Distortion Analysis

This section describes the process of conducting harmonic distortion analysis on a loaded circuit. The objective is to compute and display individual harmonic and overall voltage distortion at desired buses in response to the selected harmonic current injections in the circuit. The screenshot of this particular tab, which can be activated by clicking on the "Distortion Analysis" button on the top of the interface is shown in Figure 1-9.

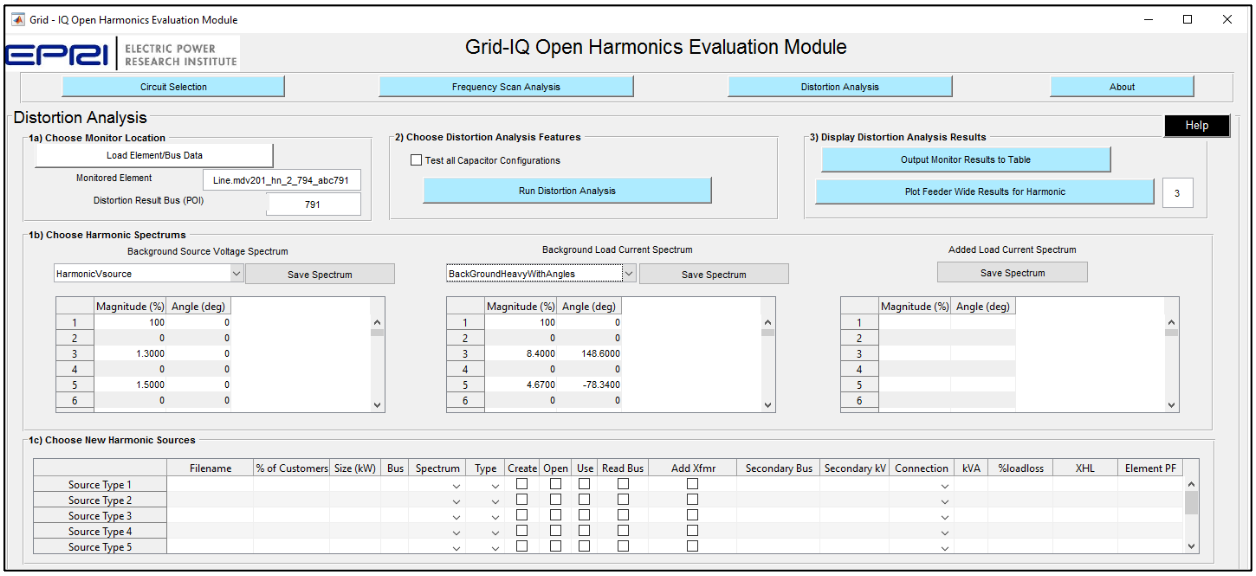


Figure 1-1
Harmonic Distortion Analysis tab

1 a) Choose Monitor Location

The bus where the distortion analysis results are desired is specified by clicking on the desired location on circuit plot to be followed by clicking on the "Load Monitored Element" button. This will cause the name of the element and "Distortion Result Bus (POI)" to populate the text boxes that are placed below the "Load Element/Bus Data" button. If the "Monitored Element" name is known, the name may be manually added by placing the cursor in the box and then typing the name.

If the distortion results are desired for a transformer secondary, the transformer must exist in the model or added as a new transformer using a new harmonic source (discussed later under the subtitle "Loads Applied to the Secondary Bus of a Transformer"). Once the transformer and associated load exist, the transformer may be manually entered into the "Monitored Element" field. If this transformer has been added with a new harmonic load, enter "Transformer.[Filename]" where [Filename] is the filename of the transformer. Alternatively, manually enter the secondary bus in the "Distortion Results Bus (POI)" field.

1 b) Choose Harmonic Spectrums

This section describes the possible ways to introduce harmonic sources to the circuit model.

Background Source Voltage Spectrum

the user has the option of attaching the desired harmonic spectrum to the voltage source that is a part of the Thevenin equivalent representing system upstream of the primary of the substation transformer. The user can populate the table by entering the desired values through the interface itself or select one of three options that have been provided in the dropdown list (See Figure 1-10).

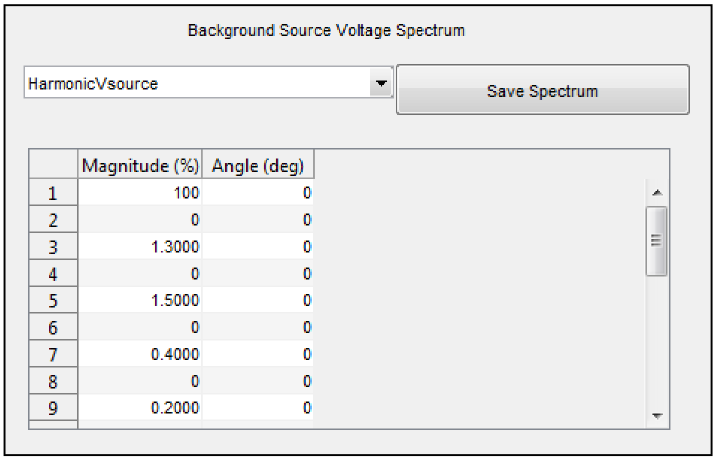


Figure 1-2
Background Source Voltage Spectrum selection

The first selection named "IdealVsource" is default and assigns zero magnitudes to all the individual harmonics. This option assumes that no harmonics are introduced in the circuit model from the upstream system. This can also be used to clear any previous and unwanted changes to the spectrum. The second option named "HarmonicVsource" assigns typical magnitudes to the individual harmonics (see Figure 1-10).

The user has the option of editing the spectrum in this table at any time. This option is useful if actual measurements are available for the circuit. The edited spectrum can be saved at any time for later use by clicking on the "Save Spectrum" button and saving it as a *.mat file in the working directory.

The third option named "OpenSaved" allows user to load and use any spectrum file that has been created by user.

Background Current Harmonic Source

The user can also select a desired harmonic spectrum that gets attached to every existing load element in the circuit model. This results in creation of harmonic sources that are distributed over the entire circuit. This selection in conjunction with the spectrum selection in the previous section will result in introduction of background harmonics into the system model. The user has been provided four selection options in the dropdown list (See Figure 1-11).

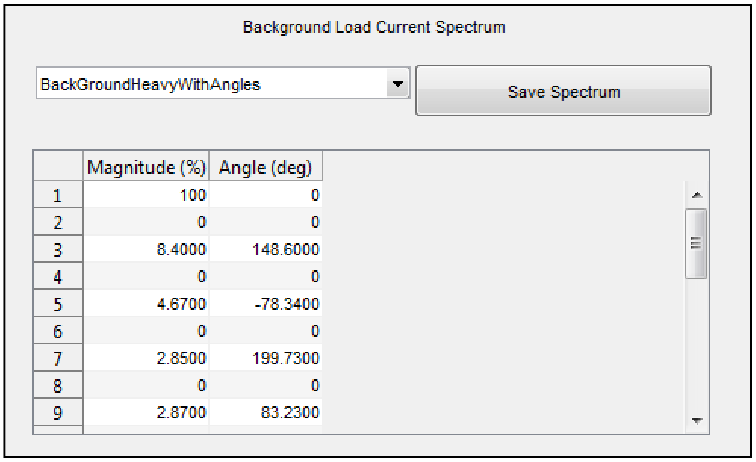


Figure 1-3
Background Load Current Spectrum selection

The first selection named "IdealLoad" assigns zero magnitudes to all the individual harmonics. This option assumes that no harmonics are introduced in the circuit model from the existing loads.

The second option named "BackgroundHeavyWithoutAngles" assigns typical magnitudes to the individual harmonics. These typical values (see Figure 1-10) are based on the example measurements that have been conducted at a typical residential service transformer. This option ignores the phase angle information of the individual harmonics and can be expected to yield conservative results.

The third option named "BackgroundHeavyWithAngles" assigns typical magnitudes to the individual harmonics. This option includes the phase angle information of the individual harmonics.

The user has the option of editing the spectrum in this table. This option is useful if actual measurements are available for the circuit model. The edited spectrum can be saved at any time for later use by clicking on the "Save Spectrum" button and saving it as a *.mat file in the working directory.

The fourth option named "OpenSaved" allows the user to load any spectrum file that has been created.

1 c) Choose New Harmonic Sources

Users have the option of adding multiple (up to ten) new harmonic source types into the circuit model. This can be accomplished using the "Choose New Harmonic Sources" part of the interface. Loads may be added directly to a medium-voltage bus (model line section), or transformation may be added and loads applied to the secondary bus of the transformer.

Loads Applied to Medium-Voltage Bus

There are two options for adding a new load type at the medium-voltage (MV) level:

- Distributed loads – The harmonic-inducing loads are distributed in nature and get assigned randomly based on the specified parameters.

- Specific Load – The harmonic-inducing load gets assigned to a specific MV bus as per the user selection.

For each new source, the user needs to provide values for the following attributes:

- Filename – Name of the file that will be created by the application and that will contain information on the new harmonic load. Note, the filename is not case specific. If the user first enters a filename of “xyz” and then later on creates a new source with a filename of “xYz” only the filename “xyz” will be stored. Every time file “xYz” is changed the changes will be applied to file “xyz”.
- % of Customers – This attribute specifies the penetration level of the new harmonic load type and is a required field only for “Distributed loads” option.
- Size(kW) – Size of the individual instances of a new load in kW.
- Bus – Name of the bus where a new harmonic load is to be added to the circuit. This is a required field for “Specific Load” option and gets ignored for “Distributed Loads” option.
- Spectrum – A dropdown list has been populated that allows a selection of the pre-defined spectrums. The available selections are as follows:
    - High_PF_CFL_With_Angles
    - High_PF_CFL_Without_Angles
    - Low_PF_CFL_With_Angles
    - Low_PF_CFL_Without_Angles
    - High_PF_LED_With_Angles
    - High_PF_LED_Without_Angles
    - Low_PF_LED_With_Angles
    - Low_PF_LED_Without_Angles
    - AC_Charger_EV_With_Angles
    - AC_Charger_EV_Without_Angles
    - DC_Charger_EV_With_Angles
    - DC_Charger_EV_Without_Angles
    - PV_With_Angles
    - PV_Without_Angles
    - Home_Entertainment_With_Angles
    - Home_Entertainment_Without_Angles
    - ECM_HVAC_With_Angles
    - ECM_HVAC_Without_Angles
    - Switch_Mode_Power_Supply_With_Angles
    - Switch_Mode_Power_Supply_Without_Angles
    - 6-Pulse_DC_Drive_With_Angles
    - 6-Pulse_DC_Drive_Without_Angles

- Single_Phase_ASD_With_Angles
- Single_Phase_ASD_Without_Angles
- Arc_Furnace_Initial_Melt
- Six_Pulse_Converter_Ideal
- Six_Pulse_Converter_Practical
- Twelve_Pulse_Converter_Ideal
- Twelve_Pulse_Converter_Practical
- Twentyfour_Pulse_Converter_Ideal
- Twentyfour_Pulse_Converter_Practical
- Wind_Plant
- Load user defined

Selection of any but the last option populates the corresponding spectrum under the “Added Load Current Spectrum” heading (see Figure 1-12). The user has the option of editing the spectrum in this table. The edited spectrum can be saved at any time for later use by clicking on the “Save Spectrum” button and saving as it as a *.mat file in the working directory. The last selection (“load user defined”) allows the user to load any spectrum file that has been created.

- Type – The provided options are “Load” and “Generator.” Both are sources of harmonic injections but need to be handled differently during modeling.
- Create – This checkbox creates an additional load file in accordance with the selections made in the attributes presented above. This file is placed in a directory called “AddedElement,” which is a subdirectory of the selected circuit that is placed immediately under the working directory.
- Load – Checking this box allows user to select any pre-defined additional load file such as the one created above.
- Use – Checking this box will include this additional harmonic load in the harmonic distortion analysis.
- Read Bus – Checking this box is needed only for the “Specific Load” option. The bus where the new harmonic source is desired is specified by clicking on the desired location on circuit plot to be followed by clicking on the “Read Bus” checkbox. This will cause the name of the selected bus to populate the “Bus” field.

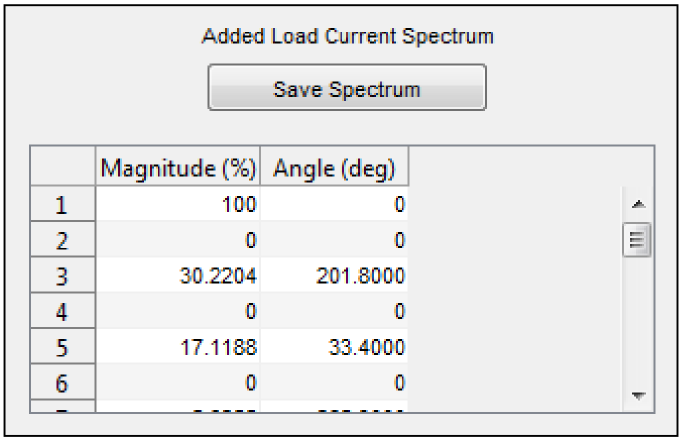


Figure 1-4
Added Load Current Spectrum selection

The user can opt to create the additional load files. Also, the user needs to make sure to check the "Use" option to apply the load(s) in the distortion analysis.

Loads Applied to the Secondary Bus of a Transformer

Transformers may only be added as a "Specific Load." Consequently, they may not be randomly distributed. To add a transformer, first determine what line segment that the transformer will be connected to. Next, complete all the steps presented above to add a "Specific Load" as a new source type. Figure 1-13 provides an example secondary load for a Transformer.XFMR_xyz_load. The load is a 2000-kW, six-Pulse DC drive with angles, applied as a load. The transformer primary is to be connected to the medium-voltage bus (segment) "14891."

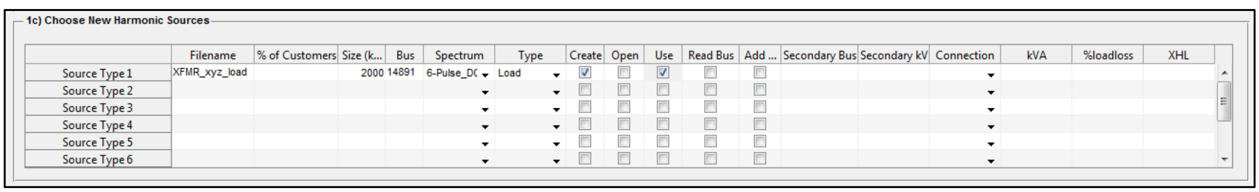


Figure 1-5
Example specific load harmonic source for a transformer prior to adding transformer data

After establishing the harmonic load filename, size, bus, spectrum, and type, the details of the new service transformer must be added:

- Add Xfmr – Click to add a transformer when the harmonic load/files are created.
- Secondary Bus – Type in an arbitrary name for the transformer secondary bus. Note that this name may be used as "Distortion Results Bus (POI)" for Std. 519 compliance calculations at the transformers secondary bus.
- Secondary kV – This is the transformers secondary line-to-line voltage rating in kV.
- Connection – Is the connection type of the three-phase transformer being added. The following connection types are available:
    - Wye, Wye

- Wye, Delta
- Delta, Wye
- Delta, Delta

- kVA – The capacity rating of the transformer.
- %loadloss – Percent load loss at full load. The %R of the High and Low windings (1 and 2) are adjusted to agree at rated kVA loading.
- XHL - Use this to specify the percent reactance, H-L (winding 1 to winding 2). Use for 2- or 3-winding transformers. This value is determined from the base kVA of winding 1.

Note that if the new harmonic load had previously been created (as illustrated in Figure 1-13), choosing to “Add Xfmr” deselects the “Create” and “Use” boxes so that the user must recreate the harmonic load/files. Consequently, the “Create” box must be first rechecked to create the new load file, and then the “Use” box must be rechecked to include the new source in future distortion analysis.

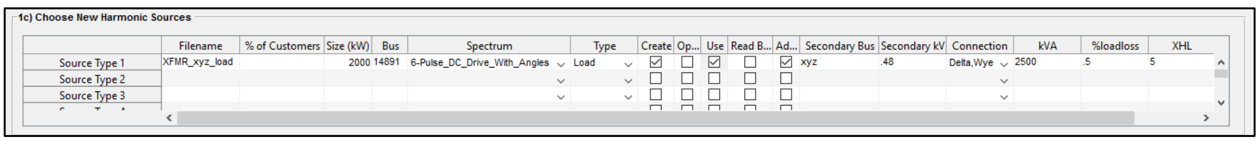


Figure 1-6
Example specific load harmonic source for a transformer after adding transformer data

2) Choose Distortion Analysis Features

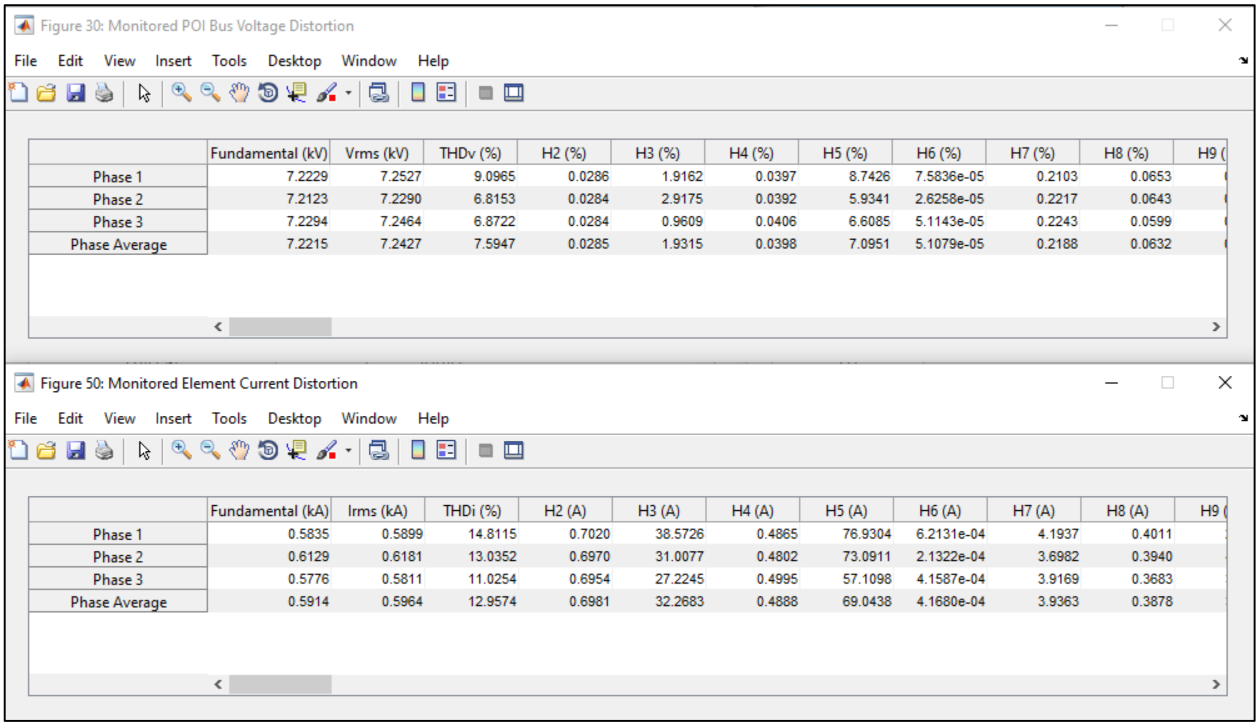
Clicking on “Run Distortion Analysis” button will prompt the solution engine to perform the harmonic solution based on the various selections, including ON/OFF status of various capacitor banks and the harmonic spectrums. During this simulation, a progress window will pop up and close once the solution is completed.

The user can also choose to perform the distortion analysis for all of the potential capacitor configurations when the user checks the checkbox titled “Test all capacitor configurations.”

3) Display Distortion Analysis Results

The simulation results can be viewed in tabular form by clicking on the “Output Monitor Results to Table” button. Multiple tables are created as follows:

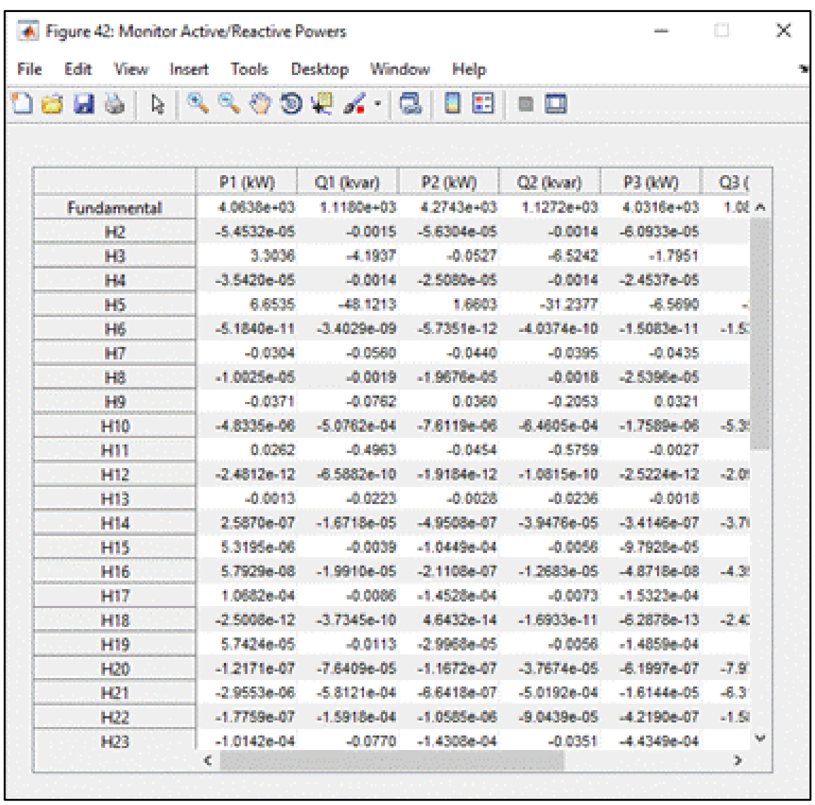
- Monitored Distortion Reports (Figure 1-15)
- Monitor Active/Reactive Powers (Figure 1-16)
- Harmonic Compliance Reports (Figure 1-19)



	Fundamental (kV)	Vrms (kV)	THDv (%)	H2 (%)	H3 (%)	H4 (%)	H5 (%)	H6 (%)	H7 (%)	H8 (%)	H9 (
Phase 1	7.2229	7.2527	9.0965	0.0286	1.9162	0.0397	8.7426	7.5836e-05	0.2103	0.0653	
Phase 2	7.2123	7.2290	6.8153	0.0284	2.9175	0.0392	5.9341	2.6258e-05	0.2217	0.0643	
Phase 3	7.2294	7.2464	6.8722	0.0284	0.9609	0.0406	6.6085	5.1143e-05	0.2243	0.0599	
Phase Average	7.2215	7.2427	7.5947	0.0285	1.9315	0.0398	7.0951	5.1079e-05	0.2188	0.0632	

	Fundamental (kA)	Irms (kA)	THDi (%)	H2 (A)	H3 (A)	H4 (A)	H5 (A)	H6 (A)	H7 (A)	H8 (A)	H9 (
Phase 1	0.5835	0.5899	14.8115	0.7020	38.5726	0.4865	76.9304	6.2131e-04	4.1937	0.4011	
Phase 2	0.6129	0.6181	13.0352	0.6970	31.0077	0.4802	73.0911	2.1322e-04	3.6982	0.3940	
Phase 3	0.5776	0.5811	11.0254	0.6954	27.2245	0.4995	57.1098	4.1587e-04	3.9169	0.3683	
Phase Average	0.5914	0.5964	12.9574	0.6981	32.2683	0.4888	69.0438	4.1680e-04	3.9363	0.3878	

Figure 1-7
Monitored distortion reports for voltage and current



	P1 (kW)	Q1 (kvar)	P2 (kW)	Q2 (kvar)	P3 (kW)	Q3 (
Fundamental	4.0638e+03	1.1180e+03	4.2743e+03	1.1272e+03	4.0316e+03	1.0
H2	-5.4532e-05	-0.0015	-5.6304e-05	-0.0014	-6.0933e-05	
H3	3.3036	-4.1937	-0.0527	-6.5242	-1.7951	
H4	-3.5420e-05	-0.0014	-2.5080e-05	-0.0014	-2.4537e-05	
H5	6.6535	-48.1213	1.6603	-31.2377	-6.5690	-
H6	-5.1840e-11	-3.4029e-09	-5.7351e-12	-4.0374e-10	-1.5083e-11	-1.5
H7	-0.0304	-0.0560	-0.0440	-0.0395	-0.0435	
H8	-1.0025e-05	-0.0019	-1.9676e-05	-0.0018	-2.5396e-05	
H9	-0.0371	-0.0762	0.0360	-0.2053	0.0321	
H10	-4.8335e-06	-5.0762e-04	-7.6119e-06	-6.4605e-04	-1.7589e-06	-5.3
H11	0.0262	-0.4963	-0.0454	-0.5759	-0.0027	
H12	-2.4812e-12	-6.5882e-10	-1.9184e-12	-1.0815e-10	-2.5224e-12	-2.0
H13	-0.0013	-0.0223	-0.0028	-0.0236	-0.0018	
H14	2.5870e-07	-1.6718e-05	-4.9508e-07	-3.9476e-05	-3.4146e-07	-3.7
H15	5.3195e-06	-0.0039	-1.0449e-04	-0.0056	-9.7928e-05	
H16	5.7929e-08	-1.9910e-05	-2.1108e-07	-1.2683e-05	-4.8718e-08	-4.3
H17	1.0682e-04	-0.0086	-1.4528e-04	-0.0073	-1.5323e-04	
H18	-2.5008e-12	-3.7345e-10	4.6432e-14	-1.6933e-11	-6.2878e-13	-2.4
H19	5.7424e-05	-0.0113	-2.9968e-05	-0.0058	-1.4859e-04	
H20	-1.2171e-07	-7.6409e-05	-1.1672e-07	-3.7674e-05	-6.1997e-07	-7.9
H21	-2.9553e-06	-5.8121e-04	-6.6418e-07	-5.0192e-04	-1.6144e-05	-6.3
H22	-1.7759e-07	-1.5918e-04	-1.0585e-06	-9.0439e-05	-4.2190e-07	-1.5
H23	-1.0142e-04	-0.0770	-1.4308e-04	-0.0351	-4.4349e-04	

Figure 1-8

Monitor Active/Reactive Power

Monitored Distortion Reports

Separate tables are created for voltage distortion and current distortion at the Monitored Element or Distortion Results Bus (POI) defined in the Section 1a of the Distortion Analysis page (Figure 1-17). The tabulated results are presented for individual phases along with the average values. Each parameter is explained below:

- Fundamental (kV) – Fundamental value of bus voltage in kV
- Vrms (kV) – True root mean square value of bus voltage in kV
- THDv (%) – Total harmonic distortion of bus voltage in %
- H2(%), H3(%), …H25(%) – Individual voltage harmonics (% of fundamental)
- Fundamental (kA) – Fundamental value of current through selected element in kA
- Irms (kA) – True root mean square value of current through selected element in kA
- THDi (%) – Total harmonic distortion of current through selected element (% of fundamental)
- H2(A), H3(A), … H25(A) – Individual current harmonics (ampere)

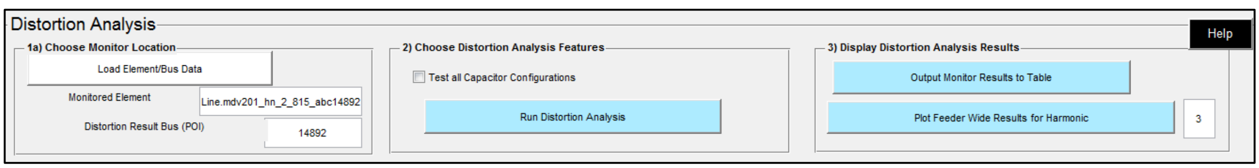


Figure 1-9
Distortion Analysis page showing Monitored Element and POI selection for Distortion Analysis

If all capacitor configurations have been analyzed and the "Test all Capacitor Configurations" remains checked, figures illustrating the range in harmonic distortion for each phase (Figure 1-18) and harmonic will be produced, as well as the previously mentioned tables. Each figure is also accompanied by a table that depicts the capacitor configuration that leads to the worst harmonic distortion for overall THDv and each individual harmonic.

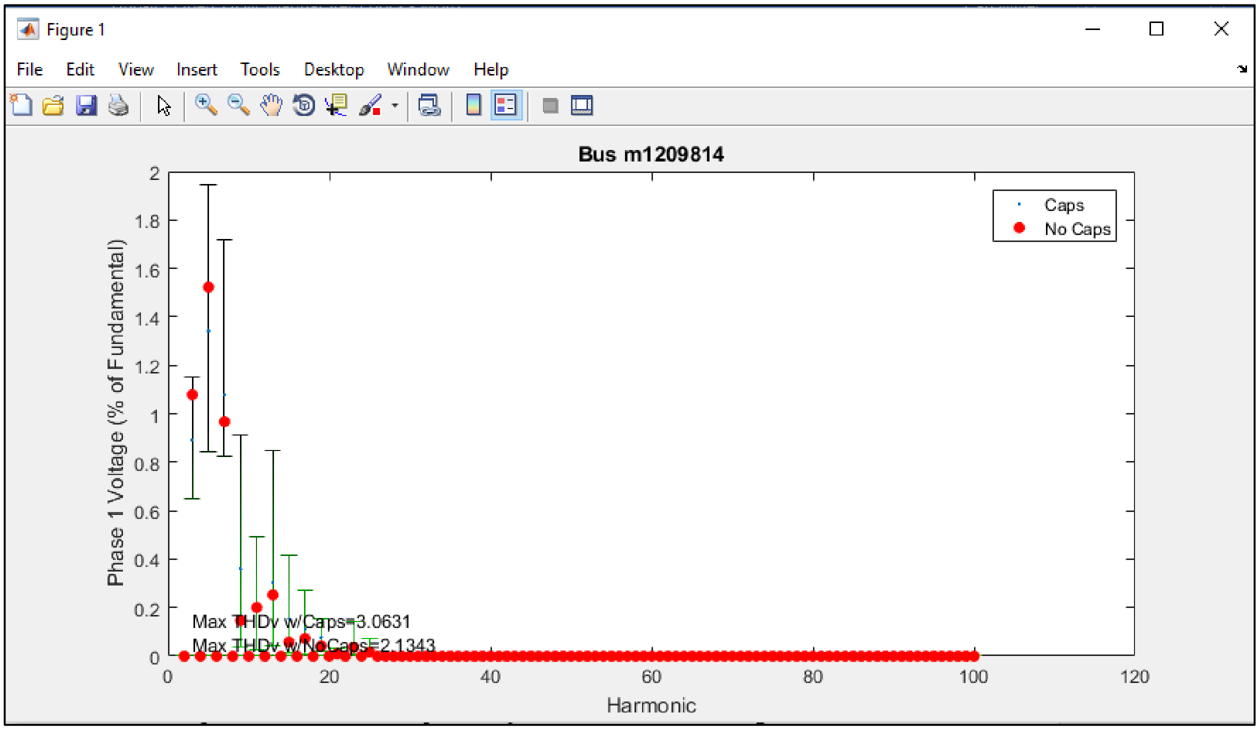
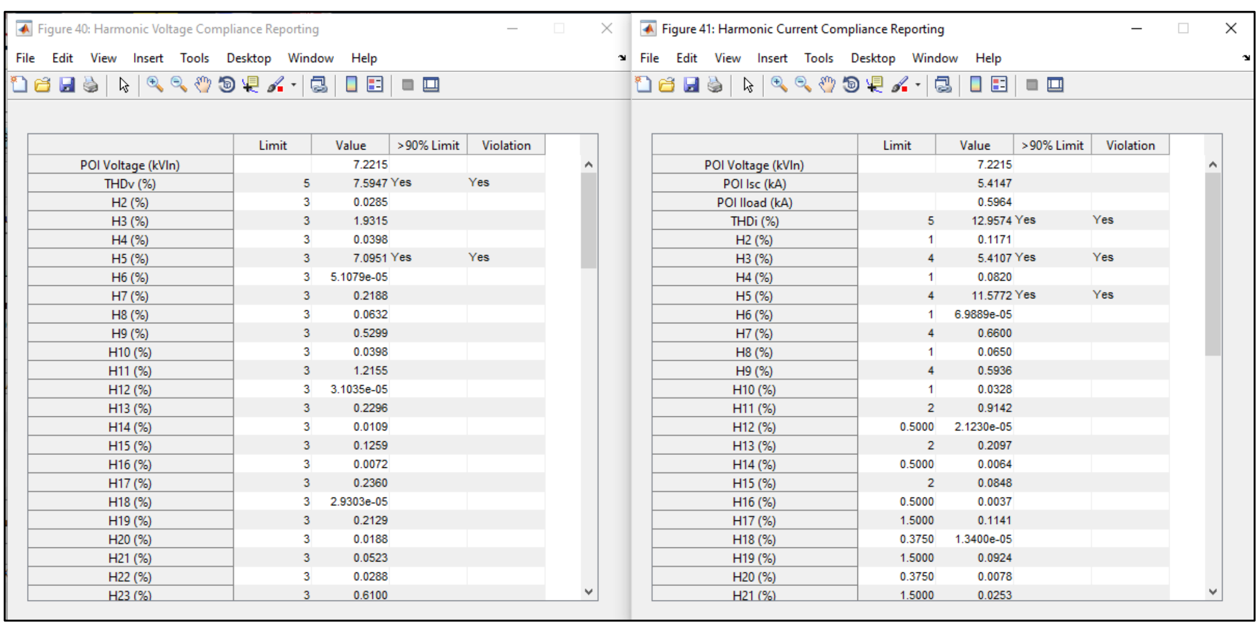


Figure 1-10
Distortion analysis range of harmonic distortion for Phase 1 after checking the box next to "Test all Capacitor Configurations"



	Limit	Value	>90% Limit	Violation
POI Voltage (kVln)		7.2215		
THDv (%)	5	7.5947	Yes	Yes
H2 (%)	3	0.0285		
H3 (%)	3	1.9315		
H4 (%)	3	0.0398		
H5 (%)	3	7.0951	Yes	Yes
H6 (%)	3	5.1079e-05		
H7 (%)	3	0.2188		
H8 (%)	3	0.0632		
H9 (%)	3	0.5299		
H10 (%)	3	0.0398		
H11 (%)	3	1.2155		
H12 (%)	3	3.1035e-05		
H13 (%)	3	0.2296		
H14 (%)	3	0.0109		
H15 (%)	3	0.1259		
H16 (%)	3	0.0072		
H17 (%)	3	0.2360		
H18 (%)	3	2.9303e-05		
H19 (%)	3	0.2129		
H20 (%)	3	0.0188		
H21 (%)	3	0.0523		
H22 (%)	3	0.0288		
H23 (%)	3	0.6100		

	Limit	Value	>90% Limit	Violation
POI Voltage (kVln)		7.2215		
POI Isc (kA)		5.4147		
POI Iload (kA)		0.5964		
THDi (%)	5	12.9574	Yes	Yes
H2 (%)	1	0.1171		
H3 (%)	4	5.4107	Yes	Yes
H4 (%)	1	0.0820		
H5 (%)	4	11.5772	Yes	Yes
H6 (%)	1	6.9889e-05		
H7 (%)	4	0.6600		
H8 (%)	1	0.0650		
H9 (%)	4	0.5936		
H10 (%)	1	0.0328		
H11 (%)	2	0.9142		
H12 (%)	0.5000	2.1230e-05		
H13 (%)	2	0.2097		
H14 (%)	0.5000	0.0064		
H15 (%)	2	0.0848		
H16 (%)	0.5000	0.0037		
H17 (%)	1.5000	0.1141		
H18 (%)	0.3750	1.3400e-05		
H19 (%)	1.5000	0.0924		
H20 (%)	0.3750	0.0078		
H21 (%)	1.5000	0.0253		

Figure 1-11
Harmonic compliant reports for voltage and current

Harmonic Compliance Reports

Harmonic compliance reporting limits are defined in IEEE Std 519-2014. Separate tables are created for voltage distortion and current distortion at the Monitored Element or Distortion Results Bus (POI) defined in the Section 1a of the Distortion Analysis page (Figure 1-17). The tabulated results are presented for the average values listed in the Monitored Distortion Reports (Figure 1-15). Each parameter is explained below:

- Harmonic Voltage Compliance Reporting:
  - POI Voltage (kVln) – Fundamental value of bus voltage at the Distortion Results Bus or Point of Interest (POI) in kV. Note that the term "POI" used in this software is synonymous with the term "PCC" (point of common coupling) used in IEEE Std 519-2014.
    - Note that the above POI Voltage value is necessary for determining the limit for THDv and individual voltage harmonics.
  - THDv (%) – Total harmonic distortion of bus voltage in %.
  - H2(%), H3(%), …H25(%) – Individual voltage harmonics (% of fundamental).
- Harmonic Current Compliance Reporting:
  - POI Voltage (kVln) – Fundamental value of bus voltage at the Distortion Results Bus or Point of Interest (POI) in kV. Note that the term "POI" used in this software is synonymous with the term "PCC" (point of common coupling) used in IEEE Std 519-2014.
  - POI Isc (kA) – Available symmetrical fault current level at the POI.
  - POI Iload (kA) – Fundamental value of load current through selected element in kA.
    - Note that the above three values are necessary for determining the limit for THDi and individual current harmonics.
  - THDi (%) – Total harmonic distortion of current through selected element (% of fundamental).
  - H2(%), H3(%), … H25(%) – Individual current harmonics (% of fundamental).

Feeder Wide Results

Distortion analysis results can be displayed over the entire circuit as well. This is achieved by clicking on "Plot Feeder Wide Results for Harmonic" button after specifying a desired harmonic value in the text box next to the button. Depending on computer speed, it may take up to 30 seconds to build the current and voltage feeder plots. Sample voltage and current values over the entire circuit are shown in the form of the heat plots in Figure 1-20 and Figure 1-21, respectively. The color index on the right of the plot can be used to read the values at desired portions of the circuit.

Figure 1-20 shows the specified harmonic and overall distortion of the bus voltages (averaged values for the individual phases). For example, comparing these plots against the circuit plot in Figure 1-5 tells us that the average THDv at feeder head is around 4.25%. In addition, there is a plot that shows the resultant voltage unbalance over the entire circuit.

The voltage imbalance is calculated as the percent deviation from the average at every feeder node. The following equations show the generic calculation used for imbalance at a three-phase node. If only one or two phases exist at a node, the equations are reduced for the number of existing phases. Single-phase nodes will have zero imbalance.

$$\text{Imbalance} = Maximum\left(\left|\frac{V_{PhaseA} - V_{AVG}}{V_{AVG}}\right|, \left|\frac{V_{PhaseB} - V_{AVG}}{V_{AVG}}\right|, \left|\frac{V_{PhaseC} - V_{AVG}}{V_{AVG}}\right|\right) \cdot 100$$

Where,

$$V_{AVG} = \frac{V_{PhaseA} + V_{PhaseB} + V_{PhaseC}}{3}$$

The plots in Figure 1-21 show the magnitudes for the specified harmonic in amperes and also the overall current distortion (averaged values for the individual phases). In addition, the neutral current and the rms current unbalance due to the unbalanced nature of circuits are also shown. It may be noted that current unbalance is calculated in the same way as voltage imbalance.

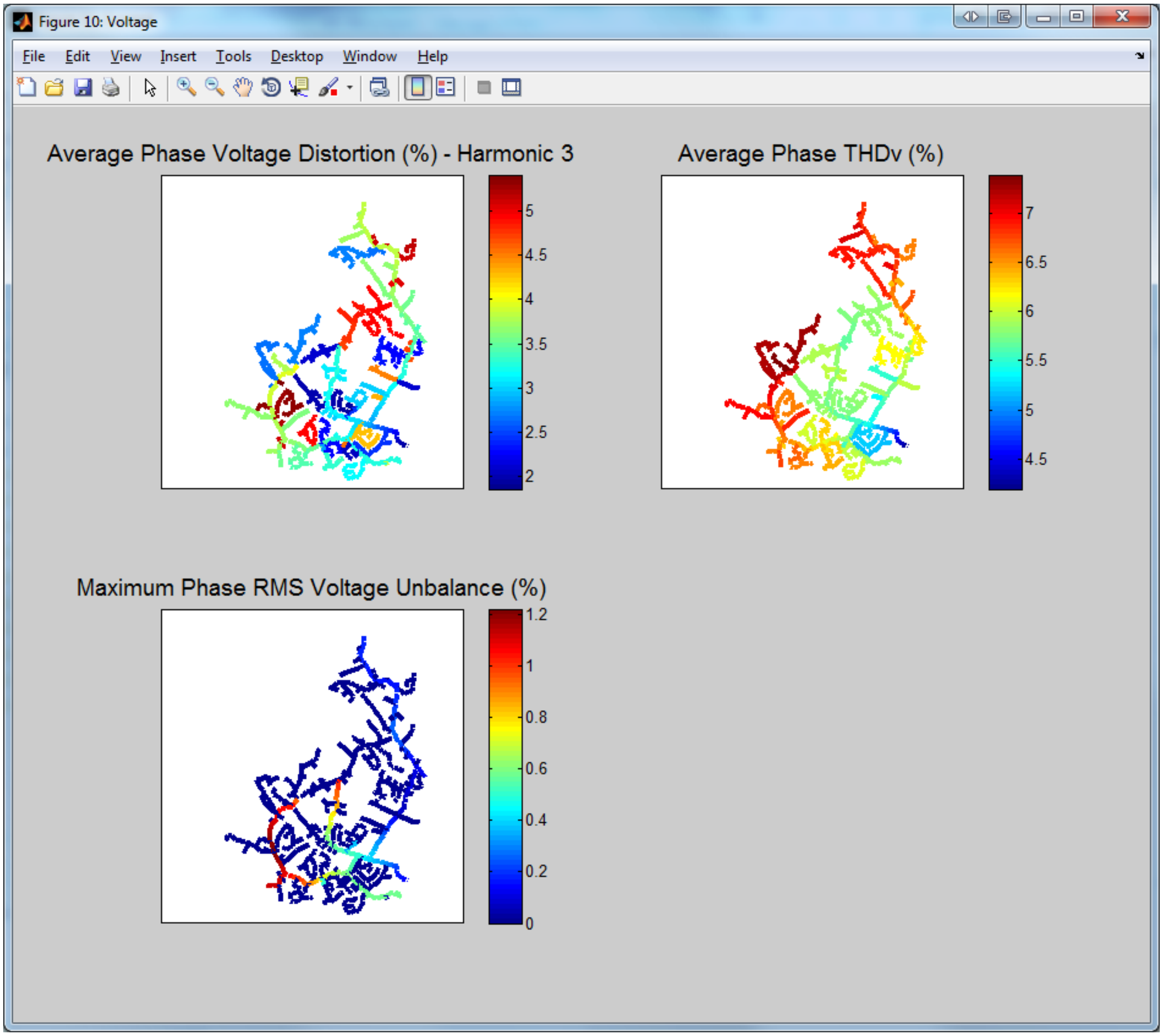


Figure 1-12
Sample voltage distortion analysis results over the entire circuit

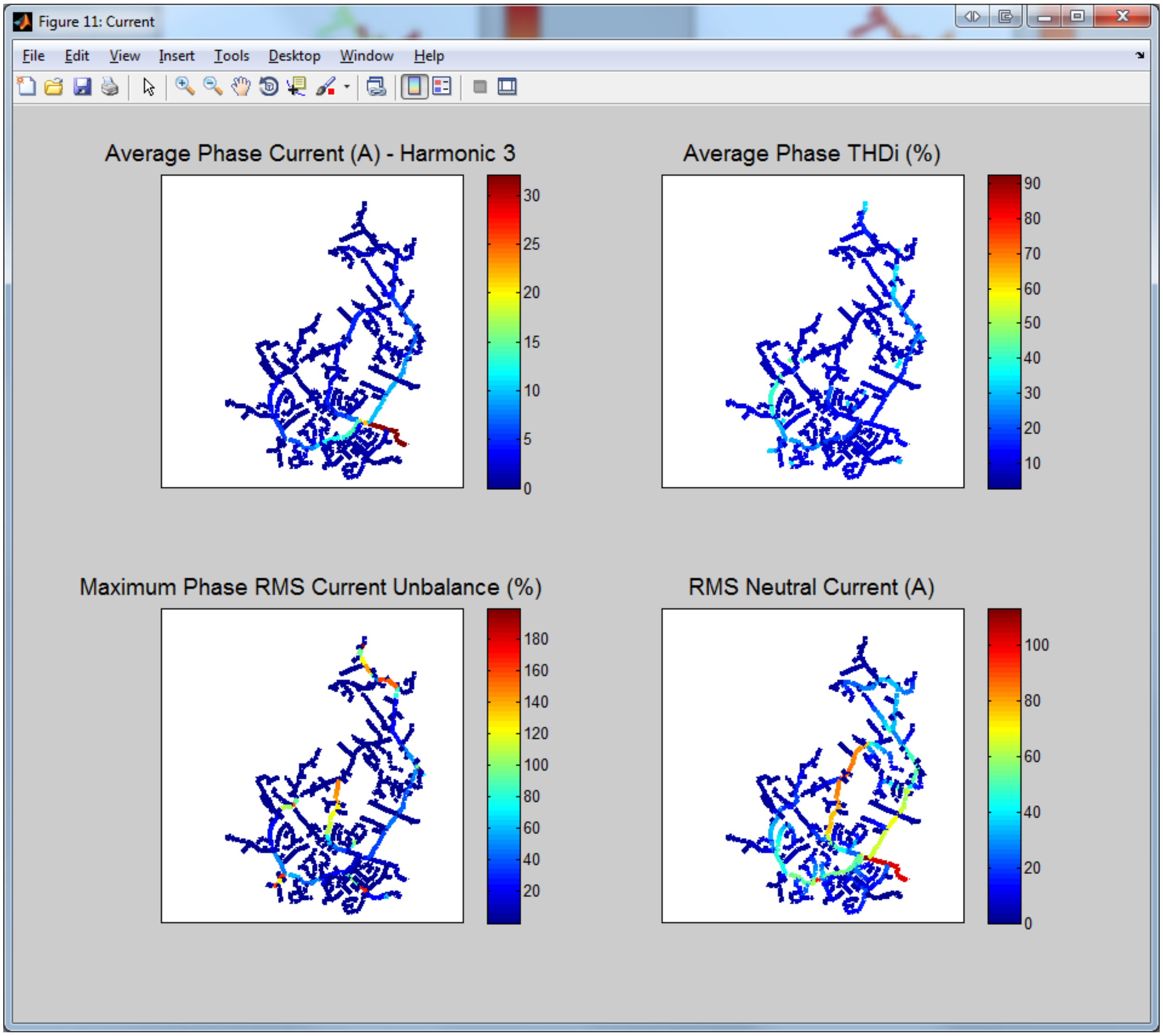


Figure 1-13
Sample current distortion analysis results over the entire circuit