PowerWorld Simulator Integration with GICHarm in Simulator Version 24

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Overview

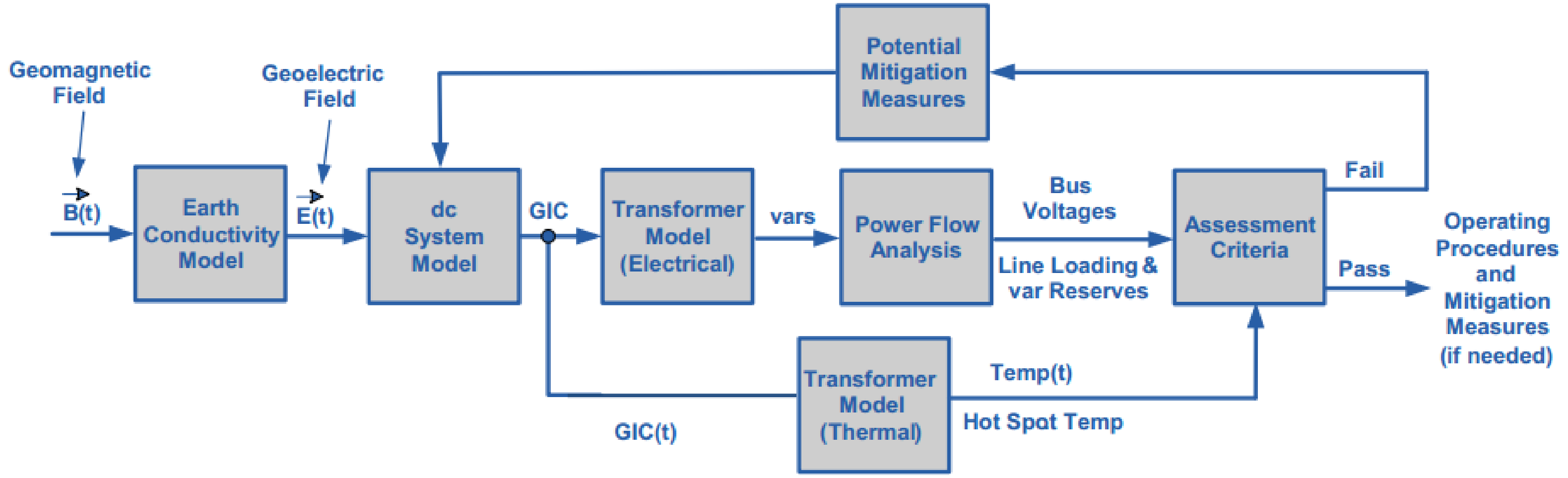
- The purpose of this presentation is to show how EPRI's GICHarm program is being integrated into PowerWorld Simulator to do harmonic analysis
  - This presentation is based on the July 9, 2025 patch, with more functionality coming soon; it requires PowerWorld Simulator with the Geomagnetically Induced Current (GIC) Add-on
- The motivation for this work is geomagnetically induced currents (GICs), whether due to geomagnetic disturbances (GMDs) or High Altitude Electromagnetic Pulses (HEMPs), can cause significant harmonics
- These harmonics can trip devices, such as capacitors
- These impacts need to be considered in doing GIC analysis

Acknowledgment

- These slides are based in part on work funded by the US Department of Energy (DoE); this support is gratefully acknowledged!
- These slides also contain contributions from my students, postdocs and staff at TAMU, from EPRI, Pacific Northwest National Laboratory (PNNL), and PowerWorld Corporation

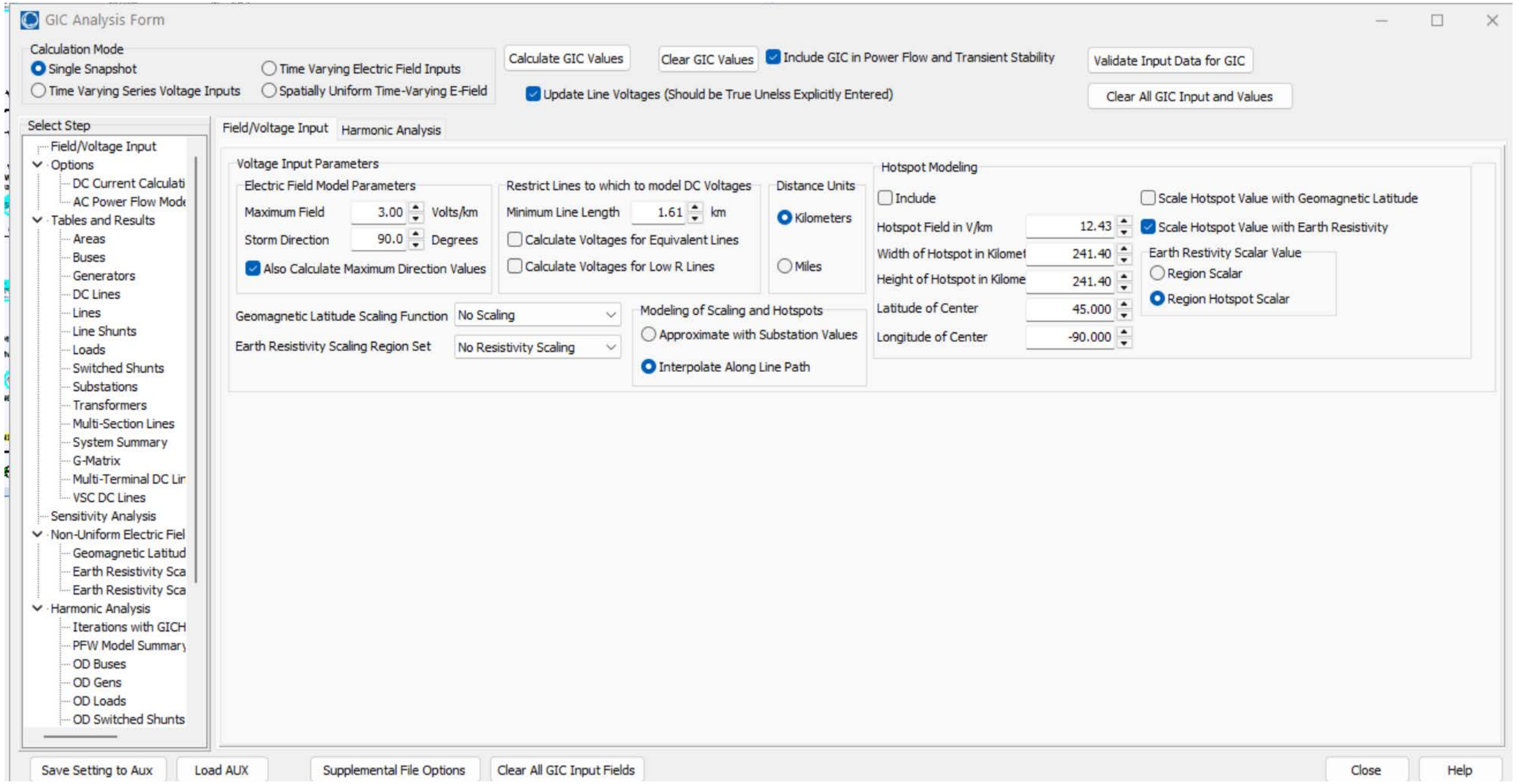
PowerWorld Simulator GIC Analysis

- Starting in 2010 PowerWorld Simulator has gradually gained the ability to model the impacts of GICs, first in the power flow, and later its time-domain stability analysis
  - Initially this as was limited to uniform magnitude and direction electric fields, but now a variety of time and spatially varying fields are supported
  - The NERC diagram shows the overall process
- This talk will add an additional feedback loop for harmonic analysis



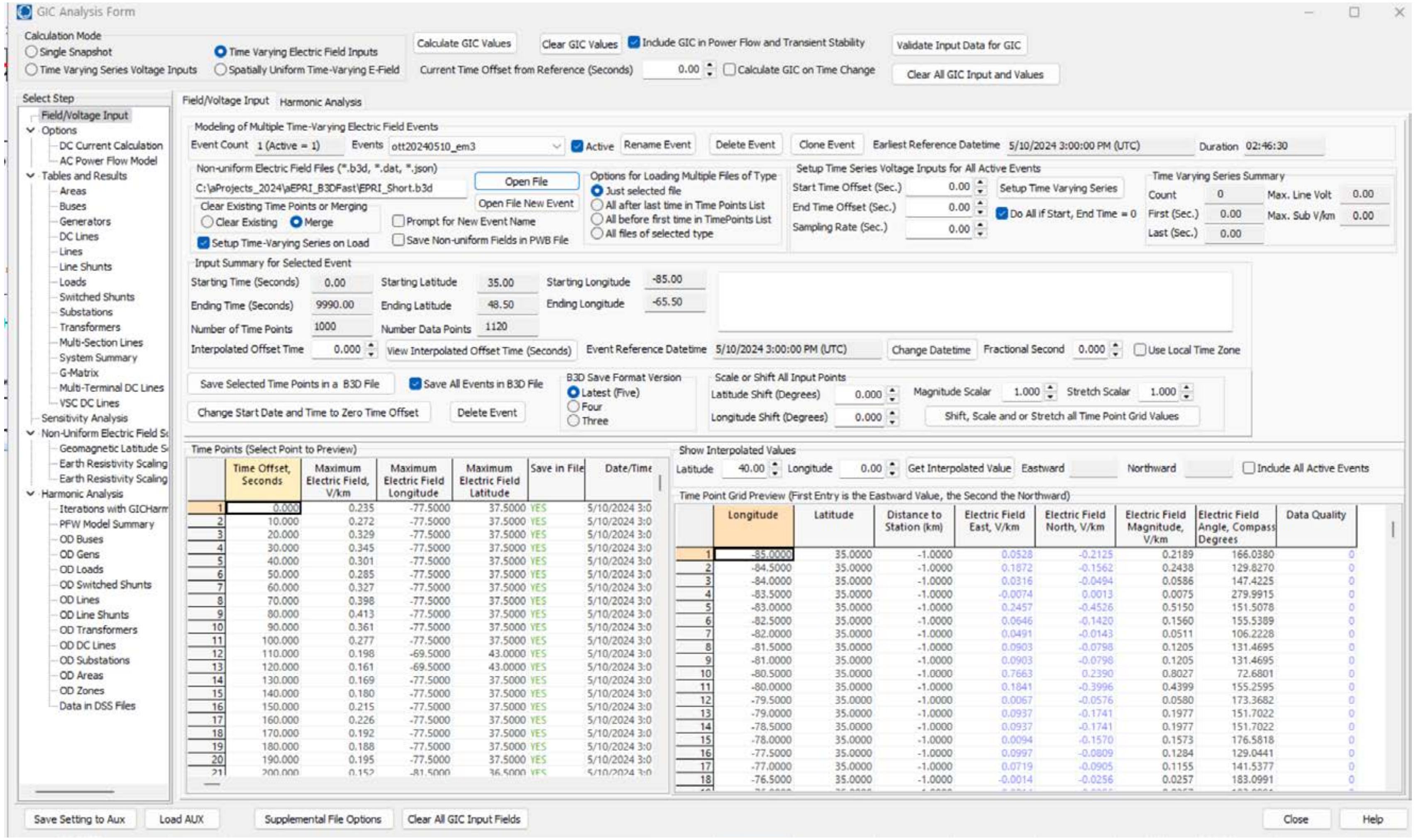
PowerWorld Simulator GIC Analysis, cont.

- Simulator allows for either Single Snapshot GIC Analysis or Time-Varying Analysis – the Image shows the Single Snapshot Page



PowerWorld Simulator GIC Analysis, cont.

- Image shows the Time-Varying Electric Field Inputs Analysis page

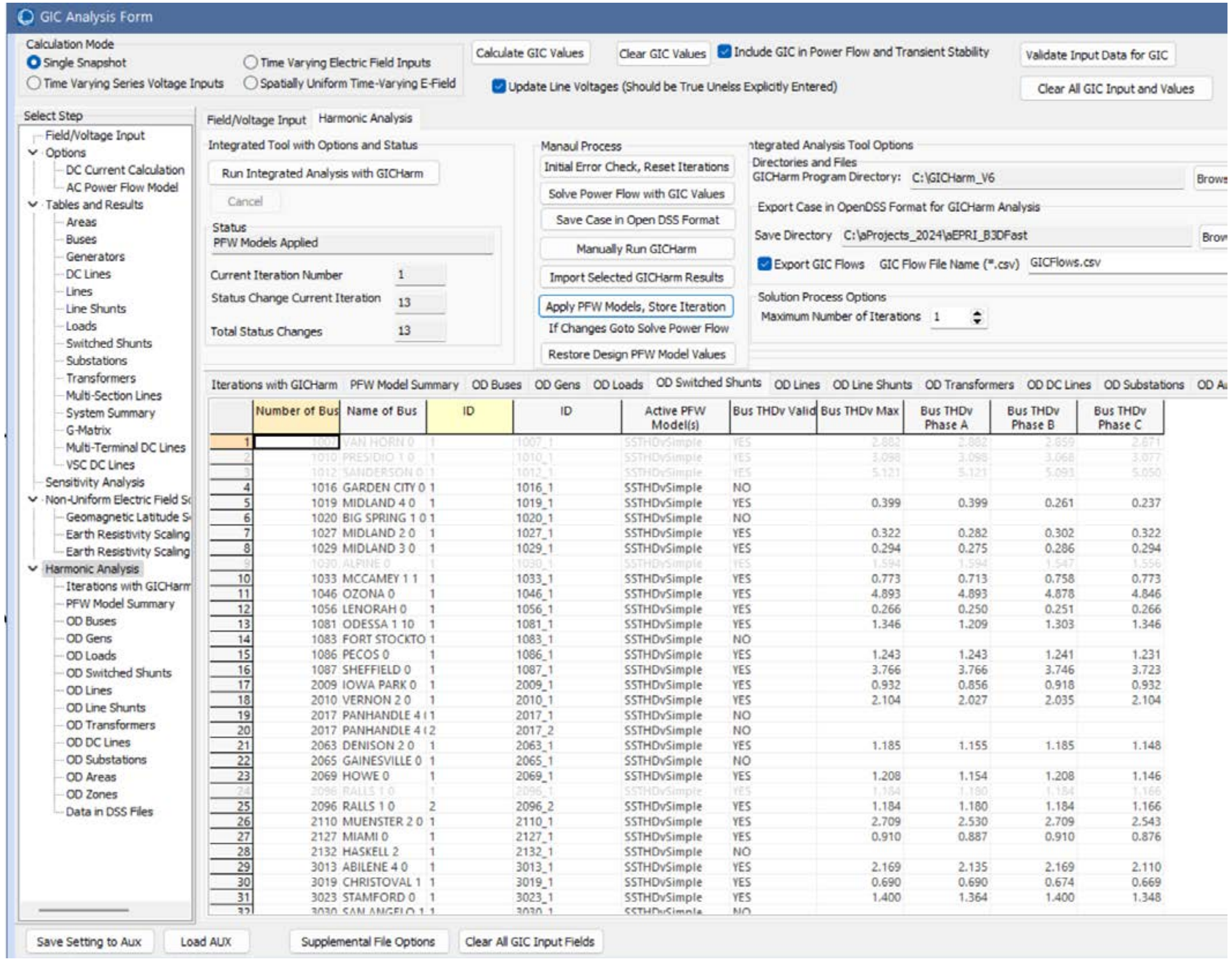


Adding Harmonic Analysis to GIC Calculations

- Standard power flow GIC analysis involves
  1. Using an assumed electric field, calculate the GICs
  2. Solve a GIC-enhanced power flow in which the transformer reactive power losses include a GIC dependent component
- With harmonic analysis this can optionally become
  1. Using an assumed electric field, calculate the GICs
  2. Solve a GIC-enhanced power flow, in which the transformer reactive power losses include a GIC dependent component
  3. Calculate the harmonics, with bus voltage total harmonic distortion (THDv) key
  4. Determine if any devices (e.g., capacitors) need to be outaged; if so, remove them and goto to 1; otherwise done

Integrated Harmonic Analysis in Simulator

- The Simulator GIC Analysis Form now has a page to make this process fully automatic
  - A manual process is also provided to help in the initial setup of a simulation
  - Scripting commands will be added in the new future
- This requires GICHarm be installed on the computer



Background: Electric Grid Harmonics

- Large-scale electric grids usually operate at 50 or 60 Hz for their fundamental frequency
  - Smaller systems (e.g., aircraft) operate at higher frequencies, which has advantages in for devices such as generators and motors
  - However, inductive reactance increases linearly with frequency, so higher frequencies are not practical for large-scale grids
- Integer multiples of the fundamental frequency are known as harmonics; harmonics have always been present in grids
- Harmonics can be created in different ways, including power electronics loads and by GICs causing transformer saturation (the focus here)

Two Useful References

- There are several good books on harmonics and the associated topic of power quality
- For people looking for a quick overview, a good reference is web.ecs.baylor.edu/faculty/grady/understanding_power_system_harmonics_grady_april_2012.pdf **(Grady2012)**
- A great (and free) document looking at the assessment of the harmonics caused by GMDs is EPRI's "Assessment Guide: Geomagnetic Disturbance Harmonic Impacts and Asset Withstand Capabilities" **(EPRI2019)**
  - Available at www.epri.com/research/products/000000003002017707

Periodic Signals, Fourier Series and Harmonics

- Almost any periodic signal with frequency f can be represented as a Fourier series consisting of the signal's dc value and sinusoidals with integer multiples of f
  - The fundamental frequency is f, 2f is the second harmonics, etc.
- A signal with half-wave symmetry will only have odd harmonics
- The image shows the Fourier components for desktop computer waveform

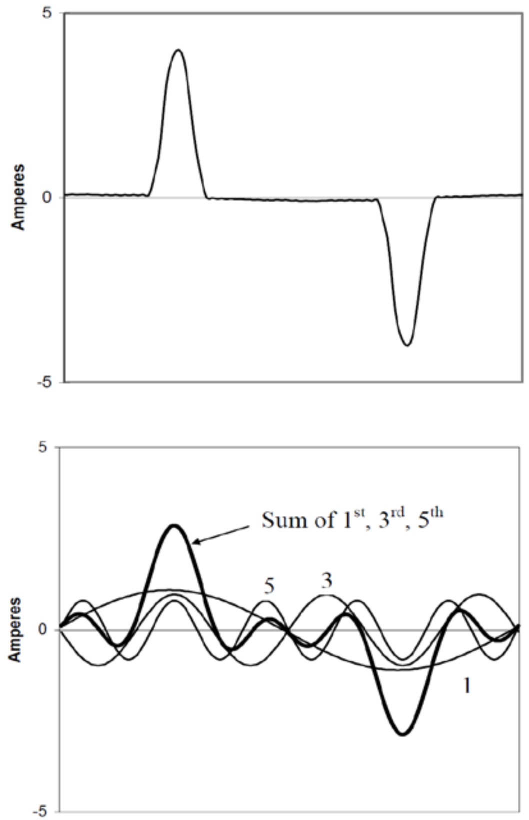


Figure 2.1. PC Current Waveform, and its 1st, 3rd, and 5th Harmonic Components (Note – in this waveform, the harmonics are peaking at the same time as the fundamental. Most waveforms do not have this property. In fact, in many cases (e.g. a square wave), the peak of the fundamental component is actually greater than the peak of the composite wave.)

Image from Grady2012

Background: Total Harmonic Distortion (THD)

- Total harmonic distortion (THD) is used to quantify the amount of harmonics in a signal; It is defined as the rms value of the harmonics above the fundamental, divided by the rms of the fundamental
  - It can be applied to currents and voltages
- If there are no harmonics then the THD is zero

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty}\left(\frac{I_k}{\sqrt{2}}\right)^2}}{\frac{I_1}{\sqrt{2}}} = \frac{\sqrt{\frac{1}{2}\sum_{k=2}^{\infty} I_k^2}}{\frac{I_1}{\sqrt{2}}} .$$

The same equation form applies to voltage THD_V .

Table from Grady2012

Background: Electric Grid Harmonics

- If a grid is balanced then each harmonic has a phase sequence:

Table 3.2. Phase Sequence of Harmonics in a Balanced Three-Phase System

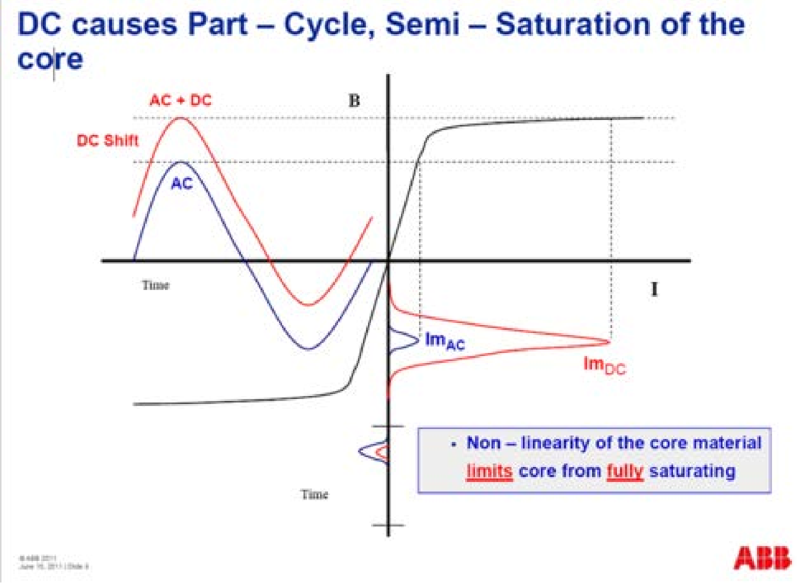
Harmonic	Phase Sequence
1	+
2	–
3	0
4	+
5	–
6	0
…	…

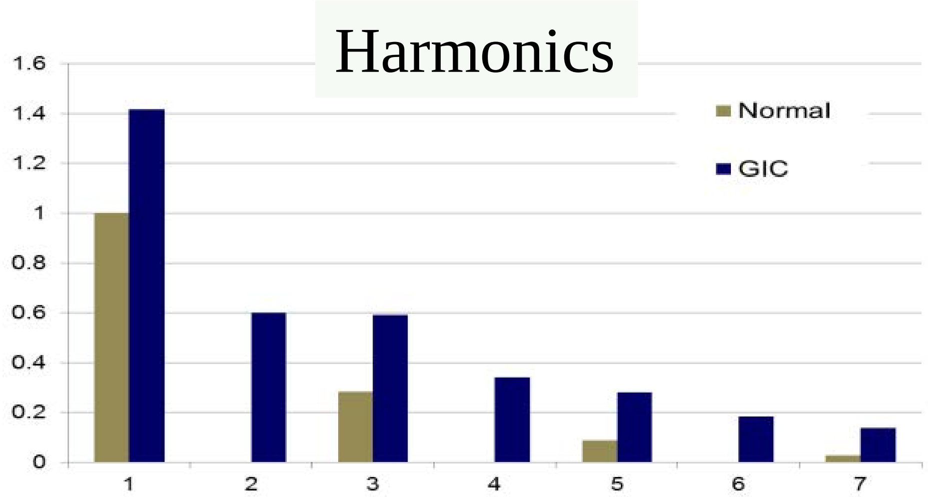
- Switching devices generate odd harmonics, whereas GICs can also cause even harmonics

Table from Grady2012

GIC-Induced Transformer Harmonics

- GMDs and HEMPs cause the quasi-dc GICs. The superimposed dc GICs can push transformers into saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence (e.g., power flow) these harmonics can be represented by increased reactive power losses in the transformer
- However, sometimes they to be explicitly considered, the focus here





Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations, June 2011

Impact of Harmonics

- In general harmonics can cause a variety of problems both on the utility side and the customer side. Grady2012 notes 1) resonance, 2) tripping of sensitive loads, 3) blown fuses/device failures, 4) transformer overheating, 5) motor heating, 6) overloaded neutrals, 7) telephone interference
- EPRI2019 notes impacts on transformers, shunt capacitors, surge arresters, transmission cables, overhead ac lines, HVDC, SVCs, voltage-source converters (VSCs), wind/solar generation, loads
  - "Although capacitors are reasonably robust to harmonics, the tendency for capacitors to amplify harmonic currents and voltages, combined with relatively short thermal time constants, make capacitors arguably the most vulnerable to GMD of the major power system components"

Resonance in LC Circuits

- An LC circuit has a resonance frequency which can amplify the voltages and currents

$$f_{res} = \frac{\omega_{res}}{2\pi} = \frac{1}{2\pi\sqrt{L_{sys}C_{cap}}} .$$

GIC-Induced Transformer Harmo...

The inductive reactance of the system at the fundamental frequency is

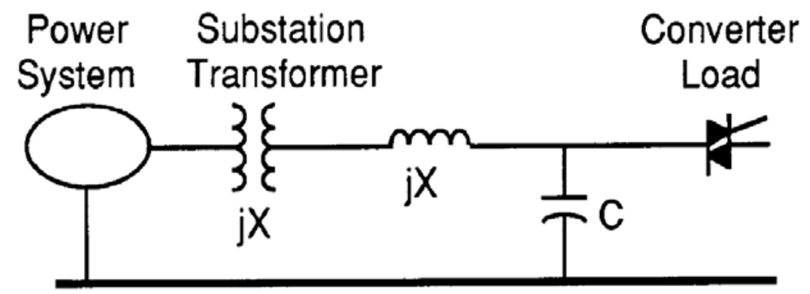
$$X_{sys} = \omega_1 L_{sys} \text{, so } L_{sys} = \frac{X_{sys}}{\omega_1} .$$

The reactance of the capacitor at the fundamental frequency is

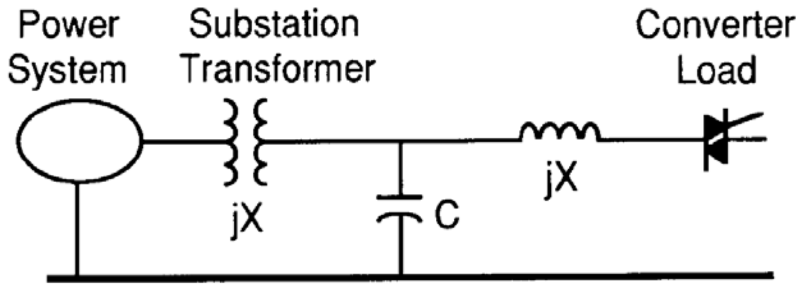
$$X_{cap} = \frac{1}{\omega_1 C_{cap}} \text{, so } C_{cap} = \frac{1}{\omega_1 X_{cap}} .$$

Substituting into the f_{res} equation yields

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{\omega_1}{X_{sys}}}\sqrt{\omega_1 X_{cap}} = \frac{\omega_1}{2\pi}\sqrt{\frac{X_{cap}}{X_{sys}}} = f_1\sqrt{\frac{X_{cap}}{X_{sys}}} .$$



Parallel Resonance (high voltage distortion at converter load, low voltage distortion at points sown the feeder)



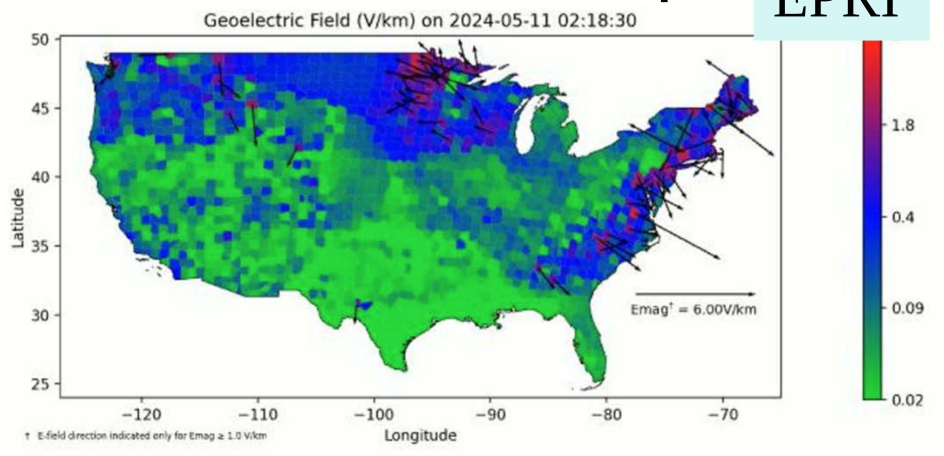
Series Resonance (low voltage distortion at converter load, high voltage distortion at points down the feeder)

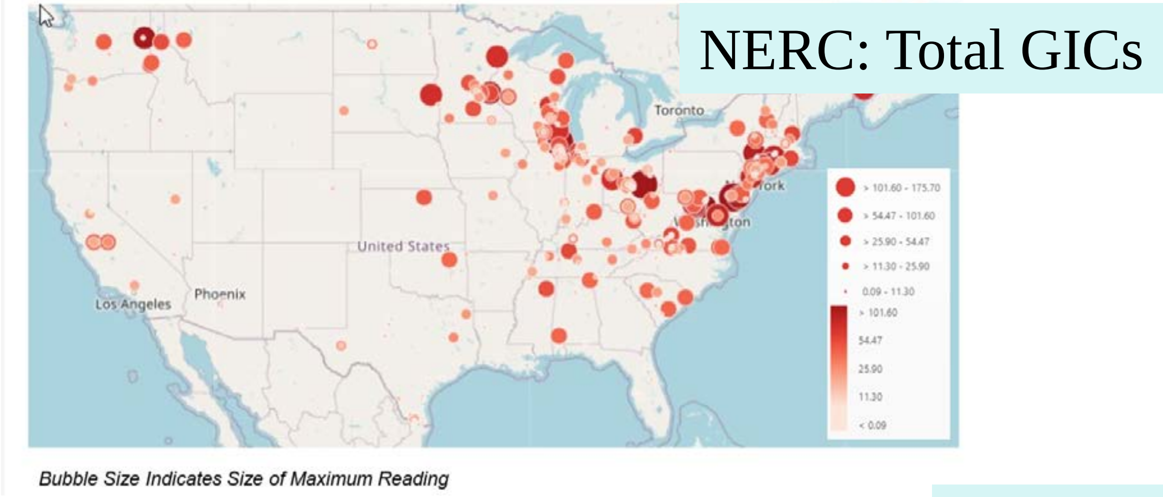
Figure 5.2. Simple Examples of Parallel and Series Resonance

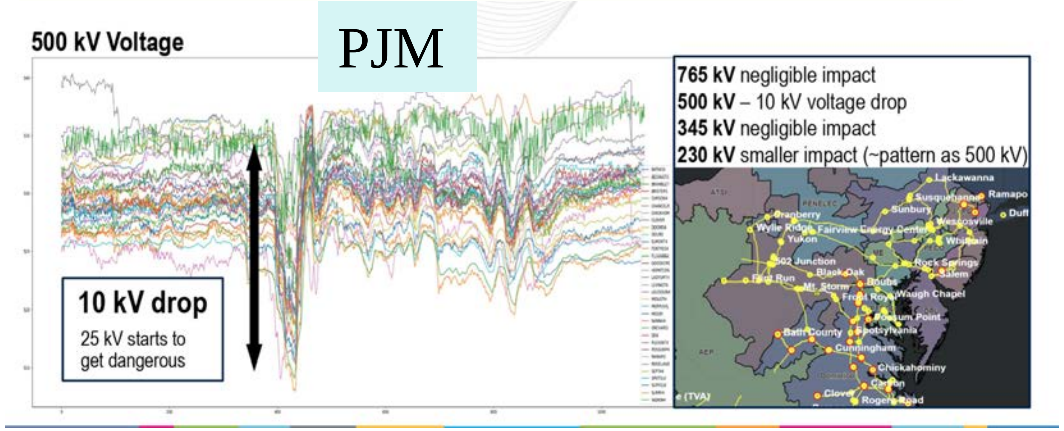
Images: Grady2012

Some Values from the May 2024 GMD

- Last year the May 2024 GMD (Gannon Storm) caused GICs of more than 100 amps



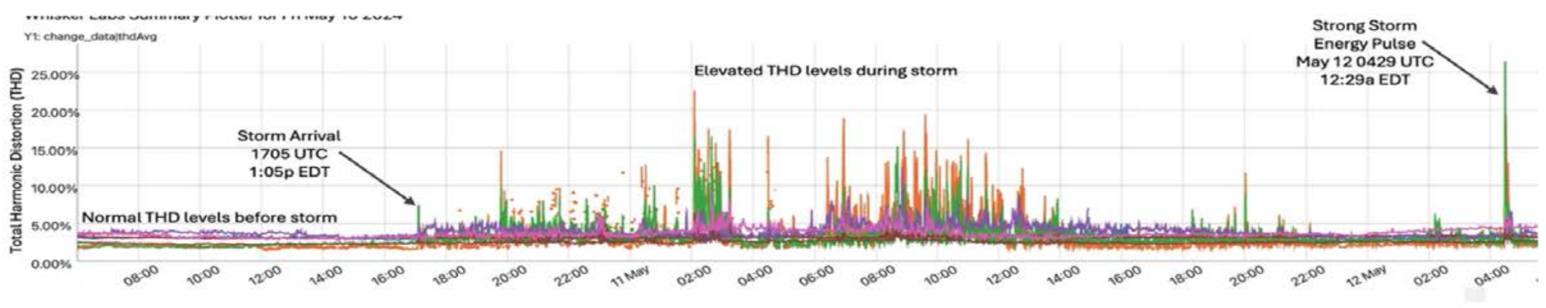


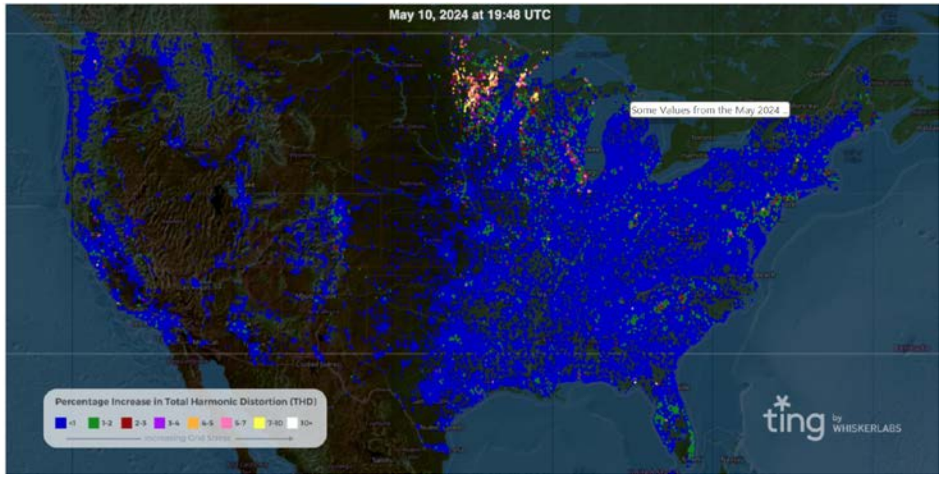


Images: www.nerc.com/pa/RAPA/GMD/Documents/October_2024_GMD_Workshop_Materials.pdf

Some Values from the May 2024 GMD, cont.

- Various measurements of THDs during the 05/2024 GMD both from utilities and from the Whisker Lab's Tin Sensor Network





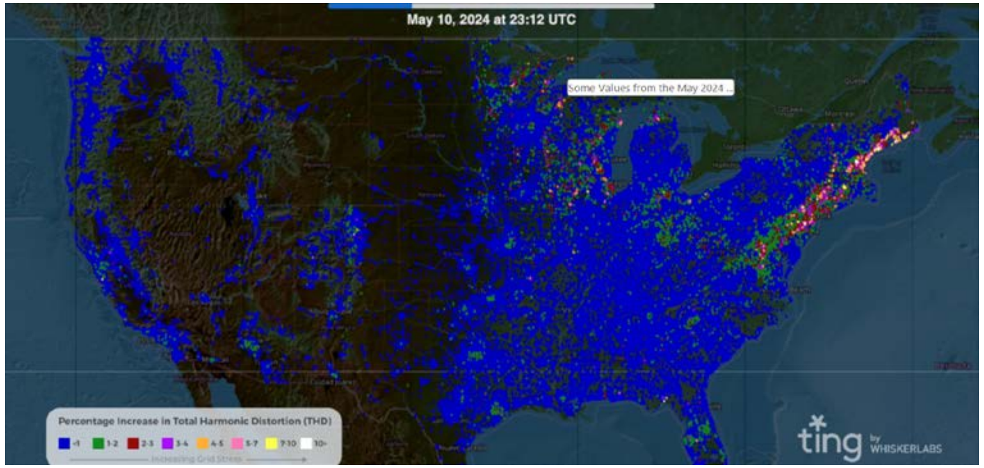
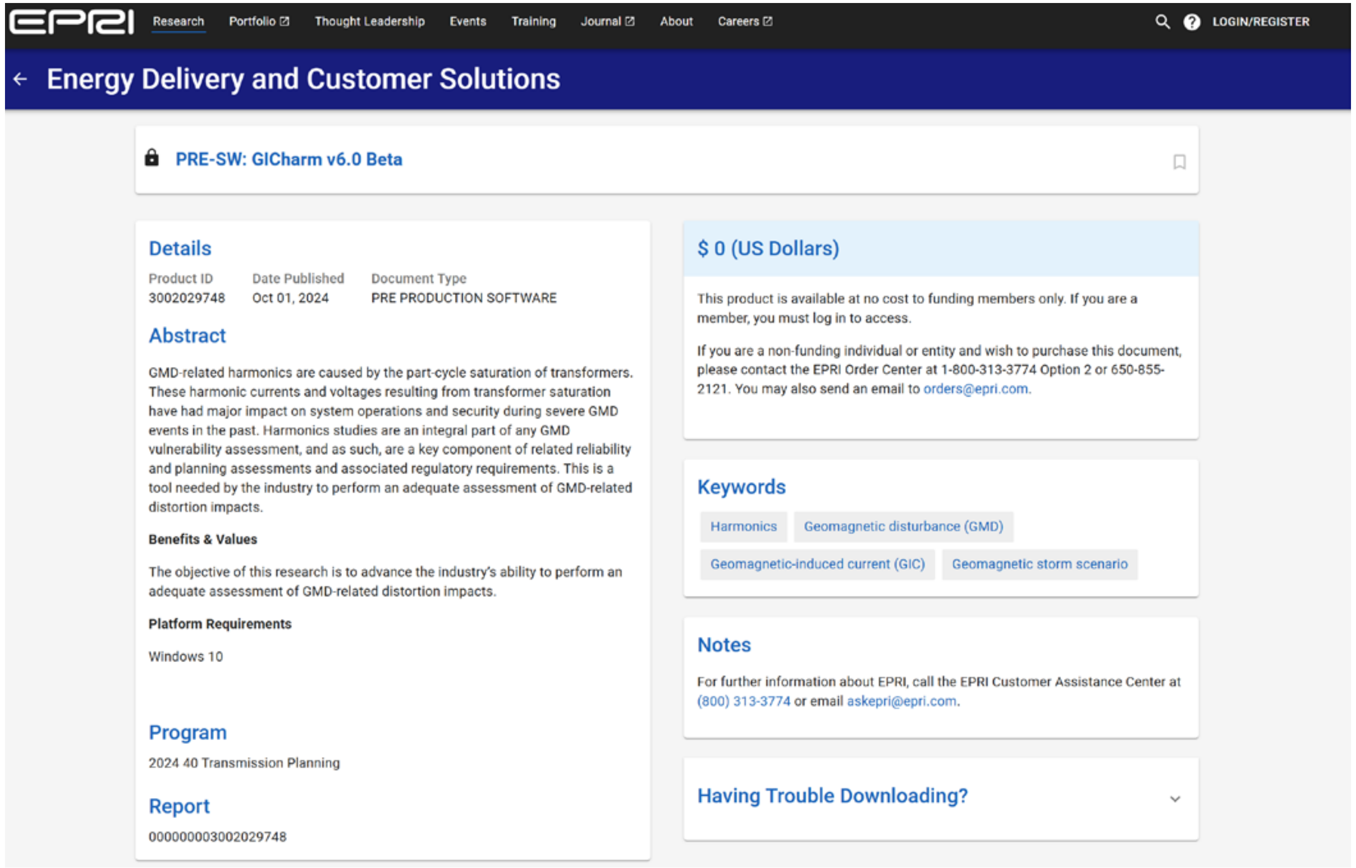


Image sources: www.whiskerlabs.com/analysis-of-total-harmonic-distortion-on-the-us-electric-grid/

GIC Harmonic Analysis in PowerWorld Simulator

- The first step is to install GICHarm (v6), which is available open source from EPRI at epri.com/research/products/000000003002029748
- GICHarm requires EPRI's OpenDSS (also open source); just use the version of OpenDSS that is included with the GICHarm download



GIC Harmonic Analysis

- Adding harmonic analysis requires performing the following steps
  1. Solve the power flow with the desired GMD (or HEMP) electric field; the power flow should include models representing the sensitivity of components (e.g., shunt capacitors) to harmonics (e.g., THDv), and should have the ability to store at least the bus THDv values
  2. Save the power flow model in OpenDSS format
  3. Use GICHarm to solve for the harmonics
  4. Load the harmonic information (e.g., bus THDv) into the power flow
  5. If harmonics are below trip values then done; others trip the associated devices and go to 1.
- The PowerWorld GICHarm integration automates this, but first we'll step through it manually

Analysis Using PowerWorld and GICHarm Separately

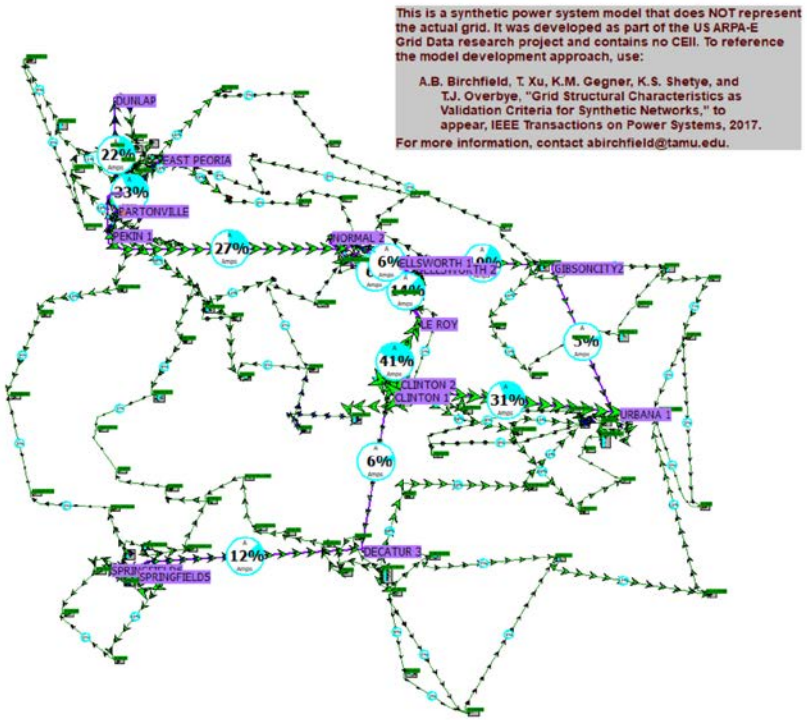
- Load a case in PowerWorld and save it in the *.raw format (version 33) and save a *.gic file (version 4)
- This example uses the 200 bus available at electricgrids.engr.tamu.edu/electric-grid-test-cases/

Synthetic Cases from ARPA-E GridData Program

Synthetic electric grid models are fictitious representations that are designed to be statistically and functionally similar to actual electric grids while containing no confidential critical energy infrastructure information (CEII). Some of these cases were developed with the support of the U.S. DOE ARPA-E Grid Data program; their support is gratefully acknowledged. Specific references for the creation and validation of these cases here.

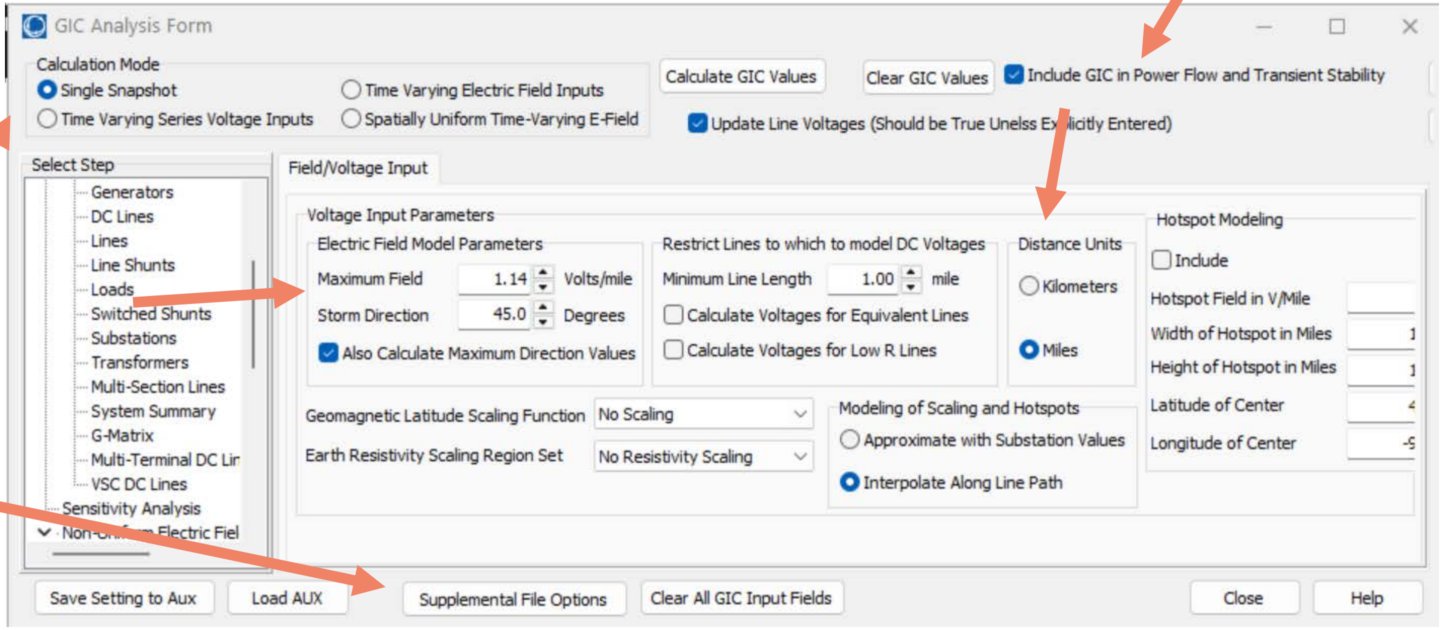
ACTIVSg200: 200 bus synthetic grid on footprint of Central Illinois – TS GMD OPF
ACTIVSg500: 500 bus synthetic grid on footprint of South Carolina – TS GMD OPF
ACTIVSg2000: 2000 bus synthetic grid on footprint of Texas – TS GMD OPF MOV PMU
ACTIVSg10k: 10,000 bus synthetic grid on footprint of western United States – TS GMD OPF MOV
ACTIVSg25k: 25,000 bus synthetic grid on footprint of northeastern United States – TS GMD OPF
ACTIVSg70k: 70,000 bus synthetic grid on footprint of eastern United States – GMD OPF

Synthetic PMU Data for the 2000-bus case



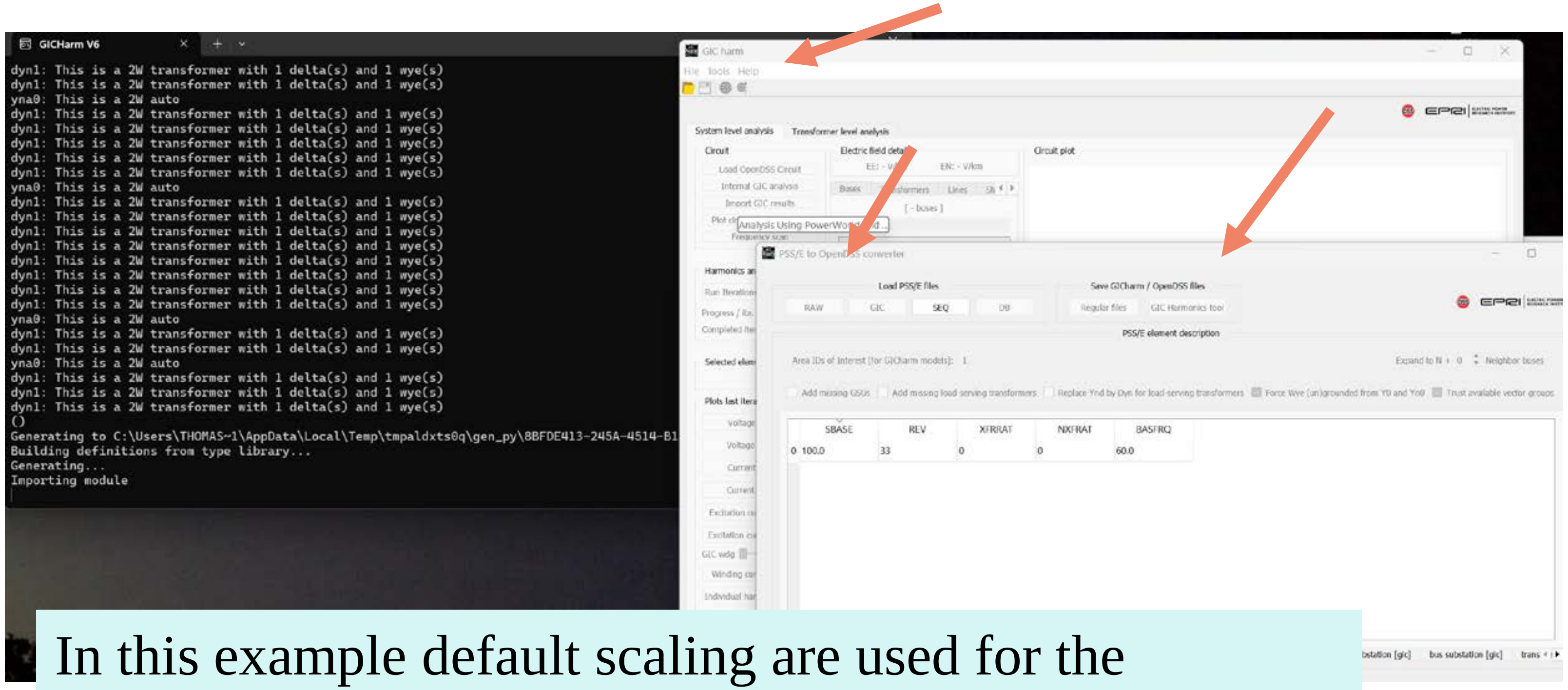
Separate Analysis: Solve for the GICs and Export

- After loading the case, select **Add Ons, GIC**; go to the Single Snapshot page, set the Maximum Electric Field to 1.14 Volts/mile and set the Storm Direction to 45 degrees; make sure **Include GIC in Power Flow and Transient Stability** is checked; solve the power flow, and then save the results as a 1) *.raw file (version 33), and 2) on the GIC Analysis Form select Supplemental File Options to save the *.gic (version 4)

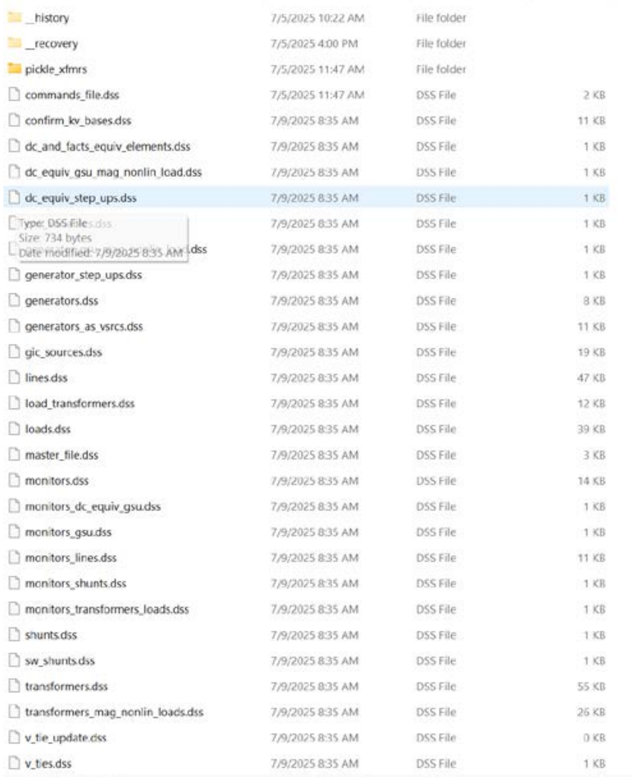


Separate Analysis: GICHarm, Creating *.dss Files

- Start GICHarm and select **Tools, PSS/E to OpenDSS Converter**
- Load the RAW and GIC files, then select **GIC Harmonics Tool** to produce the set of *.dss files; the file name should be master_file

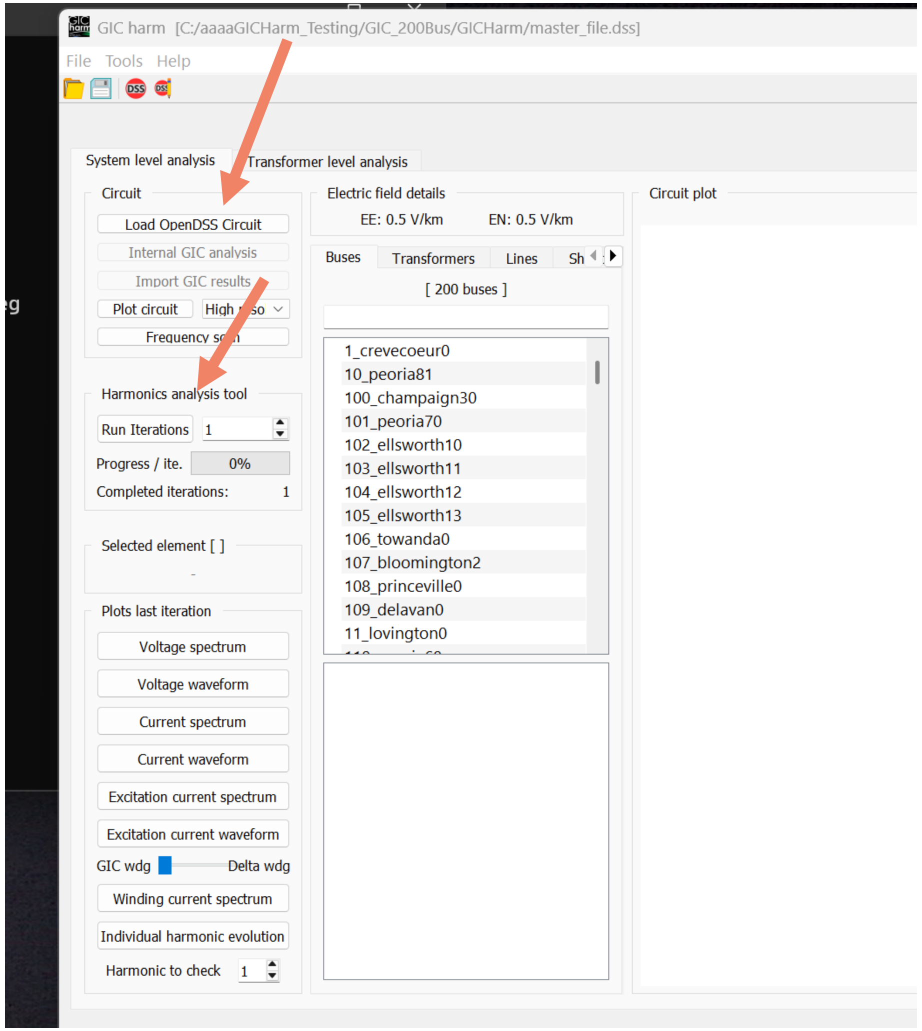


In this example default scaling are used for the sequence values, but they could be loaded as well



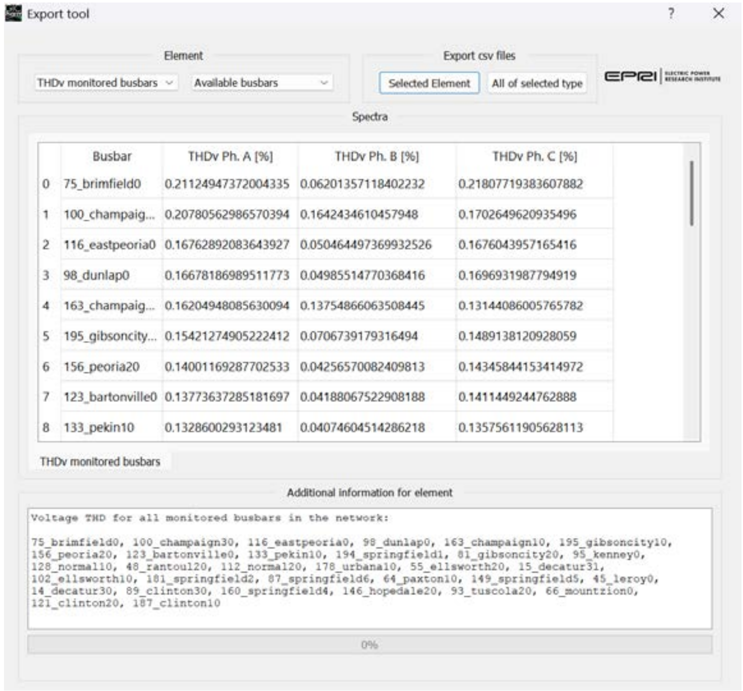
Separate Analysis: Solving Harmonics

- Then, still in GICHarm, select **File, Open** and then select the saved master_file.dss, which loads all the other files
- Select **Load OpenDSS Circuit**
- Select **Internal GIC Analysis**
- Set the number of desired internal GICHarm iterations (I use 1 for testing)
- Select **Run Iterations**
  - It takes about 14 seconds on my computer)



Separate Analysis: Exporting Results

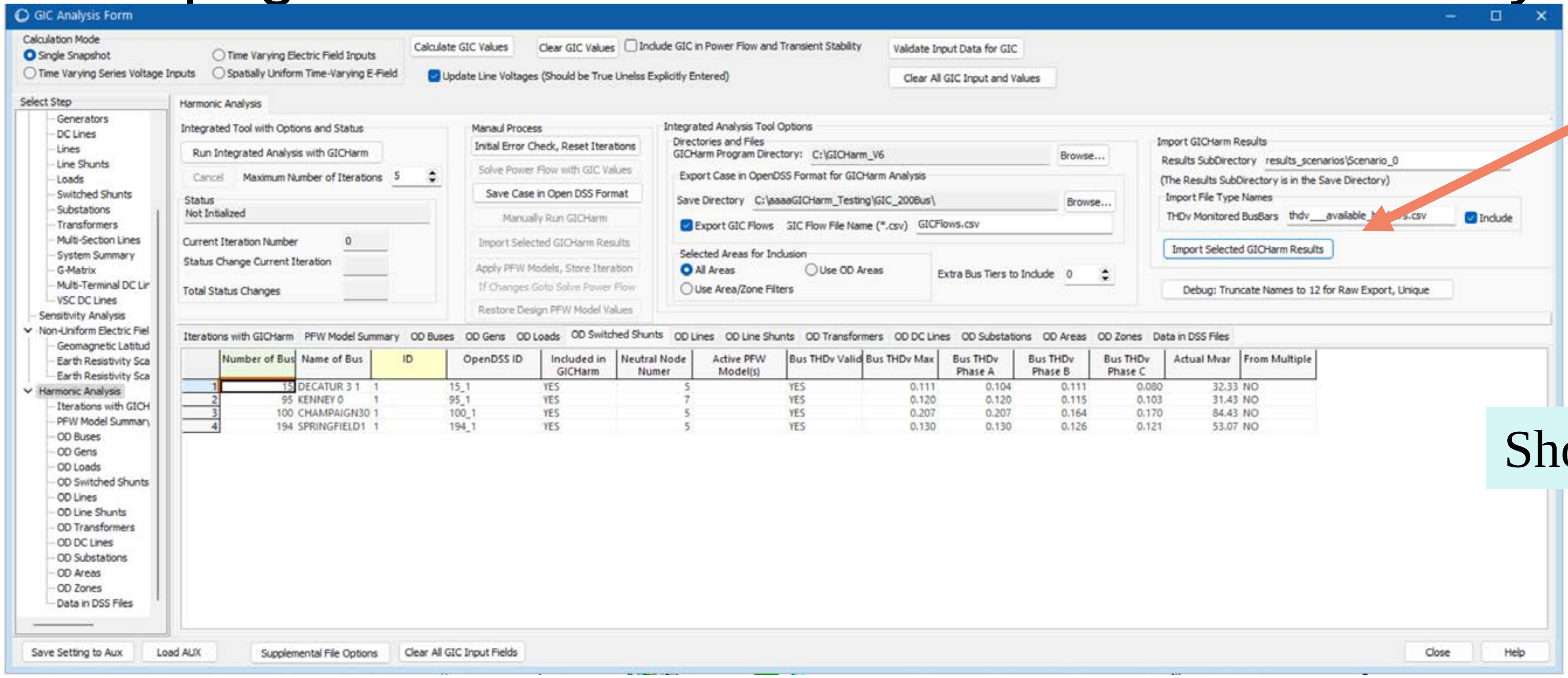
- To save the results select **Tools, Export Tool**, then select **THDv monitored busbars** and **Available busbars**
- Then select **Selected Element**, and give a directory to save the thdv__available_busbars file



Busbar	THDv Ph. A [%]	THDv Ph. B [%]	THDv Ph. C [%]
75_brimfie	0.211212665	0.061880077	0.218080481
100_cham	0.206758998	0.163955406	0.170482574
116_eastp	0.167578378	0.050340694	0.167606785
98_dunlap	0.166740831	0.049735227	0.169696653
163_cham	0.161113147	0.137227734	0.131586599
195_gibso	0.153975578	0.070389746	0.14888217
156_peori	0.139973429	0.042469503	0.143461074
123_barto	0.137699481	0.041786024	0.141147672
133_pekin	0.132819682	0.040655236	0.135758985
194_spring	0.130408106	0.126347771	0.120955602
81_gibson	0.124657908	0.068255718	0.112953835
95_kenney	0.119785532	0.115429106	0.103216083
128_norm	0.116393096	0.04928657	0.111812819
48_rantoul	0.113123774	0.070709947	0.106334474
112_norm	0.112406857	0.048311083	0.108454395
55_ellswor	0.10976094	0.051230811	0.104079029
178_urban	0.109553468	0.088365237	0.090825766
15_decatu	0.103933411	0.110794091	0.080015328
102_ellsw	0.103310512	0.048422955	0.098865679
181_spring	0.100428668	0.1010782	0.09489046
87_springf	0.099821454	0.098269067	0.090725505
64_paxton	0.099079687	0.065691636	0.08758406
149_spring	0.093183936	0.092235954	0.08492414
45_leroy0	0.092807985	0.049590348	0.08690565
14_decatu	0.089910161	0.094649492	0.067664489
89_clinton	0.086542646	0.095050901	0.067364586
160_spring	0.084575286	0.086421077	0.080432754
146_hoped	0.076268732	0.054673511	0.069610438
93_tuscola	0.074788434	0.089991648	0.058326302
66_mount	0.064910908	0.074332077	0.050413983
121_clinto	0.059743056	0.056114017	0.049716216
187_clinto	0.053588428	0.048353469	0.045039209

Separate Analysis: Loading Results into Simulator

- Simulator now has fields to store and use the bus THDv values
- These can be loaded using the new **Harmonic Analysis** page on the GIC Analysis Form
- This page is used for automatic and manual analysis

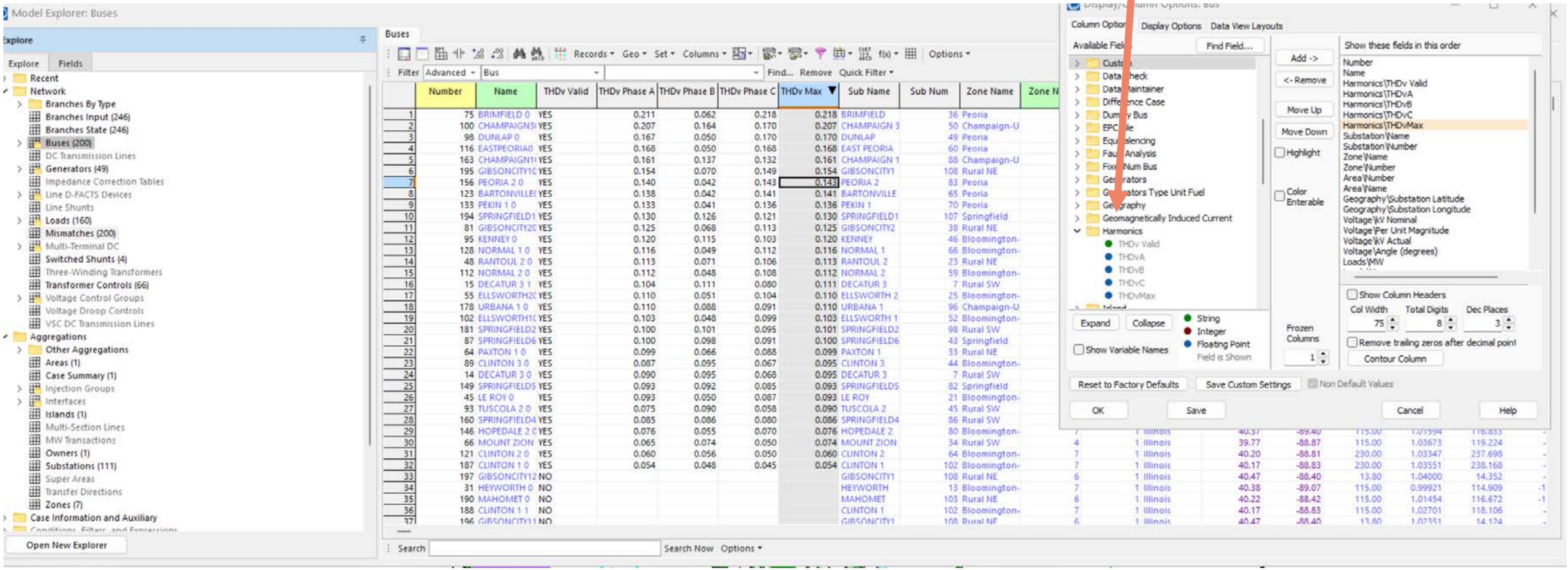


Here the values are manually loaded from the *.csv file

Showing results

Separate Analysis: Loading Results into Simulator

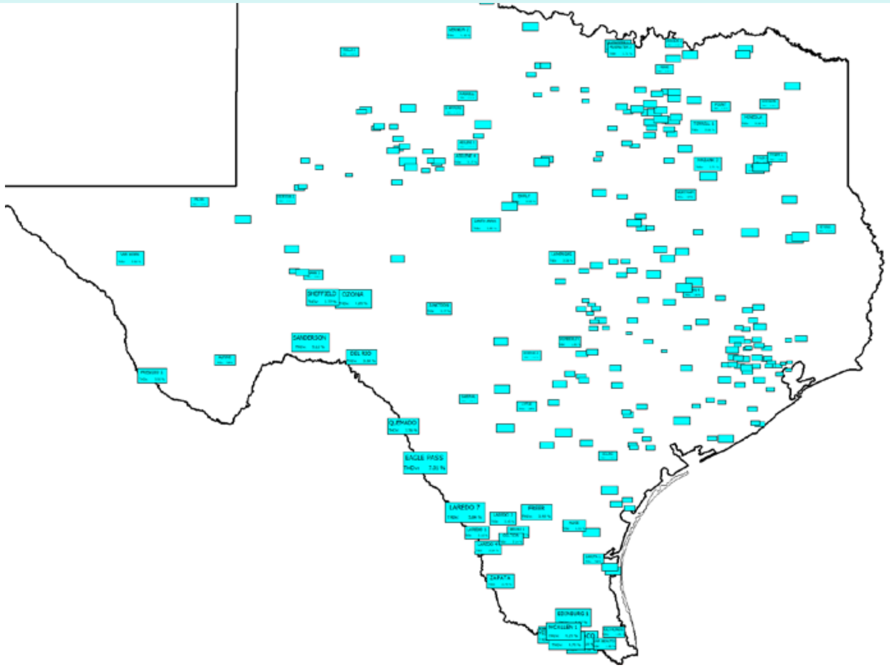
- The THDv fields are regular Simulator fields, though they are read only
  - GICHarm doesn't calculate the values at all buses



Full Simulator Support of Harmonic Information

- Since harmonics is fully integrated into Simulator, all of Simulator's capabilities are available for the display of the associated information; e.g., case information displays, dialogs, onelines including full geographic data view (GDV) support

2000 Bus Case, Substation GDV of THDv



Simulator Case Info Display Showing GICHarm Bus THDv

Switched Shunts

Filter Advanced

	Number of Bus	Name of Bus	ID	Reg Bus Num	Bus THDv Max	Status	Status Branch	Control Mode	Auto Control	Regulates	Actual Mvar	Volt High
1	1007	VAN HORN 0	1	1007	2.882	Open		Fixed	YES	Volt	0.00	1.000
2	1010	PRESIDIO 1 0	1	1010	3.098	Open		Fixed	YES	Volt	0.00	0.000
3	1012	SANDERSON (	1	1012	5.121	Closed		Fixed	YES	Volt	9.90	0.000
4	1016	GARDEN CITY (	1	1016		Closed		Fixed	YES	Volt	31.09	0.000
5	1019	MIDLAND 4 0	1	1019	0.399	Closed		Fixed	YES	Volt	140.21	0.000
6	1020	BIG SPRING 1	1	1020		Closed		Fixed	YES	Volt	79.83	0.000
7	1027	MIDLAND 2 0	1	1027	0.322	Closed		Fixed	YES	Volt	76.33	1.000
8	1029	MIDLAND 3 0	1	1029	0.294	Closed		Fixed	YES	Volt	40.27	0.000
9	1030	ALPINE 0	1	1030	1.594	Open		Fixed	YES	Volt	0.00	1.000
10	1033	MCCAMEY 1 1	1	1033	0.773	Closed		Fixed	YES	Volt	20.56	1.000
11	1046	OZONA 0	1	1046	4.893	Closed		Fixed	YES	Volt	12.51	0.000
12	1056	LENORAH 0	1	1056	0.266	Closed		Fixed	YES	Volt	84.55	0.000
13	1081	ODESSA 1 10	1	1081	1.346	Closed		Fixed	YES	Volt	146.35	1.000
14	1083	FORT STOCKT(	1	1083		Closed		Fixed	YES	Volt	27.29	0.000
15	1086	PECOS 0	1	1086	1.243	Closed		Fixed	YES	Volt	30.95	0.000
16	1087	SHEFFIELD 0	1	1087	3.766	Closed		Fixed	YES	Volt	32.12	1.000
17	2009	IOWA PARK 0	1	2009	0.932	Closed		Fixed	YES	Volt	124.74	1.000
18	2010	VERNON 2 0	1	2010	2.104	Closed		Fixed	YES	Volt	20.57	1.000
19	2017	PANHANDLE 4	1	2017		Closed		Fixed	YES	Volt	-105.76	1.000
20	2017	PANHANDLE 4	2	2017		Closed		Fixed	YES	Volt	-105.76	1.000
21	2063	DENISON 2 0	1	2063	1.185	Closed		Fixed	YES	Volt	40.95	1.000
22	2065	GAINESVILLE (	1	2065		Closed		Fixed	YES	Volt	105.02	1.000
23	2069	HOWE 0	1	2069	1.208	Closed		Fixed	YES	Volt	126.60	0.000
24	2096	RALLS 1 0	1	2096	1.184	Open		Fixed	YES	Volt	0.00	1.000
25	2096	RALLS 1 0	2	2096	1.184	Closed		Fixed	YES	Volt	-104.26	1.000
26	2110	MUENSTER 2 (	1	2110	2.709	Closed		Fixed	YES	Volt	52.46	0.000
27	2127	MIAMI 0	1	2127	0.910	Closed		Fixed	YES	Volt	-162.24	1.000
28	2132	HASKELL 2	1	2132		Closed		Fixed	YES	Volt	9.98	0.000
29	3013	ABILENE 4 0	1	3013	2.169	Closed		Fixed	YES	Volt	66.57	0.000

Separate Analysis: Using THDv Values in Simulator

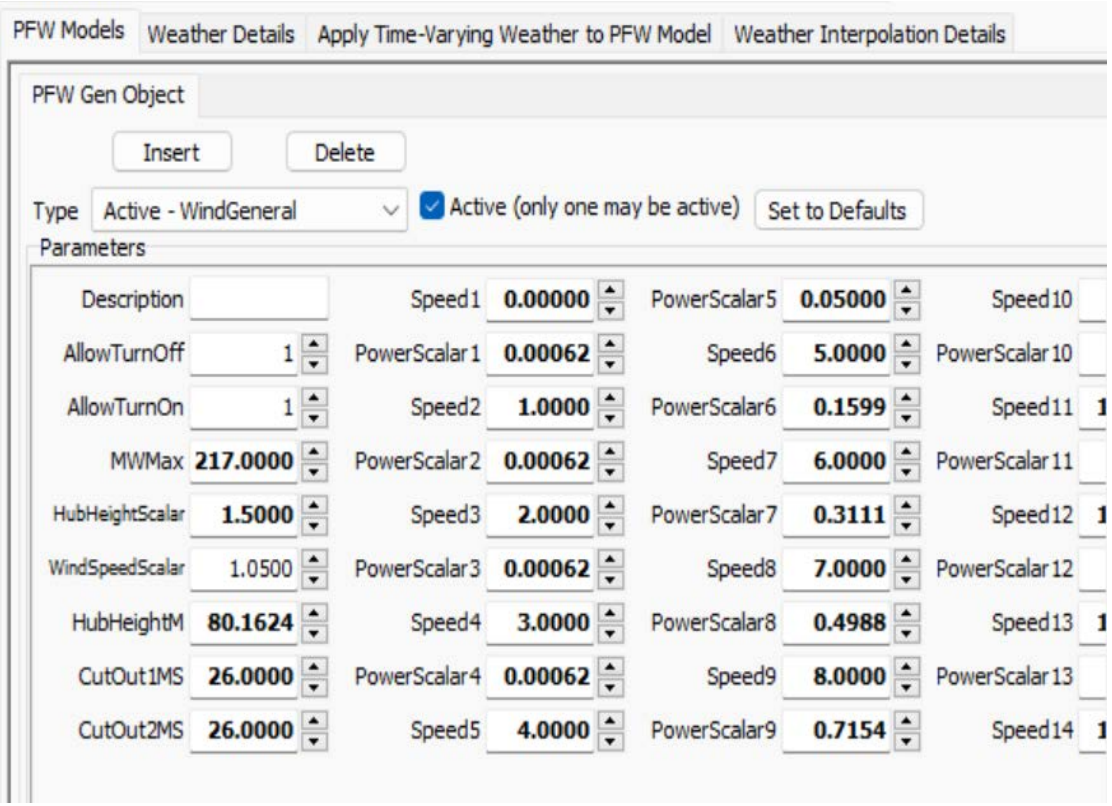
- The next step is to use the THDv models to determine which switched shunts to outage
- This could be done manually, but that would get quite tedious and could not be automated
- The solution is to define and use PFW models

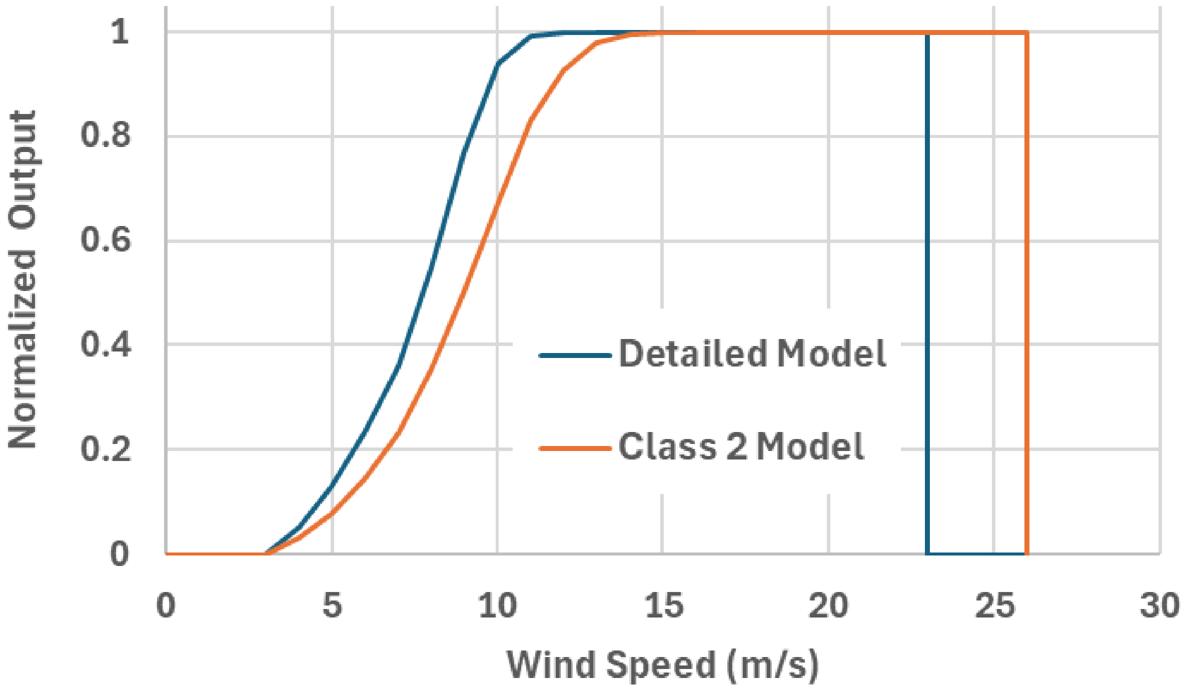
PowerWorld Simulator PFW Models

- Over the last three years PowerWorld has been developing a growing library of models to represent the impact of weather and other external events on the electric grid; these are known as PFW models
  - The first PFW models were developed to model the impact of weather on grid values, such as the maximum output values for wind and solar, or temperature on transmission line limits
- PFW originally stood for Power Flow Weather, but now it has been generalized to Power Flow Whatever models
- The approach (and actually the code itself) is similar to what is done for handing the large number of models used with power system stability; hence it is a very versatile and expandable approach
- New models are easy to implement

PFW Example: Customized Wind Power Curve

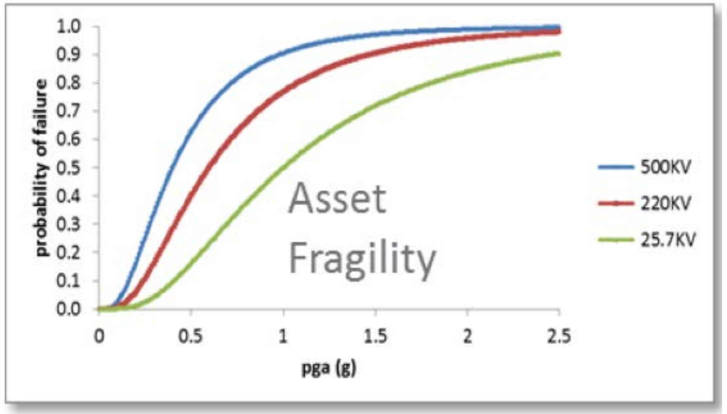
- Customized wind power curve models can also be defined; this only needs to be done once per wind generator





Additional PFWs, Including Harmonic Impacts

- Many different PFW models are possible, and they could certainly be stochastic
- Examples include ambient-adjusted line ratings, dynamic line ratings, thermal generator output variation with temperature, line outage due to wind gusts, asset failure during earthquakes (see figure with pga=Peak Ground Acceleration), incremental impacts of temperature on load, etc.

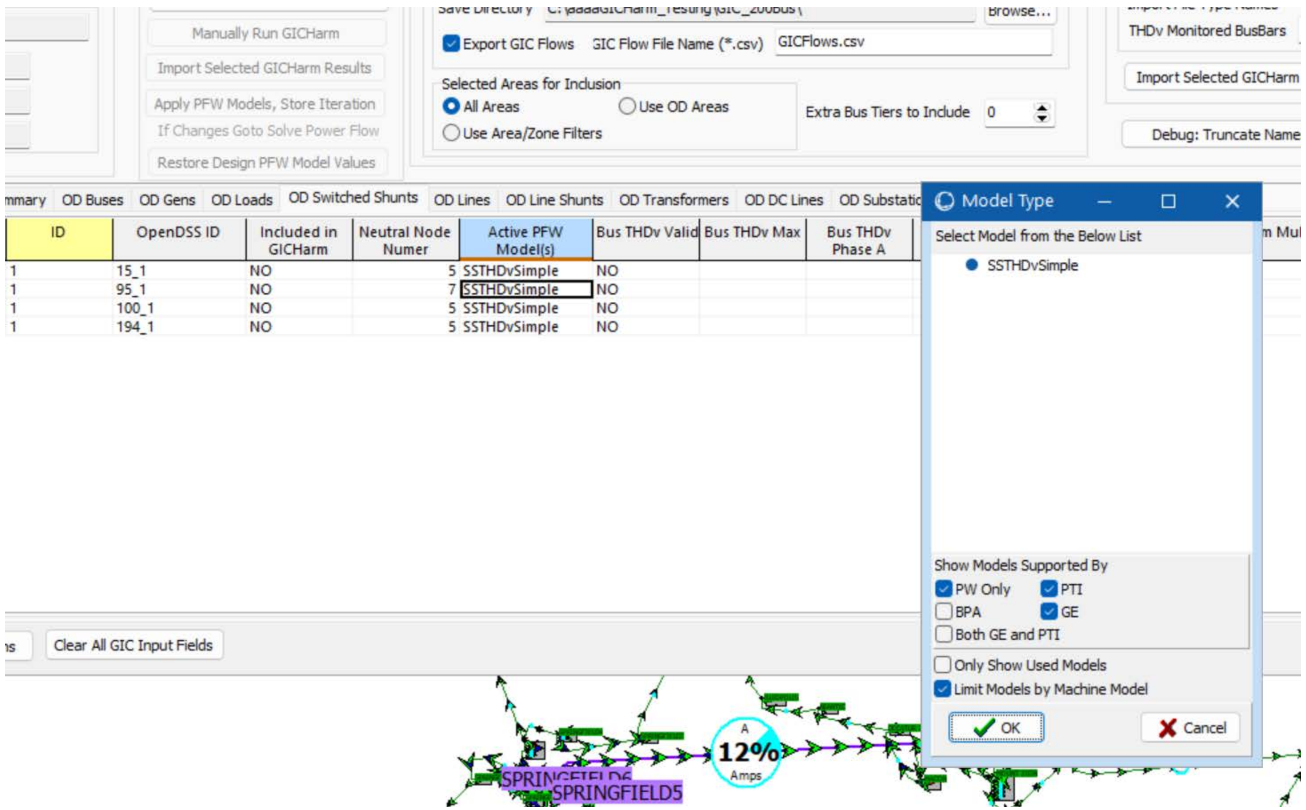


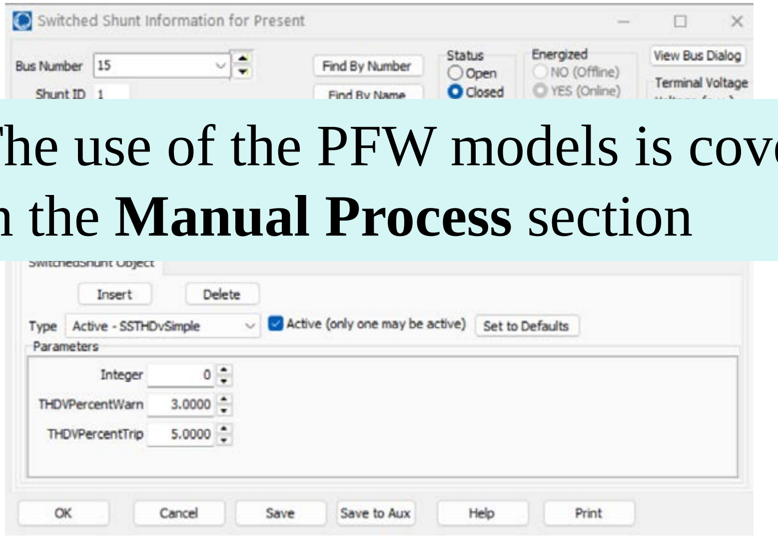
- The modeling of capacitors tripping due to the bus THDv just required creating a new, quite simple PFW model

Image source: Figure 2.1 of A. Veeramany, G.A. Coles, S.D. Unwin, T.B. Nguyen, J.E Dagle, "Trial Implementation of the High Impact, Low-Frequency Power Grid Event Risk Framework to Support Informed Decision-Making," PNNL-25667, October 2016.

Inserting Capacitor PFW Models for Harmonics

- To quickly insert PFW models for capacitors, on the OD Switched Shunts case info display select **Insert New PFW Models**
  - Like other models, the PFW models are saved in the pwb





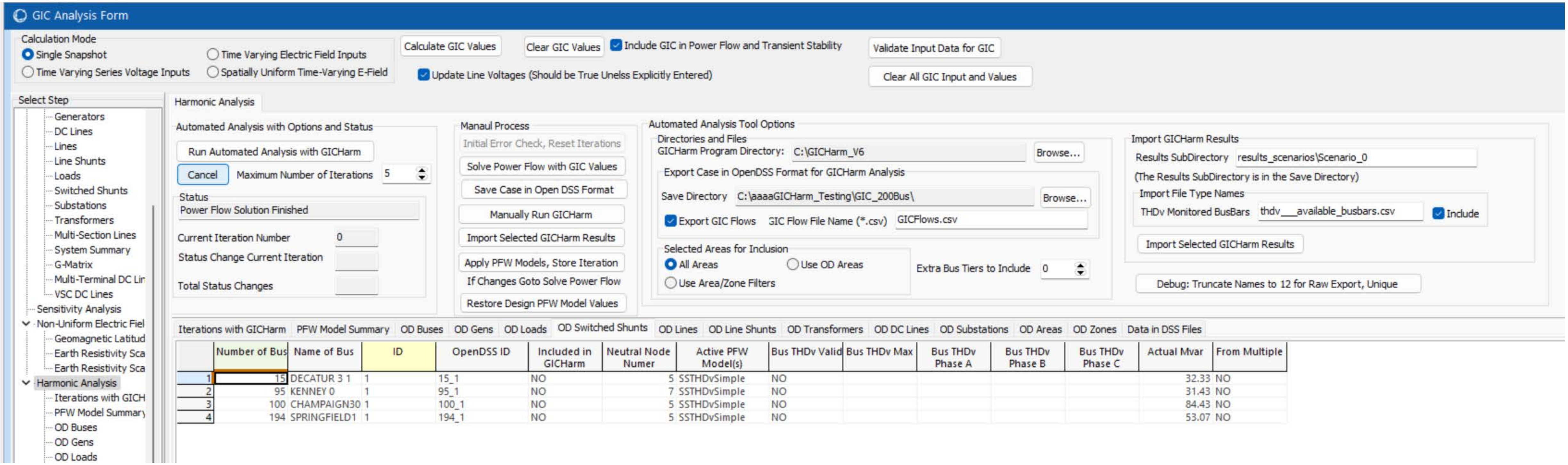
The use of the PFW models is covered next in the **Manual Process** section

Simulator Harmonic Analysis Manual Process

- What has been covered in the Separate Analysis section can be done more efficiently using either the step-by-step manual process or in the automated analysis
- When run either manually or automatically the following steps occur
  1. Initial error checking and resetting the iterations
  2. Solving the power flow with the GIC values (depends on GIC Calculation Mode)
  3. Exporting the PowerWorld data in OpenDSS format; this also exports a *.csv file with the GIC values
  4. Automatically running GICHarm to calculate the harmonics
  5. Importing the GICHarm results; currently the bus THDv values
  6. Using PFW Models to update the power flow values (e.g., capacitor statuses)
  7. Repeating until there are no power flow changes or power flow divergence

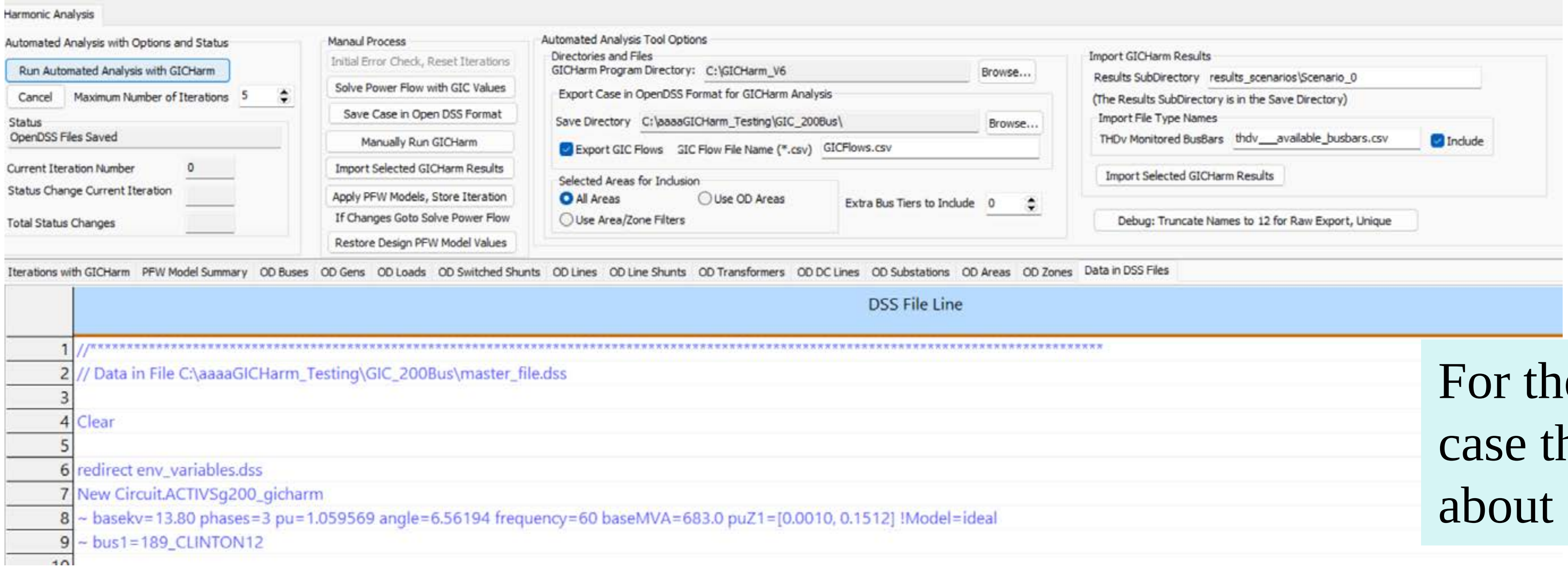
Simulator Harmonic Analysis Page

- On the Harmonic Analysis page the full simulation can be done either manually (a good place to start) or automatically
  - Simulator creates its own *.dss files and automatically runs GICHarm



Simulator Saving in OpenDSS Format

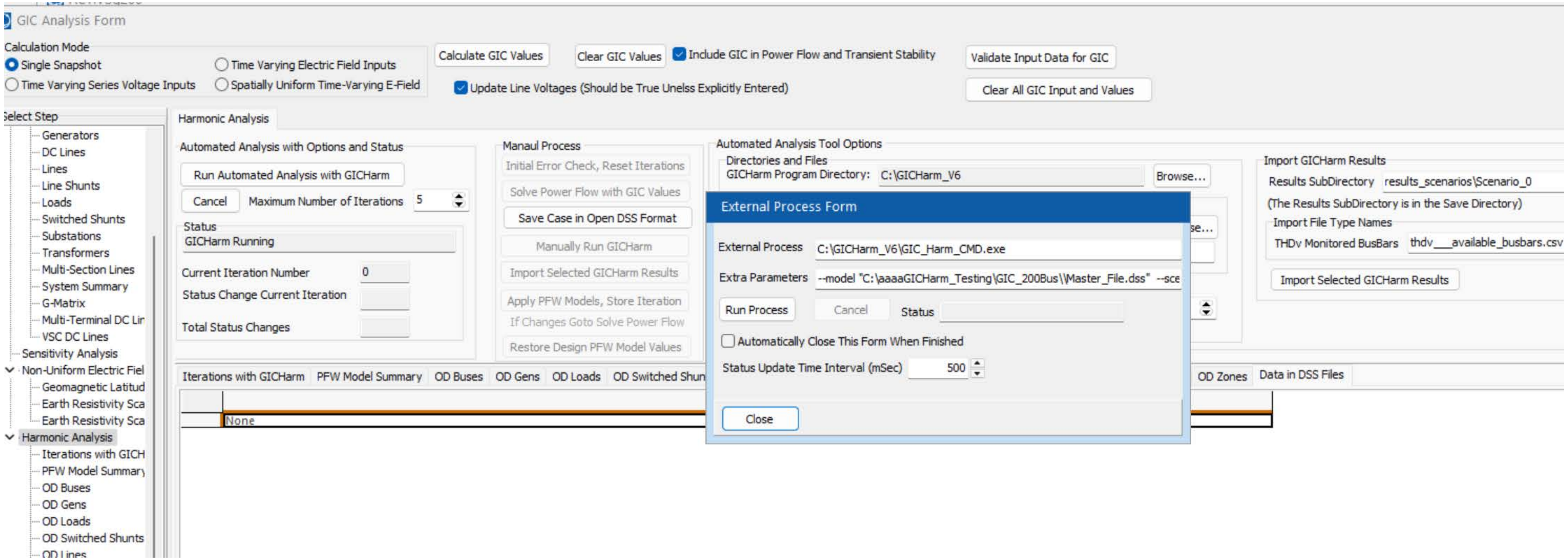
- The most challenging aspect of this process is correctly writing Simulator data in OpenDSS format
  - An OpenDSS case consist of many files (currently 24), so they are stored in their own directory
  - Simulator shows all of this data in a single case info display



For the 200 bus case this file has about 2700 lines

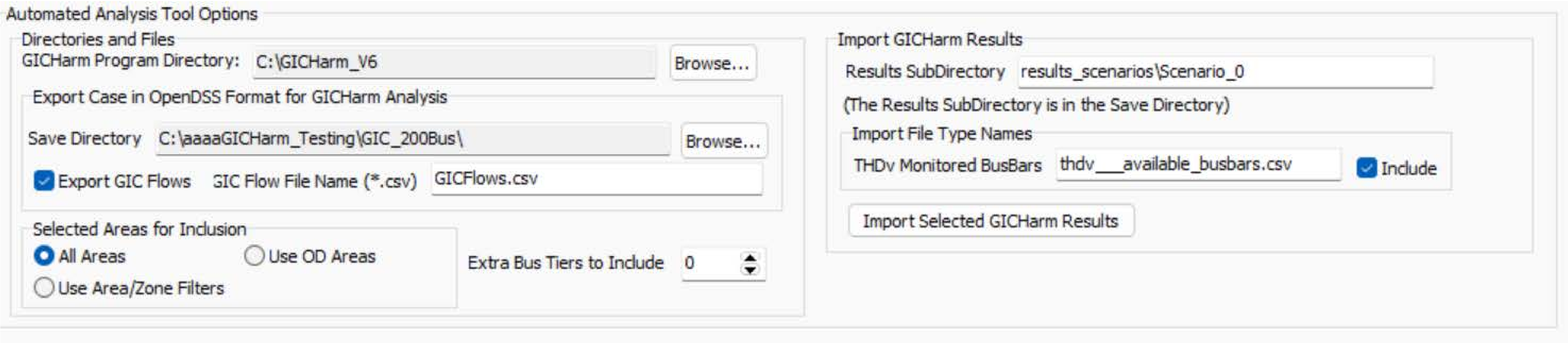
Running the GICHarm Batch Analysis Tool

- During this solution the GICHarm Batch Analysis tool is used (GIC_Harm_CMD.exe)
- Simulator has a dialog for controlling it



Process Options

- Currently there are only a few solution options, but more will be coming soon; these include
  - The directory containing the GICHarm program
  - The directory to use for saving the OpenDSS format (*.dss) files and the GIC flows
  - The results subdirectory and the OpenDSS result files to load



Summary and Future Directions

- PowerWorld Simulator is being integrated with EPRI's GICHarm program, allowing for the calculation and application of harmonics without leaving Simulator
- Beta functionality is currently available in Version 24, with development, validation and research ongoing
- Currently the focus is on useing the bus THDv values, but additional values will be available in the future
- The functionality leverages the versatility of the PFW modeling methodology, which is being applied to weather and other environment inputs
- Additional options should be added in the near future

Thank You! Questions?