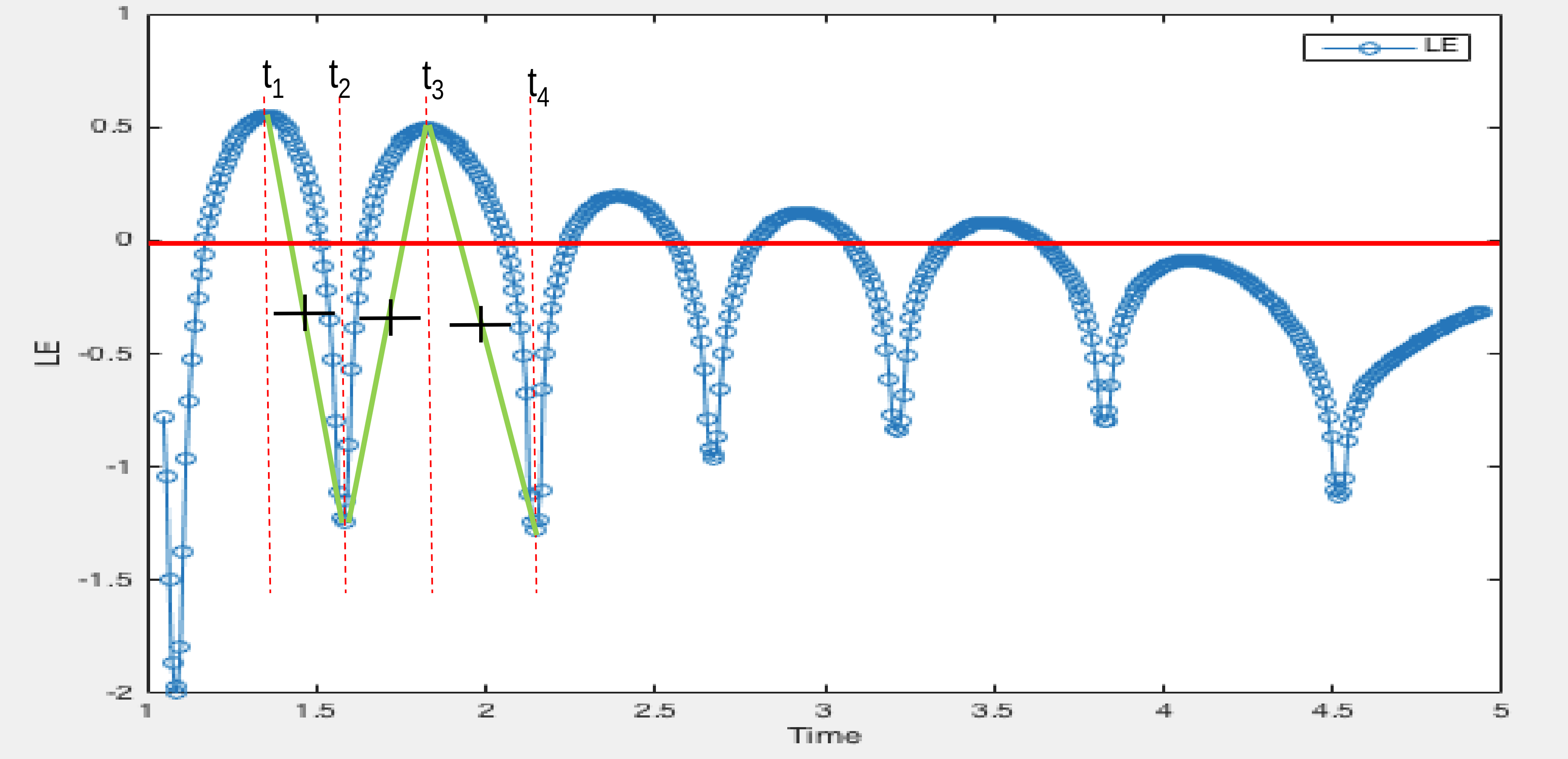
Lyapunov Exponent Time Series - Simulation



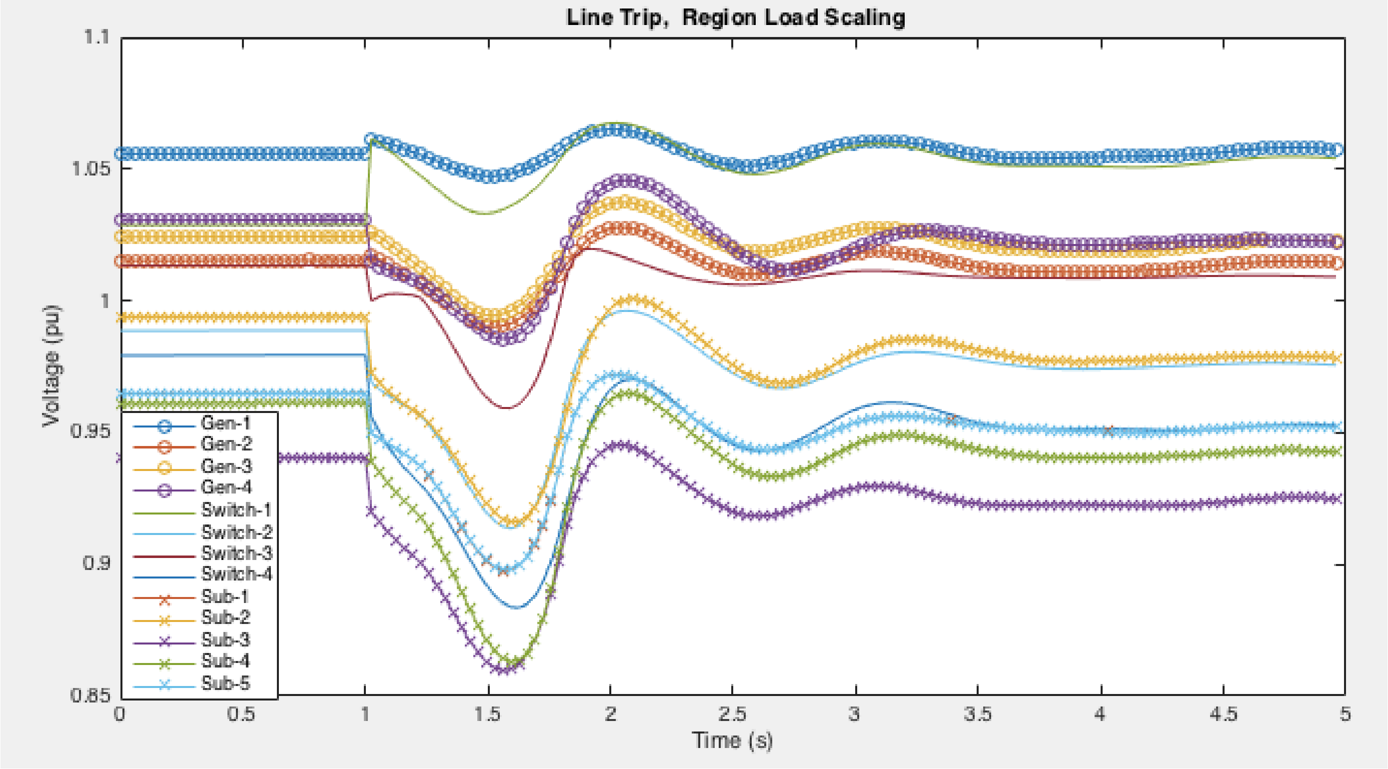
Stable System LE



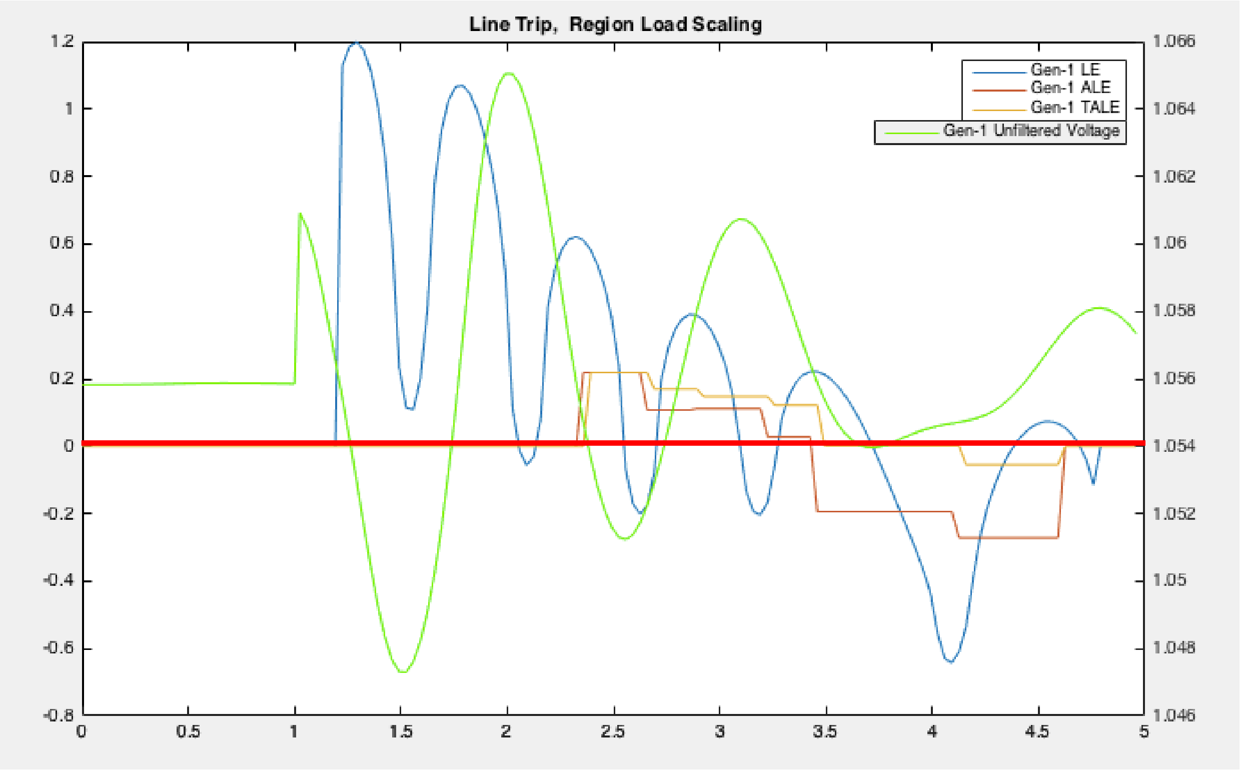
Average Value Method



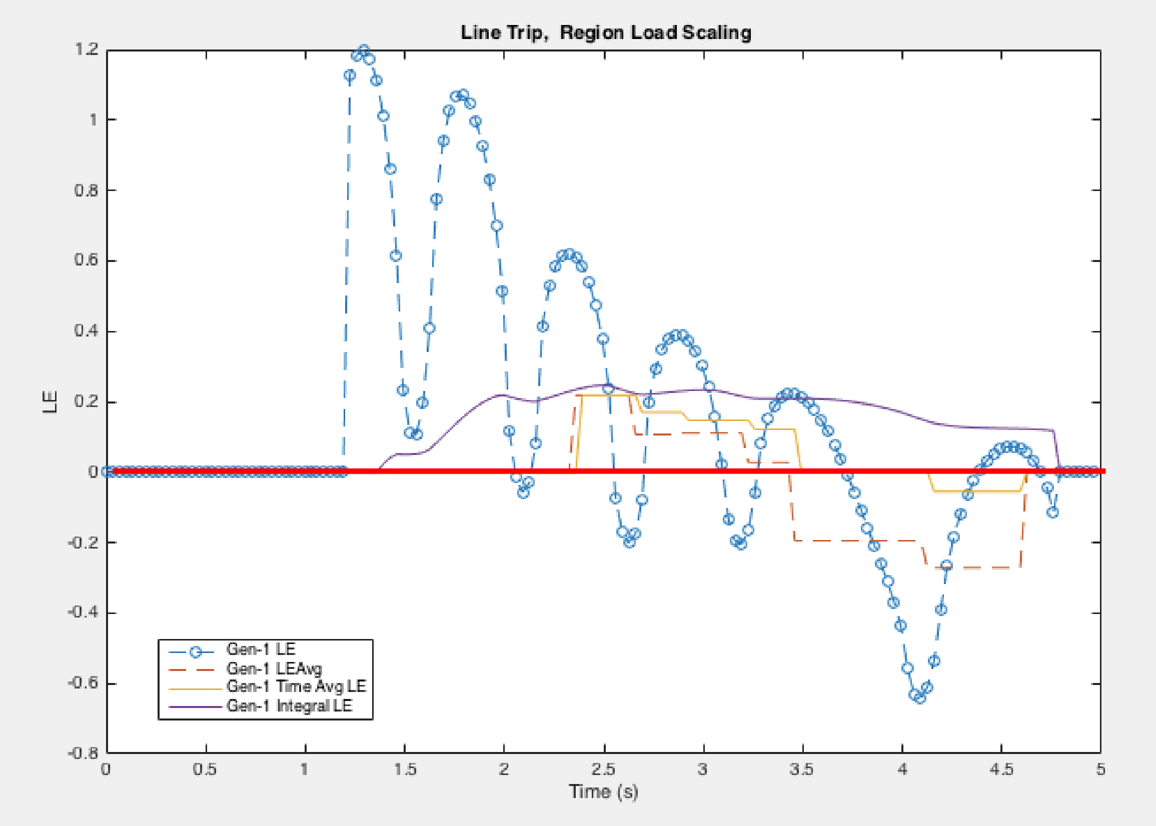
Normal System Response



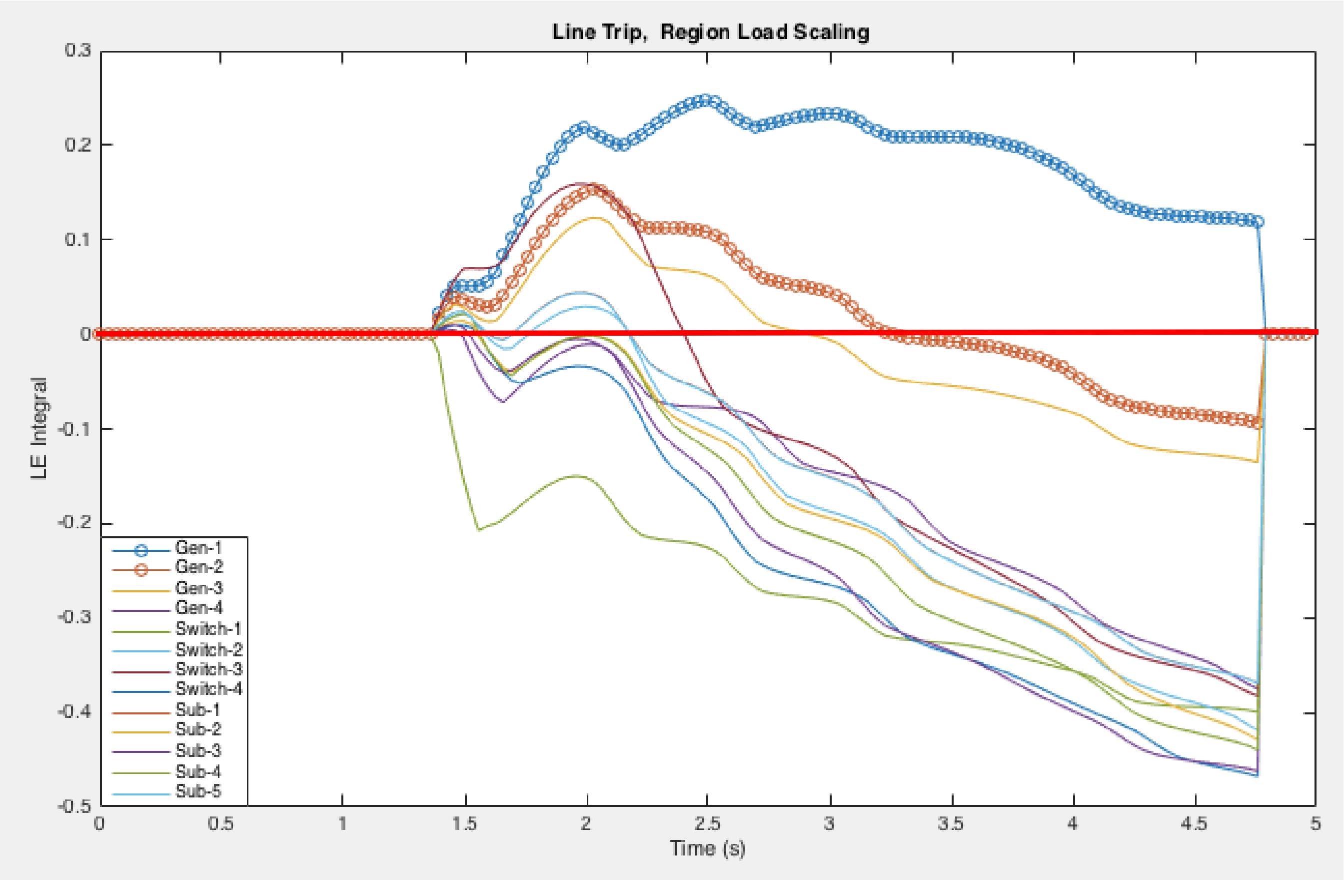
LE, Average Value LE, Time Average LE



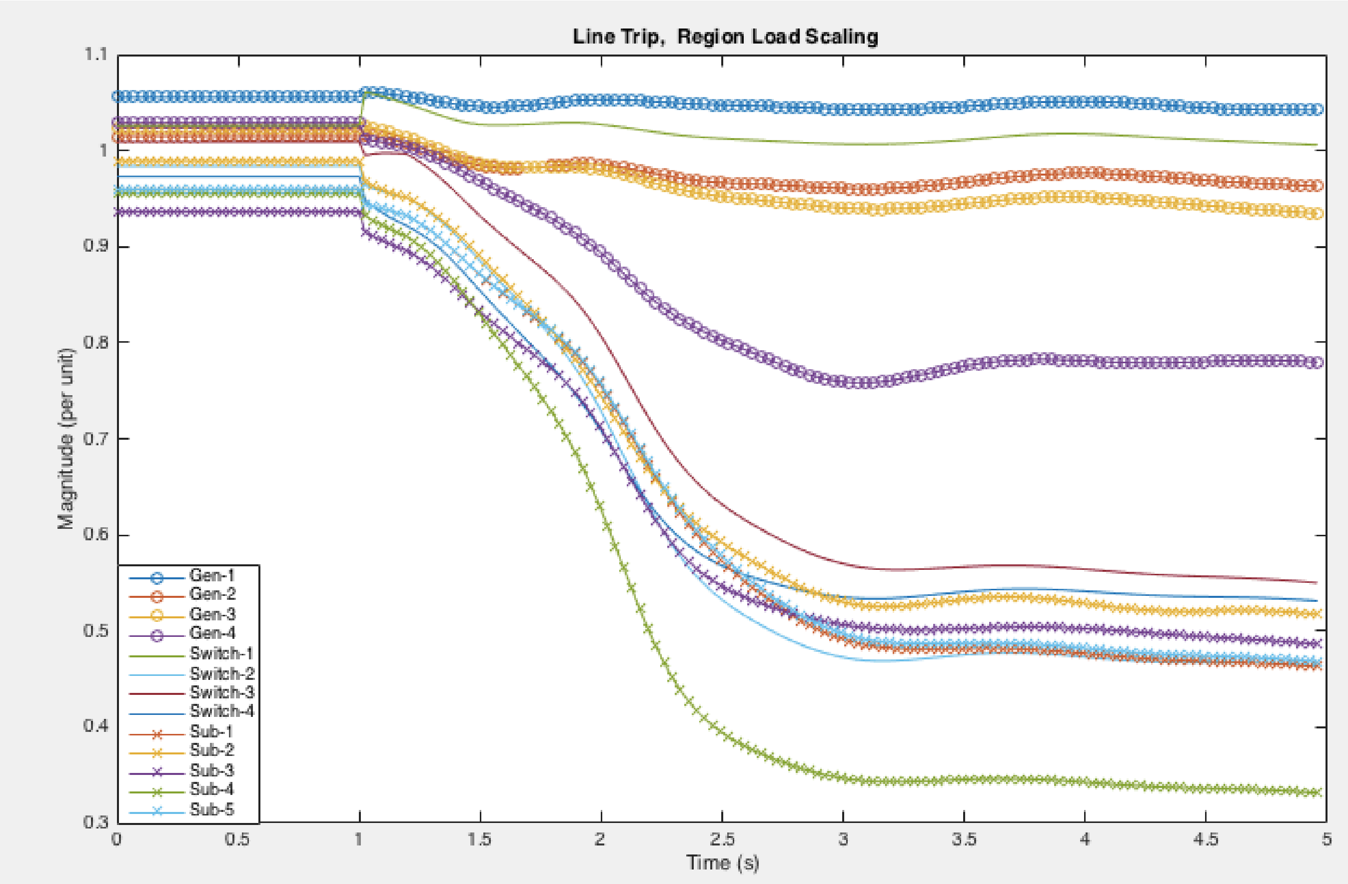
Comparison of Average Values, Time Average Value, and Integral Value



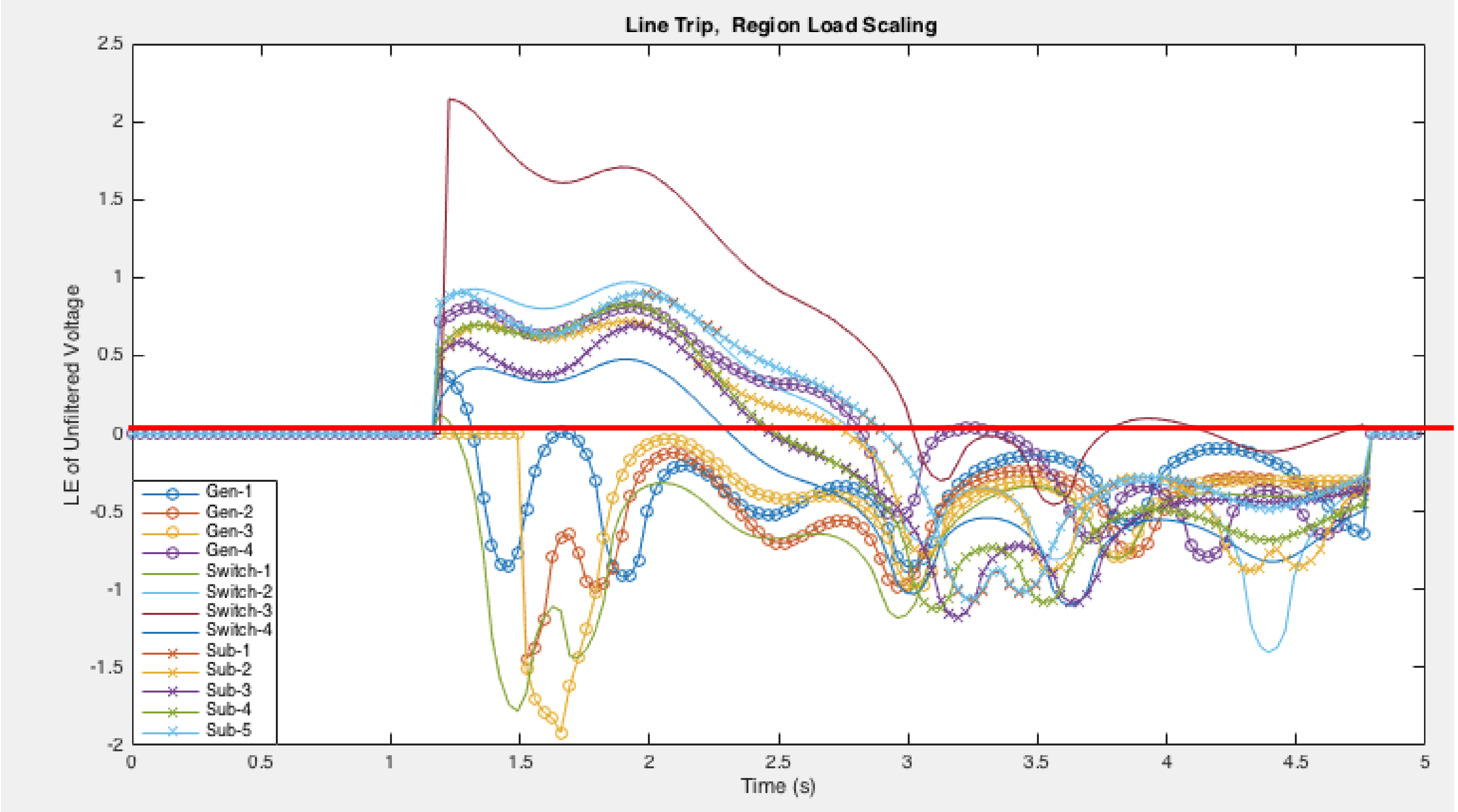
Integral of LE Values



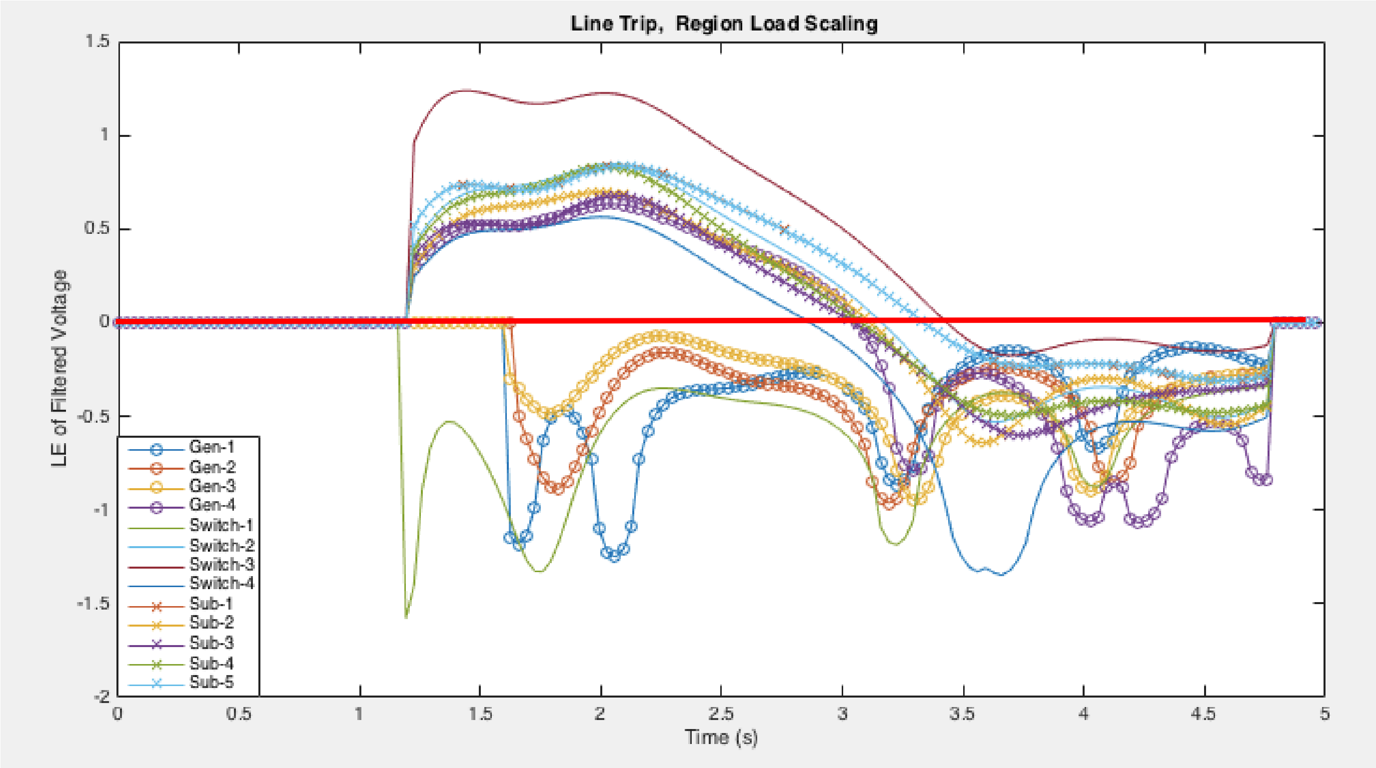
Intermediately Stable Response



Intermediately Stable System LE

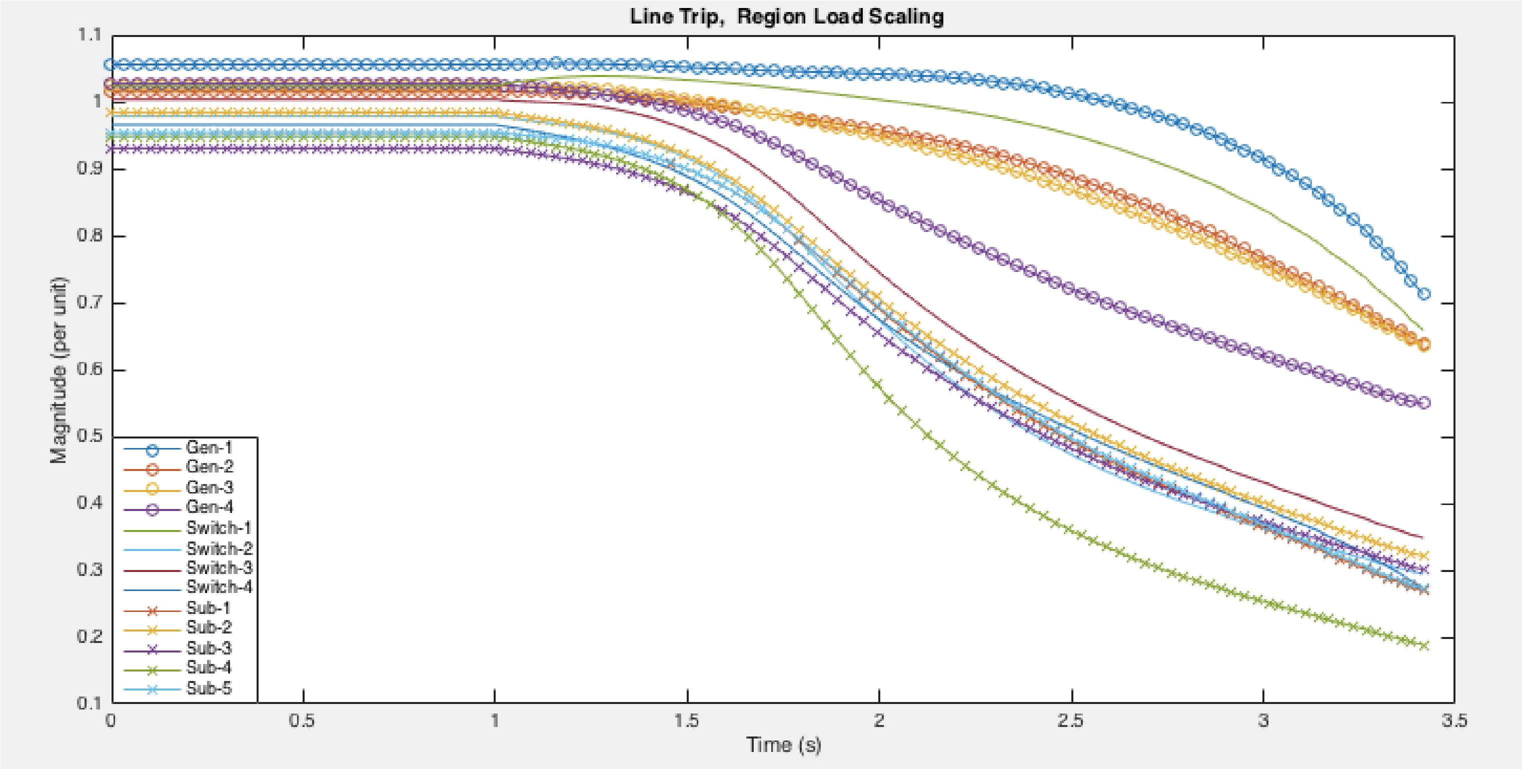


Intermediately Stable Case with Filtering



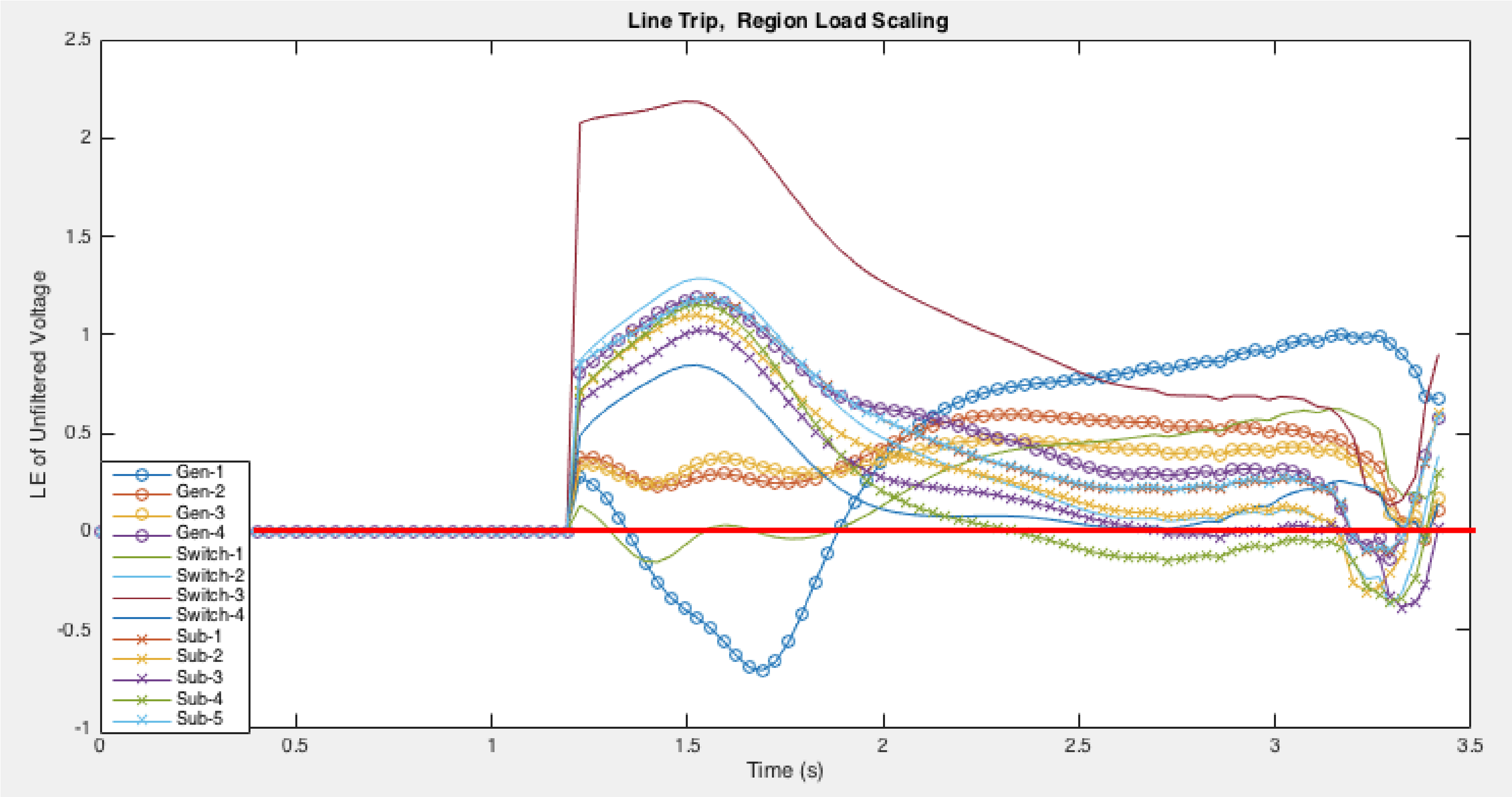
Filtering helps identifying voltage collapse at specific buses.
Higher tier buses remained stable, LEs show this as well.

Unstable System LE



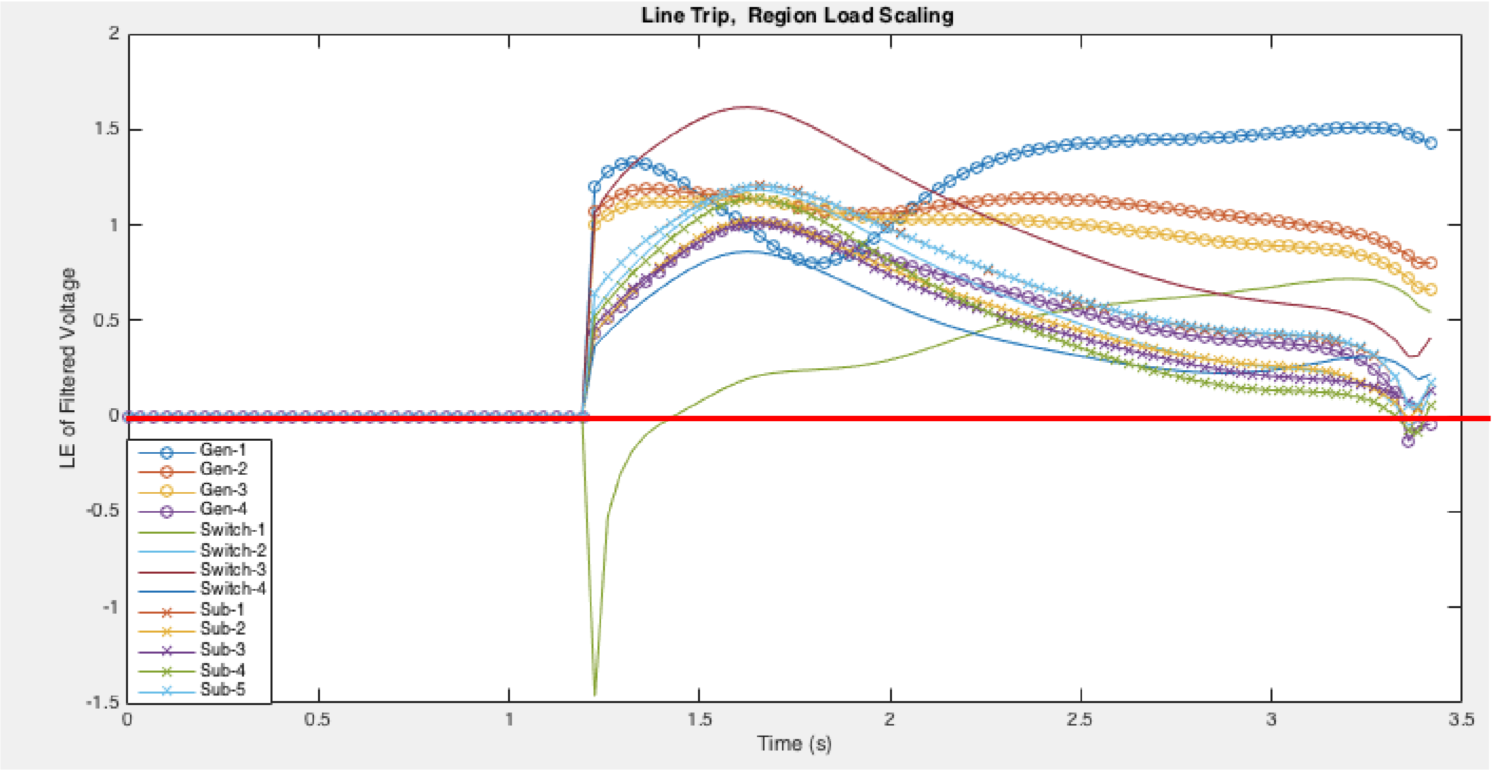
This case only ran for 2.5 seconds after the transient at 1 second.

120-BC0kwsc-GODBEY-NTH-8100



Positive LEs are shown for some buses, but this an ultimately unstable case.

Intermediately Stable Case with Filtering



Very positive LEs for all buses result from filtering voltages prior to LE calculation.

System Analysis Results

Load Change (MW)	Gen-1	Gen-2	Gen-3	Tripped Gen	Switch-1	Switch-2	Switch-3	Switch-4	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5
0	-0.862	-0.992	-0.842	-0.907	-0.971	-0.938	-0.969	-0.927	-1.143	-0.969	-0.971	-0.940	-1.142
0.2	-1.007	-1.071	-0.970	-0.855	-0.893	-0.940	-0.997	-1.004	-1.020	-1.058	-0.985	-1.093	-1.020
0.4	-0.869	-0.843	-0.823	-1.043	-0.832	-1.213	-1.331	-1.189	-1.042	-1.218	-0.970	-1.019	-1.044
0.6	-0.854	-0.911	-0.904	-0.898	-0.838	-0.973	-1.267	-0.944	-0.946	-0.969	-1.129	-1.005	-0.946
0.8	-0.402	-0.439	-0.446	-0.829	-0.503	-0.914	-1.158	-0.511	-0.857	-0.905	-0.980	-0.930	-0.857
1	1.424	1.007	0.946	0.907	0.874	1.003	1.396	0.992	0.933	0.971	0.919	-0.147	0.935
Slope	1.009	1.046	1.024	0.815	1.545	0.048	-1.265	0.721	2.817	0.735	-1.732	1.240	2.808
R^2	0.542	0.662	0.440	0.045	0.764	0.000	0.409	0.322	0.909	0.080	0.141	0.067	0.904

Load Change (MW)	Gen-1	Gen-2	Gen-3	Gen-4	Tripped Line	Switch-2	Switch-3	Switch-4	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5
0	-0.361	-0.617	-0.708	-0.756	-0.113	-0.812	-0.819	-0.824	-0.787	-0.861	-0.817	-0.781	-0.787
0.2	-0.492	-0.622	-0.734	-0.737	-0.139	-0.837	-0.788	-0.835	-0.829	-0.848	-0.818	-0.761	-0.837
0.4	-0.503	-0.681	-0.677	-0.717	-0.189	-0.761	-0.739	-0.803	-0.748	-0.794	-0.852	-0.738	-0.748
0.6	-0.495	-0.577	-0.678	-0.690	-0.157	-0.767	-0.746	-0.791	-0.757	-0.791	-0.828	-0.732	-0.759
0.8	-0.509	-0.563	-0.666	-0.707	-0.198	-0.745	-0.756	-0.773	-0.732	-0.793	-0.809	-0.716	-0.732
1	-0.520	-0.668	-0.635	-0.642	-0.162	-0.680	-0.690	-0.716	-0.663	-0.682	-0.706	-0.660	-0.662
Slope	-3.835	3.607	9.017	10.925	-7.588	6.878	7.539	11.735	6.237	8.258	1.090	12.349	5.538
R^2	0.570	0.274	0.636	0.795	0.713	0.700	0.638	0.851	0.568	0.797	0.003	0.968	0.518

- Positive LE’s result in the unstable case.
  - Exception is Sub-3 based on detection method, which is easily fixed.
- Blue boxes indicate the LE doesn’t become more positive as system load increases.
  - Substation buses don’t track well with generator events.
  - Generator buses don’t track well with line events.

Applications

- Additional information for State Awareness
- Tripping load buses during voltage collapse, will help match load to generation capability.

References

[1] Lyapunov exponent: Lecture 24 Indian Institute of Technology Kharagpur. YouTube video https://www.youtube.com/watch?v=-xSNqJQRoo4. Accessed: 2014-10-10.

[2] S. Dasgupta, M. Paramasivam, U. Vaidya, and V. Ajjarapu, “Real-Time Monitoring of Short-Term Voltage Stability using PMU Data," 2013.

DUKE ENERGY®