Geomagnetically Induced Current Harmonic Tool (GICharm)

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Technical Update, December 2019

EPRI Project Manager

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ABSTRACT

Power systems can and have been impacted by harmonics generated during geomagnetic disturbance (GMD) events. These harmonic currents are generated from the part-cycle saturation of power transformers caused by the flow of Geomagnetically Induced Currents (GIC) through grid-connected transformers. This report describes a harmonic assessment tool, GICharm, needed by the industry to perform an adequate assessment of GMD-related distortion impacts. This report provides the background, approach and features of the GICharm tool.

Keywords
Geomagnetic disturbance (GMD)
Geomagnetically induced currents (GIC)
GICHarm
Harmonic system analysis
Power system analysis

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1

INTRODUCTION

During geomagnetic disturbances (GMDs), magnetic field variations drive low-frequency electric currents along transmission lines and through transformer windings to ground. These geomagnetically-induced currents (GIC) produce part-cycle saturation. Figure 1-1 shows a typical harmonic spectrum of the current in one phase of a three-phase transformer bank with GIC in each phase that is 10% of the peak of the transformer winding's rated peak (or crest) current; i.e., 0.03 pu GIC. As can be seen in the figure, the current injections are over a range of harmonic frequencies, and include both even and odd orders.

Part-cycle saturation of a transformer can have both direct impact on the transformer itself, and various impacts on the power system performance. For example, during the March 1989 geomagnetic storm, the following reported incidents were attributed to harmonic distortion created by GIC-saturated transformers [1][2]:

- Static var compensator (SVC) tripping. In fact, seven SVCs tripped in rapid succession resulting in system instability and total blackout of one Canadian system. Post-event analysis revealed that harmonic distortion was the direct cause of the SVC trips.
- Widespread tripping of capacitor banks
- Generator trips due to negative sequence or phase imbalance protection (including one major nuclear unit).
- HVDC system trip and an HVDC filter trip
- Transmission line tripping.

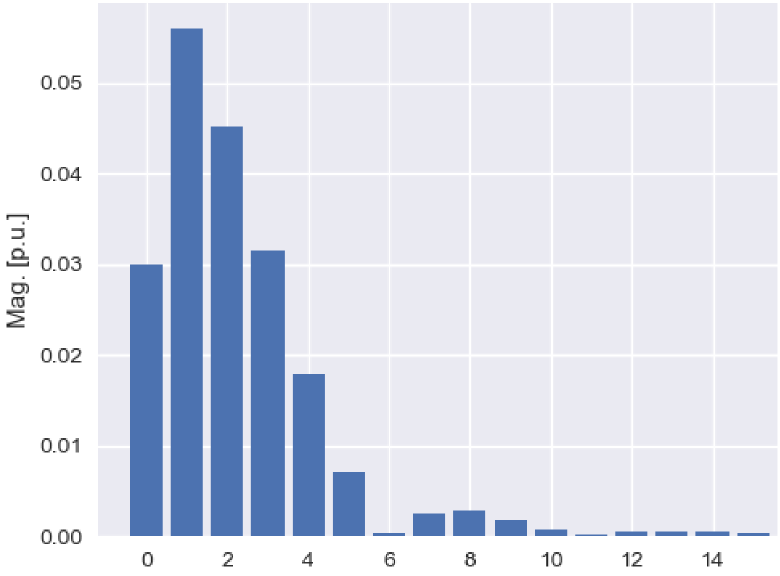


Figure 1-1
Harmonic components of a single-phase transformer with part-cycle saturation

It should be emphasized that only one wide-scale blackout has ever occurred in North America due to GMD, the 1989 Hydro Quebec event, which was initiated by the impact of harmonics [1].

As part of assessing the performance of power systems subjected to geomagnetic disturbances, it is necessary to model the GIC produced by different levels of geomagnetic activity. Assessments of bulk system operational security using only fundamental frequency analysis (e.g., load flow and dynamic stability) may underestimate the risks of severe GMD. A more complete assessment should consider the harmonic effects; particularly where they cause loss of reactive support, increase the reactive power demand, and increase the probability of faults and other abrupt disturbances that could trigger system instability and collapse.

System harmonic performance evaluation for GMD events, however, is particularly challenging due to the following factors:

- GIC-saturated transformers result in a large number of harmonic sources distributed throughout the transmission grid.
- Current injections are significant over a range of harmonic frequencies, including both even and odd orders.
- Harmonic voltage distortion interacts with the transformers to alter the magnitude and phase of the injected harmonic currents; i.e., saturated transformers do not behave as ideal harmonic current sources.
- The harmonic source characteristics of three-phase transformers are complex, and the sequence components of the harmonics produced do not appear exclusively in the classic pattern due to phase imbalance. Positive- and negative-sequence components of three-phase transformer exciting currents include triplen harmonics, and non-triplen harmonics have zero-sequence components.
- Propagation of the harmonics produced by GIC saturation is in both the ground mode (zero-sequence), as well as the line modes (positive- and negative-sequence).

EPRI has developed a tool that meets the above requirements. The background, approach and features of this tool (GICharm) are discussed in the proceeding chapters.

2
APPROACH

Overview

The overall GIC harmonics approach is illustrated in the flow chart in Figure 2-1. The software is named GICharm and is based on the EPRI OpenDSS program with auxiliary programs for time-domain solution and for importing data from other sources. The main network model is first constructed in the OpenDSS program. The GIC values are either computed using the OpenDSS model or imported from any of a number of computer tools in the industry capable of computing the GIC values given the GMD electric field values. A basic power flow calculation at fundamental frequency is then made. This may also be imported from another computer program's results. This initializes the process.

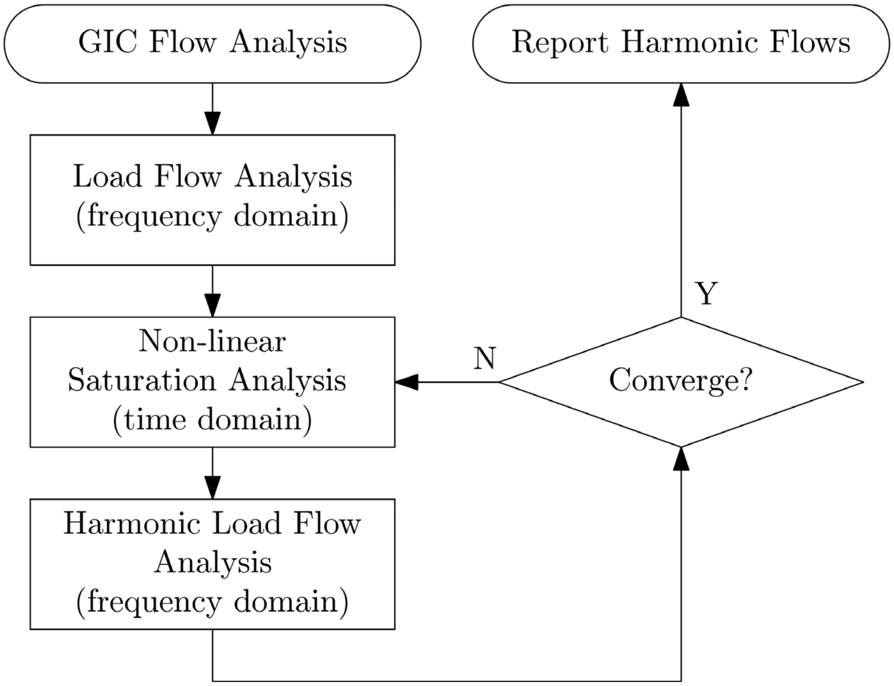


Figure 2-1
GICharm Software Approach.

The voltage computed at each transformer is applied to time-domain models of the transformers that include saturable elements. The part-cycle saturated current is computed with time-domain analysis. The harmonic currents are computed from the time-domain waveform data and used to populate the injection currents for the frequency-domain harmonic load flow analysis in the OpenDSS program. The resulting distorted voltages are passed back to the time domain analysis for a refined estimate of the current distortion. This process is repeated until there is a suitable convergence of the harmonic components of the current.

Transformer Modeling

To characterize the excitation currents drawn by GIC exposed transformers, GICharm uses the magnetic circuit models of Figure 2-2, for 3-leg core, 5-leg core, shell-form and banks of 3 single-phase core transformers [3][4]. Detailed values of the model parameters depend on the user input to the tool. If a power-cycle is discretized in K time steps, the flux linkage at each time step for each source in these models is determined by the numerical integration of the voltage across the corresponding winding terminals, over the power cycle. GICharm reconstructs the time-domain voltages across transformers winding terminals from the voltage spectra obtained from the harmonics solution, and then numerically integrates it to get the flux linkage values over the discretized power-cycle.

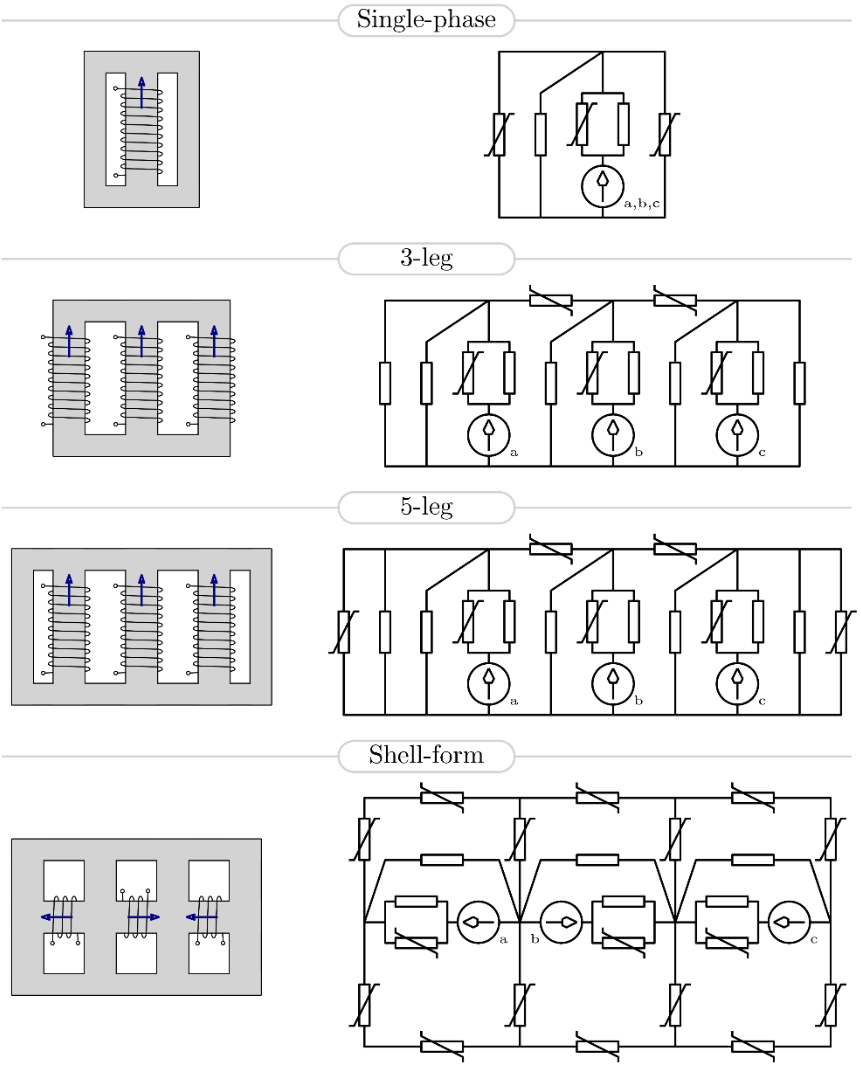


Figure 2-2
Core-topologies and magnetic circuit models in GICharm v1.0

As shown in Figure 2-2, the magnetic behavior of the transformer core is modeled by a set of reluctances and flux linkage sources connected to form a magnetic circuit. For the terminology of this section, it is important to remember that in magnetic circuits, reluctance is analog to resistance in electric circuits, while current (magnetomotive force over ampere-turns) is analog to voltage, and flux linkage is to current. This justifies the use of terms like "node current" or current "across" a reluctance.

In an ideal scenario, the flux paths on the core topology have linear reluctance and the magnetic circuit can be described by a linear expression in nodal "permeance" form (analog to nodal admittance form),

$$\lambda = \mathrm{P}\, i$$ **Eq. 2-1**

where λ is a vector of flux linkages inputs, P is the permeance matrix of the magnetic circuit, and i is a vector of "node currents". Node currents can be found by taking the inverse of P and solving (Eq. 2-1) for i. However, since the flux paths in a transformer core saturate under certain conditions, (Eq. 2-1) cannot accurately represent the core behavior without some additional considerations.

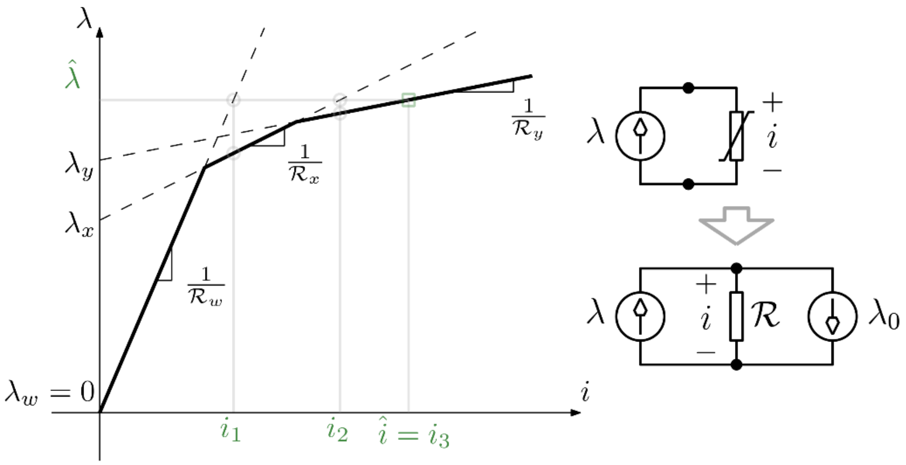


Figure 2-3
Piece-wise linear representation of saturable reluctances

A flux path with saturable reluctance can be modeled as a piece-wise linear function like the one shown in Figure 2-3. The saturable element is then represented by a linear reluctance element R in parallel with a flux linkage source λ^0. These parameters are functions of the current value i "across" the reluctance. If the flux linkage $\hat{\lambda}$ is known, it is possible to iteratively find the corresponding current value $\hat{\imath}$ "across" the saturable reluctance. First, it is assumed to be unsaturated and $\mathcal{R} = \mathcal{R}_w$ and $\lambda^0 = 0$. Thus, $i_1 = \mathcal{R}_w \hat{\lambda}$, where the sub-index 1 stands for the first iteration. The new current value is then used to update the slope of the curve and the flux linkage offset to $\mathcal{R} = \mathcal{R}_x$ and $\lambda^0 = \lambda_x$. The new current value is then $i_2 = \mathcal{R}_x(\hat{\lambda} - \lambda_x)$. This current value can be used to update the slope and offset parameters again, leading to $i_3 = \mathcal{R}_y(\hat{\lambda} - \lambda_y)$. Since the new current value doesn't produce an update, the routine stops and $\hat{\imath} = i_3 = \mathcal{R}_y(\hat{\lambda} - \lambda_y)$.

The previous case is trivial, but it serves to illustrate the algorithm used by the GICharm tool to solve more complex magnetic circuits. To represent a non-linear magnetic circuit formed by flux linkage sources, linear reluctances, and piece-wise linear reluctance paths, let us consider,

$$\lambda_k = \mathrm{P}_{i\,k} i_k + \lambda_{i\,k}^0, \qquad k = \{1,2,\ldots,K\} \tag*{Eq. 2-2}$$

where k is the sub-index for discrete time steps in a power cycle, and for time step k, $\boldsymbol{\lambda}_k$ is a vector of flux linkages, $\mathbf{P}_{i\,k}$ is the permeance matrix of the magnetic circuit, $\boldsymbol{\lambda}_{i\,k}^0$ is the vector of flux linkage offsets, and $\boldsymbol{i}_k$ is a vector of "node currents". Sub-index $\boldsymbol{i}$ in matrices $\mathbf{P}_{i\,k}$ and vectors $\boldsymbol{\lambda}_{i\,k}^0$ is only used to highlight the dependence of their elements on the value of "node current" elements in $\boldsymbol{i}_k$ at time step k.

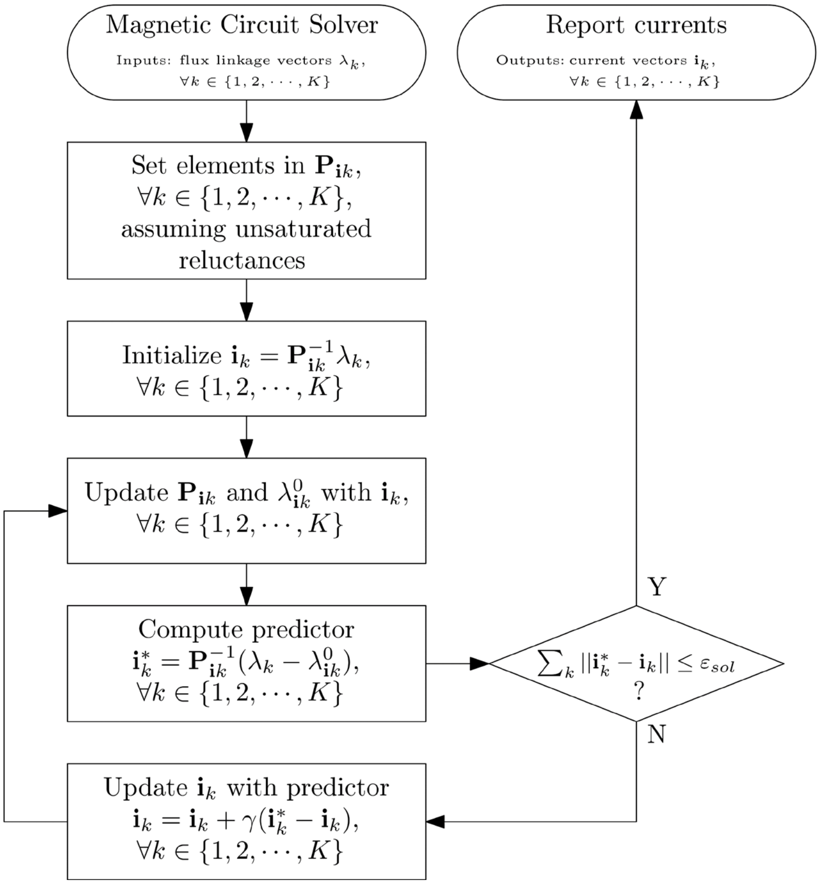


Figure 2-4
Magnetic circuit solver algorithm flow chart

Equation (2-2) can be solved for each time step using the magnetic circuit solver algorithm in Figure 2-4. This algorithm is based on the one proposed in [6] for solving monotone non-linear resistive networks. As it is shown in Figure 2-4, all saturable reluctances across the magnetic circuit are initially assumed to be unsaturated. The initial "node currents" are computed with this assumption. The saturable reluctances are then updated in subsequent iterations, resulting in updates to $\mathbf{P}_{i\,k}$ and $\boldsymbol{\lambda}_{i\,k}^0$. In each iteration, a predictor $\boldsymbol{i}_k^*$ is computed and the "node currents" vector $\boldsymbol{i}_k$ are updated in the direction dictated by the error $(\boldsymbol{i}_k^* - \boldsymbol{i}_k)$ and a positive factor $\gamma \leq 1$. The stopping criterion is defined by the norm of the error reaching values below a tolerance ε_{sol}.

To solve for all the time steps simultaneously in each iteration, the implementation of the solver algorithm takes advantage of the linear algebra capabilities of the Python's NumPy package [7], [8] (i.e., simultaneously finding the inverses of a packet of matrices $\mathbf{P}_i$, as well as the simultaneous computation of the matrix products $\mathbf{P}_i^{-1}(\boldsymbol{\lambda} - \boldsymbol{\lambda}_i^0)$)

The availability of the harmonic content of the flux linkage sources allows the use of the solver algorithm to find the "node currents" of the magnetic circuit. However, in the GIC scenario, additional parameters must be considered. In such cases, the harmonic content of the flux linkage sources is known, but the DC flux linkage is unknown. On the contrary, the DC components of currents "across" flux linkage sources are known, but their harmonic content is unknown. To solve this, the GICharm tool uses the DC flux finder algorithm proposed in Figure 2-5 before applying the magnetic circuit solver algorithm.

The purpose of the proposed DC flux linkage finder algorithm is to find the DC flux linkage levels at the sources that result in the DC currents "across" their terminals (i.e., the GIC currents). The finder algorithm works with matrices $\mathbf{P}_{i\,k}^{-1}$ in (Eq. 2-2), after a few manipulations. To explain this, it is important to highlight that the DC components of the currents "across" terminals of flux linkage sources are known, but DC components of "node currents" are completely unknown. Therefore, the algorithm reduces $\mathbf{P}_{i\,k}^{-1}$ to a $N \times N$ matrix, $\mathbf{A}_{i\,k}$ that considers only the N flux linkage sources and N the "currents across" their terminals. For that, it considers only rows and columns of $\mathbf{P}_{i\,k}^{-1}$ corresponding to nodes where flux linkage sources are directly connected, the rest is neglected. Then, row and column operations are applied to the remaining matrix until a N-dimensional matrix is reached. The row and column operations are dictated by the nodes where the sources are connected. For instance, if a source fixes a certain flux linkage value going from node 2 to node 4, row 2 is subtracted from row 4, and column 2 is subtracted from column 4 as well. The contribution of the flux linkage source to the currents "across" their terminals is given by,

$$i_k^s = \mathrm{A}_{i\,k}\lambda_k^s, \qquad k = \{1,2,\dots,\mathrm{K}\}, \tag{Eq. 2-3}$$

where $\boldsymbol{\lambda}_k^s$ is the $N \times 1$ vector of flux linkages sources at time step k, and $\boldsymbol{i}_k^s$ is the $N \times 1$ vector of currents "across" the source terminals. The super-index s is used here to differentiate from the expressions in (2-2). From (2-3), the DC currents "across" the source terminals can be found using,

$$i_{DC}^s = \frac{1}{K}\begin{bmatrix}\mathrm{I} & \mathrm{I} & \cdots & \mathrm{I}\end{bmatrix}\begin{bmatrix}\mathrm{A}_{i\,1}\\ \mathrm{A}_{i\,2}\\ \vdots\\ \mathrm{A}_{i\,K}\end{bmatrix}\lambda_{DC}^s = \mathrm{S}\,\lambda_{DC}^s, \tag{Eq. 2-4}$$

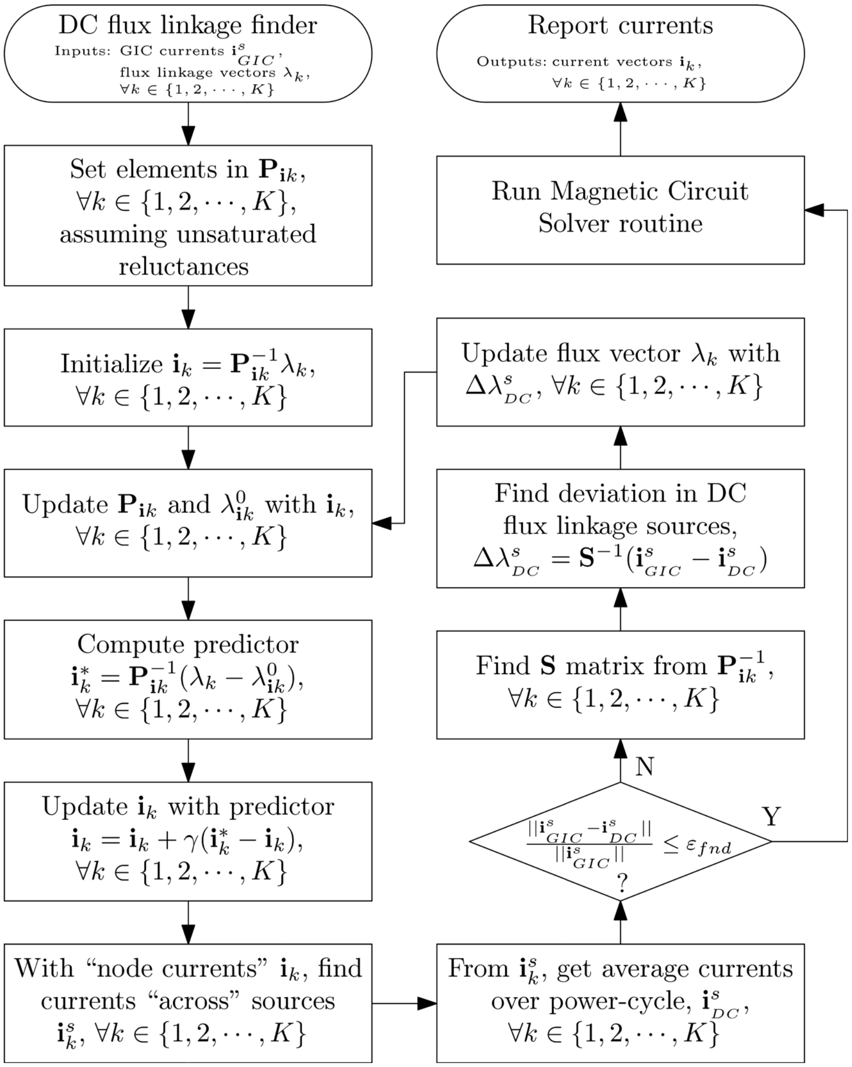


Figure 2-5
DC flux linkage finder algorithm flow chart

where $\boldsymbol{\lambda}^s_{DC}$ is the $N \times 1$ vector of DC components of the flux linkages sources, $\boldsymbol{i}^s_{DC}$ is the $N \times 1$ vector of DC components of the currents "across" the source terminals, and the block matrix $[\mathbf{I} \quad \mathbf{I} \quad \cdots \quad \mathbf{I}]$ is built with K identity $N \times N$ matrices. It should be noticed that $\boldsymbol{i}^s_{DC}$ and $\boldsymbol{\lambda}^s_{DC}$ don't have a sub-index k because they are common to all the time steps in the power cycle (since they are DC components). The product of block matrices in (Eq. 2-4) is replaced by the **S** matrix whose elements are the average of elements of matrices $\mathbf{A}_{\boldsymbol{i}\,k}$ over the time steps in a power cycle. From (Eq. 2-4), it is possible to notice that for $\boldsymbol{i}^s_{DC}$ to reach values equal to the GIC currents, the flux DC level would need to change by,

$$\Delta\lambda^s_{DC} = \mathrm{S}^{-1}(i^s_{GIC} - i^s_{DC}) \qquad \textbf{Eq. 2-5}$$

Since saturable reluctances don't have discontinuities in their piece-wise linear expressions, small changes in the flux linkage sources don't result in drastic changes in matrices $\mathbf{P}_{\boldsymbol{i}\,k}$ and vectors $\boldsymbol{\lambda}^0_{\boldsymbol{i}\,k}$. The DC flux finder algorithm takes advantage of this and uses (Eq. 2-5) to gradually increase the DC component of flux linkage sources until the DC component of currents "across" the flux source terminal is equal to the GIC currents. At the same time, the algorithm progressively solves the magnetic circuit, and when the normalized magnitude of the error $(\boldsymbol{i}_{GIC}^{s} - \boldsymbol{i}_{DC}^{s})$ goes below the tolerance ε_{fnd}, the DC flux linkage finder stops and the magnetic circuit solver routine is run to get the final solution.

The DC flux linkage finder algorithm produces time-domain waveforms for the excitation currents drawn by a GIC exposed transformer. These are post-processed to get the harmonic spectra, which are later used as inputs for the magnetizing branch representation of the transformer in the network model. The magnetizing branch of each transformer is defined by 3 separate load objects (one per phase) in OpenDSS, whose fundamental active and reactive power parameters are defined using the magnitudes and angles of the fundamental components of voltage across each winding, and of the excitation currents. Each load object is also assigned with a spectrum object that defines its response for harmonic orders higher than the fundamental. More details on the load object model of OpenDSS are provided in the next section. Finally, these loads are attached to a fictitious extra wye-connected winding created at the transformer object in the network model to solely host the magnetizing branch.

System Modeling

The OpenDSS program is perhaps better known as a power flow tool for simulating such things as solar PV profiles. However, it is a general frequency-domain nodal admittance solver and can perform a wide variety of analyses. In fact, the original application for the solver algorithm was harmonics analysis of arbitrary networks, and was later adapted for power flow analysis.

The basic equation solved by the program is the familiar nodal admittance formulation,

$$\mathrm{i}_{\mathrm{injection}} = \mathrm{Y}_{\mathrm{SYSTEM}}\, \mathrm{v} \qquad \textbf{Eq. 2-6}$$

where $\mathbf{v}$ is the vector of node voltages, $\mathbf{i}_{\mathrm{injection}}$ is the vector of injection currents at each node from non-linear elements, harmonic sources, etc., and $\mathbf{Y}_{\mathrm{SYSTEM}}$ is the Nodal admittance matrix representing linear element admittances.

The linear admittances in the circuit model are included in $\mathbf{Y}_{\mathrm{SYSTEM}}$ while nonlinear elements such as loads, generator, and transformer magnetizing impedances are modeled as Norton equivalents as shown in Figure 2-6. The linear admittances of the Norton equivalents are also included in the $\mathbf{Y}_{\mathrm{SYSTEM}}$ matrix, while the current sources make up the components of the $\mathbf{i}_{\mathrm{injection}}$ vector.

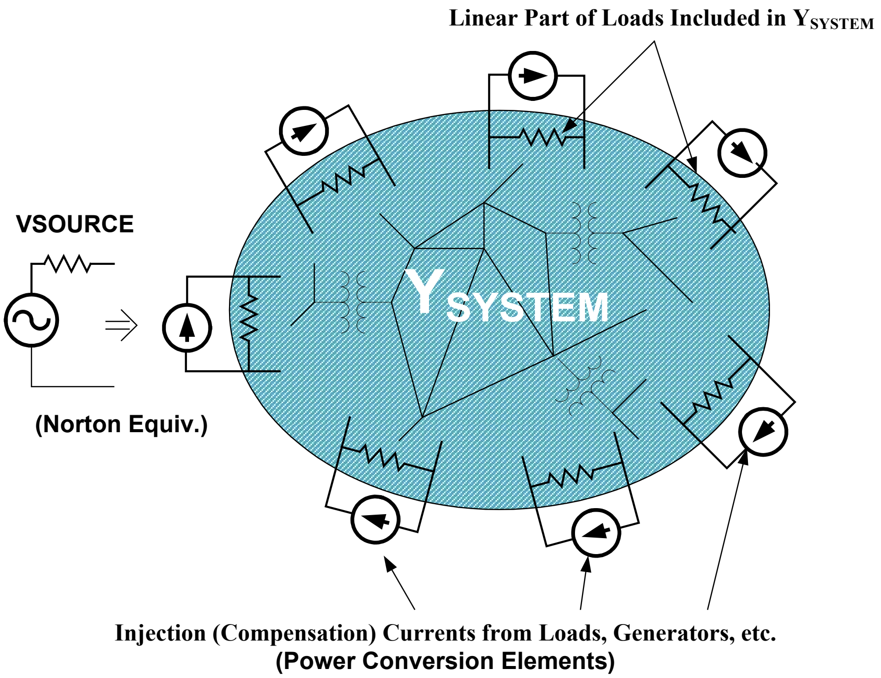


Figure 2-6
Overall OpenDSS Circuit Model

For power flow analysis, the injection currents typically represent the nonlinear voltage dependence of the loads and Eq. (2-6) is solved iteratively at fundamental frequency. For harmonics analysis, the injection currents represent the harmonic currents from the various nodes with distorted currents. After a fundamental frequency solution, OpenDSS executes a linear, non-iterative solution at each frequency present in the various harmonic sources in the problem.

All load-class elements in OpenDSS have a harmonic spectrum associated with them. The detail of the model of an OpenDSS Load element for harmonics analysis is shown in Figure 2-7. The load model is used to represent transformer magnetizing currents in the GICharm analysis procedure. The injection current sources at harmonic frequencies are based on the fundamental frequency currents as indicated in Figure 2-7. In the Harmonic Load-Flow analysis, the magnetizing element of each transformer in the model is represented by an OpenDSS Load element with its fundamental frequency reactive power value set to the value determined from the time-domain simulation.

The shunt admittances of the Load model can represent a specified mixture of series and parallel R-L branches. Each configuration has a different frequency response. These shunt branches can be neglected entirely (Set NeglectLoadY=Yes) so that the model consists solely of a current source. This is what is done in GICharm so that the harmonic currents computed in the time-domain simulation are injected directly into the frequency-domain network for the harmonics solution.

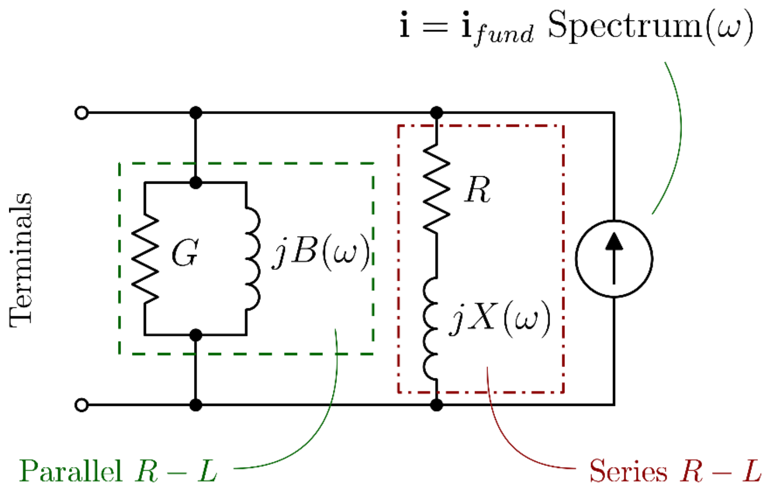
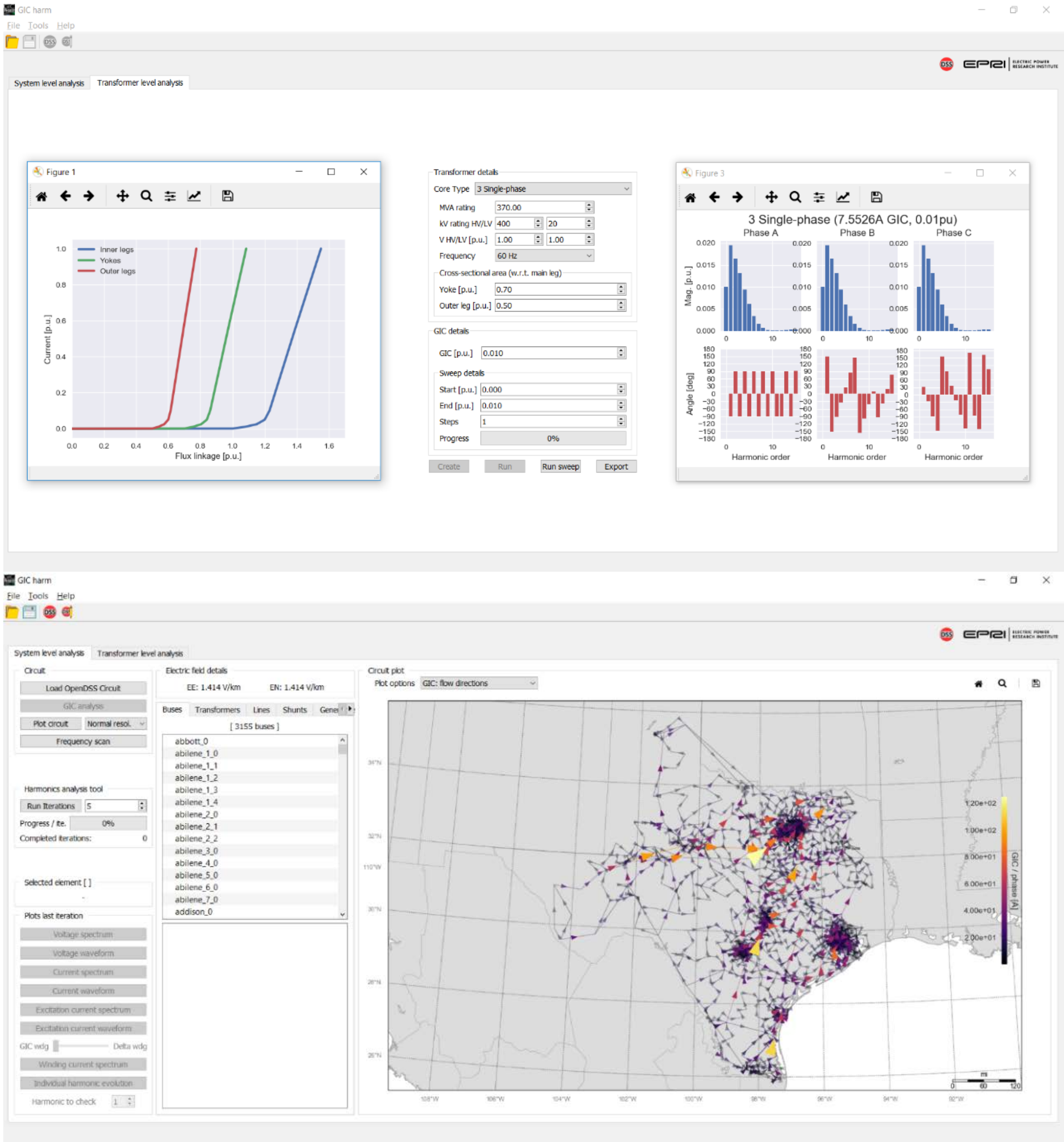


Figure 2-7
Detail on Load Model for Harmonics Solution

3

GETTING STARTED

The main Graphical User Interface (GUI) for EPRI's GICharm is shown in Figure 3-1. The workspace of the program consists of two independent analysis tools: *System Level Analysis* and *Transformer Level Analysis*.



Transformer details

Core Type: 3 Single-phase

MVA rating: 370.00

kV rating HV/LV: 400 | 20

V HV/LV [p.u.]: 1.00 | 1.00

Frequency: 60 Hz

Cross-sectional area (w.r.t. main leg)

Yoke [p.u.]: 0.70

Outer leg [p.u.]: 0.50

GIC details

GIC [p.u.]: 0.010

Sweep details

Start [p.u.]: 0.000

End [p.u.]: 0.010

Steps: 1

Progress: 0%

Circuit

Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 0

Selected element [ ]

Harmonic to check: 1

Electric field details

EE: 1.414 V/km EN: 1.414 V/km

[3155 buses]

abbott_0
abilene_1_0
abilene_1_1
abilene_1_2
abilene_1_3
abilene_1_4
abilene_2_0
abilene_2_1
abilene_2_2
abilene_3_0
abilene_4_0
abilene_5_0
abilene_6_0
abilene_7_0
addison_0

Plot options: GIC: flow directions

Figure 3-1
Main workspace in GICharm: Transformer Level (top) and System Level Analysis (bottom)

The *Transformer Level Analysis* tool is intended to assess the response of different 3-phase transformer core topologies to various GIC inputs. In its current version, it can consider four core topologies: 3 single-phase core-form, 3-limb, 5-limb and Shell-form. Once the user selects a given core-topology, the tool automatically populates default parameter values that the user can modify to check their impact on the harmonics response. This tool offers two analysis options:

1. *Single GIC value analysis*: This analysis allows the user to check the response of the chosen core-topology to a given GIC input in terms of excitation current waveforms and harmonic spectra per phase. The result of the analysis is in the form of waveforms whose values can be exported to **.csv* files
2. *GIC sweep analysis*: This analysis allows the user to define a range of GIC values and perform stepped simulations with a user selected step-size value. The results are in the form of excitation current waveforms per phase per GIC step, excitation current harmonic order magnitudes per phase against GIC value from the DC component up to the 8th harmonic order, and total reactive power loss against GIC values. The results of this analysis can also be exported to **.csv* files.

These two analysis options use the DC-flux finder algorithm of Figure 2-5. While solving the user-selected core topology for various GIC values in the *GIC sweep analysis,* the program takes advantage of the availability of multiple processor cores in the hosting machine to run several simulations simultaneously using parallel processing.

The System Level Analysis tool on the other hand is developed to assess the impact of GIC related harmonics at the bulk system level. This tool works with OpenDSS models with characteristics that make it suitable for the proposed analysis. The program includes a converter from PSS/E to GICharm / OpenDSS that takes PSS/E **.raw* and **.gic* files as inputs and creates **.dss* files to use with GICharm. The system level analysis tool works with the same transformer magnetic circuit core-topology models as the *Transformer Level Analysis* tool, allowing the system model to have transformers with any of the four core topologies mentioned before: 3 single-phase core-form, 3-limb, 5-limb and Shell-form. The capabilities of the tool include:

1. *GIC flow analysis*: GICharm uses the OpenDSS engine to run a quasi-DC (0.1Hz) analysis of the system under test. This analysis depends on a user-defined geomagnetic disturbance-induced electric field, and on the geographic coordinates of the buses in the system. The GIC flows in this analysis, as well as the harmonic content of winding voltages determine the transformer's core saturation, and therefore the excitation currents' harmonic content and reactive power losses. A future revision of GICharm will include a tool to import the GIC flows directly from external sources. Presently GICs are computed with a defined uniform field in GICharm.
2. *Frequency Scan:* To assess the impact of harmonics injected at a given bus in the system, this analysis tool allows the user to select an inject 1 Ampere at frequencies ranging from the fundamental to a user-defined higher harmonic order. As a result, the tool prompts the user with a figure of impedance magnitude against frequency. This frequency scan is useful to check for possible resonant frequencies in the system that might coincide with harmonic currents produced by transformer saturation.

3. *Harmonic Loop Analysis*: This is the primary function of the program, this analysis option allows the user to run a user-defined amount of iterations of the harmonics loop described in Figure 2-1. The iterations are cumulative, which means that each time the tool runs a user-defined number of iterations, the system will be solved starting from the result of the previous iteration. The evolution of the system over all the cumulative iterations can be plotted for each of the GIC-affected transformers across the system. At each iteration of the harmonics loop, GICharm solves each of the transformer magnetic circuit models in the system for its own GIC level (obtained from the GIC flow analysis or imported from an external source). This task is performed using the DC-flux finder algorithm of Figure 2-5, taking advantage of the availability of multiple processor cores in the host machine to run simultaneous simulations using parallel processing. The higher the number of processor cores in the machine, the lower the solution time of the harmonics loop.
4. *Edit relevant system components*: The OpenDSS models of some of the system components that are relevant to the GIC harmonics analysis can be edited through the GICharm user interface. The details that can be modified include the core-topology of transformers, and the connection status of capacitors and reactors. Other parameters can be directly modified using a text editor on the **.dss* files containing the representation of each element.
5. *Evaluate the response of Transformers, Generators, Capacitors and Reactors:* At each iteration of the harmonics loop, the program allows the user to check the excitation current waveforms and spectra for each GIC-affected transformer. The user can also check voltage waveforms and spectra at buses where transformers, generators, capacitors or reactors are connected. It is also possible to check waveforms and spectra of currents in the delta-connected windings of transformers, as well as the currents flowing through generators, capacitors or reactors. All these variables can be exported to **.csv* files for external analysis. The exported results include the sequence components of each harmonic order.
6. *Geographic referenced circuit plots*: GICharm includes a pane in its graphical user interface that allows the user to check variables like GIC flows, voltage total harmonic distortion (THDv), and fundamental voltage magnitudes over the geographic footprint of the system under test. The geographical circuit plot also allows the user to explore the system topology and locate circuit elements, access their analysis variables, or select a bus for a frequency scan analysis.
7. *PSS/E to GICharm/OpenDSS converter*: To allow users to import data from external industry software programs, GICharm includes a converter that takes *.raw and *.gic files from PSS/E as inputs, and creates two sets of **.dss* files: one for work with OpenDSS and another one for work with GICharm.

For a quick reference to the GICharm capabilities, the *Help* menu includes a submenu called *Help documents* which contains links to quick guides in PDF format. Additionally, some of the pop-up tool dialogs in GICharm have a "*?*" button at the top right corner which, once pressed, allow the user to hover the mouse cursor over the dialog window and click to get context information about editable fields or tables in the window itself.

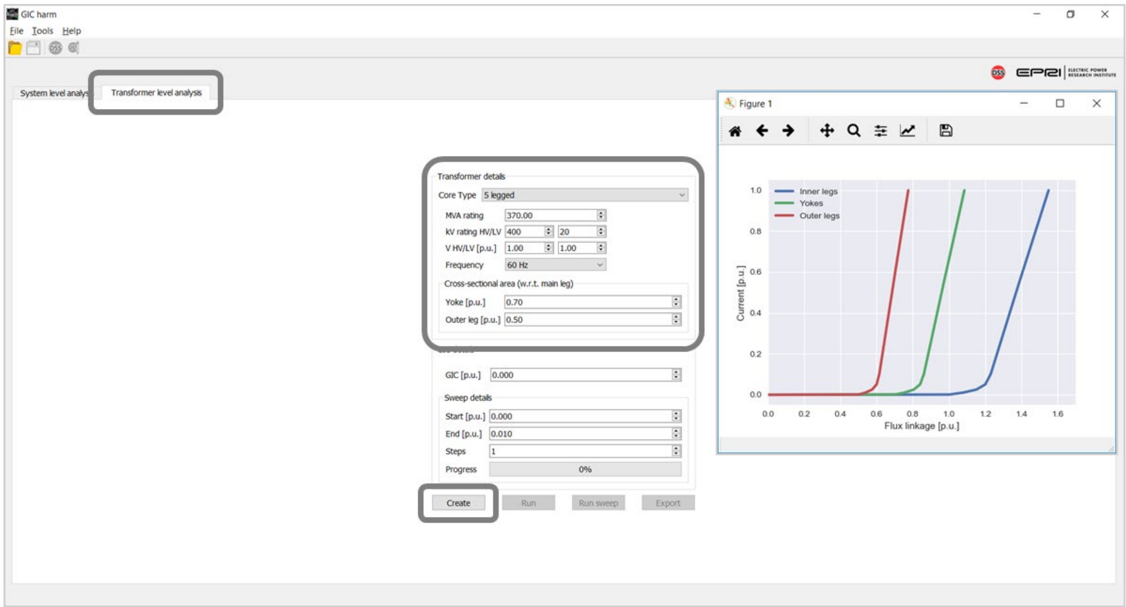
The following sections include step by step descriptions for each of the tools and capabilities described above.

4

FEATURES AND EXAMPLES

Transformer Level Analysis

The *Transformer Level Analysis* tool uses the same magnetic circuit solver (Figure 2-4) and DC-flux finder (Figure 2-5) algorithms as the *System Level Analysis* tool, but they work independently of each other. This means that the transformer level tool does not require a **.dss* system model be loaded in GICharm to perform simulations. The tool interface is shown in Figure 4-1. To run transformer level simulations, a magnetic circuit model must be first created. To create this model, the user must select a core topology among the available options in the *Transformer details* frame and then click on the *Create* button. Available options include: 3 single-phase, 5-limb, 3-limb and Shell-form. Selecting one of the available topologies results in the population of default values for transformer and core-topology parameters.

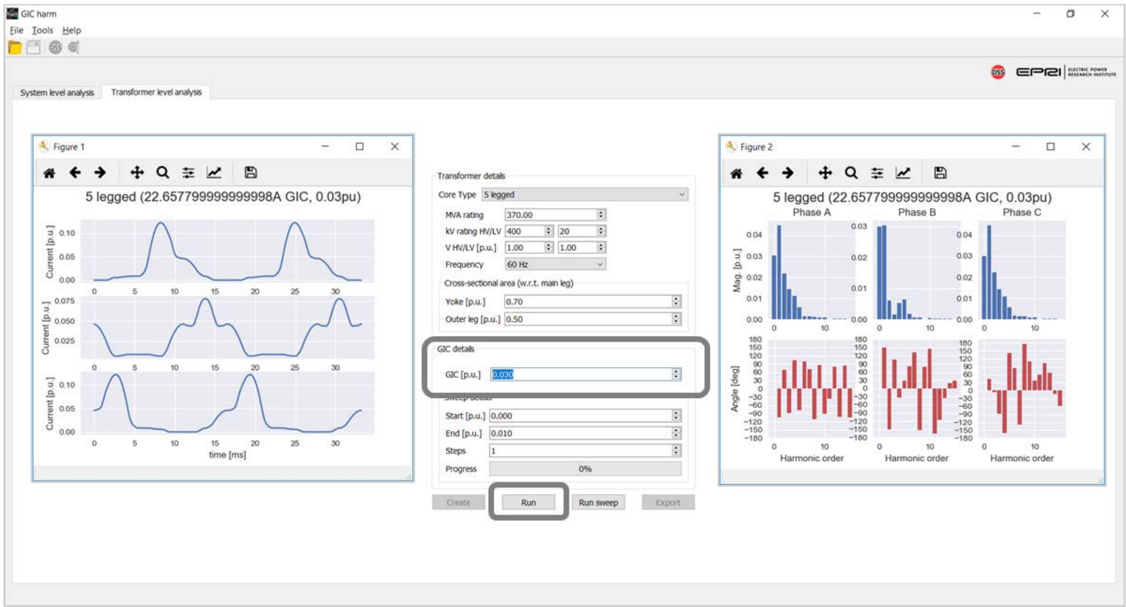


Transformer details
Core Type: 5 legged
MVA rating: 370.00
kV rating HV/LV: 400 / 20
V HV/LV [p.u.]: 1.00 / 1.00
Frequency: 60 Hz
Cross-sectional area (w.r.t. main leg)
Yoke [p.u.]: 0.70
Outer leg [p.u.]: 0.50
GIC [p.u.]: 0.000
Sweep details
Start [p.u.]: 0.000
End [p.u.]: 0.010
Steps: 1
Progress: 0%

Figure 4-1
Defining transformer core-topology parameters

Once a magnetic circuit model is created, the *Create* button gets disabled. If changes are made to the model parameters or the core topology is changed, then the *Create* button becomes enabled again.

With a created magnetic circuit model, the user can run two types of analysis: A *Single GIC* value analysis, and a *GIC sweep* analysis. Figure 4-2 shows the results of the first of these analysis types. To run the single value analysis the user must define a GIC per phase value in per-unit of the rated peak current per phase for the transformer and click on the *Run* button. The results are waveform per phase figures and spectra per phase figures of the excitation currents.



Transformer details

Core Type 5 legged

MVA rating 370.00

kV rating HV/LV 400 20

V HV/LV [p.u.] 1.00 1.00

Frequency 60 Hz

Cross-sectional area (w.r.t. main leg)

Yoke [p.u.] 0.70

Outer leg [p.u.] 0.50

GIC details

GIC [p.u.] 0.030

Sweep details

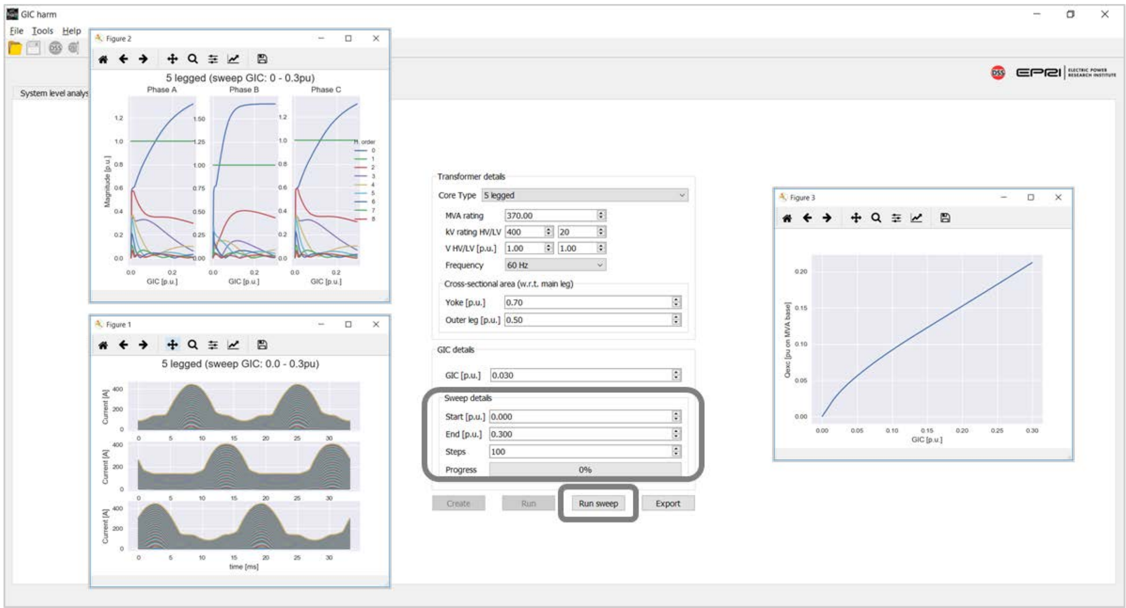
Start [p.u.] 0.000

End [p.u.] 0.010

Steps 1

Progress 0%

Figure 4-2
Running single GIC value analysis



Transformer details

Core Type 5 legged

MVA rating 370.00

kV rating HV/LV 400 20

V HV/LV [p.u.] 1.00 1.00

Frequency 60 Hz

Cross-sectional area (w.r.t. main leg)

Yoke [p.u.] 0.70

Outer leg [p.u.] 0.50

GIC details

GIC [p.u.] 0.030

Sweep details

Start [p.u.] 0.000

End [p.u.] 0.300

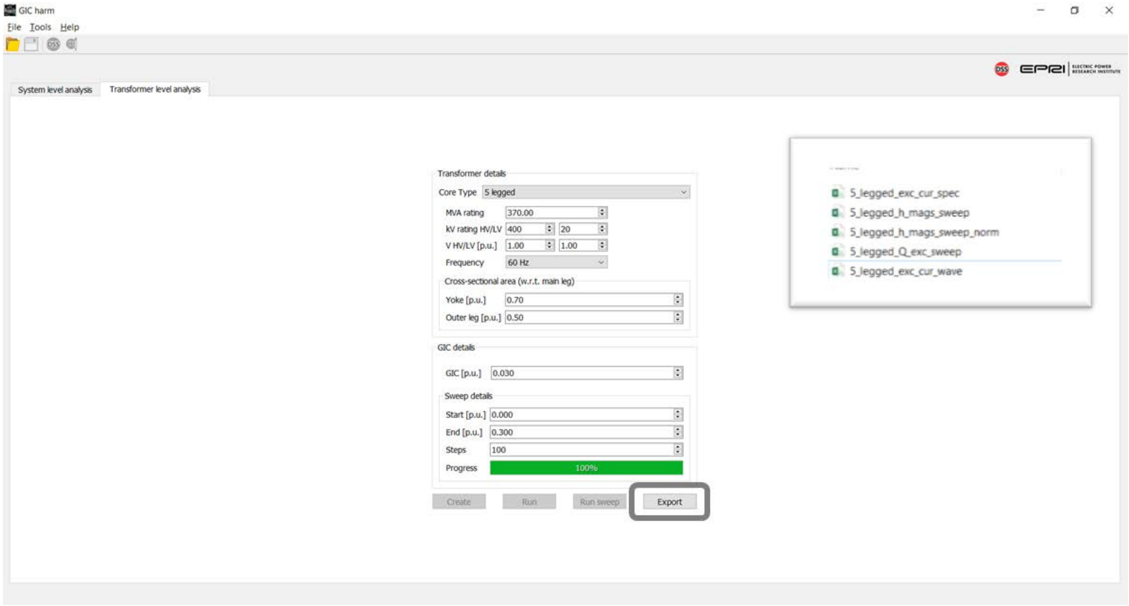
Steps 100

Progress 0%

Figure 4-3
Running GIC sweep analysis

On the other hand, to run a *GIC sweep* analysis, the user must define the sweep range limits and the steps to divide the range as shown in Figure 4-3. The boundaries of the GIC sweep range are in per-unit of the rated peak current per phase of the transformer. The result of this simulation is made of figures of: reactive power losses versus GIC value, excitation current waveforms per phase for all the GIC values in the sweep range, and excitation current harmonic order magnitudes per phase versus GIC value (from DC up to the 8th harmonic order).

The data contained in the figures for both analysis types can be exported in the form of **.csv* files as shown in Figure 4-4.



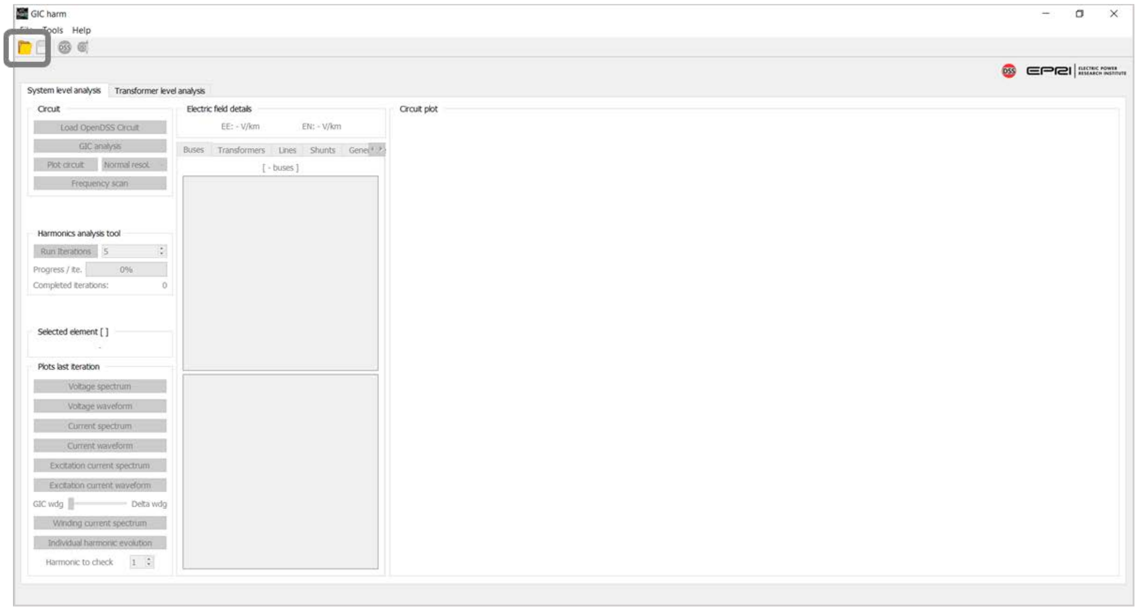
Transformer details
Core Type 5 legged
MVA rating 370.00
kV rating HV/LV 400 20
V HV/LV [p.u.] 1.00 1.00
Frequency 60 Hz
Cross-sectional area (w.r.t. main leg)
Yoke [p.u.] 0.70
Outer leg [p.u.] 0.50
GIC details
GIC [p.u.] 0.030
Sweep details
Start [p.u.] 0.000
End [p.u.] 0.300
Steps 100
Progress 100%

5_legged_exc_cur_spec
5_legged_h_mags_sweep
5_legged_h_mags_sweep_norm
5_legged_Q_exc_sweep
5_legged_exc_cur_wave

Figure 4-4
Exporting single GIC and GIC sweep analysis results

System Level Analysis

The following step by step guide is intended to help the user run a harmonics loop simulation in GICharm. Before starting, it is important to mention that the **.dss* files used in the example of this section were converted from a set of **.raw* and **.gic* files obtained from [9]. From the *file* menu click on the *Open* button or directly click the *Open* button in the toolbar as shown in Figure 4-5. This will enable the *Load OpenDSS circuit* button. GICharm will scan the selected case and the user will be prompted with an information dialog in case the chosen file is invalid.



EE: - V/km EN: - V/km

Run Iterations 5

Progress / ite. 0%

Completed iterations: 0

Harmonic to check 1

Figure 4-5
Browse for and open the master **.dss* file for your case

Once a valid file has been selected, the next step is to load the circuit model as shown in Figure 4-6. This will populate relevant circuit element data in the frames highlighted in Figure 4-6. The available element data can be explored by selecting an element from a given *Element tab* (Buses, Transformers, Lines, Shunts and Generators) in the top frame. The details of the chosen element will be updated in the bottom frame. Additionally, loading the circuit model will also load any previously saved progress in the harmonics tool.

The next step in the process is to run the GIC flow analysis, as shown in Figure 4-7. This analysis takes place only once unless the system configuration or the geomagnetic disturbance-related electric field change. As a result, other analysis options become enabled: Frequency Scan analysis, Harmonics loop analysis, and circuit plot options.

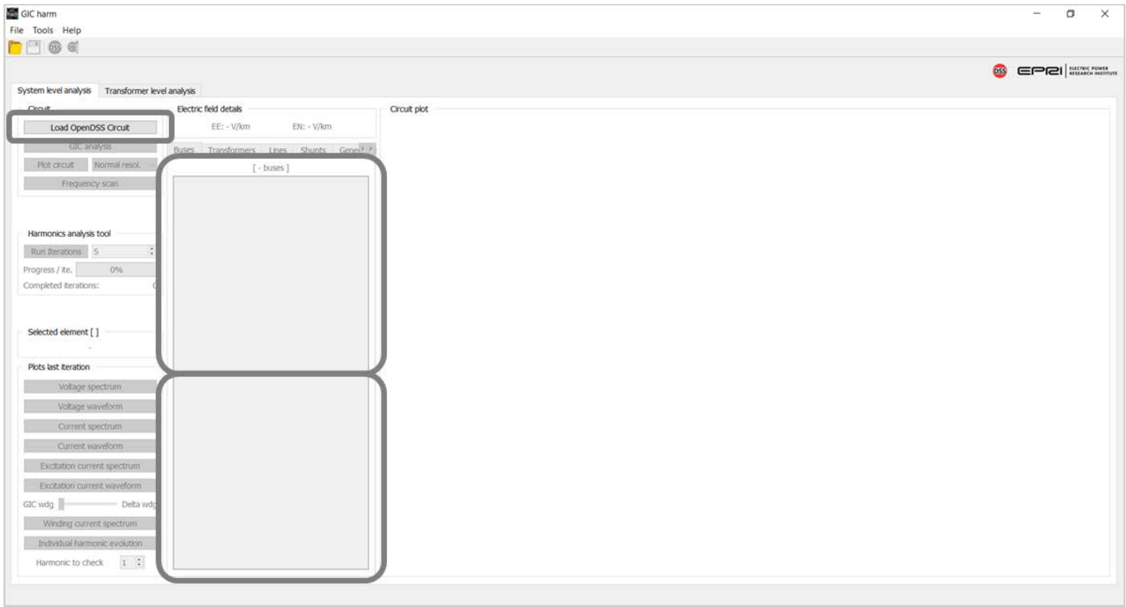
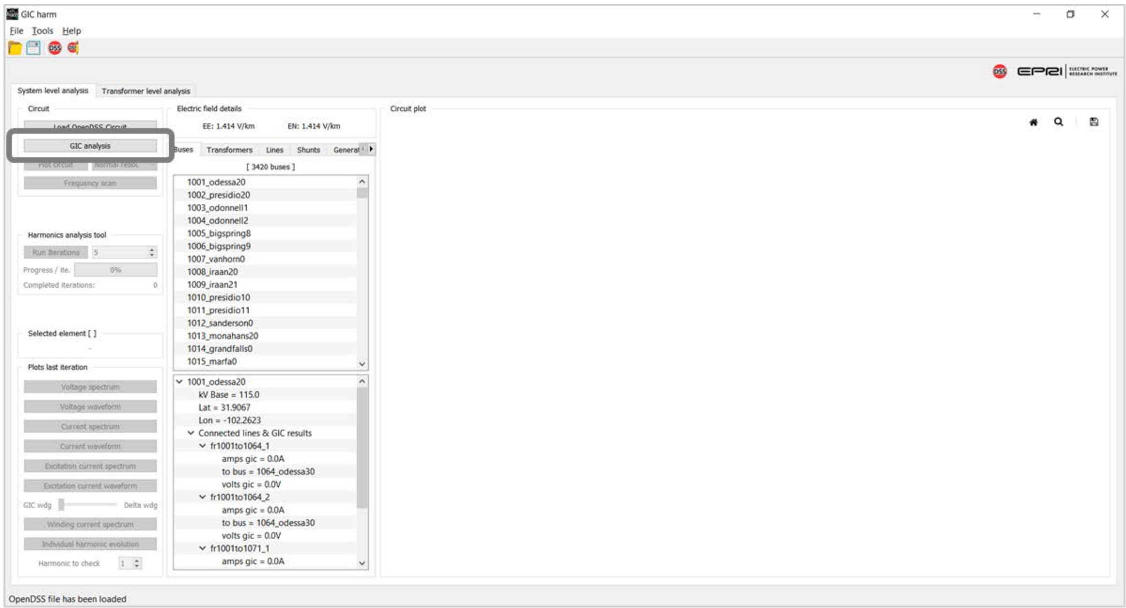


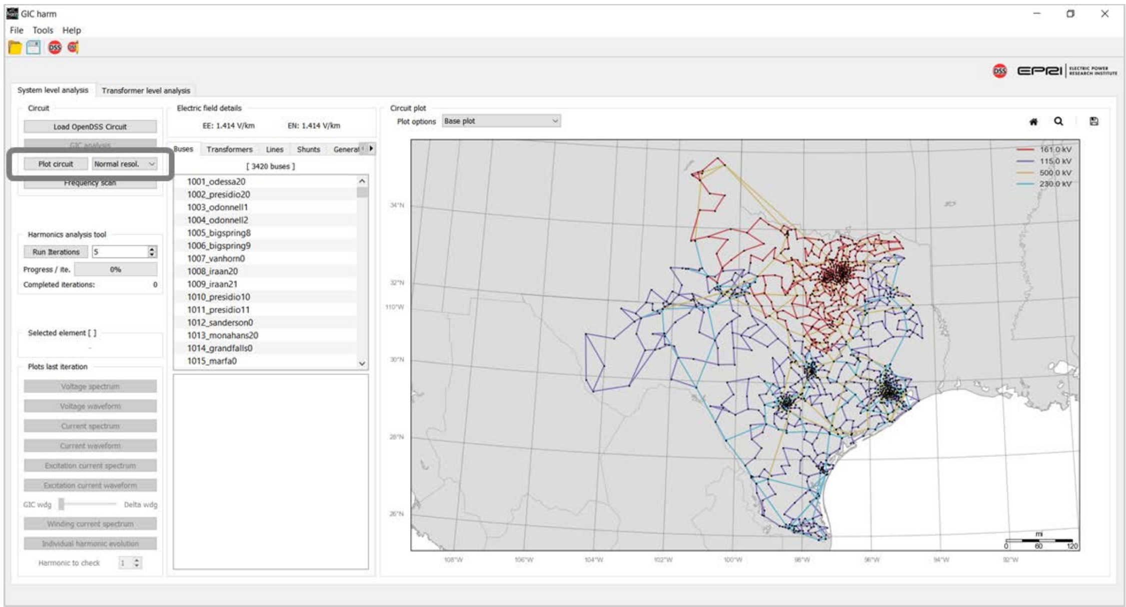
Figure 4-6
Load the master **.dss* file of your case



```
EE: 1.414 V/km        EN: 1.414 V/km

[ 3420 buses ]
1001_odessa20
1002_presidio20
1003_odonnell1
1004_odonnell2
1005_bigspring8
1006_bigspring9
1007_vanhorn0
1008_iraan20
1009_iraan21
1010_presidio10
1011_presidio11
1012_sanderson0
1013_monahans20
1014_grandfalls0
1015_marfa0

v 1001_odessa20
    kV Base = 115.0
    Lat = 31.9067
    Lon = -102.2623
  v Connected lines & GIC results
    v fr1001to1064_1
        amps gic = 0.0A
        to bus = 1064_odessa30
        volts gic = 0.0V
    v fr1001to1064_2
        amps gic = 0.0A
        to bus = 1064_odessa30
        volts gic = 0.0V
    v fr1001to1071_1
        amps gic = 0.0A

OpenDSS file has been loaded
```

Figure 4-7
Run the GIC flow analysis

At this point, the circuit can be plotted and the user can explore it in the program's graphic interface. As shown in Figure 4-8, beside the *Plot Circuit* button, a map resolution selector is available for the user to change the resolution of the plot (*High* and *Normal* resolutions are available). The capabilities of the circuit plot are detailed in the **Circuit Plot capabilities** subsection.

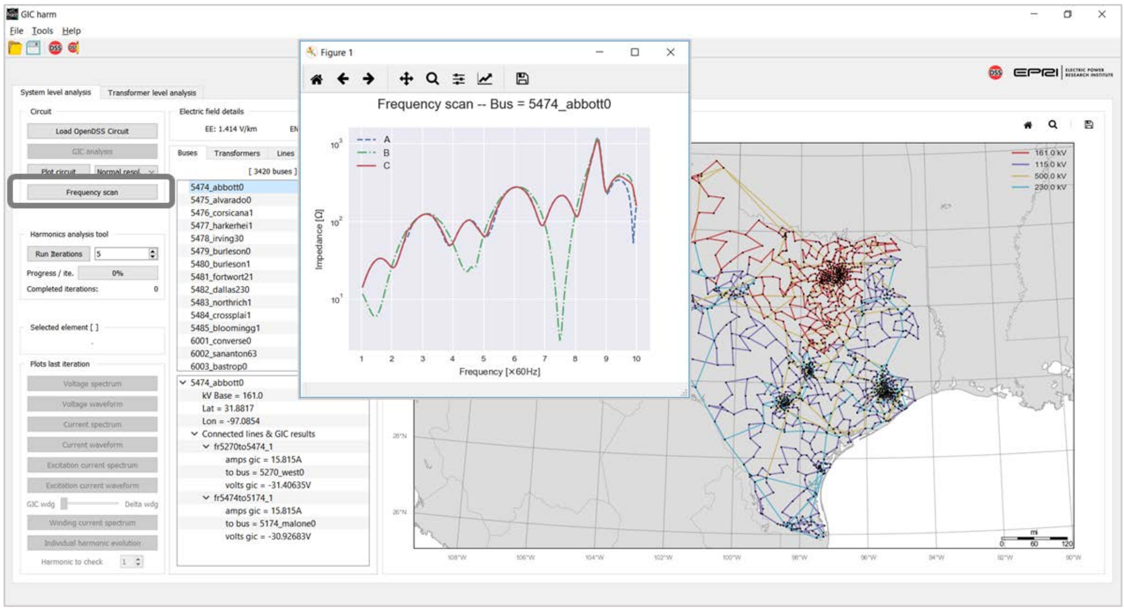


EE: 1.414 V/km
EN: 1.414 V/km
[3420 buses]
Run Iterations: 5
Progress / ite.: 0%
Completed iterations: 0
Plot options: Base plot

1001_odessa20
1002_presidio20
1003_odonnell1
1004_odonnell2
1005_bigspring8
1006_bigspring9
1007_vanhorn0
1008_iraan20
1009_iraan21
1010_presidio10
1011_presidio11
1012_sanderson0
1013_monahans20
1014_grandfalls0
1015_marfa0

Figure 4-8
Plot the geographic footprint of the system

At this point, it is also possible to run a frequency scan. For this, the user must select a bus on the *Buses* tab and click on the *Frequency Scan* button. This function will place a current source of 1 Ampere and will vary its frequency from the fundamental up to a user-defined higher harmonic order. The result is an impedance versus frequency plot as shown in Figure 4-9. The bus where the frequency scan analysis is performed can also be selected using the circuit plot as described in the **Circuit Plot capabilities** subsection.



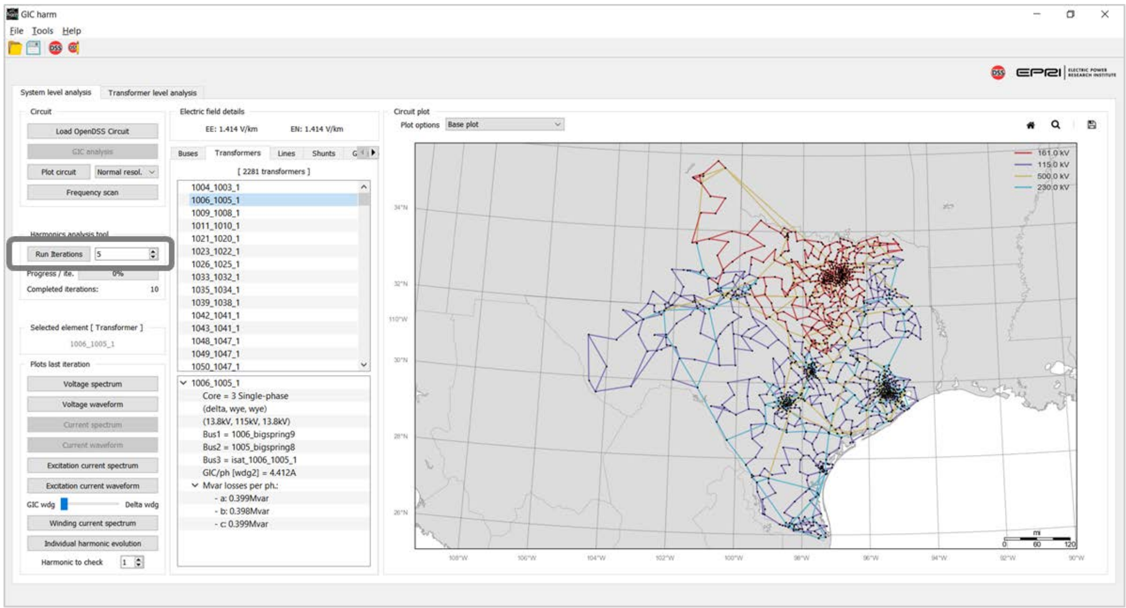
EE: 1.414 V/km
[3420 buses]
Run Iterations: 5
Progress / ite.: 0%
Completed iterations: 0

5474_abbott0
5475_alvarado0
5476_corsicana1
5477_harkerhei1
5478_irving30
5479_burleson0
5480_burleson1
5481_fortwort21
5482_dallas230
5483_northrich1
5484_crossplai1
5485_bloomingg1
6001_converse0
6002_sananton63
6003_bastrop0

5474_abbott0
  kV Base = 161.0
  Lat = 31.8817
  Lon = -97.0854
  Connected lines & GIC results
    fr5270to5474_1
      amps gic = 15.815A
      to bus = 5270_west0
      volts gic = -31.40635V
    fr5474to5174_1
      amps gic = 15.815A
      to bus = 5174_malone0
      volts gic = -30.92683V

Figure 4-9
Running a frequency scan at a user-selected bus

The most important analysis in GICharm is the harmonics loop. To run this analysis, the user must define a number of iterations (5 by default) and then click on the *Run Iterations* button as shown in Figure 4-10. As mentioned before, the iterations are cumulative. In other words, each iteration starts where the previous one ends. If progress is saved, when loading the system again, a dialog will ask if the user wants to start from the previously saved state of the simulation.

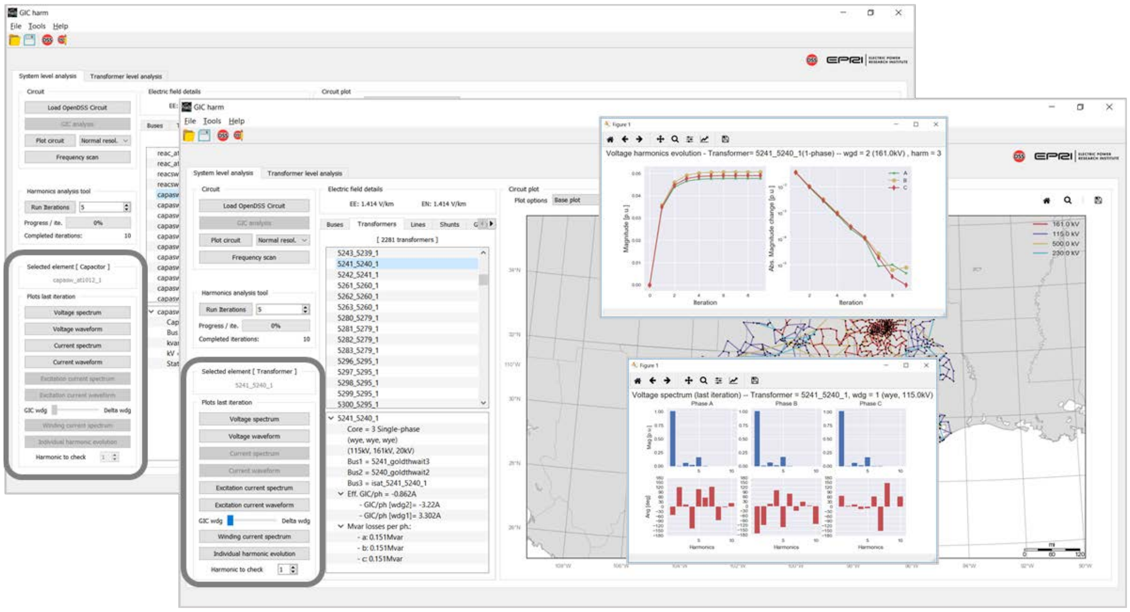


Normal resol.
Run Iterations: 5
Progress / ite. 0%
Completed iterations: 10
Selected element [Transformer]
1006_1005_1
Harmonic to check: 1
EE: 1.414 V/km EN: 1.414 V/km
[2281 transformers]
1004_1003_1
1006_1005_1
1009_1008_1
1011_1010_1
1021_1020_1
1023_1022_1
1026_1025_1
1033_1032_1
1035_1034_1
1039_1038_1
1042_1041_1
1043_1041_1
1048_1047_1
1049_1047_1
1050_1047_1

1006_1005_1
- Core = 3 Single-phase
- (delta, wye, wye)
- (13.8kV, 115kV, 13.8kV)
- Bus1 = 1006_bigspring9
- Bus2 = 1005_bigspring8
- Bus3 = isat_1006_1005_1
- GIC/ph [wdg2] = 4.412A
- Mvar losses per ph.:
  - a: 0.399Mvar
  - b: 0.398Mvar
  - c: 0.399Mvar

Plot options: Base plot

Figure 4-10
Running a user-defined amount of iterations of the harmonics loop



Selected element [Capacitor]

Normal resol.
Run Iterations: 5
Progress / ite. 0%
Completed iterations: 10
Selected element [Transformer]
5241_5240_1
Harmonic to check: 1
EE: 1.414 V/km EN: 1.414 V/km
[2281 transformers]
5243_5239_1
5241_5240_1
5242_5241_1
5261_5260_1
5262_5260_1
5263_5260_1
5280_5279_1
5281_5279_1
5282_5279_1
5283_5279_1
5296_5295_1
5297_5295_1
5298_5295_1
5299_5295_1
5300_5295_1

5241_5240_1
- Core = 3 Single-phase
- (wye, wye, wye)
- (115kV, 161kV, 20kV)
- Bus1 = 5241_goldthwait3
- Bus2 = 5240_goldthwait2
- Bus3 = isat_5241_5240_1
- Eff. GIC/ph = -0.862A
  - GIC/ph [wdg2]= -3.22A
  - GIC/ph [wdg1]= 3.302A
- Mvar losses per ph.:
  - a: 0.151Mvar
  - b: 0.151Mvar
  - c: 0.151Mvar

Plot options: Base plot

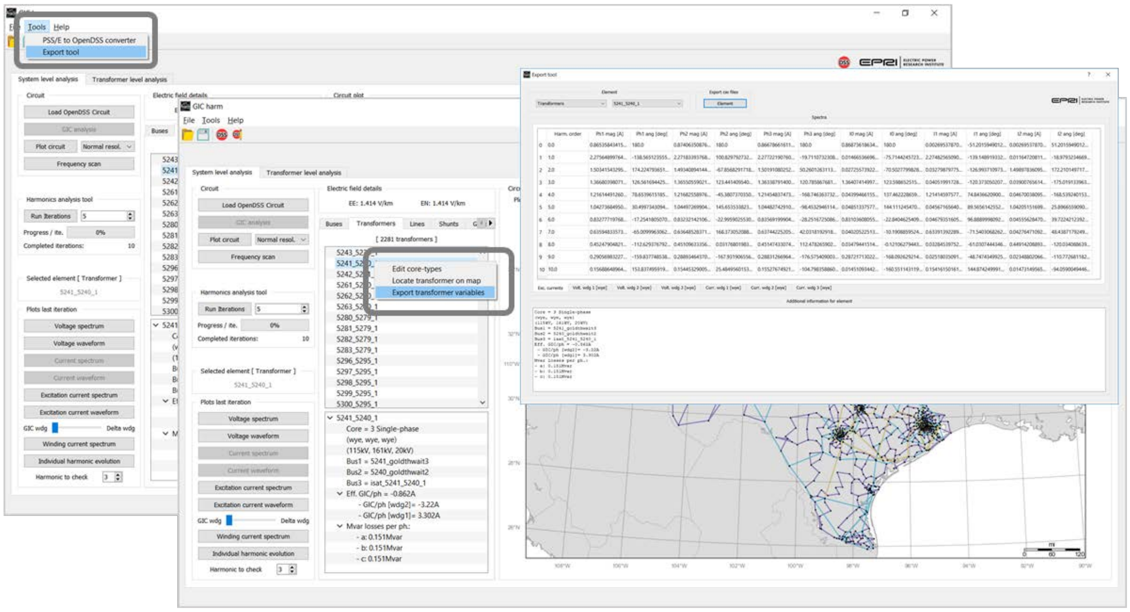
Voltage harmonics evolution - Transformer= 5241_5240_1(1-phase) -- wgd = 2 (161.0kV) , harm = 3

Voltage spectrum (last iteration) -- Transformer = 5241_5240_1, wdg = 1 (wye, 115.0kV)

Figure 4-11
Plotting last iteration results

After running the harmonics loop for the first time, the program enables plots for relevant variables of elements in the system. As shown in Figure 4-11, at the end of each iteration of the harmonics loop, the user can plot waveforms and spectra of voltage and currents for capacitors, reactors, and generators, and of winding currents and voltages for transformers. It is also possible to check the evolution of the voltage magnitude for each harmonic for the GIC affected. To do this, the user must select an element from the desired *Element* tab. This will enable the plot options for the chosen element in the *Plot last iteration* section of the program interface.

At this point, it is also possible to export **.csv* files of the spectra of variables that belong to a user-selected element as shown in Figure 4-12. To do this, the user can right click over the name of the desired element in the *Element* tabs, and then select the *Export element variables* option from the context menu. Another option to export the variables of an element is to open the *Export tool* directly from the *Tools* menu. In both cases, the *Export tool* shown in Figure 4-12 will appear. This tool allows the user to select all the possible elements that have exportable variables, and it also provides information about the user-selected element. The *Export tool* displays tables with the magnitudes and angles for the voltages and currents per harmonic order per phase, as well as the sequence components per harmonic order. Once the user has selected an element, the next step is to click on the *Element* button from the *Export csv files* section and select a path to save the files.



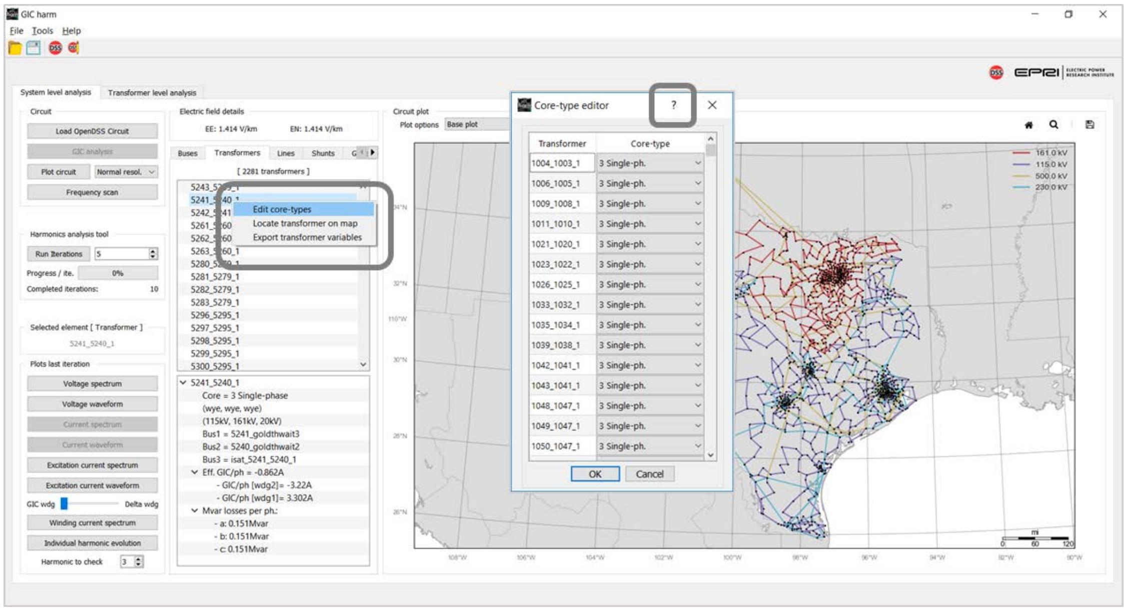
Selected element [Transformer]
5241_5240_1

EE: 1.414 V/km
EN: 1.414 V/km

5241_5240_1
Core = 3 Single-phase
(wye, wye, wye)
(115kV, 161kV, 20kV)
Bus1 = 5241_goldthwait3
Bus2 = 5240_goldthwait2
Bus3 = isat_5241_5240_1
Eff. GIC/ph = -0.862A
- GIC/ph [wdg2]= -3.22A
- GIC/ph [wdg1]= 3.302A
Mvar losses per ph.:
- a: 0.151Mvar
- b: 0.151Mvar
- c: 0.151Mvar

Figure 4-12
Exporting results from last harmonics loop iteration

The results of a system level simulation depend on several variables like the core-topology of transformers, the GMD related electric field components, or the capacitors connected on the system. To check the influence of these variables, the user can modify them as shown in Figure 4-13, Figure 4-14, and Figure 4-15. To modify the core-topologies of transformers in the system, the user must right click over the *Transformers* tab and select the option *Edit core-types* from the context menu. This will prompt the user with a *Core-type editor* tool that allows them to select the core-type of each of the transformers in the system as shown in Figure 4-13. Any change made in this editor will not be considered by the program unless the user clicks on the *Ok* button and accepts to restart the harmonics loop. Additionally, the user can modify all the transformers at once by right clicking on the *Core-type* header of the editor table and selecting one of the available options: *Reset all* will reset any changes to the core-type that the user has not saved since the core-type editor was opened; *Set all as* will define all the core-types of all the transformers in the system as one of the four options available (3 Single-phase, 3-lib, 5-lib, Shell-form).



Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 5241_5240_1

Harmonic to check: 3

EE: 1.414 V/km EN: 1.414 V/km

[2281 transformers]

5243_5
5241_5240_1
5242_5241
5261_5260
5262_5260
5263_5260_1
5280_52
5281_5279_1
5282_5279_1
5283_5279_1
5296_5295_1
5297_5295_1
5298_5295_1
5299_5295_1
5300_5295_1

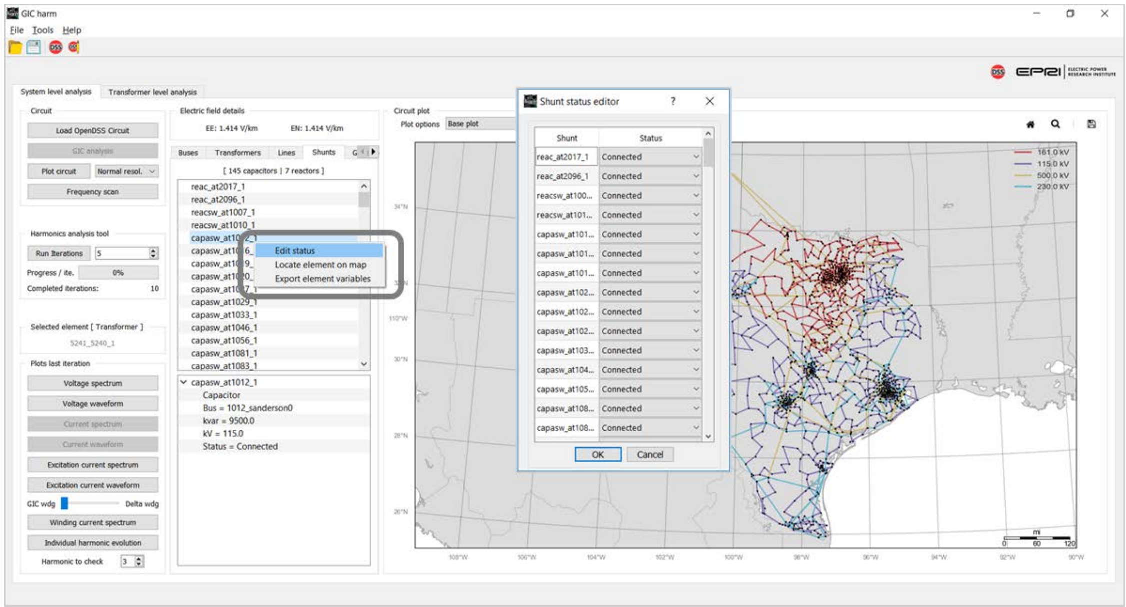
5241_5240_1
- Core = 3 Single-phase
- (wye, wye, wye)
- (115kV, 161kV, 20kV)
- Bus1 = 5241_goldthwait3
- Bus2 = 5240_goldthwait2
- Bus3 = isat_5241_5240_1
- Eff. GIC/ph = -0.862A
  - - GIC/ph [wdg2]= -3.22A
  - - GIC/ph [wdg1]= 3.302A
- Mvar losses per ph.:
  - - a: 0.151Mvar
  - - b: 0.151Mvar
  - - c 0.151Mvar

Transformer	Core-type
1004_1003_1	3 Single-ph.
1006_1005_1	3 Single-ph.
1009_1008_1	3 Single-ph.
1011_1010_1	3 Single-ph.
1021_1020_1	3 Single-ph.
1023_1022_1	3 Single-ph.
1026_1025_1	3 Single-ph.
1033_1032_1	3 Single-ph.
1035_1034_1	3 Single-ph.
1039_1038_1	3 Single-ph.
1042_1041_1	3 Single-ph.
1043_1041_1	3 Single-ph.
1048_1047_1	3 Single-ph.
1049_1047_1	3 Single-ph.
1050_1047_1	3 Single-ph.

Figure 4-13
Editing the transformer core topologies

On the other hand, to modify the connection status of capacitors and reactors in the system, the user must right click over the *Shunts* tab and select the option *Edit status* from the context menu. This will prompt the user with a *Shunt status editor* tool that allows them to select the connection status of each of the capacitors and reactors in the system as shown in Figure 4-14. Any change made in this editor will not be considered by the program unless the user clicks on the *Ok* button and accepts to restart the harmonics loop. Additionally, the user can modify all the status of shunt elements at once by right clicking on the *Status* header of the editor table and selecting one of the available options: *Reset all* will reset any connection status changes that the user has not saved since the editor was opened; *Set all as* will define all the status to either *Connected* or *Disconnected*.

Similarly, to modify the electric field component magnitudes, the user must do a right click over the *Electric field details* section of the program interface and select the option *Edit components* from the context menu (it's the only option in this case). This will prompt the user with a *E. field parameters editor* tool that allows them to modify the V/km value of the electric field components as shown in Figure 4-15. Other parameters are available for edition, but these do not influence the simulation in this version of GICharm. Again, any change made in the editor will not be considered by the program unless the user clicks on the *Ok* button and accepts to restart the harmonics loop. Additionally, the user can reset any unsaved changes by right clicking on the *Value* header of the editor table and selecting the *Reset all* option.



Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 5241_5240_1

Harmonic to check: 3

EE: 1.414 V/km EN: 1.414 V/km

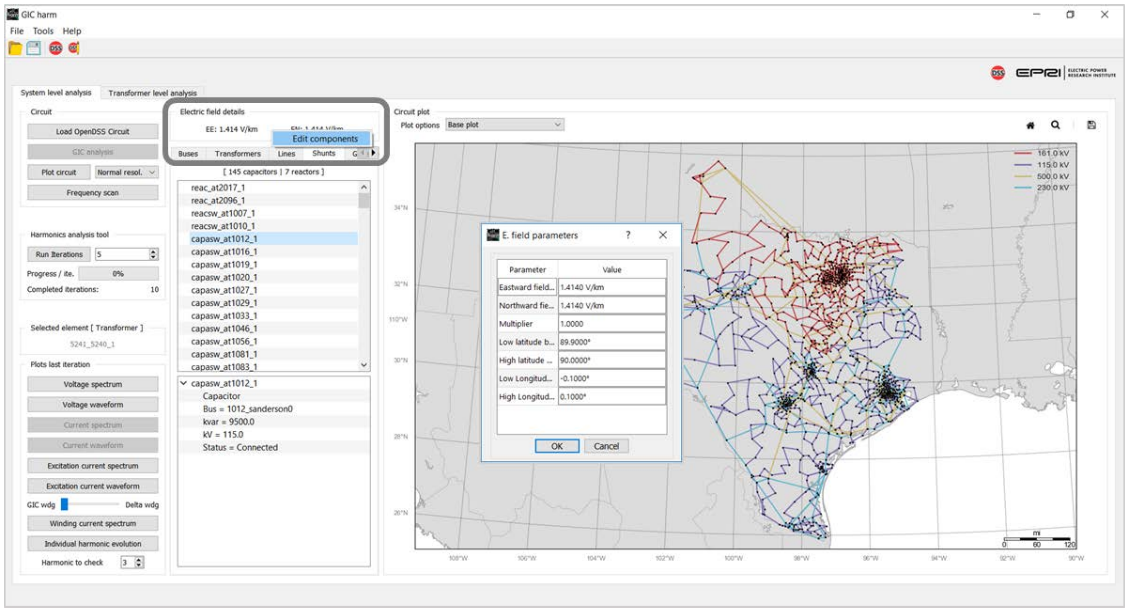
[145 capacitors | 7 reactors]

reac_at2017_1
reac_at2096_1
reacsw_at1007_1
reacsw_at1010_1
capasw_at1012_1
capasw_at1016_
capasw_at1019_
capasw_at1020_
capasw_at1027_1
capasw_at1029_1
capasw_at1033_1
capasw_at1046_1
capasw_at1056_1
capasw_at1081_1
capasw_at1083_1

capasw_at1012_1
Capacitor
Bus = 1012_sanderson0
kvar = 9500.0
kV = 115.0
Status = Connected

Shunt	Status
reac_at2017_1	Connected
reac_at2096_1	Connected
reacsw_at100...	Connected
reacsw_at101...	Connected
capasw_at101...	Connected
capasw_at101...	Connected
capasw_at101...	Connected
capasw_at102...	Connected
capasw_at102...	Connected
capasw_at102...	Connected
capasw_at103...	Connected
capasw_at104...	Connected
capasw_at105...	Connected
capasw_at108...	Connected
capasw_at108...	Connected

Figure 4-14
Editing the status of capacitors and reactors

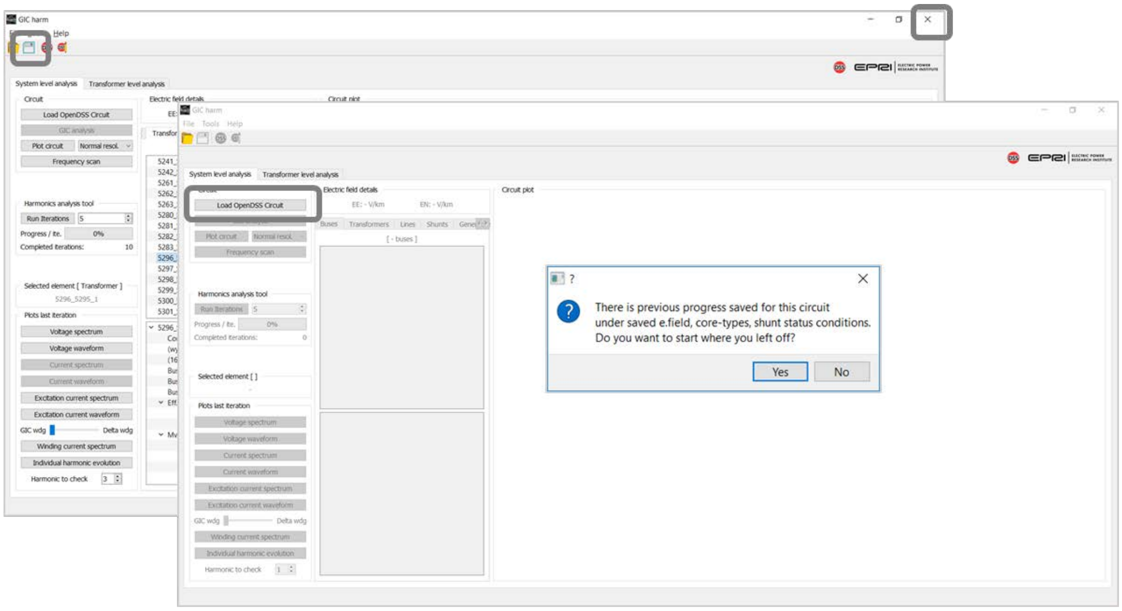


EE: 1.414 V/km

Parameter	Value
Eastward field...	1.4140 V/km
Northward fie...	1.4140 V/km
Multiplier	1.0000
Low latitude b...	89.9000°
High latitude ...	90.0000°
Low Longitud...	-0.1000°
High Longitud...	0.1000°

Figure 4-15
Editing the electric field components

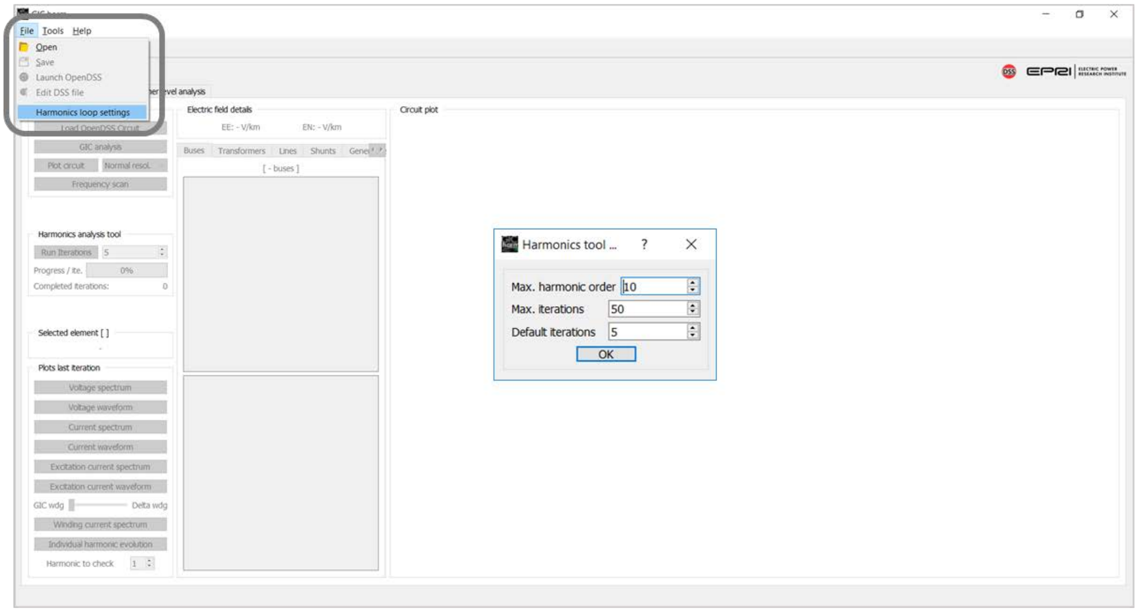
To save any progress or changes in the system, the user can click on the *Save* button as in Figure 4-16, or try to close application. Every time GICharm is asked to close, the program will remind the user to save changes. Another option to save progress is to go to the *File* menu and select the *Save* option.



?

There is previous progress saved for this circuit under saved e.field, core-types, shunt status conditions. Do you want to start where you left off?

Figure 4-16
Saving and loading work progress



Max. harmonic order 10
Max. iterations 50
Default iterations 5

Figure 4-17
Changing default simulation settings

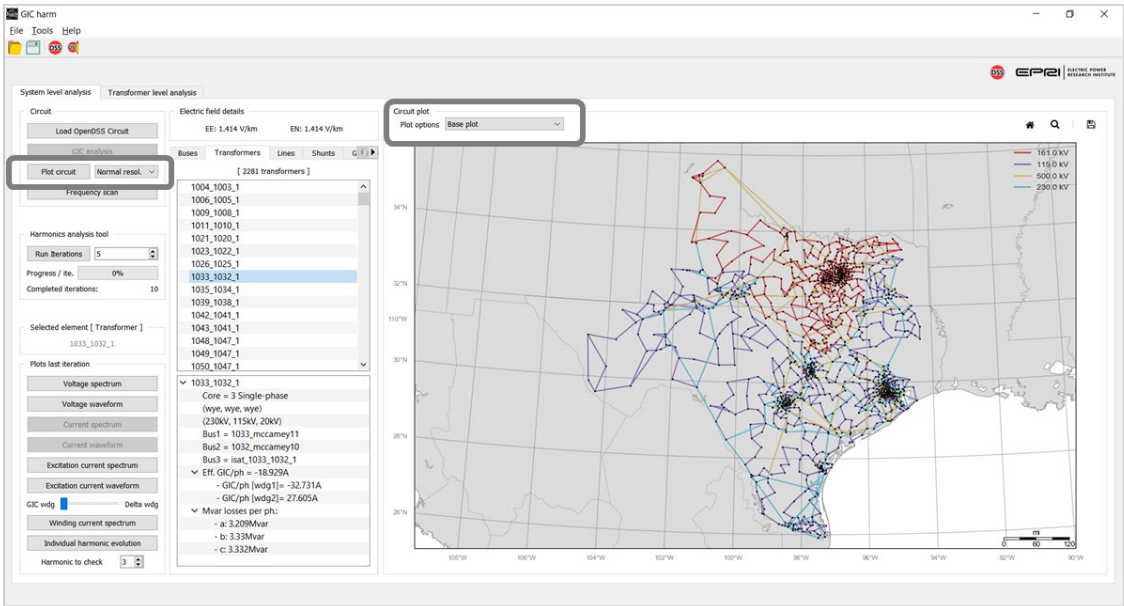
Finally, the user can reset three simulation settings with values defined by default: the maximum harmonic order, the maximum number of iterations to run for the harmonics loop, and the default number of iterations to run each time the *Run Iterations* button is clicked. To make these changes, go to the *File* menu, select the *Harmonics loop settings* option and use the dialog that appears to save new default values.

The *File* menu also includes options to launch *OpenDSS* with the currently open **.dss* system files or launch a text editor to modify the master **.dss* file (a system must be loaded in GICharm to enable these options). When using GICharm for the first time, it is likely that the user will be required to define paths for external program executables like the PDF reader, the preferred text editor (*notepad.exe* by default), or the OpenDSS executable. To do this, the user must select the option that corresponds in the *Help* menu (*Reset preferred OpenDSS.exe*, *Reset preferred text editor*, and *Reset preferred PDF reader*). The *Help* menu also includes the *Help documents* submenu that opens help PDF files that summarize this guide.

Circuit Plot Capabilities

GICharm has a number of circuit plot capabilities developed to help users in the analysis of their simulation results. Before starting, it is important to mention that the **.dss* files used in the example of this section were converted from a set of **.raw* and **.gic* files obtained from [9]. Once the user has loaded a valid system and run the GIC flow analysis, the program enables the *Plot circuit* button to plot the geographic footprint of the system, along with details of relevant variables overlaid on top of the circuit. A map resolution selector is available with two options: *Normal* and *High* resolution. High resolution is intended to be used when the system spans a relatively small area. In that scenario, the geographic details (water bodies, rivers, state lines, etc.) can be enhanced with a high map resolution plot.

The circuit plot has four plot layer options: *Base plot*, *GIC flow directions*, *Fundamental voltage*, and *Voltage THD*. The user can change between these layers in the *Plot options* selector highlighted in Figure 4-18. This figure also shows the *Base plot* which is the default option. The *Base plot* shows the voltage kV base of each line and the position of buses in the system. If the user hovers the mouse cursor over the lines of the system, the name of the buses connected by the line appear in labels at the left side of the map, and the GIC per phase flowing through the line is displayed beside the line and in the bottom left corner of the map.



Normal resol.

Run Iterations: 5

Progress / ite. 0%

Completed iterations: 10

Selected element [Transformer]
1033_1032_1

Harmonic to check: 3

Electric field details
EE: 1.414 V/km
EN: 1.414 V/km

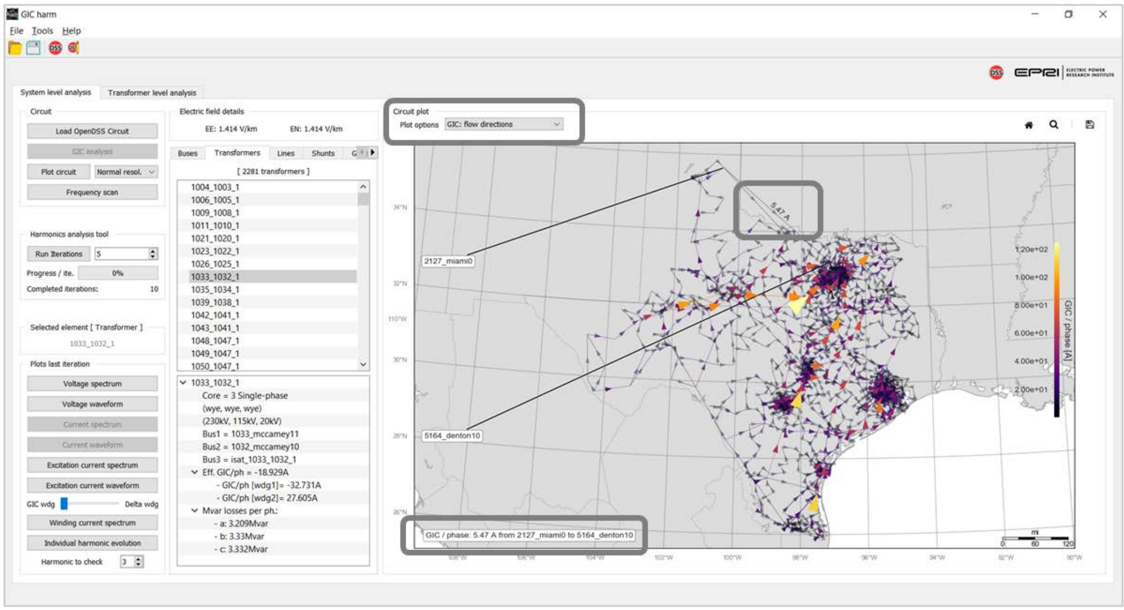
[2281 transformers]
1004_1003_1
1006_1005_1
1009_1008_1
1011_1010_1
1021_1020_1
1023_1022_1
1026_1025_1
1033_1032_1
1035_1034_1
1039_1038_1
1042_1041_1
1043_1041_1
1048_1047_1
1049_1047_1
1050_1047_1

- 1033_1032_1
  - Core = 3 Single-phase
  - (wye, wye, wye)
  - (230kV, 115kV, 20kV)
  - Bus1 = 1033_mccamey11
  - Bus2 = 1032_mccamey10
  - Bus3 = isat_1033_1032_1
  - Eff. GIC/ph = -18.929A
    - GIC/ph [wdg1]= -32.731A
    - GIC/ph [wdg2]= 27.605A
  - Mvar losses per ph.:
    - a: 3.209Mvar
    - b: 3.33Mvar
    - c: 3.332Mvar

Plot options: Base plot

Figure 4-18
Circuit plot - Base plot

The second circuit plot option is *GIC flow directions* which can be observed in Figure 4-19. This plot option allows the user to identify the lines with the highest GIC flows per phase. It uses arrow tips and a heatmap to identify the magnitude of GIC per phase flowing through a line. It can also be used, together with the *Base plot,* to visually identify the amount of GIC that arrives at a given transformer. If the user hovers over the lines of the system, the information that appears is similar to that of the *Base plot* option (bus names and GIC per phase).



Normal resol.

Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 1033_1032_1

Harmonic to check: 3

EE: 1.414 V/km EN: 1.414 V/km

[2281 transformers]

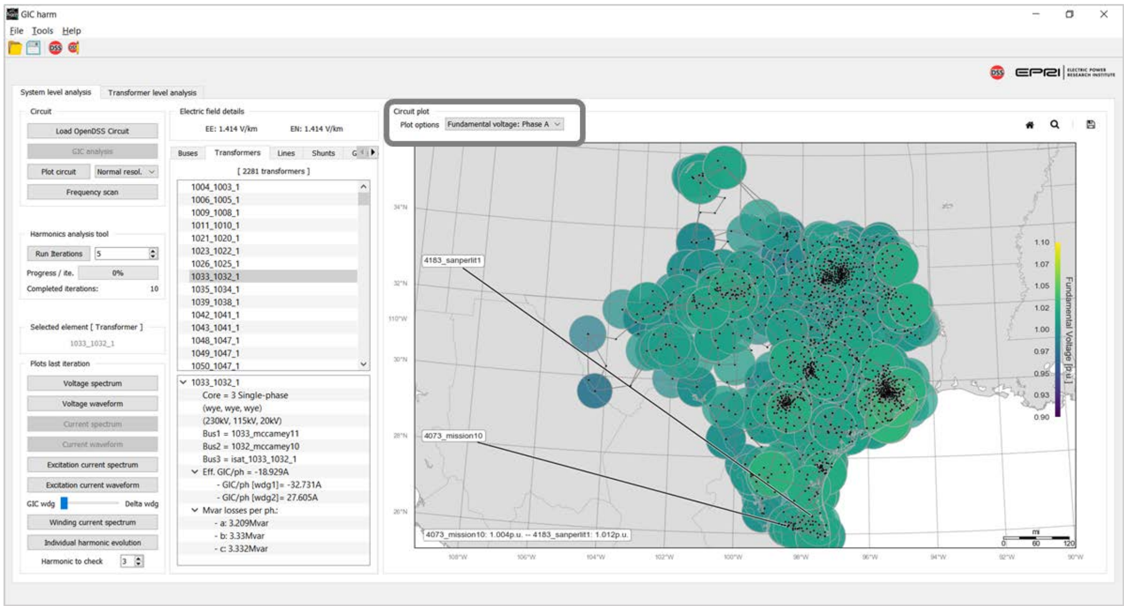
1004_1003_1
1006_1005_1
1009_1008_1
1011_1010_1
1021_1020_1
1023_1022_1
1026_1025_1
1033_1032_1
1035_1034_1
1039_1038_1
1042_1041_1
1043_1041_1
1048_1047_1
1049_1047_1
1050_1047_1

- 1033_1032_1
  - Core = 3 Single-phase
  - (wye, wye, wye)
  - (230kV, 115kV, 20kV)
  - Bus1 = 1033_mccamey11
  - Bus2 = 1032_mccamey10
  - Bus3 = isat_1033_1032_1
  - Eff. GIC/ph = -18.929A
    - GIC/ph [wdg1]= -32.731A
    - GIC/ph [wdg2]= 27.605A
  - Mvar losses per ph.:
    - a: 3.209Mvar
    - b: 3.33Mvar
    - c: 3.332Mvar

Plot options: GIC: flow directions

GIC / phase: 5.47 A from 2127_miami0 to 5164_denton10

Figure 4-19
GIC flow circuit plot



Normal resol.

Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 1033_1032_1

Harmonic to check: 3

EE: 1.414 V/km EN: 1.414 V/km

[2281 transformers]

1004_1003_1
1006_1005_1
1009_1008_1
1011_1010_1
1021_1020_1
1023_1022_1
1026_1025_1
1033_1032_1
1035_1034_1
1039_1038_1
1042_1041_1
1043_1041_1
1048_1047_1
1049_1047_1
1050_1047_1

- 1033_1032_1
  - Core = 3 Single-phase
  - (wye, wye, wye)
  - (230kV, 115kV, 20kV)
  - Bus1 = 1033_mccamey11
  - Bus2 = 1032_mccamey10
  - Bus3 = isat_1033_1032_1
  - Eff. GIC/ph = -18.929A
    - GIC/ph [wdg1]= -32.731A
    - GIC/ph [wdg2]= 27.605A
  - Mvar losses per ph.:
    - a: 3.209Mvar
    - b: 3.33Mvar
    - c: 3.332Mvar

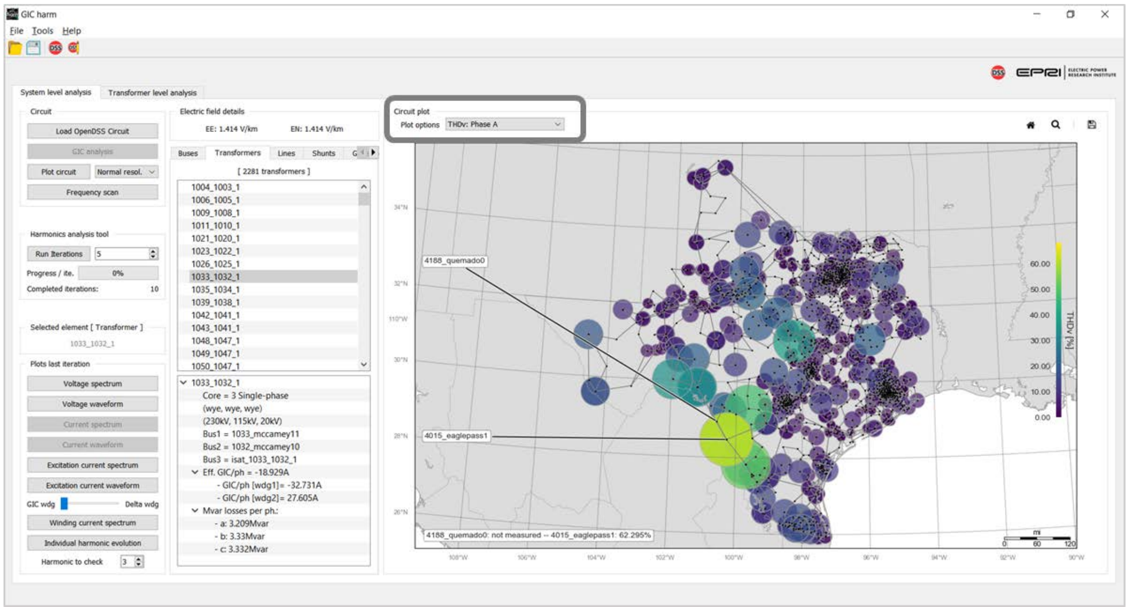
Plot options: Fundamental voltage: Phase A

4073_mission10: 1.004p.u. -- 4183_sanperlit1: 1.012p.u.

Figure 4-20
Fundamental voltage magnitude per phase circuit plot

The third circuit option is called *Fundamental voltage* and it corresponds to three separate options, one per phase. As shown in Figure 4-20, this option overlays circles on top of the system footprint, centered where buses, reactors, capacitors, generators or transformers are connected. The color and size of the circle varies with the fundamental voltage magnitude per phase. The heatmap that defines the color and magnitude scale is defined with the same range for all three phases to easily compare between phases. The default range is 0.9 p.u. to 1.1 p.u. unless the voltages in the system lie outside that range (this resets the range). This plot option is useful to identify buses where the fundamental voltage magnitude decreases considerably due to reactive power losses caused by the saturation of transformers during GMD events. When this plot option is active, if the mouse cursor is hovered over a line in the system, the line's buses names are displayed and the fundamental voltage magnitudes at these buses are also displayed at the bottom left corner of the map.

The fourth plot option is called *voltage THD* per phase, and it also corresponds to three separate options, one per phase. Like the third option, it also overlays circles on top of the system footprint centered on buses where it has reactors, capacitors, generators or transformers, as shown in Figure 4-21. The colors and sizes of circles vary with the voltage THD per phase. The heatmap that defines the color of the circles and the THD scale is defined with the same range for all three phases to easily compare between phases. The range is determined by the maximum and minimum voltage THD values found across the system over the three phases. Additionally, when the user selects this plot option, if the mouse cursor is hovered over a line in the system, the line's buses names are displayed and the voltage THD at these buses is also displayed at the bottom left corner of the map.



Normal resol.

Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 1033_1032_1

EE: 1.414 V/km EN: 1.414 V/km

[2281 transformers]

1004_1003_1
1006_1005_1
1009_1008_1
1011_1010_1
1021_1020_1
1023_1022_1
1026_1025_1
1033_1032_1
1035_1034_1
1039_1038_1
1042_1041_1
1043_1041_1
1048_1047_1
1049_1047_1
1050_1047_1

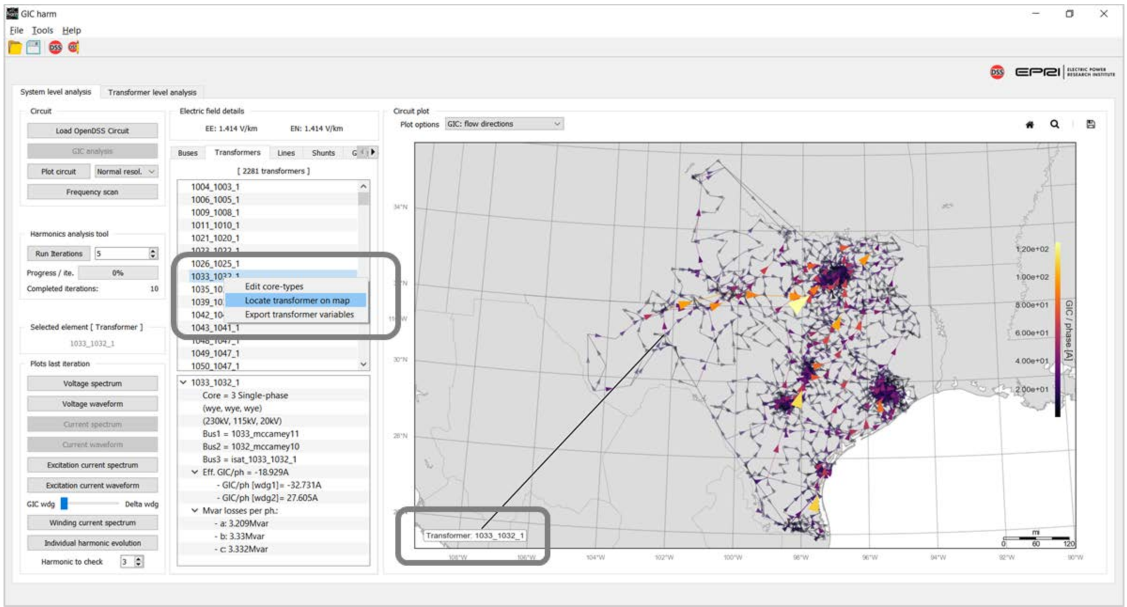
1033_1032_1
  Core = 3 Single-phase
  (wye, wye, wye)
  (230kV, 115kV, 20kV)
  Bus1 = 1033_mccamey11
  Bus2 = 1032_mccamey10
  Bus3 = isat_1033_1032_1
  Eff. GIC/ph = -18.929A
    - GIC/ph [wdg1]= -32.731A
    - GIC/ph [wdg2]= 27.605A
  Mvar losses per ph.:
    - a: 3.209Mvar
    - b: 3.33Mvar
    - c: 3.332Mvar

Harmonic to check: 3

Plot options: THDv: Phase A

4188_quemado0: not measured -- 4015_eaglepass1: 62.295%

Figure 4-21
Voltage THD per phase circuit plot



Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 1033_1032_1

Harmonic to check: 3

EE: 1.414 V/km EN: 1.414 V/km

[2281 transformers]

1004_1003_1
1006_1005_1
1009_1008_1
1011_1010_1
1021_1020_1
1026_1025_1
1033_1032_1
1043_1041_1
1049_1047_1
1050_1047_1

1033_1032_1
  Core = 3 Single-phase
  (wye, wye, wye)
  (230kV, 115kV, 20kV)
  Bus1 = 1033_mccamey11
  Bus2 = 1032_mccamey10
  Bus3 = isat_1033_1032_1
  Eff. GIC/ph = -18.929A
    - GIC/ph [wdg1]= -32.731A
    - GIC/ph [wdg2]= 27.605A
  Mvar losses per ph.:
    - a: 3.209Mvar
    - b: 3.33Mvar
    - c: 3.332Mvar

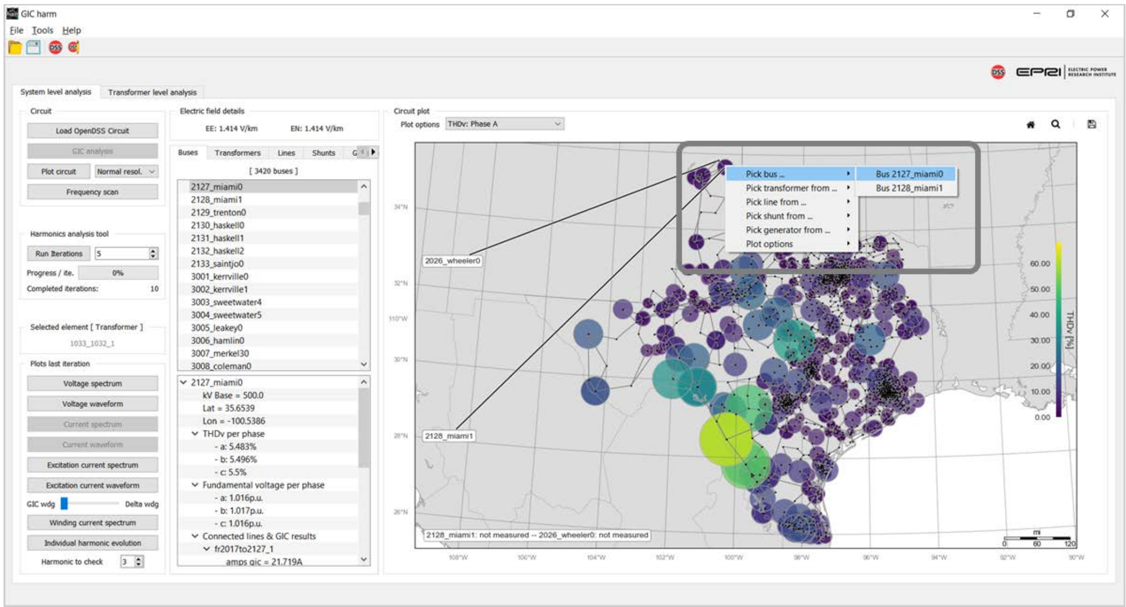
Plot options: GIC: flow directions

Transformer: 1033_1032_1

Figure 4-22
Locating an element or bus on the circuit plot

Besides the plot options, the circuit plot is also useful to explore the results of the simulation or the circuit itself. By going to an *Element* tab, doing a right click over a given element name, and selecting the *Locate element on map* option from the context menu, the user can locate most of the elements on the map. As a result, a label will show up on the map pointing at the bus where the chosen element lies, as shown in Figure 4-22. Similarly, the user can do a right click over a bus in the circuit plot and, from the context menu that appears, pick a bus or a circuit element connected to that bus. As a result, the chosen element will be selected in the corresponding element tab and its details will be displayed in the details frame. Figure 4-23 shows an example of this last capability.

Additionally, the user can right click over the map and, depending on the active circuit plot option, filter or modify the order of plot objects being displayed (markers for buses, lines, and circles for THD and fundamental voltage). This is helpful, for example, when several buses are concentrated around a geographic region (a big city for instance) and their markers hide information making it difficult to check results. For instance, Figure 4-24 shows the *THDv: Phase A* plot and the options for this include hiding higher or lower THD bubbles, showing all THD bubbles, bringing bus markers to front, and bringing lines to front.



EE: 1.414 V/km EN: 1.414 V/km

Plot options: THDv: Phase A

Normal resol.

[3420 buses]

Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

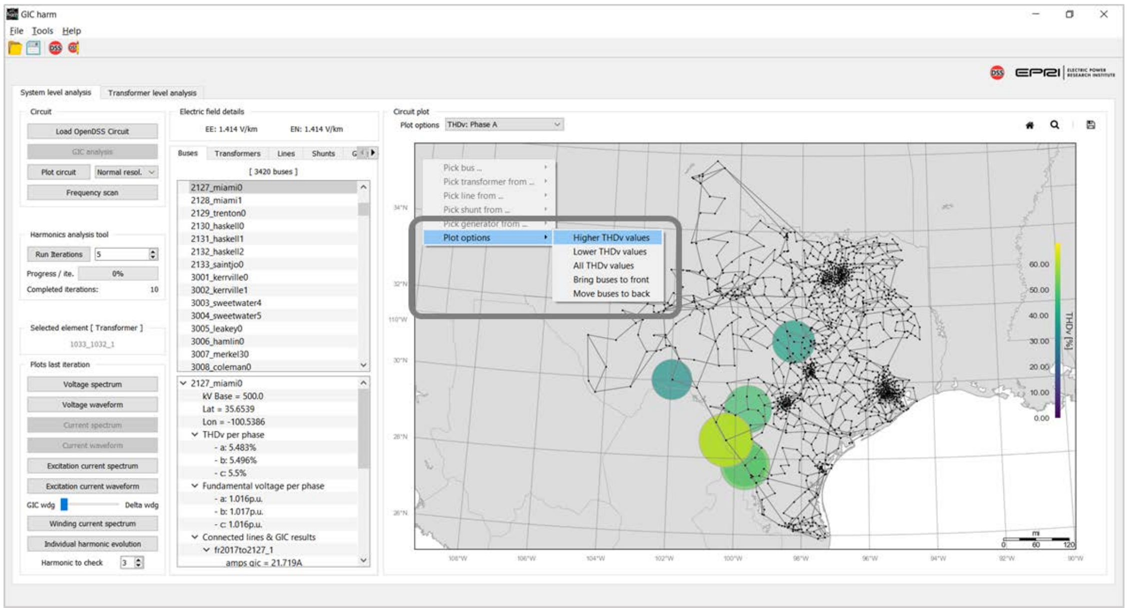
Selected element [Transformer]: 1033_1032_1

Harmonic to check: 3

- 2127_miami0
  - kV Base = 500.0
  - Lat = 35.6539
  - Lon = -100.5386
  - THDv per phase
    - a: 5.483%
    - b: 5.496%
    - c: 5.5%
  - Fundamental voltage per phase
    - a: 1.016p.u.
    - b: 1.017p.u.
    - c: 1.016p.u.
  - Connected lines & GIC results
    - fr2017to2127_1
      - amps gic = 21.719A

2128_miami1: not measured -- 2026_wheeler0: not measured

Figure 4-23
Picking a bus or element from the circuit plot



EE: 1.414 V/km EN: 1.414 V/km

Plot options: THDv: Phase A

Normal resol.

[3420 buses]

Run Iterations: 5

Progress / ite.: 0%

Completed iterations: 10

Selected element [Transformer]: 1033_1032_1

Harmonic to check: 3

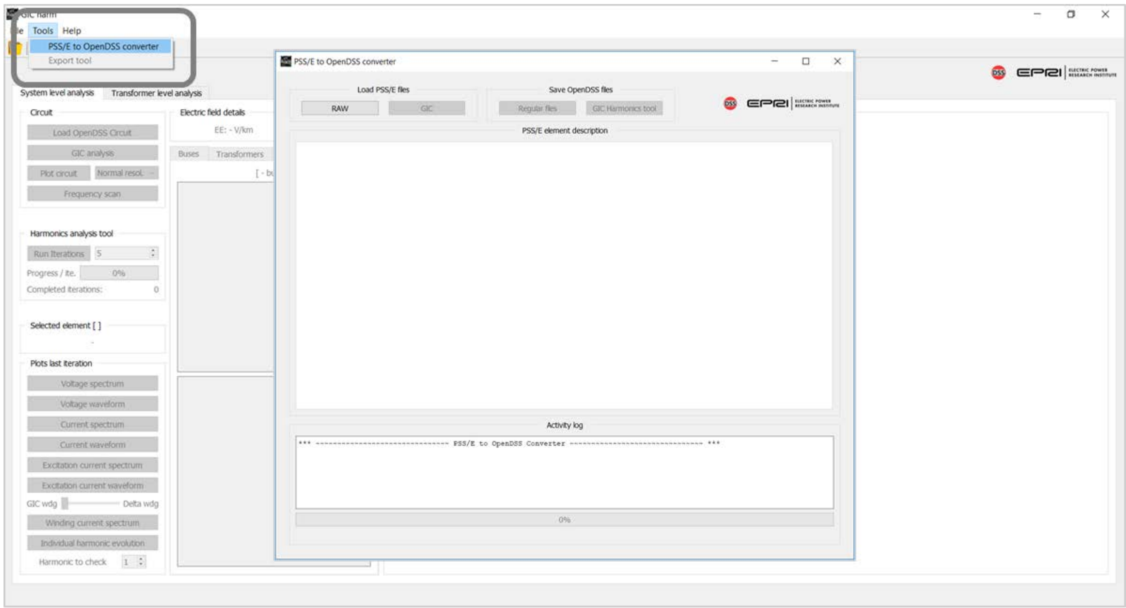
- 2127_miami0
  - kV Base = 500.0
  - Lat = 35.6539
  - Lon = -100.5386
  - THDv per phase
    - a: 5.483%
    - b: 5.496%
    - c: 5.5%
  - Fundamental voltage per phase
    - a: 1.016p.u.
    - b: 1.017p.u.
    - c: 1.016p.u.
  - Connected lines & GIC results
    - fr2017to2127_1
      - amps gic = 21.719A

Figure 4-24
Changing the order of plot objects

PSS/E to GICharm / OpenDSS Converter

GICharm has a built-in converter that takes PSS/E **.raw* and **.gic* files as inputs and creates OpenDSS/GICharm models stored as **.dss* files. It is important to clarify that PSS/E **.gic* files are required for the converter to generate **.dss* files for GICharm. This is since the **.raw* file does not contain information on geographic coordinates of buses nor grounding resistance values for substations. GICharm makes assumptions for missing grounding resistances, but it can't make assumptions for coordinates, which are required to determine GIC flows. If only PSS/E **.raw* files are available, the converter can still generate **.dss* files for an OpenDSS model to work directly with OpenDSS but not with GICharm. The conversion process is illustrated in the paragraphs.

As it can be observed in Figure 4-25, to launch the converter, the user should go to the *Tools* menu and select the *PSS/E to OpenDSS converter* option. The converter window will appear at this point. On top of the window, the user has access to the *Load PSS/E files* buttons which allow the user to import the model input files, and the *Save OpenDSS files* buttons which allow the user to save the converted **.dss* models. The successful import of a **raw* file enables the button to save *Regular files* for external OpenDSS work (not usable for GICharm). It also enables the import of **.gic* files. The successful import of a **.gic* file enables the *GIC harmonics tool* save button to save **.dss* files for GICharm. It also disables the save button for regular **.dss* files because the information on the **.gic* file modifies the converted model. However, the **.dss* files for GICharm can also be loaded directly in OpenDSS.

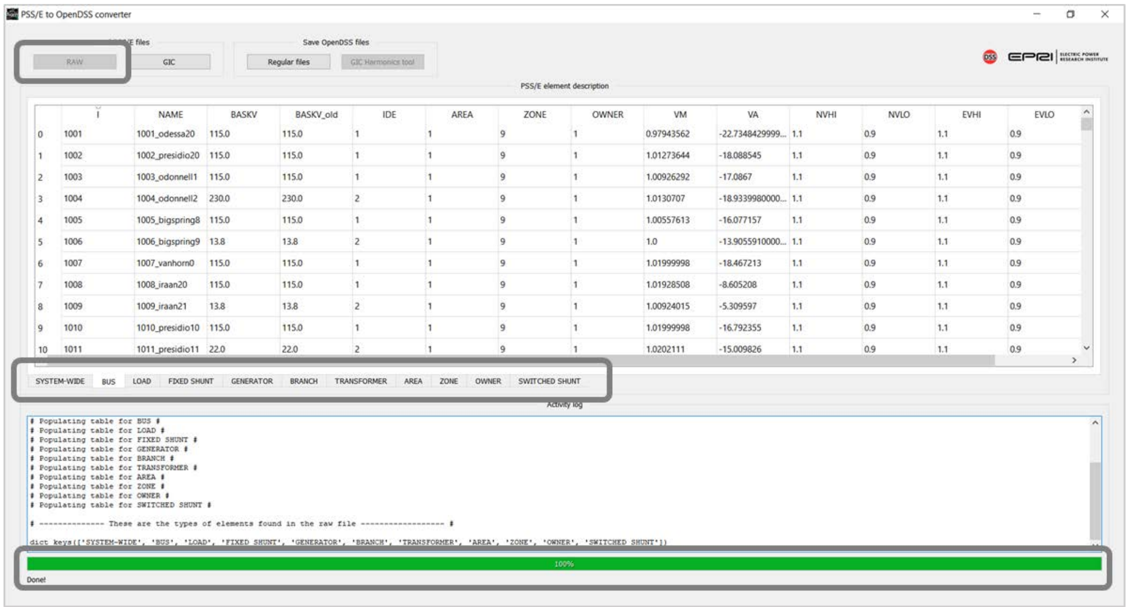


```
*** ------------------------------ PSS/E to OpenDSS Converter ------------------------------ ***
```

Figure 4-25
Launching the PSS/E to GICharm / OpenDSS converter

The converter window also includes a frame called *PSS/E element description* which is intended to display all the table records stored in both the **.raw* and **.gic* files. This frame is populated when the PSS/E files are successfully loaded. The converter window also contains an *Activity Log* which is used to display the progress of the converter during all the conversion activities (loading the **.raw* file, loading the **.gic* file, saving regular **.dss* files or saving GICharm **.dss* files). This activity log also displays information about the number of converted elements and the number of disabled elements found in the input files. Additionally, the converter window also has a progress bar which provides feedback to the user during all the activities and routines performed by the converter during the process. All these window sections are intended to be used as tools to verify that the input files are being correctly converted to be used in GICharm or directly in OpenDSS.

Once a **.raw* file is loaded in the converter, the *PSS/E element description* frame is populated with tables containing the records for each device in the PSS/E model. An example of this is shown in Figure 4-26 for a synthetic case found at the Texas A&M University – Electric Grid Test Case Repository website [9, 10].



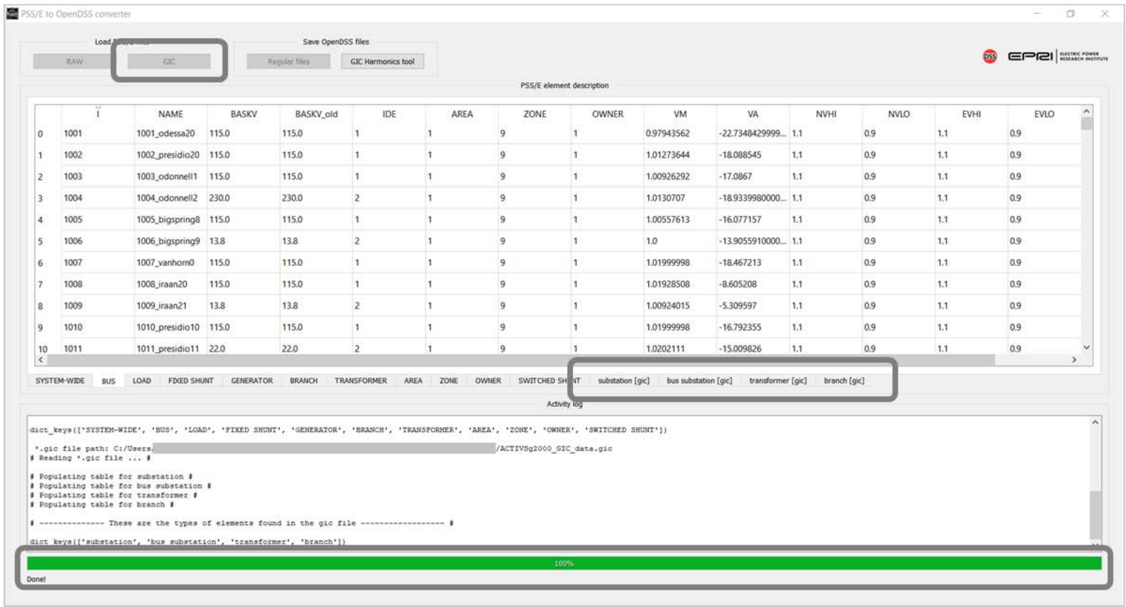
	I	NAME	BASKV	BASKV_old	IDE	AREA	ZONE	OWNER	VM	VA	NVHI	NVLO	EVHI	EVLO
0	1001	1001_odessa20	115.0	115.0	1	1	9	1	0.97943562	-22.7348429999...	1.1	0.9	1.1	0.9
1	1002	1002_presidio20	115.0	115.0	1	1	9	1	1.01273644	-18.088545	1.1	0.9	1.1	0.9
2	1003	1003_odonnell1	115.0	115.0	1	1	9	1	1.00926292	-17.0867	1.1	0.9	1.1	0.9
3	1004	1004_odonnell2	230.0	230.0	2	1	9	1	1.0130707	-18.9339980000...	1.1	0.9	1.1	0.9
4	1005	1005_bigspring8	115.0	115.0	1	1	9	1	1.00557613	-16.077157	1.1	0.9	1.1	0.9
5	1006	1006_bigspring9	13.8	13.8	2	1	9	1	1.0	-13.9055910000...	1.1	0.9	1.1	0.9
6	1007	1007_vanhorn0	115.0	115.0	1	1	9	1	1.01999998	-18.467213	1.1	0.9	1.1	0.9
7	1008	1008_iraan20	115.0	115.0	1	1	9	1	1.01928508	-8.605208	1.1	0.9	1.1	0.9
8	1009	1009_iraan21	13.8	13.8	2	1	9	1	1.00924015	-5.309597	1.1	0.9	1.1	0.9
9	1010	1010_presidio10	115.0	115.0	1	1	9	1	1.01999998	-16.792355	1.1	0.9	1.1	0.9
10	1011	1011_presidio11	22.0	22.0	2	1	9	1	1.0202111	-15.009826	1.1	0.9	1.1	0.9

```
# Populating table for BUS #
# Populating table for LOAD #
# Populating table for FIXED SHUNT #
# Populating table for GENERATOR #
# Populating table for BRANCH #
# Populating table for TRANSFORMER #
# Populating table for AREA #
# Populating table for ZONE #
# Populating table for OWNER #
# Populating table for SWITCHED SHUNT #

# ------------- These are the types of elements found in the raw file ----------------- #

dict_keys(['SYSTEM-WIDE', 'BUS', 'LOAD', 'FIXED SHUNT', 'GENERATOR', 'BRANCH', 'TRANSFORMER', 'AREA', 'ZONE', 'OWNER', 'SWITCHED SHUNT'])
```

Done!

Figure 4-26
Loading the **.raw* file from PSS/E

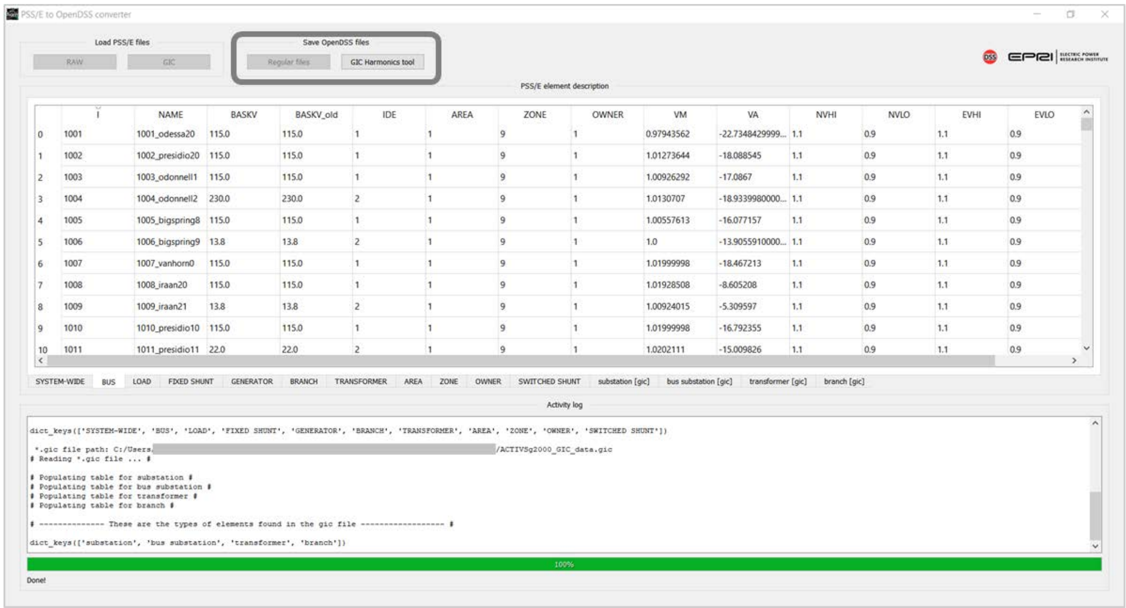
At this point the user can either save regular **.dss* files or import a **.gic* file for the already loaded **.raw* file. Figure 4-27 shows the result of loading a **.gic* file for the same synthetic case example found at [9]: the tables and record found in that file are also displayed in the *PSS/E element description* field. A consequence of loading the **.gic* file is that some of the element tables are updated with new information or some fields are added in tables like TRANSFORMER, TRANSFORMER_3WDG and BUS (coordinate-related).



	I	NAME	BASKV	BASKV_old	IDE	AREA	ZONE	OWNER	VM	VA	NVHI	NVLO	EVHI	EVLO
0	1001	1001_odessa20	115.0	115.0	1	1	9	1	0.97943562	-22.7348429999...	1.1	0.9	1.1	0.9
1	1002	1002_presidio20	115.0	115.0	1	1	9	1	1.01273644	-18.088545	1.1	0.9	1.1	0.9
2	1003	1003_odonnell1	115.0	115.0	1	1	9	1	1.00926292	-17.0867	1.1	0.9	1.1	0.9
3	1004	1004_odonnell2	230.0	230.0	2	1	9	1	1.0130707	-18.9339980000...	1.1	0.9	1.1	0.9
4	1005	1005_bigspring8	115.0	115.0	1	1	9	1	1.00557613	-16.077157	1.1	0.9	1.1	0.9
5	1006	1006_bigspring9	13.8	13.8	2	1	9	1	1.0	-13.9055910000...	1.1	0.9	1.1	0.9
6	1007	1007_vanhorn0	115.0	115.0	1	1	9	1	1.01999998	-18.467213	1.1	0.9	1.1	0.9
7	1008	1008_iraan20	115.0	115.0	1	1	9	1	1.01928508	-8.605208	1.1	0.9	1.1	0.9
8	1009	1009_iraan21	13.8	13.8	2	1	9	1	1.00924015	-5.309597	1.1	0.9	1.1	0.9
9	1010	1010_presidio10	115.0	115.0	1	1	9	1	1.01999998	-16.792355	1.1	0.9	1.1	0.9
10	1011	1011_presidio11	22.0	22.0	2	1	9	1	1.0202111	-15.009826	1.1	0.9	1.1	0.9

```
dict_keys(['SYSTEM-WIDE', 'BUS', 'LOAD', 'FIXED SHUNT', 'GENERATOR', 'BRANCH', 'TRANSFORMER', 'AREA', 'ZONE', 'OWNER', 'SWITCHED SHUNT'])

 *.gic file path: C:/Users/[redacted]/ACTIVSg2000_GIC_data.gic
# Reading *.gic file ... #

# Populating table for substation #
# Populating table for bus substation #
# Populating table for transformer #
# Populating table for branch #

# ------------- These are the types of elements found in the gic file ----------------- #

dict_keys(['substation', 'bus substation', 'transformer', 'branch'])
```

Figure 4-27
Loading the **.gic* file from PSS/E



	I	NAME	BASKV	BASKV_old	IDE	AREA	ZONE	OWNER	VM	VA	NVHI	NVLO	EVHI	EVLO
0	1001	1001_odessa20	115.0	115.0	1	1	9	1	0.97943562	-22.7348429999...	1.1	0.9	1.1	0.9
1	1002	1002_presidio20	115.0	115.0	1	1	9	1	1.01273644	-18.088545	1.1	0.9	1.1	0.9
2	1003	1003_odonnell1	115.0	115.0	1	1	9	1	1.00926292	-17.0867	1.1	0.9	1.1	0.9
3	1004	1004_odonnell2	230.0	230.0	2	1	9	1	1.0130707	-18.9339980000...	1.1	0.9	1.1	0.9
4	1005	1005_bigspring8	115.0	115.0	1	1	9	1	1.00557613	-16.077157	1.1	0.9	1.1	0.9
5	1006	1006_bigspring9	13.8	13.8	2	1	9	1	1.0	-13.9055910000...	1.1	0.9	1.1	0.9
6	1007	1007_vanhorn0	115.0	115.0	1	1	9	1	1.01999998	-18.467213	1.1	0.9	1.1	0.9
7	1008	1008_iraan20	115.0	115.0	1	1	9	1	1.01928508	-8.605208	1.1	0.9	1.1	0.9
8	1009	1009_iraan21	13.8	13.8	2	1	9	1	1.00924015	-5.309597	1.1	0.9	1.1	0.9
9	1010	1010_presidio10	115.0	115.0	1	1	9	1	1.01999998	-16.792355	1.1	0.9	1.1	0.9
10	1011	1011_presidio11	22.0	22.0	2	1	9	1	1.0202111	-15.009826	1.1	0.9	1.1	0.9

```
dict_keys(['SYSTEM-WIDE', 'BUS', 'LOAD', 'FIXED SHUNT', 'GENERATOR', 'BRANCH', 'TRANSFORMER', 'AREA', 'ZONE', 'OWNER', 'SWITCHED SHUNT'])

 *.gic file path: C:/Users/[redacted]/ACTIVSg2000_GIC_data.gic
# Reading *.gic file ... #

# Populating table for substation #
# Populating table for bus substation #
# Populating table for transformer #
# Populating table for branch #

# ------------- These are the types of elements found in the gic file ----------------- #

dict_keys(['substation', 'bus substation', 'transformer', 'branch'])
```

Figure 4-28
Saving **.dss* files for regular OpenDSS work or for GICharm

Finally, the converted model files can be saved at a location defined by the user. Clicking the *Save OpenDSS files* buttons prompts the user with a save dialog that allows the user to define a path to save the converted model files. Please remember to store the files for *GICharm* work in a separate folder than those for *Regular* OpenDSS work.

5
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