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**An Evaluation of Harmonic Mitigation Techniques**  
**A Major Qualifying Project**

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## Abstract

Non-linear loads (NLLs) cause distortion also known as harmonic pollution; this pollution creates power quality issues. Issues including: voltage supply distortion, power losses, electromagnetic interference, resonance, metering errors, and instability. This is due to the current harmonics that are a byproduct of devices that convert electrical to other forms of energy such as mechanical, thermal, and electrical. Devices such as these are common in industrial plants or large-scale office buildings. The reduction of harmonic pollution is necessary to avoid the costs, or fines, associated with the poor power quality they are responsible for. The goal of this project is to evaluate two harmonic mitigation techniques minimizing the Total Harmonic Distortion of voltage on a power system. Both methods involved the addition of an active filter across the NLLs; for Method I the active filter and the NLL act as an equivalent resistance, while for Method II the active filter and NLL produce the current of only the fundamental harmonic. Based on the simulation results it was determined that Method I is more efficient at mitigating current harmonics.

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# 1 Introduction

Electrical energy is a product; it is produced, sold, and distributed to consumers. Good quality energy is produced at substations as a 60 Hz, 3 phase, 120° balanced sinusoidal waves, it is then sold to consumers with the expectation that they are receiving the same good quality characteristics. It is becoming more common that this is not the case. Often, as electrical energy is used by the consumer it is converted into other forms of energy such as thermal, mechanical, and electrical. This conversion process produces harmful byproducts called current harmonics. Current harmonics operate at the fundamental frequency (60Hz) and at integer multiples of this frequency; the most harmful of these harmonics occur at the odd integers (180Hz, 300Hz, 420Hz, 540Hz, etc.). However, there are known situations when the harmonic order is a non-integer. The current harmonics are injected into the power system and cause electromagnetic pollution; this pollution prevents the next consumers from receiving the expected electrical energy. Some of the negative effects the harmonic pollution have on a power system include:

- Voltage distortion
- Resonances
- Metering and relay errors
- Waveform notching
- Instability and mechanical vibrations
- Power line overheating
- Sensitive equipment failure.
- Additional power losses due to skin effect

## 1.1 Total Harmonic Distortion

The current harmonics mix with the power system's voltage and current waveforms causing distortions. The degree of distortion on a waveform is evaluated using the Total Harmonic Distortion (THD). The equation takes the square root of the summation of all the harmonic components of the voltage or current squared divided by the fundamental component of the voltage or current wave, Equation 1.1 is used for THD of voltage ( $THD_v$ ) and Equation 1.2 is used for THD of current ( $THD_i$ ). This equation compares the harmonic component to the fundamental component of a signal; a higher THD percentage results in more signal distortions present.

$$\%THD_V = \frac{\sqrt{\sum_{h \neq 1} V_h^2}}{V_1} * 100 \quad (1.1)$$

$$\%THD_I = \frac{\sqrt{\sum_{h \neq 1} I_h^2}}{I_1} * 100 \quad (1.2)$$

The IEEE Standard 519-1992, titled, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems" limits the individual and total distortion for harmonics in a power system. The standard is to keep voltage distortion at the consumer's connection point to the power grid below 5% THD<sub>V</sub>. The current distortion limit depends on the type of customer receiving power; small consumers on the power system have higher current distortion limits than large consumers, this limit can be as high as 20% THD<sub>I</sub> [2]. For the purpose of this project the main concern will be the total harmonic distortion of the voltage (THD<sub>V</sub>) because of its more concise standard.

## 1.2 Active Filters

Harmonic filters are used to absorb or minimize the unwanted current harmonics providing improved power quality. Some types of harmonic filters are passive, active and hybrid. For the purpose of this project, active filters will be used. Active filters are more desirable than passive filters because:

- Active filters do not resonate with the system, where as passive filters resonate with system.
- They can address more than one harmonic at a time
- They can be programmed to correct harmonics as well as power factor [1].

Active filters are used to compensate the current harmonics. These filters are effective because they automatically adjust to mitigate the current harmonics for each nonlinear load. The active filter is added in parallel to the nonlinear load. It works by having a current that is the inverse of the current harmonics. When the current harmonics and the current of the active filter combine they cancel each other out.



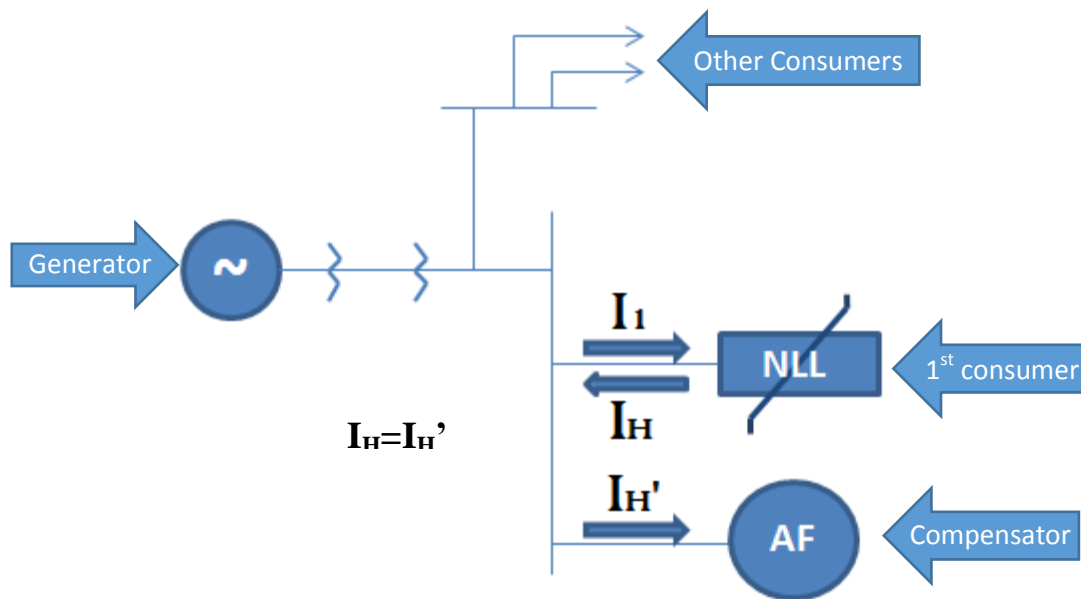


Figure 1-1-Simple feeder system showing effects of Active Filter (AF)

Figure 1.1 represents a simple feeder system to explain the effects of an Active Filter (AF) on a system. The generator produces current  $I_1$  that the 1<sup>st</sup> consumer receives. The nonlinear load of the 1<sup>st</sup> consumer takes in current  $I_1$  and outputs current harmonics  $I_H$  onto the system. If these harmonics are not mitigated they will affect the power quality of the electrical energy for neighboring consumers. Therefore, an active filter is added in parallel with the nonlinear load to compensate for the current  $I_H$ . The active filter has a current,  $I_H'$ , that is equal to the inverse of the current harmonics,  $I_H$ . When the current  $I_H$  and  $I_H'$  combine, they cancel out.

### 1.3 Project Goal

The goal of this project is to find the most effective method of eliminating the current harmonics in a system to reduce the  $THD_V$ . This evaluation is necessary because there is much debate in the power industry as to which method is superior. PSpice simulation will be used to evaluate two harmonic mitigation methods and well as two compensator input methods.

### 1.4 Report Outline

Chapter 2, Methodology, discusses the methodology used to collect data on both harmonic mitigation techniques.

Chapter 3, Results, evaluates the data collected to determine which method is more effective.

Chapter 4, Conclusion, concludes the final observation of the results.

Appendix A lists all of the data, tables, code that were used to analyze and evaluate the goal of this project.

## 2 Methodology

A radial feeder system was modeled with components and values representative of the power industry using PSpice simulation. The circuit model includes five nonlinear loads, randomly placed at nodes toward the end of the feeder distribution system. Nonlinear loads were compensated using two different methods and three compensator input orders. This section of the report describes the details by which harmonic compensation was evaluated.

### 2.1 Circuit

#### 2.1.1 Circuit Diagram

The following figure, Figure 2.1, depicts the radial feeder system supplied from a substation. The feeder consists of ten linear loads and five nonlinear loads.

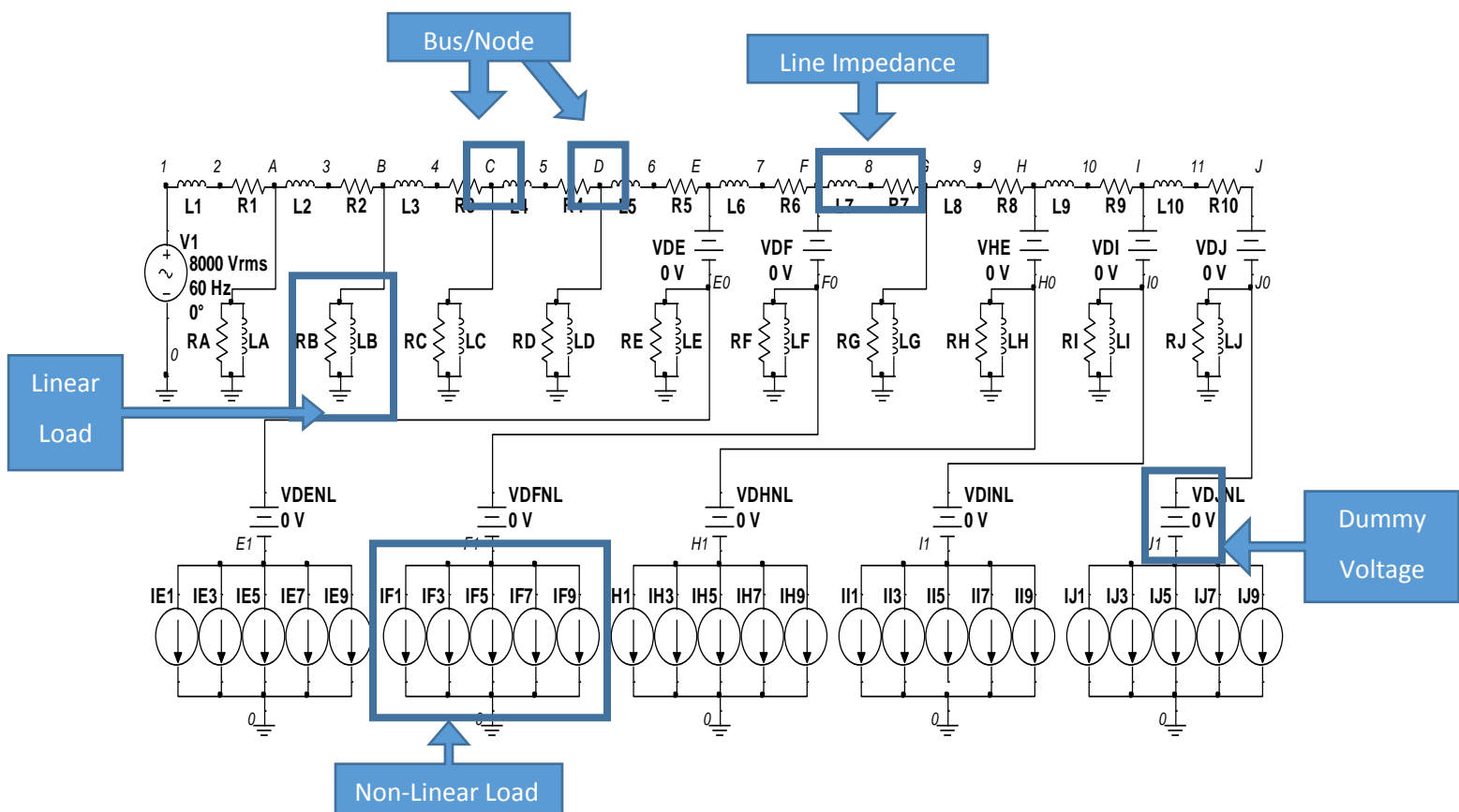


Figure 2-1- The Radial Feeder System used for harmonic mitigation evaluation

The substation supplies  $8kV_{RMS}$ , 60Hz sine wave and the system has 9MVA total apparent power. The buses, labeled as letters A-J (from here forth be referred to as nodes A-J); thus, bus C is synonymous

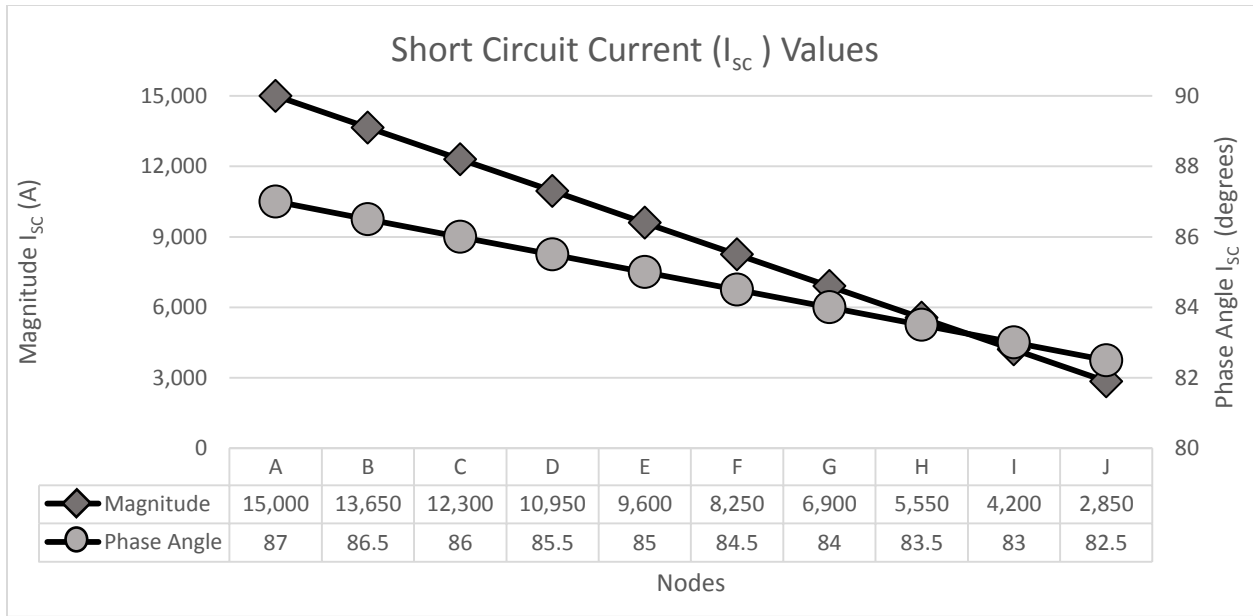
to Node C. Each node was connected by a wire with characteristic line impedance. Linear loads, modeled consumers of the power system, located at each node A - J. For clarification, the linear load connected to Node B is labeled as RB and it is in parallel with LB. The above representations are consistent throughout the power system.

Five nonlinear loads exist on the system prior to the addition of any active filters for harmonic compensation. The NLLs are modeled by five paralleled current sources flowing from the node to ground. These NLLs represent the current harmonics injected into the power system. Each respective harmonic is labeled consistently. For example, the harmonics occurring at Node E are IE1, IE3, IE5, IE7, and IE9. "IE1" is equal to the fundamental current harmonic.

Finally, to conduct measurements using PSpice the system requires "dummy" voltages, which act as ammeters, at the nodes with nonlinear loads; these "dummy" voltages do not alter the system. It is at these dummy voltages where measurements have been taken for each node, unless stated otherwise.

#### 2.1.2 Circuit Diagram Values

The circuit diagram was created to model a realistic power system with loads and line impedances. The chosen values for the short circuit current ( $I_{sc}$ ) were based upon the graph presented in Figure 2.2. The  $I_{sc}$  range of 15,000 A to 2850 A was chosen from the linearly decreasing line from Node A to Node J. Similarly, the phase angle was chosen using the same linear decreasing method from Node A to Node J at a corresponding range of 90 degrees to 80 degrees. This method can be seen in Figure 2.2.



*Figure 2-2-Values for Short Circuit Current*

Using the values for the short circuit current vector and the RMS voltage ( $V_{RMS}$ ) of the generator, the characteristic line impedance values were calculated for the lines connecting each A - J node. This was determined using Equation 2.1; the  $V_{RMS}$  vector divides by the  $I_{sc}$  vector resulting in the impedance vector of the source to the node. To find the characteristic line impedance of the lines connecting the sections Equation 2.1 was used. This equation takes the more radial impedance ( $Z_{Node}$ ) from the source and subtracts the preceding node impedance ( $Z_{Node - 1}$ ), which is closer to the source. For example, the impedance for line section CD is produced by subtracting node impedance  $Z_C$  from node impedance  $Z_D$ . This solution can then be converted from polar to rectangular form utilizing Euler's formula. The real part of the rectangular form is the value of the resistor, while the imaginary part is the reactance of the inductor. Using equation 2.1 a value for the inductor is derived.

$$Z_{Node} = \frac{V_{RMS}}{I_{Node}} \quad (2.1)$$

$$Z_{Line} = Z_{Node} - Z_{Node - 1} \quad (2.2)$$

$$X_L = \omega L = 2\pi f L \Rightarrow L = \frac{X_L}{2\pi f} \quad (2.3)$$

The following process was used:

1. Find source to node impedance ( $Z_{\text{Node}}$ ) using Equation 2.1
2. Find line impedance ( $Z_{\text{Line}}$ ) using Equation 2.3. For  $Z_{\text{Line}}$  of source to node A,  $Z_{\text{Line0A}} = Z_A$
3. Convert  $Z_{\text{Line}}$  from polar for rectangular using Euler's formula.
4. Identify the value of the resistor, the real part of Euler's formula.
5. Calculate the inductor value with Equation 2.3
6. Repeat for all nodes.

Example:

$$Z_A = \frac{8000 \angle 0^\circ}{15000 \angle -87^\circ} = 0.533 \angle 87^\circ = 0.533 [\cos(87^\circ) + j \sin(87^\circ)] = \mathbf{0.028 + j 0.533 \Omega}$$

$$Z_A = Z_{\text{Line}} = \mathbf{0.028 + j 0.533 \Omega}$$

$$0.028 + j 0.533 \Omega \Rightarrow \mathbf{R_1 = 0.028 \Omega}$$

$$X_L = \omega L = 2 * \pi * 60 * L_1 = 0.533 \Omega \Rightarrow \mathbf{L_1 = 1.4 \text{mH}}$$

$$Z_B = \frac{8000 \angle 0^\circ}{13650 \angle -86.5^\circ} = 0.586 \angle 86.5^\circ = 0.586 [\cos(86.5^\circ) + j \sin(86.5^\circ)] = \mathbf{0.036 + j 0.586 \Omega}$$

$$Z_{\text{LineAB}} = Z_B - Z_A = \mathbf{0.036 + j 0.586 - 0.028 - j 0.533 = 0.008 + j 0.053 \Omega}$$

$$0.008 + j 0.053 \Omega \Rightarrow \mathbf{R_2 = 0.008 \Omega}$$

$$X_L = \omega L = 2\pi 60 * L_2 = 0.053 \Omega \Rightarrow \mathbf{L_2 = 14 \mu\text{H}}$$

Resistor Name	Resistor Value (mΩ)	Inductor Name	Inductor Value (mH)
R1	28	L1	1.4
R2	8	L2	14
R3	9	L3	1.64
R4	12	L4	215
R5	16	L5	268
R6	20	L6	361
R7	28	L7	496
R8	42	L8	3.058
R9	69	L9	1.22
R10	134	L10	2.37

Table 2.1-Line Component Values

Table 2.1 is the final values that were determined for the line impedance components for the radial feeder system.

Apparent power at each node was chosen so that the sum of the apparent power resulted in 9MVA; the apparent power at each node A - J was distributed arbitrarily. The values were chosen arbitrarily because the power drawn from the power system by each consumer is unique. The power factor (PF) was also chosen at random for each node. These values are the parameters used to first develop real and reactive power at the nodes and subsequently the resistor and inductor values that model the load impedance. The following process for calculation resulted in the feeder values of Table 2.2. The calculation process for each node is dependent only on the apparent power and power factor at that node.

1. First the PF is manipulated to produce  $\theta$  for all nodes using Equation 2.4.

$$\theta = \cos^{-1}(PF) \quad (2.4)$$

2. Next, using Equations 2.5 and 2.6, calculate the real power (P) and the reactive power (Q) of the linear load, do this for nodes A-J.

$$P = S \cos(\theta^\circ) \quad (2.5)$$

$$Q = S \sin(\theta^\circ) \quad (2.6)$$

3. Finally, using Equations 2.7 and 2.8 determine the component values that will be used to model impedance of the linear load. In these equations it is necessary to multiply by three because the system is 3-phase.

$$R = \frac{V_{RMS}^2}{P} * 3 \quad (2.7)$$

$$L = \frac{V_{RMS}^2}{Q} * 3 \quad (2.8)$$

Node	Linear Load Parameters					Linear Load Values			
	S (MVA)	PF	$\theta^\circ$	P (MW)	Q (MVAR)	Resistor Name	$\Omega$	Inductor Name	mH
A	0.5	0.80	36.86	0.40	.30	RA	480.000	LA	1.698
B	0.9	0.85	31.78	0.68	0.421	RB	282.353	LB	1.209
C	1.0	0.90	25.84	0.90	0.436	RC	213.333	LC	1.168
D	1.5	0.70	45.57	1.05	0.107	RD	182.857	LD	0.475
E	0.8	0.75	41.10	0.60	0.529	RE	320.000	LE	0.963
F	0.4	0.50	60.00	0.20	0.346	RF	960.000	LF	1.470
G	0.2	0.82	34.91	0.164	0.114	RG	1170.732	LG	4.450
H	1.8	0.45	63.25	0.81	1.607	RH	237.037	LH	0.317
I	0.5	0.65	49.45	0.325	380	RI	590.769	LI	1.341
J	1.5	0.70	45.57	1.05	1.071	RJ	182.857	LJ	0.475

Table 2.2-Feeder Table Components

The last step for creating the circuit is inserting the harmonics. For the purpose of this evaluation harmonics were modeled to the 9<sup>th</sup> order. Harmonics were chosen arbitrarily within their corresponding ranges. Phase angle values were chosen from the range:  $-40^\circ \leq Phase \leq 40^\circ$ ; although harmonics can have phase angles  $0^\circ \leq \theta_h \leq 360^\circ$ . The peak values for the amplitude were chosen such



that the fundamental peak was large and all preceding harmonic peak values were some arbitrary fraction of the fundamental peak, these values, seen in Table 2.3, completes the circuit of Figure 2.1.

Sinusoidal Current Harmonic	E		F		H		I		J	
	Peak (v)	Phase angle	Peak (v)	Phase angle	Peak (v)	Phase angle	Peak (v)	Phase angle	Peak (v)	Phase angle
1	80	-30	70	20	125	-30	40	-30	28	-30
3	1.25	25	13.75	30	1.25	40	2.5	30	5	20
5	10	-35	8.75	10	12.5	-35	10	-20	10.625	-40
7	13.75	-40	11.25	20	10	-10	5	20	9.125	35
9	9.375	30	6.125	30	16.25	20	9.375	-40	18.75	30

Table 2.3-Non-Linear Load Harmonics

Initial values of the completed system with all harmonics were measured, including: apparent power at each node, PF, and total harmonic distortion for voltage and current. Total harmonic distortion discussed in the introduction was calculated using PSpice simulation tools; the calculations followed Equations 2.9 and 2.10.

$$\%THD_V = \frac{\sqrt{\sum_{h \neq 1} V_h^2}}{V_1} * 100 \quad (2.9)$$

$$\%THD_I = \frac{\sqrt{\sum_{h \neq 1} I_h^2}}{I_1} * 100 \quad (2.10)$$

The equation is the square root of the summation of all the harmonic components of the voltage or current squared divided by the fundamental component of the voltage or current wave. This equation compares the harmonic component to the fundamental component of a signal; the higher percentage THD there is, the more distortions are present in the signal.

		Linear Load		Nonlinear Load Uncompensated			
	Chosen	Chosen		Measured	Calculated	Measured	
Node	ISC $\angle\theta$ (A)	S(MVA)	PF	S(MVA)	S1(kVA) Single Phase	%THD_I	%THD_V
A	15,000 $\angle$ 87°	0.5	0.80	0.474306	158.102	10.156	2.634
B	13,650 $\angle$ 86.5°	0.9	0.85	0.735965	245.322	10.555	2.910
C	12,300 $\angle$ 86°	1.0	0.90	0.856356	285.452	11.259	6.218
D	10,950 $\angle$ 85.5°	1.5	0.70	1.392500	464.167	12.270	6.667
E	9,600 $\angle$ 85°	0.8	0.75	1.542700	514.233	14.208	7.232
F	8,250 $\angle$ 84.5°	0.4	0.50	0.952192	317.397	14.645	7.843
G	6,900 $\angle$ 84°	0.2	0.82	0.175920	58.640	13.027	8.549
H	5,550 $\angle$ 83.5°	1.8	0.45	2.781100	927.033	13.423	13.037
I	4,200 $\angle$ 83°	0.5	0.65	0.979352	326.451	18.582	14.145
J	2,850 $\angle$ 82.5°	1.5	0.70	1.569100	523.033	18.678	15.518

Table 2.4-Radial Feeder System Values with no Compensation

The values in Table 2.4 describe the radial feeder system with no compensation and will be used as the initial point for the evaluation of harmonic mitigation.

## 2.2 Compensator Input Strategies

The effectiveness of placing an active filter on a system depends on its location within the system. This has resulted in the necessity for multiple placement approaches. For this project active filters will only be placed at nodes where NLLs exist. After each placement of an active filter the system will be evaluated.

The first approach, called A to J, for active filter placement is represented in Figure 2.3. This placement method is termed “A to J” because the filters were added to the nodes with the NLLs from points in the system closer to the generation source to points in the system farthest from the generation

source also known as the most radial node. This method placement can also be described relative to node location; the filters were added in a direction from Node A to Node J. Meaning that, the first active filter was placed at the NLL closet to Node A and then evaluated for THD<sub>v</sub>. Next, a second compensator was added at the second closest NLL then evaluated and continued in this manner until all NLLs had been compensated.

Number of Compensators	Nodes
1	E
2	E F
3	E F H
4	E F H I
5	E F H I J

*Figure 2-3-Input Strategy A to J*

The second approach, called J to A, for active filter placement is represented in Figure 2.4. The compensators are first added to the most radial node containing a NLL on the system with respect to the generating source. Then each subsequent filter is added at the next most radial node containing a NLL in the direction of the source generator.

Number of Compensators	Nodes
1	J
2	I J
3	H I J
4	F H I J
5	E F H I J

*Figure 2-4-Input Strategy J to A*

The third and last active filter placement approach is represented in Figure 2.5. A random strategy was used; the first filter was added to Node J and analyzed. The next filter was added at Node H and the evaluation of the two filters, placed at Nodes J and H, was performed. Subsequently, three filters were at Nodes J, H and E; four filters at Nodes J, H, E, F; and finally, five filters at Nodes J, H, E, F, and I.

Number of Compensators	Nodes				
1					J
2		H			J
3	E	H			J
4	E	F	H		J
5	E	F	H	I	J

Figure 2-5-Random Input Strategy

## 2.3 Methods

This section describes how the injected current harmonics are mitigated by the active filter. In this project the active filter will not be simulated, instead the effect of an active filter with the NLL is simulated. The following two methods were evaluated using the compensator input strategies described in Section 2.2.

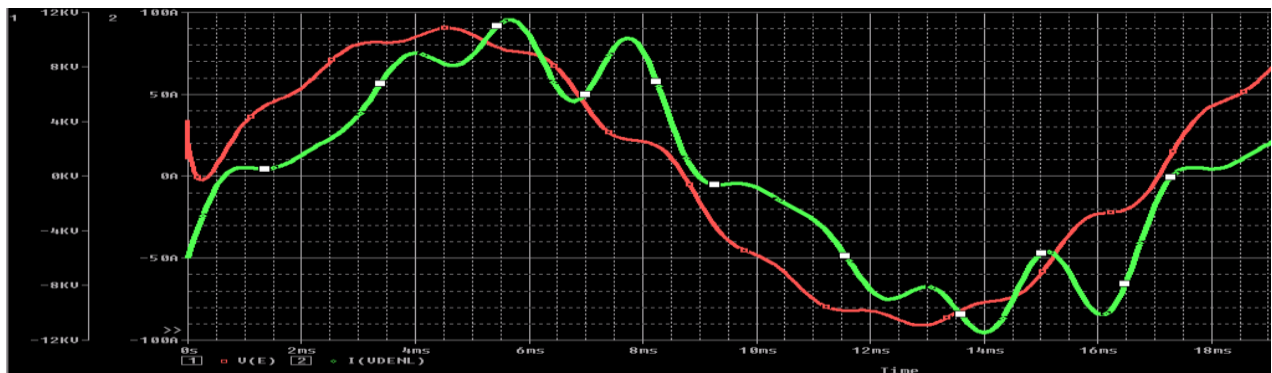


Figure 2-6-Voltage at Node E (pink) and current injected at Node E (green). No Compensators on system.

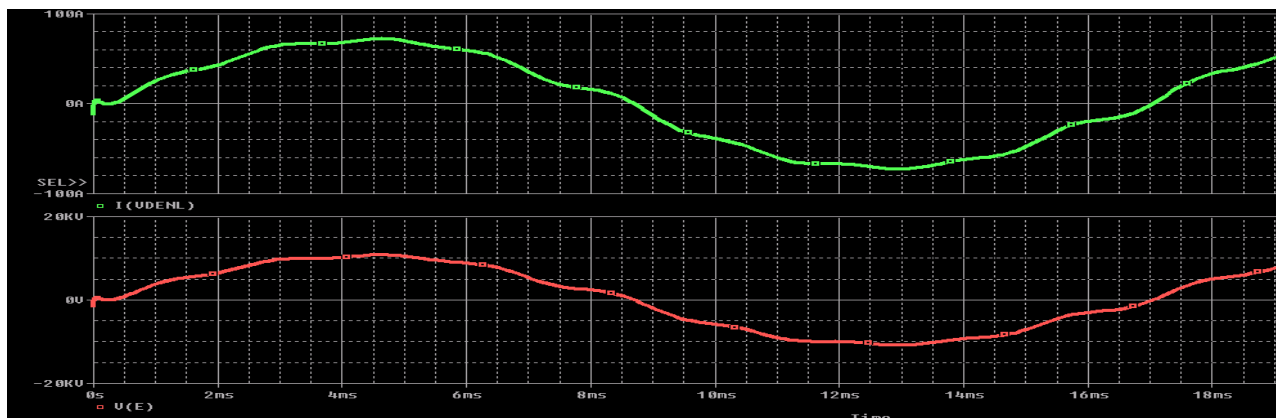


Figure 2-7-Method I: Current through the equivalent resistance at Node E. (green) Voltage at Node E (pink). Compensators at E and F; NLL at H, I and J.



Figure 2-8 - Method II Current through the equivalent resistance at Node E. (green) Voltage at Node E (pink). Compensators at E and F and NLLs at H, I, and J.

### 2.3.1 Method I

Method I begins with the non-sinusoidal voltage and current waveforms, Figure 2.6, caused by the NLL and mitigates these harmonics with an active filter placed in parallel with the NLL, Figure 2.9A. In Method I, the active filter together with the current harmonics results in an equivalent load that acts as a linear resistance, Figure 2.9B. This produces a current waveform that follows the voltage waveform seen in Figure 2.7. This resistive load is a linear load and therefore the current and voltage gradually become sinusoidal. To evaluate the equivalent resistance value of the NLL in parallel with the active filter, Equation 2.11 is used.

The power, in kW, and  $V_{RMS}$  are measured at the node where the NLL is located.

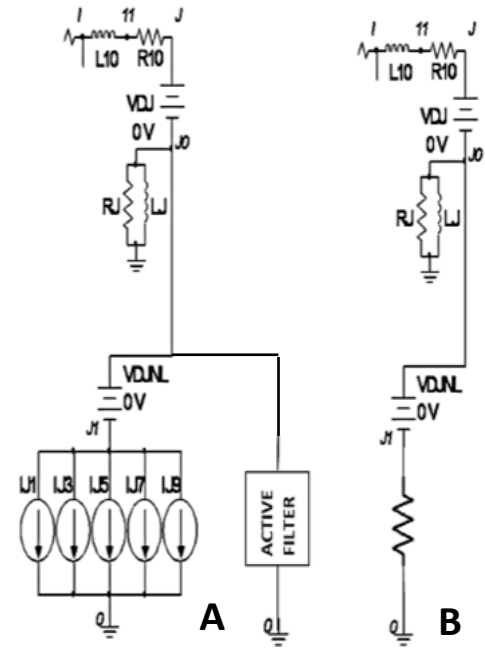


Figure 2-9: Method I

$$\frac{V_{RMS}^2(kV)}{P_{avg}(kW)} = R_{COMP} = |R_{COMP}| \quad (2.11)$$

The calculated resistor absorbs the same amount of power, within 3%, of the power absorbed by the current harmonics. To keep the amount of power absorbed within 2%, the resistor value was

manually adjusted. The resistor values are determined during the process of inputting compensators and are dependent upon the particular active filter placement strategy being used. The process flow is as follows:

1. Identify node of NLL to be mitigated.
2. Perform resistor calculation at that node.
3. Replace current harmonics with resistor.
4. Evaluate  $THD_V$  and  $THD_I$ .
5. Repeat, according to strategy, until all NLLs are compensated.

The following tables present the resistor value calculations for each strategy:

<b>A to J</b>	<b>w/out Comp</b>		<b>CALCULATED</b>			<b>ADJUSTED</b>		
<b>Node</b>	<b>P<sub>AVG</sub>(KW)</b>	<b>V<sub>RMS</sub>(KV)</b>	<b>R(<math>\Omega</math>)</b>	<b>P(KW)</b>	<b>%error</b>	<b>R(<math>\Omega</math>)</b>	<b>P(KW)</b>	<b>%error</b>
<b>E</b>	383	7.57	149.621149	386	-0.78	N/A	N/A	100.00
<b>F</b>	338.5	7.57	169.290694	335.5	0.89	N/A	N/A	100.00
<b>H</b>	584	7.315	91.6253853	595	-1.88	N/A	N/A	100.00
<b>I</b>	189.8	7.35	284.628556	191	-0.63	N/A	N/A	100.00
<b>J</b>	129.6	7.33	414.574846	130.2	-0.46	N/A	N/A	100.00

*Table 2.5-Method I resistor values for input strategy A to J*

J to A	w/out Comp		CALCULATED			ADJUSTED		
Node	P <sub>avg</sub> (KW)	V <sub>RMS</sub> (KV)	R( $\Omega$ )	P(KW)	%error	R( $\Omega$ )	P(KW)	%error
J	121.2	7.27	436.080033	120.4	0.66	N/A	N/A	N/A
I	187.5	7.29	283.4352	188.5	-0.53	N/A	N/A	N/A
H	589	7.34	91.4696095	602	-2.21	92	599	-1.70
F	341.6	7.6	169.086651	339	0.76	N/A	N/A	N/A
E	385.5	7.6	149.831388	388.5	-0.78	N/A	N/A	N/A

Table 2.6-Method I resistor values for input strategy J to A

Random	w/out Comp		CALCULATED			ADJUSTED		
Node	P <sub>avg</sub> (KW)	V <sub>RMS</sub> (KV)	R( $\Omega$ )	P(KW)	%error	R( $\Omega$ )	P(KW)	%error
J	121.2	7.27	436.080033	120.4	0.66	N/A	N/A	N/A
H	586	7.3200	91.4375427	595	-1.54	N/A	N/A	N/A
E	386	7.6100	150.031347	389	-0.78	N/A	N/A	N/A
F	342.5	7.6200	169.531095	339.5	0.88	N/A	N/A	N/A
I	189.8	7.3600	285.403583	191.4	-0.84	N/A	N/A	N/A

Table 2.7-Method I resistor values for random input strategy

### 2.3.2 Method II

Method II begins with the non-sinusoidal voltage and current waveforms, Figure 2.6, caused by the NLLs and mitigates these harmonics with an active filter, Figure 2.10A. The combination of the current harmonics in parallel with the active filter results in the mitigation of all current harmonics except the fundamental. The idea behind this is that the active filter is injecting identical current harmonics that are 180° out-of-phase, these are inverse current harmonics, thus eliminating the current harmonics through additive properties, Equation 2.12.

$$i_{Node} = i_{NL} + i_{Comp} \Rightarrow i_{Comp} = i_{Node} - i_{NL} \quad (2.12)$$

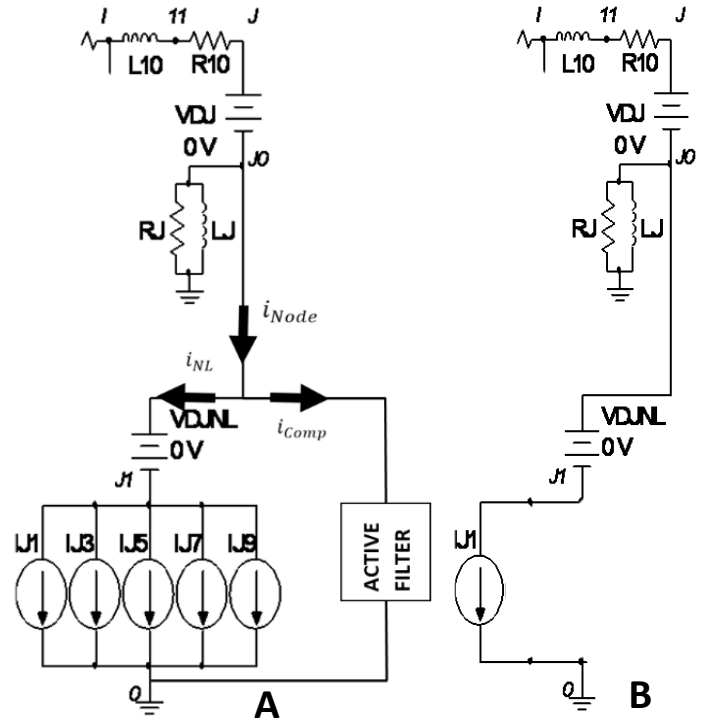


Figure 2-10: Method II

Figure 2.10A depicts the load on the node with all of its current harmonics and the active filter and Figure 2.10B depicts the equivalent load after the active filter compensates the current harmonics. The process is as follows:

1. Identify node of NLL to be mitigated.
2. Remove all NLL current harmonics except the fundamental.
3. Evaluate  $THD_V$  and  $THD_I$ .
4. Repeat, according to strategy, until all NLLs are compensated.



### 3 Results

#### 3.1 Amount of THD with the Addition of Compensators

Figure 3.1 shows how adding a compensator affects the THD in a system. The top line represents the amount of THD at each node for the uncompensated NLLs, the solid black circles on the line identify where in the system a NLL is present. The next line down has an empty circle at Node E, this circle represents that there has been a compensator added to the NLL at Node E. The third line down from the top has two empty circles at Nodes E and F, and the line represents the THD curve when there are two compensators. Each line represents the addition of another compensator until all NLLs have been mitigated. From this graph it is clear that when there is a compensator added to the circuit the amount of THD decreases. The amount of this decrease varies for each method and when different compensator input methods are used. However, it is consistent, for all methods, that once a NLL has been compensated the amount of  $THD_V$  for the system will decrease; yet,  $THD_I$  carries some exceptions. When all of the NLLs have been compensated the system the  $THD_V$  and  $THD_I$  will be approximately zero.

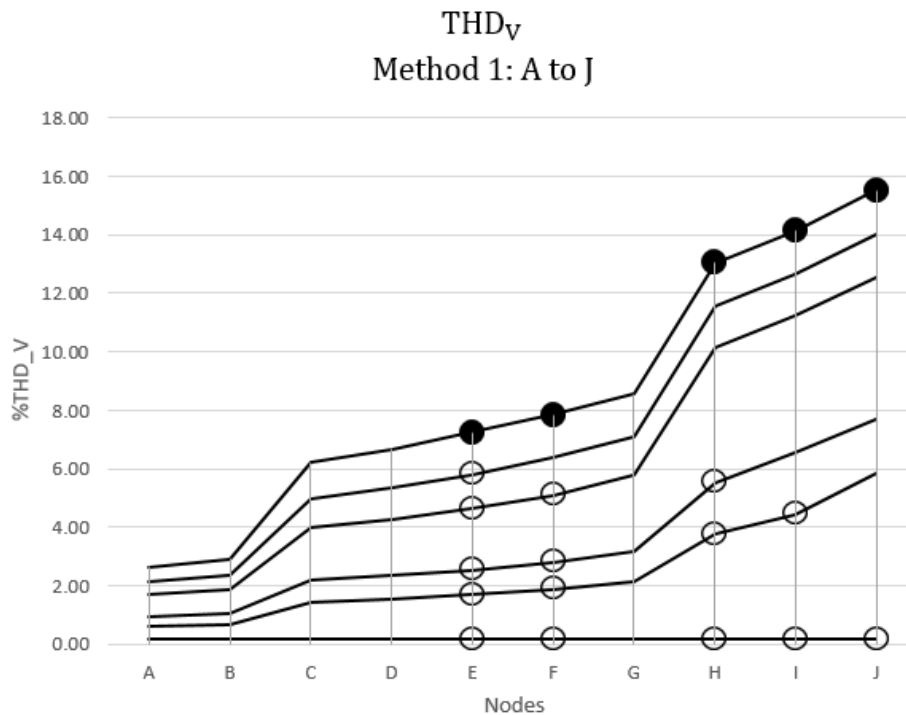


Figure 3-1-Method I THD of Voltage using A to J strategy

For  $THD_I$  the addition of a compensator does not always decrease the amount of distortion. There are cases that the  $THD_I$  was slightly higher after the addition of another compensator, reference

Figure 3.2. The top line on the graph represents the amount of THD<sub>I</sub> when there is no compensation; the solid black circles on this line identify where there is a NLL. The next line down has an empty circle at Node E which signifies that the NLL has been compensated. The amount of THD<sub>I</sub> with one compensator at Node E is less than when there are no compensators. The THD<sub>I</sub> continues to drop when the next compensator is added at Node F. When a compensator is added in at Node H there are 3 compensators; the THD<sub>I</sub> at the end of the line with 3 compensators in the system is greater than when there are only 2 compensators. Again, when there is another compensator at Node I and there are 4 compensators in the system, the THD<sub>I</sub> is greater at the end of the line than when there are only 3 compensators. Ideally, the addition of a compensator reduces the THD<sub>I</sub> in the system, however, there are cases when the removing a harmonic has negative effects on a system. In Figure 3.2, When there are 3 and 4 compensators in the THD is worse when there are less compensators in. This occurs by chance when the harmonic that had been cancelled was actually providing some compensation for the system. When a harmonic has an opposite effect on another harmonic neither harmonic can cause harm on a system. However, when one of these harmonics are cancelled, the other harmonic disrupts the system. Although, there are unpredictable cases where once a NLL has been compensated and the THD<sub>I</sub> is worsened, once all of the NLLs have been compensated the final THD<sub>I</sub> will be approximately zero.

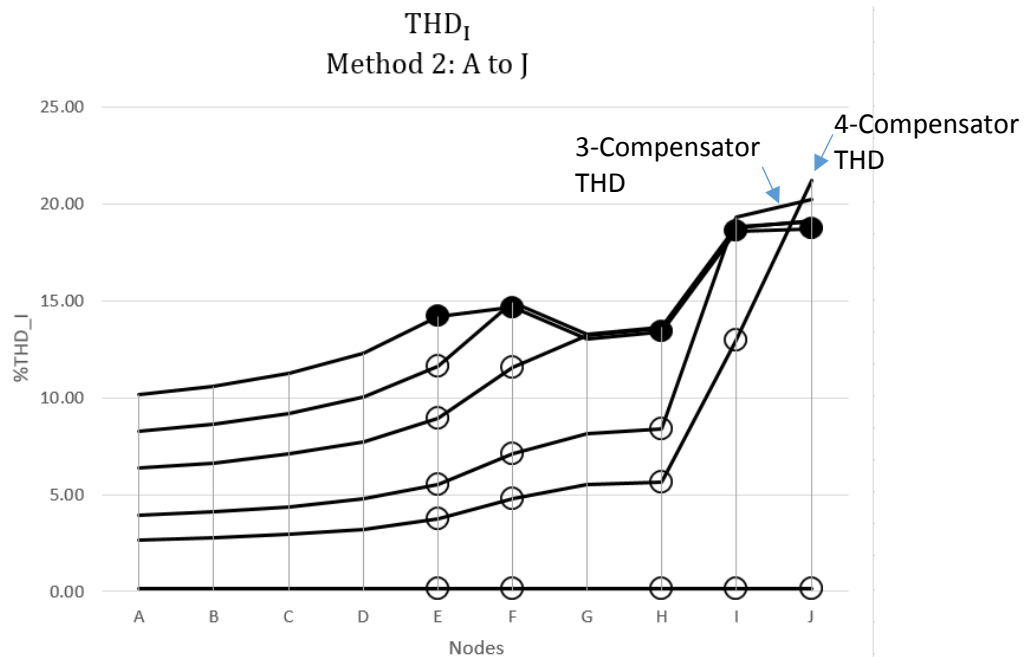


Figure 3-2-THD of Current for Method II, A to J strategy

### 3.2 Input strategy comparison of A to J and J to A

Once all NLLs have been compensated the THD is approximately zero, therefore there is no difference to which compensation and input method was used. However, until all the compensators have been added to a system the compensator input method does have an effect on THD. When the compensators are added in a J to A order the THD decreases at a faster rate than when the compensators are added to the system in an A to J order. The  $THD_v$  and  $THD_i$  for both Method 1 and Method 2 decreased faster when the compensators were added from J to A. This was evaluated by finding the  $Difference_{AtoJ}$ , Equation 4.4, the difference of the integral of the THD curve with n compensators in an A to J order, Equation 4.2, was taken from the integral of the THD curve with no compensation, Equation 4.1.

Then the  $Difference_{JtoA}$  was evaluated using Equation 4.5, the difference of the integral of the THD curve with n compensators added in a J to A order, Equation 4.3, was taken from the integral of the THD curve with no compensation, Equation 4.1.

$$A_{NoComp} = \int_A^J THD_{NoComp}(x)dx \quad (4.1)$$

$$A_{nComps(AtoJ)} = \int_A^J THD_{nComps(AtoJ)}(x)dx \quad (4.2)$$

$$A_{nComps(JtoA)} = \int_A^J THD_{nComps(JtoA)}(x)dx \quad (4.3)$$

$$Difference_{AtoJ} = A_{NoComp} - A_{nComps(AtoJ)} \quad (4.4)$$

$$Difference_{JtoA} = A_{NoComp} - A_{nComps(JtoA)} \quad (4.5)$$

These two differences,  $Difference_{AtoJ}$  and  $Difference_{JtoA}$ , were then compared to one another. The larger value means that its corresponding input method is more effective at minimizing THD. The calculations were performed for both methods each time a compensator was added and  $THD_v$  and  $THD_i$  was measured, the comparisons of these measurements can be seen in Table 3.1 and Table 3.2. In each case the compensator input order J to A was more effective at eliminating THD of voltage and of current.

Input Order Comparison for 1 and 2 compensators					
1 COMPENSATOR			2 COMPENSATORS		
THD <sub>v</sub>			THD <sub>v</sub>		
METHOD 1			METHOD 1		
	THD <sub>v</sub>			THD <sub>v</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	64.259	58.128	A TO J	54.103	68.284
J TO A	<b>50.980</b>	71.407	J TO A	<b>40.268</b>	82.119
METHOD 2			METHOD 2		
	THD <sub>v</sub>			THD <sub>v</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	64.977	57.410	A TO J	55.808	66.578
J TO A	<b>52.167</b>	70.220	J TO A	<b>42.743</b>	79.643
THD <sub>i</sub>			THD <sub>i</sub>		
METHOD 1			METHOD 1		
	THD <sub>i</sub>			THD <sub>i</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	112.695	9.691	A TO J	97.870	24.517
J TO A	<b>80.600</b>	41.787	J TO A	<b>60.100</b>	62.286
METHOD 2			METHOD 2		
	THD <sub>i</sub>			THD <sub>i</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	113.743	8.643	A TO J	100.264	22.123
J TO A	<b>78.822</b>	43.564	J TO A	<b>57.483</b>	64.903

Table 3.1 - Input Order Comparison of Methods for 1 and 2 compensators

Input Order Comparison for 3 and 4 compensators					
3 COMPENSATORS			4 COMPENSATORS		
THD <sub>v</sub>			THD <sub>v</sub>		
METHOD 1			METHOD 1		
	THD <sub>v</sub>			THD <sub>v</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	30.429	91.957	A TO J	20.781	101.605
J TO A	<b>19.344</b>	103.042	J TO A	<b>11.617</b>	110.769
METHOD 2			METHOD 2		
	THD <sub>v</sub>			THD <sub>v</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	34.888	87.498	A TO J	25.948	96.439
J TO A	<b>21.815</b>	100.572	J TO A	<b>13.071</b>	109.315
THD <sub>i</sub>			THD <sub>i</sub>		
METHOD 1			METHOD 1		
	THD <sub>i</sub>			THD <sub>i</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	71.022	51.364	A TO J	50.802	71.584
J TO A	<b>33.010</b>	89.377	J TO A	<b>16.883</b>	105.504
METHOD 2			METHOD 2		
	THD <sub>i</sub>			THD <sub>i</sub>	
No Comp	122.386	DIFFERENCE	No Comp	122.386	DIFFERENCE
A TO J	73.831	48.556	A TO J	53.608	68.778
J TO A	<b>29.821</b>	92.565	J TO A	<b>14.957</b>	107.429

Table 3.2 - Input Order Comparison for Methods for 3 and 4 compensators

### 3.3 Comparison of Method 1 and Method 2

#### 3.3.1 THD<sub>v</sub> Elimination

Method 1 is the most effective at eliminating THD<sub>v</sub>. This was determined by quantifying the advantage of Method 2 over Method 1. The integral of the THD curve for Method 1 ( $A_1$ ), evaluated in Equation 4.7, was subtracted from the integral of the THD curve for Method 2 ( $A_2$ ), evaluated in Equation 4.6. The  $\text{Difference}_{\text{THD}}$  is found by using Equation 4.8. If this difference was positive then Method 1 was more effective because the area underneath the curve was smaller, thus Method 1 created less THD in the system. This evaluation was performed for all the THD<sub>v</sub> data collected and can be seen in Table 3.3. In the table when  $M1 \approx M2$  there was not a more effective method for compensation, this is because the difference was not significant. After the evaluation was performed it

was found that Method 1 is more effective than Method 2 in eliminating THD<sub>V</sub> when using the input strategies A to J, J to A, and random.

$$A_2 = \int_A^J THD_{Method2}(x)dx \quad (4.6)$$

$$A_1 = \int_A^J THD_{Method1}(x)dx \quad (4.7)$$

$$Difference_{THD} = A_2 - A_1 \quad (4.8)$$

Comparison of Methods for THD <sub>V</sub> for compensator input order:				
A TO J				
Comp @	A1	A2	Difference <sub>THD</sub>	More Effective
E	<b>64.259</b>	64.977	0.718	M1
E,F	<b>54.103</b>	55.808	1.706	M1
E,F,H	<b>30.429</b>	34.888	4.459	M1
E,F,H,I	<b>20.781</b>	25.948	5.166	M1
E,F,H,I,J	1.566	1.282	-0.284	<b>M1≈M2</b>
J TO A				
Comp @	A1	A2	Difference <sub>THD</sub>	More Effective
J	<b>50.980</b>	52.167	1.187	M1
J,I	<b>40.268</b>	42.743	2.476	M1
J,I,H	<b>19.344</b>	21.815	2.471	M1
J,I,H,F	<b>11.617</b>	13.071	1.454	M1
J,I,H,F,E	1.521	1.282	-0.239	<b>M1≈M2</b>
RANDOM				
Comp @	A1	A2	Difference <sub>THD</sub>	More Effective
J	<b>50.980</b>	52.167	1.187	M1
J,H	<b>28.984</b>	31.969	2.985	M1
J,H,E	<b>19.868</b>	22.233	2.365	M1
J,H,E,F	<b>12.269</b>	14.339	2.070	M1
J,H,E,F,I	1.548	1.282	-0.266	<b>M1≈M2</b>

Table 3.3- Comparison between compensation methods for THD<sub>V</sub>

This can be seen visually in Figure 3.3 and Figure 3.4. Figure 3.3 also shows the THD<sub>V</sub> of the system when there is one compensator at Node E, the compensator was added in the A to J order. Here we can see the THD<sub>V</sub> without any compensation (the NLL line), Method 1 with compensation at Node E (the line with squares), and Method 2 (the line with triangles) with compensation at Node E; the

location of the compensator is shown with the empty circle. With one compensator the THD of both Method 1 and Method 2 is less than the THD<sub>v</sub> without any compensation but there is not a distinction between the two methods.

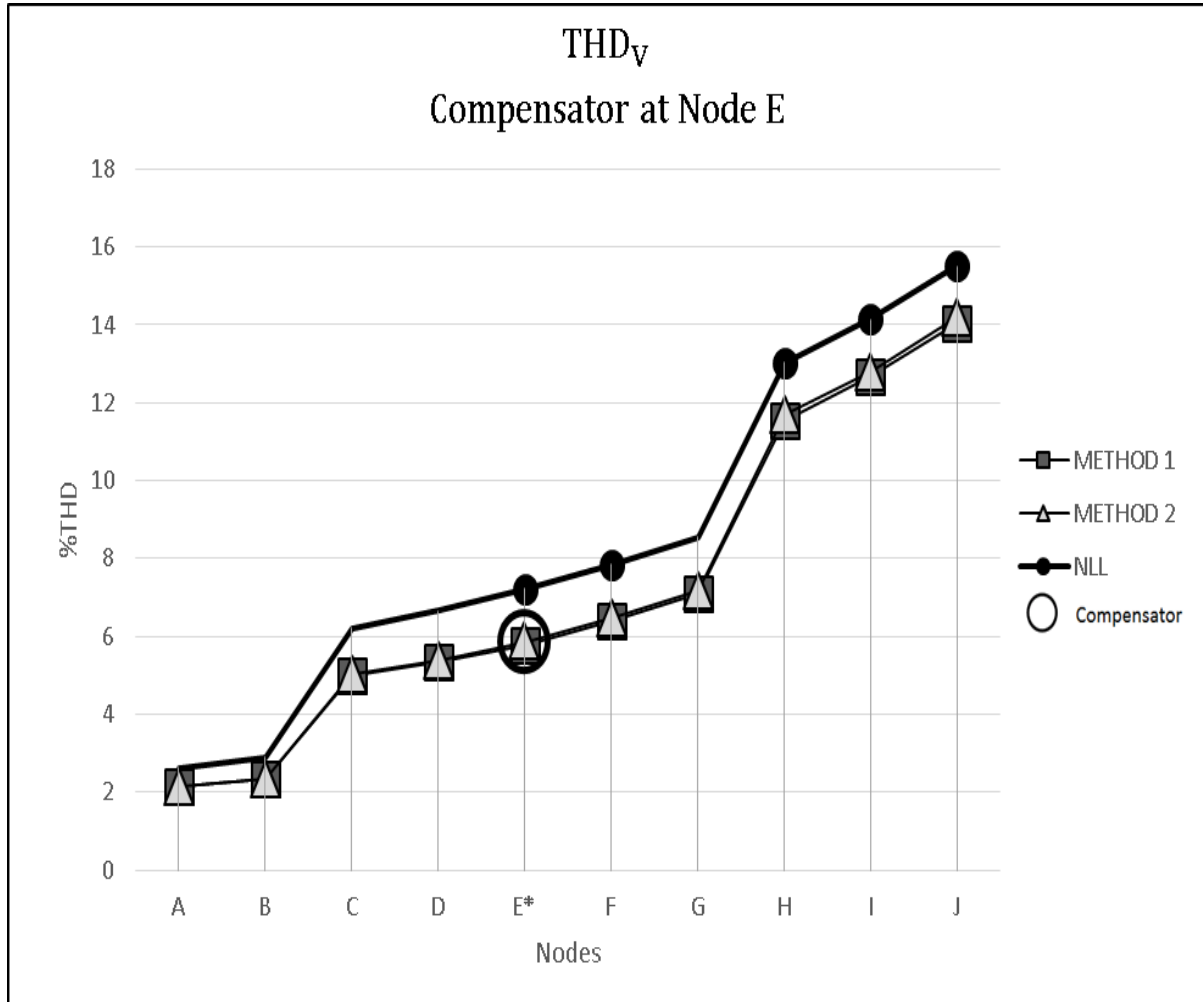


Figure 3-3 - THD<sub>v</sub> comparison of methods for Input order A to J with 1 compensator

In Figure 3.4, there are two more compensators than in Figure 3.3; at this time, the THD<sub>v</sub> in the system drastically decreased from when there are no compensators in the system and there is a distinguishable difference between Methods 1 and 2. It is clear that Method 1 is more effective at eliminating the THD<sub>v</sub>.

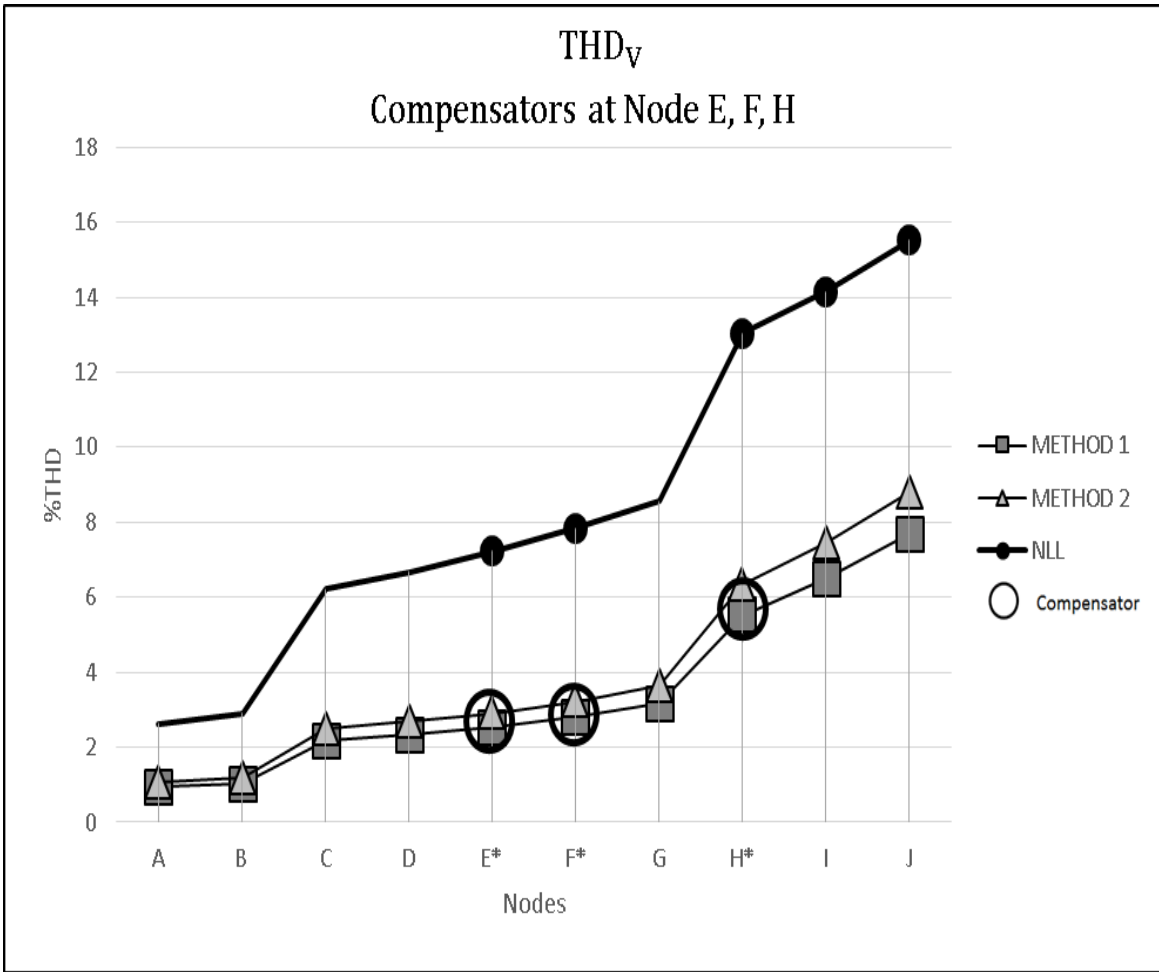


Figure 3-4 - THD<sub>v</sub> comparison of methods for Input order A to J with 3 compensators



When the compensators are added in J to A order Method 1 is again more effective than Method 2 at eliminating THD<sub>v</sub>. Figure 3.5, shows the THD<sub>v</sub> when there is one compensator in at Node J for Methods 1 and 2 compared to the THD<sub>v</sub> when there are no compensators. The addition of a compensator reduced the amount of THD<sub>v</sub> in the system and Method 1 is slightly more effective.

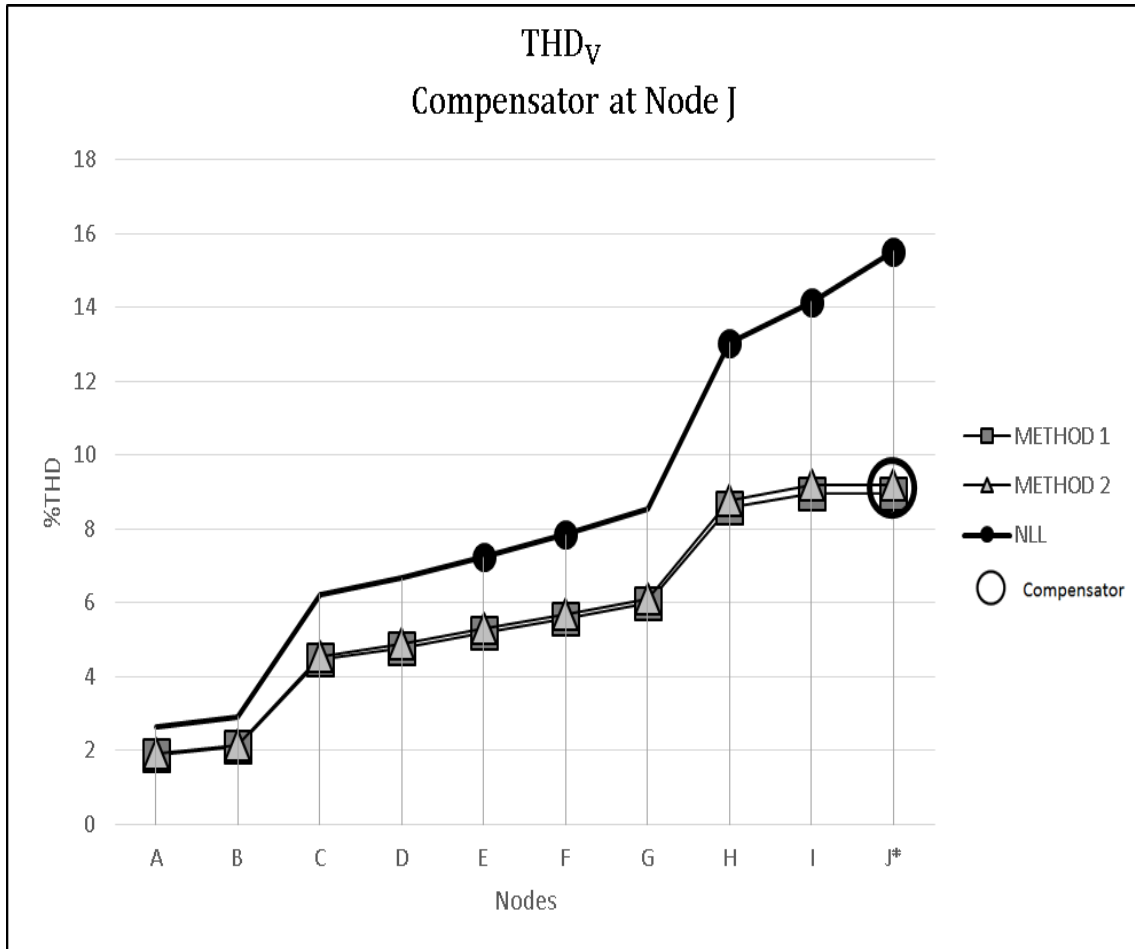


Figure 3-5 - THD<sub>v</sub> comparison of methods for Input order J to A with 1 compensator

In Figure 3.6, two more compensators are added. At this point there is a more noticeable difference and Method 1 is more effective.

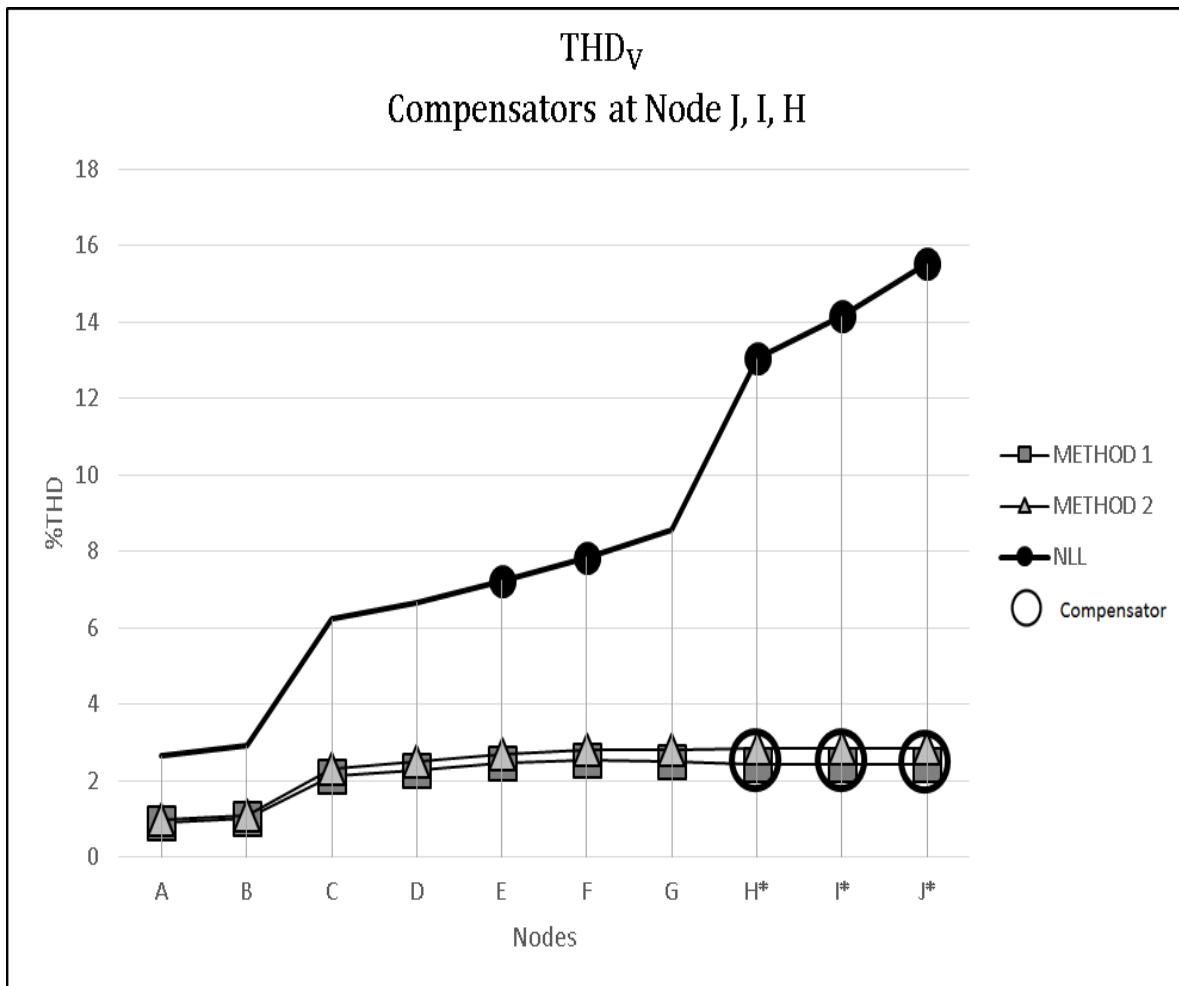


Figure 3-6 - THDV comparison of methods for Input order J to A with 3 compensators

### 3.3.2 THD<sub>I</sub> Elimination

The method used to evaluate THD<sub>V</sub> elimination was also used to evaluate THD<sub>I</sub> elimination and can be seen in Table 3.4. It was found that when moving in an A to J, left to right order, Method 1 is more effective in eliminating THD<sub>I</sub>. Method 2 is more effective when moving in a J to A, right to left order or when compensation is applied in a random order.

Comparison of Methods for THD <sub>i</sub> for compensator input order:				
A TO J				
Comp @	A1	A2	Difference <sub>THD</sub>	More Effective
E	112.695	113.743	1.048	M1
E,F	97.870	100.264	2.394	M1
E,F,H	71.022	73.831	2.809	M1
E,F,H,I	50.802	53.608	2.806	M1
E,F,H,I,J	1.566	1.356	-0.210	M1≈M2
J TO A				
Comp @	A1	A2	Difference <sub>THD</sub>	More Effective
J	80.600	78.822	-1.778	M2
J,I	60.100	57.483	-2.617	M2
J,I,H	33.010	29.821	-3.189	M2
J,I,H,F	16.883	14.957	-1.926	M2
J,I,H,F,E	1.522	1.356	-0.166	M1≈M2
RANDOM				
Comp @	A1	A2	Difference <sub>THD</sub>	More Effective
J	80.600	78.822	-1.778	M2
J,H	54.236	52.075	-2.161	M2
J,H,E	44.445	42.922	-1.523	M2
J,H,E,F	26.917	27.876	0.959	M2
J,H,E,F,I	1.548	1.356	-0.192	M1≈M2

Table 3.4 - Comparison between methods for THD<sub>i</sub>

## 4 Conclusion

Evaluation was performed on two different harmonic mitigation methods using PSpice simulation. Method I is when an active filter in parallel with a NLL acts as an equivalent resistance and Method II is when an active filter in parallel with a NLL is equivalent to the fundamental harmonic of the NLL. The desire was to find which of these methods is more effective at eliminating the current harmonics in a power system by looking at the THD in the system. It was found that Method 1 is more effective at minimizing the  $THD_v$ , Method I was more effective than Method II with each different compensator input strategy. Method I was most effective at minimizing  $THD_i$  when the compensator input strategy was in the A to J order, the beginning of the line to the end of the line, and Method II was most effective when the compensator input strategy was random and in a J to A order, when the compensators were added from the end of the line to the beginning of the line.

## 5 References

- [1] Bhakti I. Chaugule, A. L. (2013, June). *Reduction In Harmonic Distortion Of The System Using Active Power Filter In Matlab/Simulink*. Retrieved from International Journal of Computational Engineering Research:  
[http://www.ijceronline.com/papers/Vol3\\_issue6/part%201/J0361059064.pdf](http://www.ijceronline.com/papers/Vol3_issue6/part%201/J0361059064.pdf)
- [2] *Power System Harmonics*. (2001, April). Retrieved from Rockwell Automation:  
[http://literature.rockwellautomation.com/idc/groups/literature/documents/wp/mvb-wp011\\_en-p.pdf](http://literature.rockwellautomation.com/idc/groups/literature/documents/wp/mvb-wp011_en-p.pdf)

## Appendix A – PSPice Circuit Code

```
V 1 0 sin(0 8000 60)

R1 1 2 0.028
L1 2 A 1.4m IC=0
RA A 0 480MEG
LA A 0 1.75MEG IC=0

R2 A 3 0.008
L2 3 B 0.14m IC=0
RB B 0 282meg
LB B 0 1.21MEG IC=0

R3 B 4 0.009
L3 4 C 1.64m IC=0
RC C 0 213.33MEG
LC C 0 1.168MEG IC=0

R4 C 5 0.012
L4 5 D 215u IC=0
RD D 0 183MEG
LD D 0 0.475MEG IC=0

R5 D 6 0.016
L5 6 E 268u IC=0
VDE E E1 0
IE1 E1 0 sin(0 80 60 0 0 -30)
IE3 E1 0 sin(0 1.25 180 0 0 25)
IE5 E1 0 sin(0 10 300 0 0 -35)
IE7 E1 0 sin(0 13.75 420 0 0 -40)
IE9 E1 0 sin(0 9.375 540 0 0 30)
RE E 0 320MEG
LE E 0 0.979MEG IC=0

R6 E 7 0.02
L6 7 F 361u IC=0
VDF F F1 0
IF1 F1 0 sin(0 70 60 0 0 20)
IF3 F1 0 sin(0 13.75 180 0 0 30)
IF5 F1 0 sin(0 8.75 300 0 0 10)
IF7 F1 0 sin(0 11.25 420 0 0 20)
IF9 F1 0 sin(0 6.125 540 0 0 30)
RF F 0 960MEG
LF F 0 1.49MEG IC=0

R7 F 8 0.028
L7 8 G 496u IC=0
RG G 0 1170MEG
LG G 0 4.62MEG IC=0

R8 G 9 0.042
L8 9 H 3058u IC=0
VDH H H1 0
IH1 H1 0 sin(0 125 60 0 0 -30)
IH3 H1 0 sin(0 1.25 180 0 0 40)
IH5 H1 0 sin(0 12.5 300 0 0 -35)
IH7 H1 0 sin(0 10 420 0 0 -10)
IH9 H1 0 sin(0 16.25 540 0 0 20)
RH H 0 237MEG
LH H 0 0.316MEG IC=0

R9 H 10 0.069
L9 10 I 1.22m IC=0
VDI I I1 0
II1 I1 0 sin(0 40 60 0 0 -30)
II3 I1 0 sin(0 2.5 180 0 0 30)
II5 I1 0 sin(0 10 300 0 0 -20)
II7 I1 0 sin(0 5 420 0 0 20)
II9 I1 0 sin(0 9.375 540 0 0 -40)
RI I 0 590MEG
LI I 0 1.37MEG IC=0

R10 I 11 0.134
L10 11 J 2.37m IC=0
VDJ J J1 0
IJ1 J1 0 sin(0 28 60 0 0 -30)
IJ3 J1 0 sin(0 5 180 0 0 20)
IJ5 J1 0 sin(0 10.625 300 0 0 -40)
IJ7 J1 0 sin(0 9.125 420 0 0 35)
IJ9 J1 0 sin(0 18.75 540 0 0 30)
RJ J 0 182MEG
LJ J 0 .475MEG IC=0

.PROBE
.TRAN 5 5 0 100u UIC
.END
```

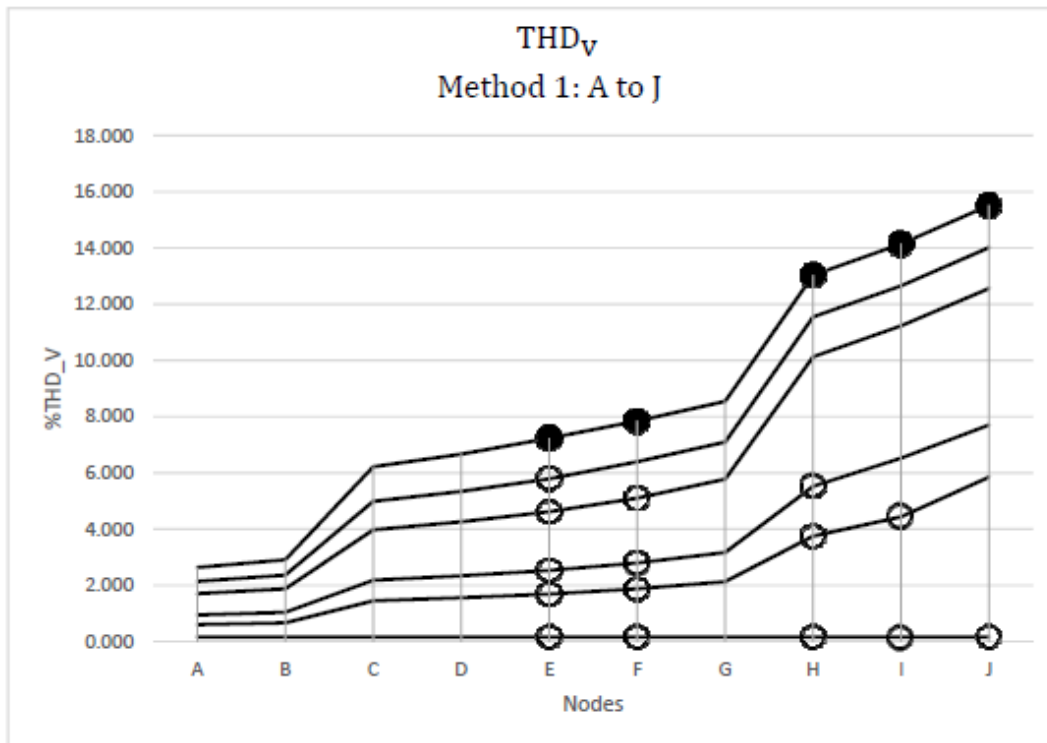
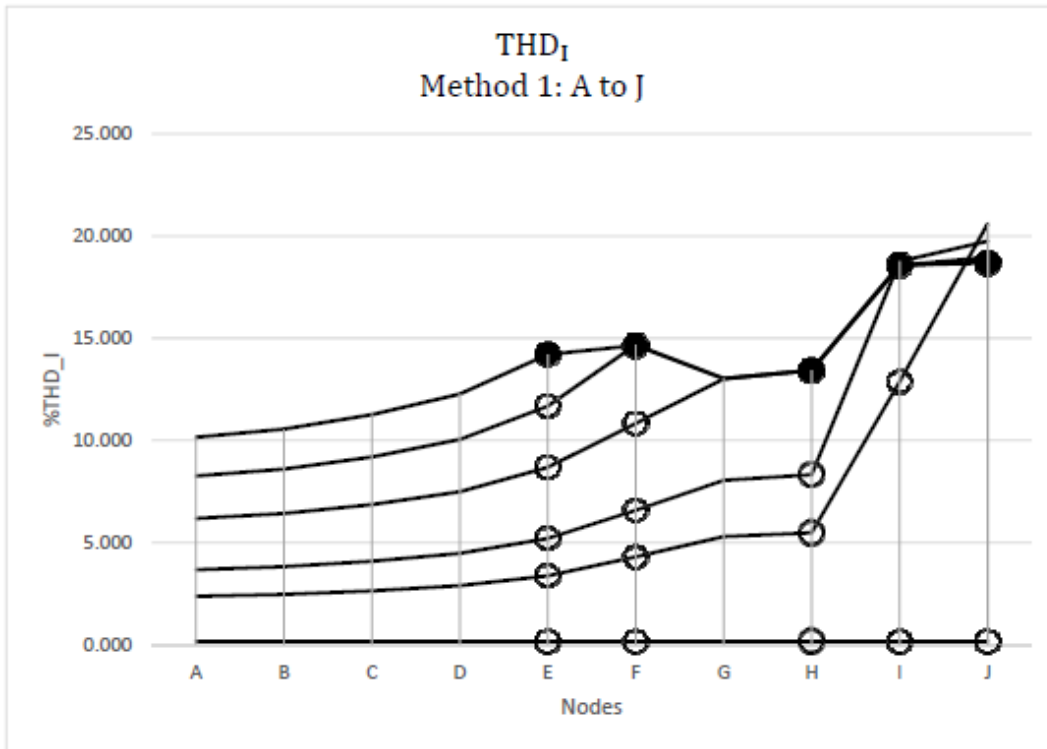
## Appendix B – Method 1 for Input Order A to J Data

<b>Method 1: A to J</b>	Without Comp			Comp @ E		
	Node	%THD_I	%THD_V	Node	%THD_I	%THD_V
	A	10.156	2.634	A	8.26	2.14
	B	10.555	2.910	B	8.60	2.36
	C	11.259	6.218	C	9.19	4.99
	D	12.270	6.667	D	10.05	5.34
	E	14.208	7.232	E*	11.67	5.79
	F	14.645	7.843	F	14.68	6.40
	G	13.027	8.549	G	13.02	7.10
	H	13.423	13.037	H	13.43	11.55
	I	18.582	14.145	I	18.53	12.66
	J	18.678	15.518	J	18.80	14.02
Comp @ E,F			Comp @ E,F,H			
Node	%THD_I	%THD_V	Node	%THD_I	%THD_V	
A	6.18	1.70	A	3.68	0.95	
B	6.43	1.88	B	3.82	1.04	
C	6.86	3.97	C	4.09	2.18	
D	7.49	4.26	D	4.48	2.34	
E*	8.68	4.62	E*	5.20	2.53	
F*	10.83	5.10	F*	6.58	2.80	
G	13.02	5.78	G	8.05	3.17	
H	13.44	10.13	H*	8.33	5.53	
I	18.56	11.23	I	18.76	6.52	
J	18.96	12.56	J	19.75	7.70	
Comp @ E,F,H,I			Comp @ E,F,H,I,J			
Node	%THD_I	%THD_V	Node	%THD_I	%THD_V	
A	2.37	0.60	A	0.17	0.17	
B	2.47	0.67	B	0.17	0.17	
C	2.64	1.45	C	0.17	0.17	
D	2.90	1.56	D	0.17	0.17	
E*	3.37	1.69	E*	0.17	0.17	
F*	4.30	1.87	F*	0.17	0.17	
G	5.29	2.13	G	0.17	0.17	
H*	5.48	3.75	H*	0.17	0.17	
I*	12.87	4.44	I*	0.17	0.17	
J	20.59	5.85	J*	0.17	0.17	

Node	w/out Comp		CALCULATED			ADJUSTED		
	Pavg(KW)	VRMS(KV)	R( $\Omega$ )	P(KW)	%error	R( $\Omega$ )	P(KW)	%error
E	383	7.57	149.621149	386	-0.78			100.00
F	338.5	7.57	169.290694	335.5	0.89			100.00
H	584	7.315	91.6253853	595	-1.88			100.00
I	189.8	7.35	284.628556	191	-0.63			100.00
J	129.6	7.33	414.574846	130.2	-0.46			100.00

power across the nl load



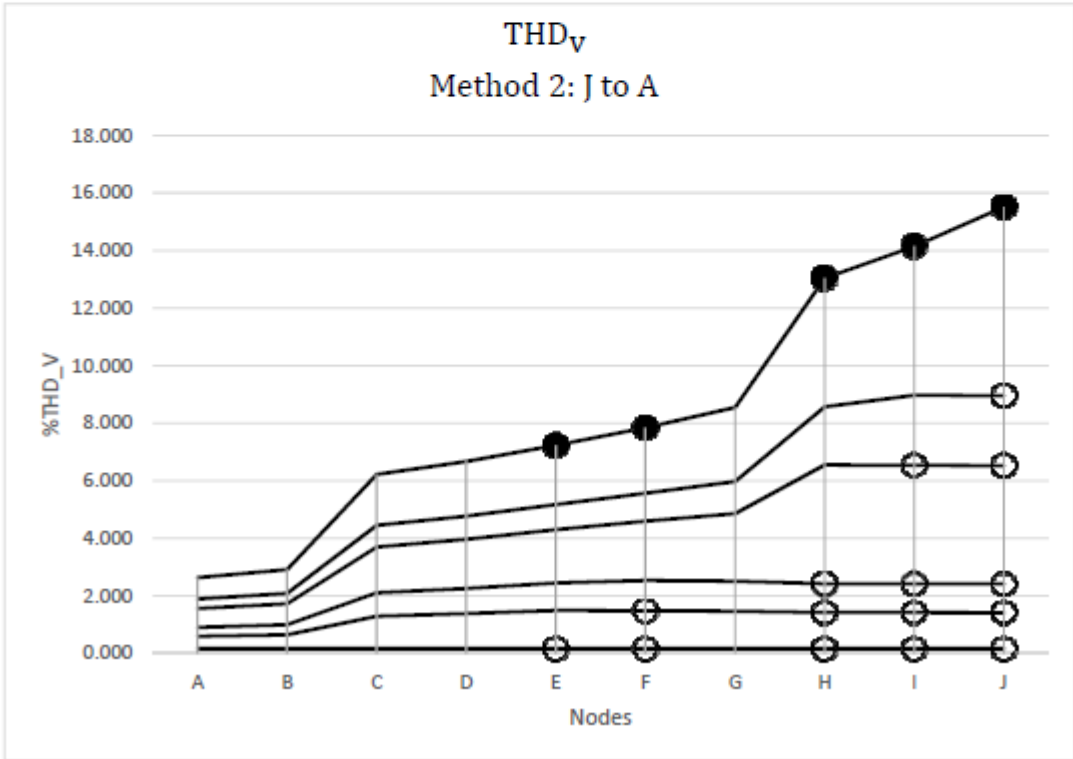
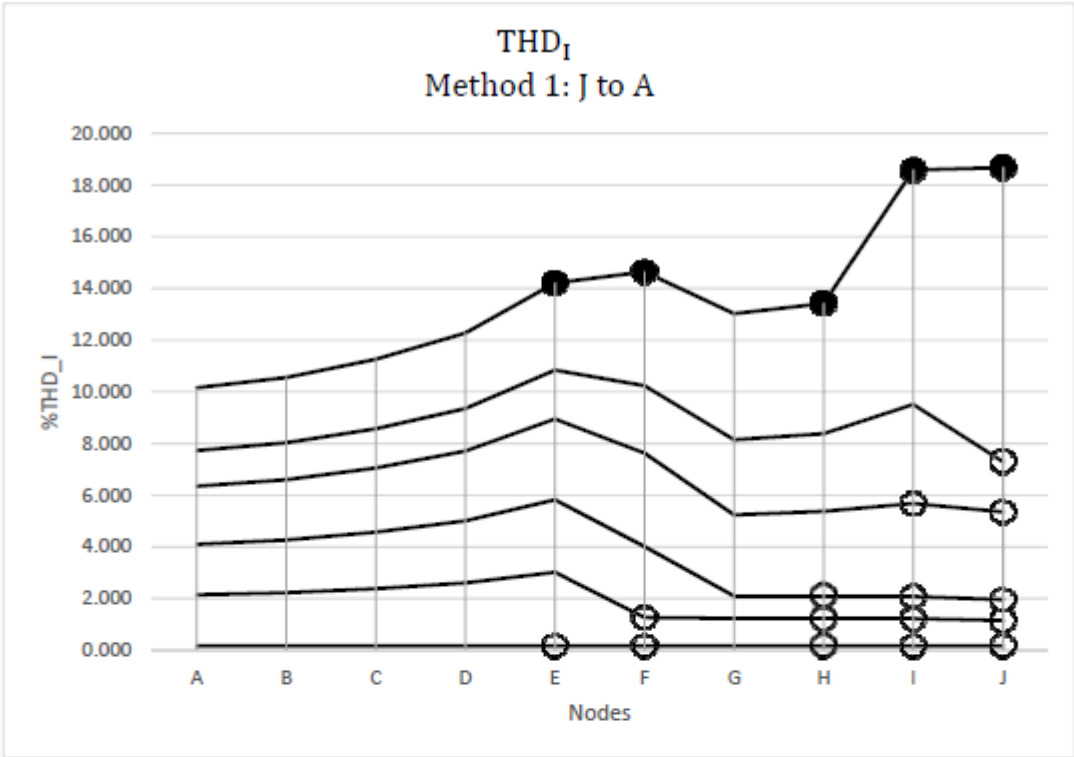


## Appendix C – Method 1 for Input Order J to A Data

<b>Method 1: J to A</b>	<b>Without Comp</b>			<b>Comp @ J</b>		
	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>
	A	10.156	2.634	A	7.73	1.89
	B	10.555	2.910	B	8.04	2.09
	C	11.259	6.218	C	8.58	4.45
	D	12.270	6.667	D	9.35	4.77
	E	14.208	7.232	E	10.84	5.18
	F	14.645	7.843	F	10.24	5.57
	G	13.027	8.549	G	8.15	5.97
	H	13.423	13.037	H	8.38	8.57
	I	18.582	14.145	I	9.51	8.97
	J	18.678	15.518	J*	7.30	8.96
	<b>Comp @ J, I</b>			<b>Comp @ J, I, H</b>		
<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	
A	6.35	1.56	A	4.11	0.90	
B	6.60	1.72	B	4.27	1.00	
C	7.05	3.70	C	4.57	2.11	
D	7.71	3.97	D	5.01	2.26	
E	8.95	4.30	E	5.82	2.45	
F	7.63	4.59	F	4.02	2.54	
G	5.24	4.86	G	2.10	2.51	
H	5.38	6.55	H*	2.10	2.42	
I*	5.68	6.53	I*	2.09	2.41	
J*	5.35	6.53	J*	1.96	2.41	
<b>Comp @ J, I, H, F</b>			<b>Comp @ J, I, H, F, E</b>			
<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	
A	2.15	0.59	A	0.17	0.17	
B	2.23	0.65	B	0.17	0.17	
C	2.39	1.29	C	0.17	0.17	
D	2.61	1.38	D	0.17	0.17	
E	3.03	1.49	E*	0.17	0.17	
F*	1.27	1.48	F*	0.17	0.17	
G	1.24	1.47	G	0.17	0.17	
H*	1.24	1.42	H*	0.17	0.17	
I*	1.23	1.42	I*	0.17	0.17	
J*	1.16	1.42	J*	0.17	0.17	

Node	w/out Comp		CALCULATED			ADJUSTED		
	P(KW)	VRMS(KV)	R(Ω)	P(KW)	%error	R(Ω)	P(KW)	%error
J	121.2	7.27	436.080033	120.4	0.66			100.00
I	187.5	7.29	283.4352	188.5	-0.53			100.00
H	589	7.34	91.4696095	602	-2.21	92	599	-1.70
F	341.6	7.6	169.086651	339	0.76			100.00
E	385.5	7.6	149.831388	388.5	-0.78			100.00

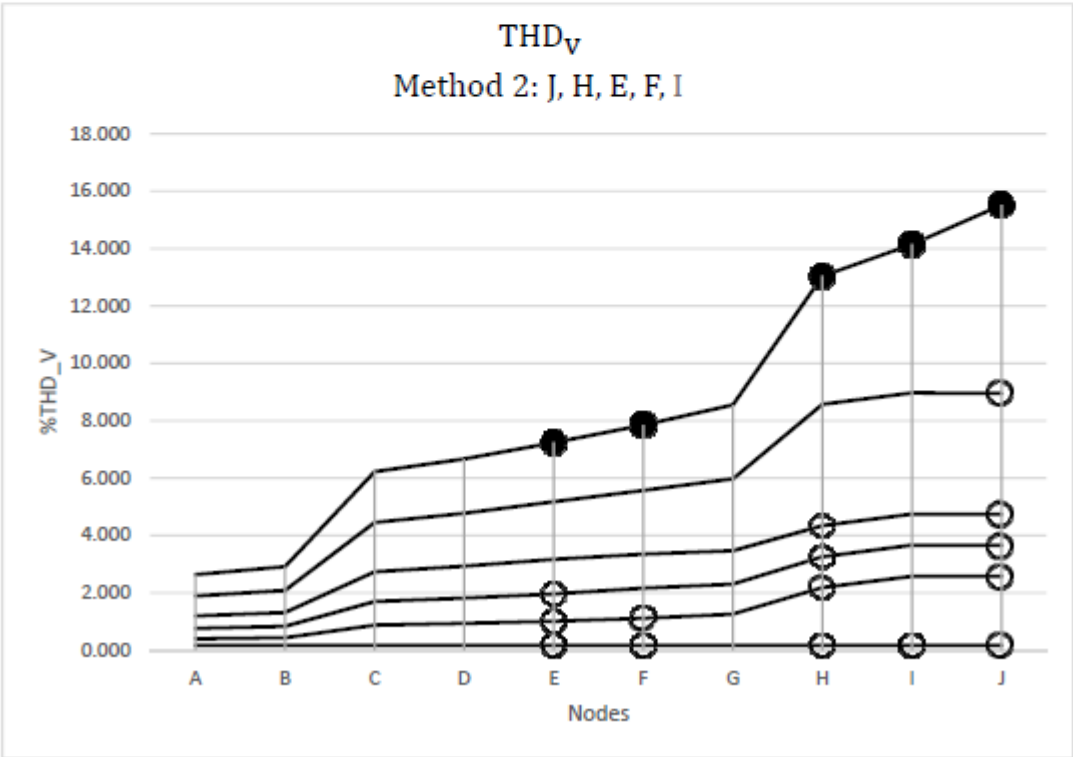
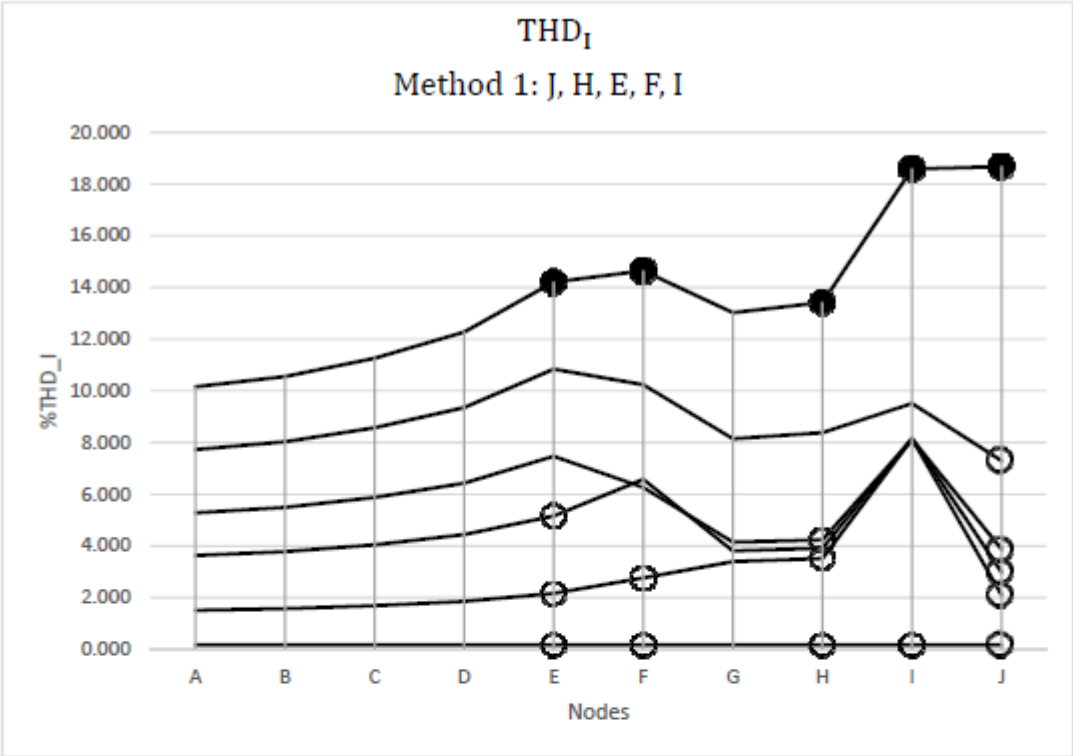


## Appendix D – Method 1 for Random Input Order Data

<b>Method 1: Random (J, H, E, F, I)</b>	Without Comp			Comp @ J		
	Node	%THD_I	%THD_V	Node	%THD_I	%THD_V
	A	10.156	2.634	A	7.73	1.89
	B	10.555	2.910	B	8.04	2.09
	C	11.259	6.218	C	8.58	4.45
	D	12.270	6.667	D	9.35	4.77
	E	14.208	7.232	E	10.84	5.18
	F	14.645	7.843	F	10.24	5.57
	G	13.027	8.549	G	8.15	5.97
	H	13.423	13.037	H	8.38	8.57
	I	18.582	14.145	I	9.51	8.97
	J	18.678	15.518	J*	7.30	8.96
	Comp @ J,H			Comp @ J,H,E		
	Node	%THD_I	%THD_V	Node	%THD_I	%THD_V
A	5.28	1.19	A	3.63	0.76	
B	5.50	1.31	B	3.78	0.83	
C	5.88	2.73	C	4.05	1.69	
D	6.43	2.92	D	4.44	1.81	
E	7.47	3.17	E*	5.16	1.96	
F	6.26	3.35	F	6.58	2.16	
G	4.15	3.46	G	3.81	2.30	
H*	4.23	4.34	H*	3.91	3.25	
I	8.12	4.74	I	8.16	3.66	
J*	3.87	4.73	J*	2.98	3.66	
Comp @ J,H,E,F			Comp @ J,H,E,F,I			
Node	%THD_I	%THD_V	Node	%THD_I	%THD_V	
A	1.51	0.39	A	0.17	0.17	
B	1.58	0.43	B	0.17	0.17	
C	1.69	0.87	C	0.17	0.17	
D	1.86	0.93	D	0.17	0.17	
E*	2.17	1.01	E*	0.17	0.17	
F*	2.76	1.11	F*	0.17	0.17	
G	3.40	1.26	G	0.17	0.17	
H*	3.52	2.18	H*	0.17	0.17	
I	8.14	2.58	I*	0.17	0.17	
J*	2.10	2.57	J*	0.17	0.17	

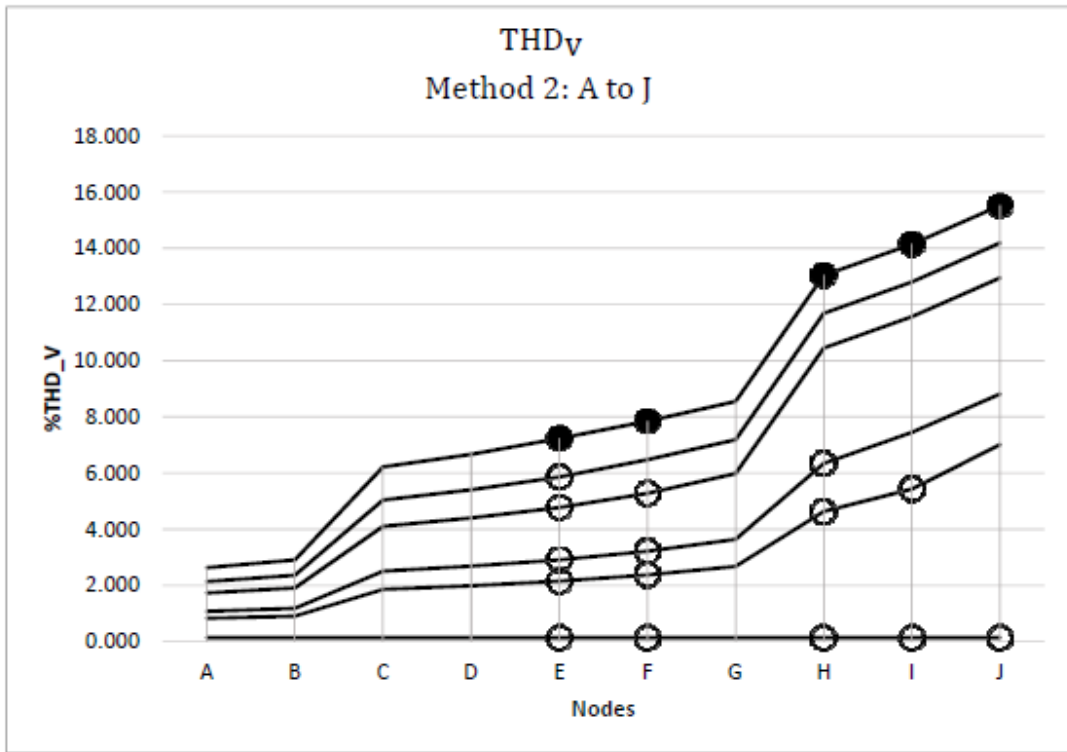
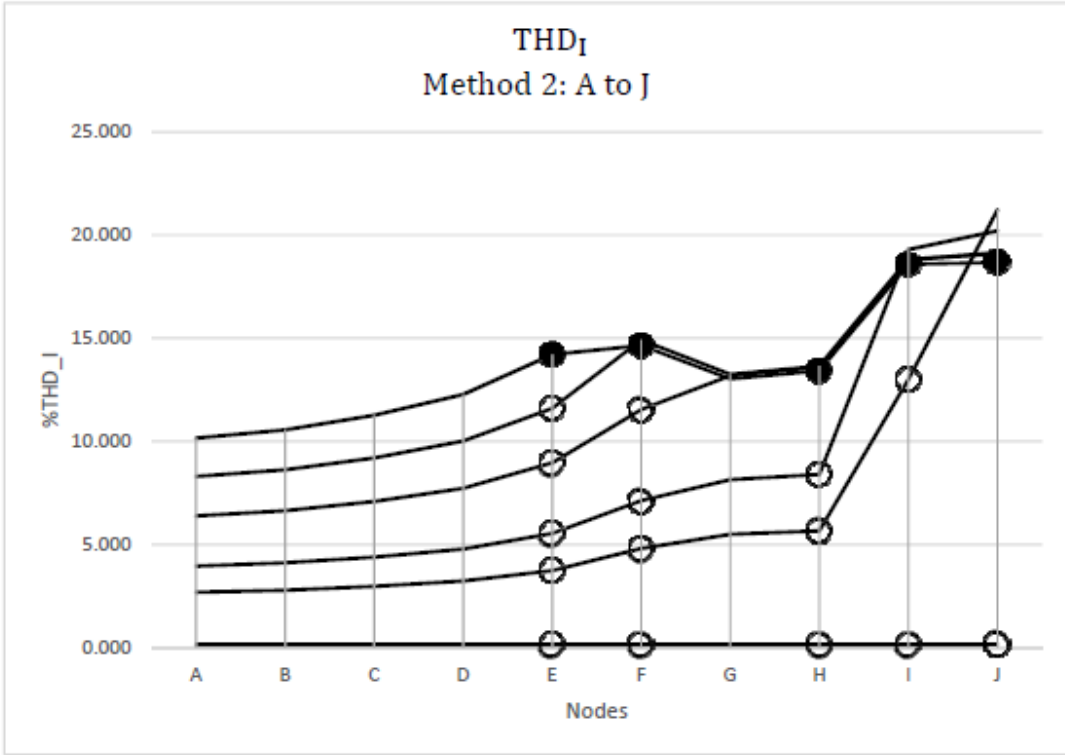
  

Node	w/out Comp		CALCULATED			ADJUSTED		
	P(KW)	VRMS(KV)	R( $\Omega$ )	P(KW)	%error	R( $\Omega$ )	P(KW)	%error
J	121.2	7.27	436.080033	120.4	0.66	N/A	N/A	N/A
H	586	7.3200	91.4375427	595	-1.54	N/A	N/A	N/A
E	386	7.6100	150.031347	389	-0.78	N/A	N/A	N/A
F	342.5	7.6200	169.531095	339.5	0.88	N/A	N/A	N/A
I	189.8	7.3600	285.403583	191.4	-0.84	N/A	N/A	N/A



## Appendix E – Method 2 for Input Order A to J Data

<b>Method 2: A to J</b>	<b>Without Comp</b>			<b>Comp @ E</b>		
	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>
	A	10.156	2.634	A	8.29	2.14
	B	10.555	2.910	B	8.62	2.36
	C	11.259	6.218	C	9.19	5.04
	D	12.270	6.667	D	10.02	5.40
	E	14.208	7.232	E*	11.59	5.86
	F	14.645	7.843	F	14.92	6.48
	G	13.027	8.549	G	13.25	7.19
	H	13.423	13.037	H	13.65	11.68
	I	18.582	14.145	I	18.83	12.80
	J	18.678	15.518	J	19.08	14.19
	<b>Comp @ E,F</b>			<b>Comp @ E,F,H</b>		
	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>
A	6.39	1.73	A	3.95	1.08	
B	6.64	1.91	B	4.11	1.19	
C	7.08	4.10	C	4.38	2.51	
D	7.72	4.40	D	4.78	2.69	
E*	8.95	4.78	E*	5.53	2.91	
F*	11.54	5.28	F*	7.13	3.22	
G	13.18	5.98	G	8.14	3.64	
H	13.59	10.45	H*	8.39	6.34	
I	18.79	11.57	I	19.29	7.45	
J	19.15	12.94	J	20.20	8.81	
<b>Comp @ E,F,H,I</b>			<b>Comp @ E,F,H,I,J</b>			
<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	<b>Node</b>	<b>%THD_I</b>	<b>%THD_V</b>	
A	2.68	0.83	A	0.15	0.14	
B	2.78	0.91	B	0.15	0.14	
C	2.97	1.86	C	0.15	0.14	
D	3.23	1.99	D	0.15	0.14	
E*	3.73	2.15	E*	0.15	0.14	
F*	4.80	2.37	F*	0.15	0.14	
G	5.49	2.68	G	0.15	0.14	
H*	5.66	4.63	H*	0.15	0.14	
I*	13.00	5.43	I*	0.15	0.14	
J	21.22	7.01	J*	0.15	0.14	
		<b>Power (W)</b>				
	<b>Without Comp</b>	<b>With Comp</b>				
E	208.42	279.20				
F	250.16	251.63				
H	435.46	435.53				
I	141.53	139.29				
J	97.34	97.45				



Appendix F – Method 2 for Input Order J to A Data

**Method 2: J to A**

Without Comp		
Node	%THD_I	%THD_V
A	10.156	2.634
B	10.555	2.910
C	11.259	6.218
D	12.270	6.667
E	14.208	7.232
F	14.645	7.843
G	13.027	8.549
H	13.423	13.037
I	18.582	14.145
J	18.678	15.518

Comp @ J, I		
Node	%THD_I	%THD_V
A	6.51	1.67
B	6.79	1.85
C	7.21	3.91
D	7.86	4.19
E	9.09	4.54
F	7.83	4.86
G	5.24	5.14
H	5.38	6.96
I*	2.98	6.97
J*	3.67	6.97

Comp @ J		
Node	%THD_I	%THD_V
A	7.78	1.93
B	8.08	2.13
C	8.62	4.55
D	9.39	4.87
E	10.87	5.29
F	10.28	5.69
G	8.11	6.11
H	8.34	8.78
I	8.80	9.20
J*	4.86	9.20

Comp @ J, I, H		
Node	%THD_I	%THD_V
A	4.14	0.99
B	4.31	1.09
C	4.60	2.32
D	5.01	2.49
E	5.80	2.70
F	4.14	2.82
G	0.96	2.82
H*	0.92	2.83
I*	1.25	2.83
J*	1.54	2.84

These values were double checked.

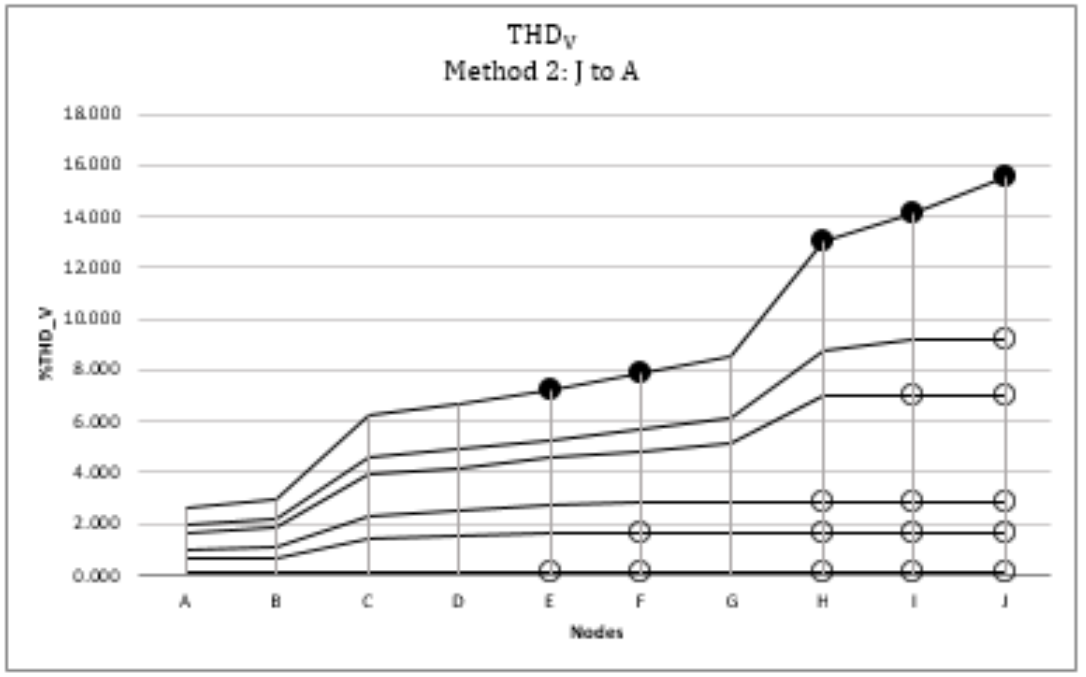
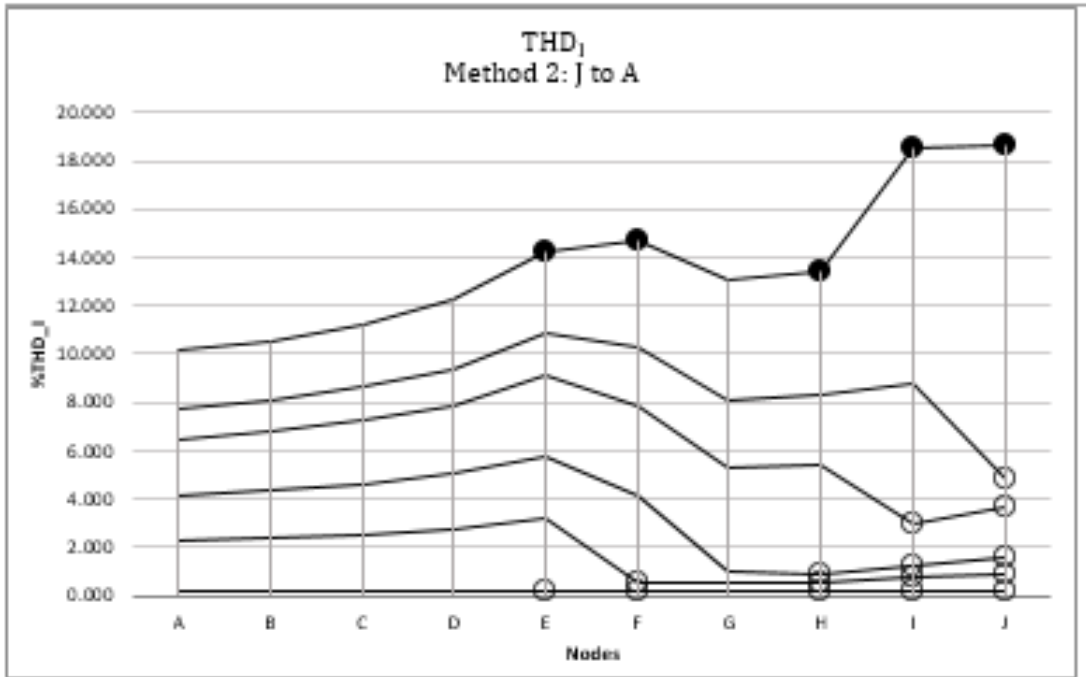
Comp @ J, I, H, F		
Node	%THD_I	%THD_V
A	2.30	0.63
B	2.39	0.69
C	2.55	1.43
D	2.78	1.53
E	3.21	1.65
F*	0.55	1.65
G	0.57	1.65
H*	0.55	1.66
I*	0.74	1.66
J*	0.90	1.66

Comp @ J, I, H, F, E		
Node	%THD_I	%THD_V
A	0.15	0.14
B	0.15	0.14
C	0.15	0.14
D	0.15	0.14
E*	0.15	0.14
F*	0.15	0.14
G	0.15	0.14
H*	0.15	0.14
I*	0.15	0.14
J*	0.15	0.14

I double checked the above table, it is accurate.

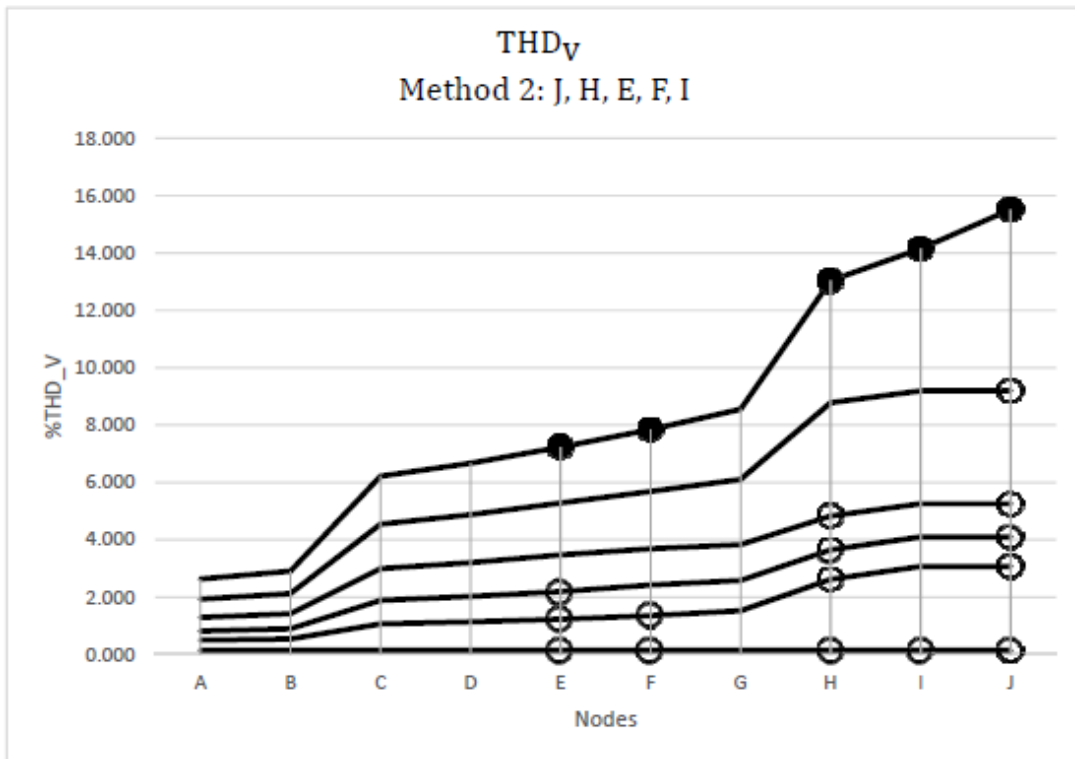
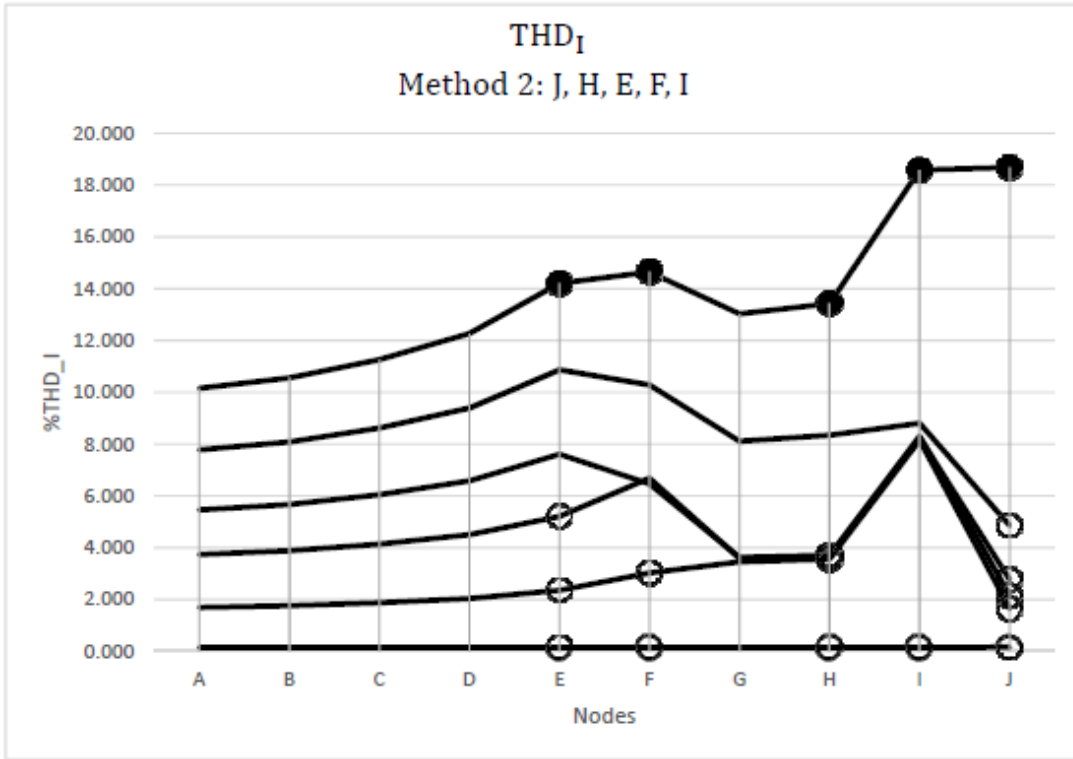
	Power (W)	
	Without Comp	With Comp
J	93.86	97.44
I	141.00	139.28
H	436.20	435.56
F	251.60	251.63
E	279.18	279.16





## Appendix G – Method 2 for Random Input Order Data

<b>Method 2: Random (J, H, E, F, I)</b>	Without Comp			Comp @ J		
	Node	%THD_I	%THD_V	Node	%THD_I	%THD_V
	A	10.156	2.634	A	7.78	1.93
	B	10.555	2.910	B	8.08	2.13
	C	11.259	6.218	C	8.62	4.55
	D	12.270	6.667	D	9.39	4.87
	E	14.208	7.232	E	10.87	5.29
	F	14.645	7.843	F	10.28	5.69
	G	13.027	8.549	G	8.11	6.11
	H	13.423	13.037	H	8.34	8.78
	I	18.582	14.145	I	8.80	9.20
	J	18.678	15.518	J*	4.86	9.20
	Comp @ J,H			Comp @ J,H,E		
	Node	%THD_I	%THD_V	Node	%THD_I	%THD_V
A	5.46	1.29	A	3.74	0.82	
B	5.67	1.42	B	3.88	0.90	
C	6.04	2.99	C	4.14	1.89	
D	6.58	3.21	D	4.50	2.03	
E	7.61	3.47	E*	5.20	2.20	
F	6.46	3.69	F	6.68	2.42	
G	3.62	3.83	G	3.59	2.58	
H*	3.70	4.83	H*	3.68	3.65	
I	8.27	5.26	I	8.30	4.10	
J*	2.77	5.26	J*	2.16	4.10	
The table above was double checked, it is accurate						
Comp @ J,H,E,F			Comp @ J,H,E,F,I			
Node	%THD_I	%THD_V	Node	%THD_I	%THD_V	
A	1.69	0.50	A	0.15	0.14	
B	1.76	0.54	B	0.15	0.14	
C	1.87	1.07	C	0.15	0.14	
D	2.04	1.14	D	0.15	0.14	
E*	2.35	1.23	E*	0.15	0.14	
F*	3.02	1.35	F*	0.15	0.14	
G	3.45	1.53	G	0.15	0.14	
H*	3.56	2.62	H*	0.15	0.14	
I	8.15	3.07	I*	0.15	0.14	
J*	1.66	3.07	J*	0.15	0.14	
Power (W)						
	Without Comp		With Comp			
J	93.86		97.44			
H	434.75		435.56			
E	279.90		279.19			
F	251.05		251.53			
I	139.25		139.29			



## Appendix H - Method Comparison of THD<sub>v</sub> for A to J Input Order

A to J of VOLTAGE: This page is a comparison of the two methods by which we measured voltage THD. The compensators were added from closer to the generator to the farthest point in the network; E, F, H, I, J to compensate harmonics at the locations of non-linear

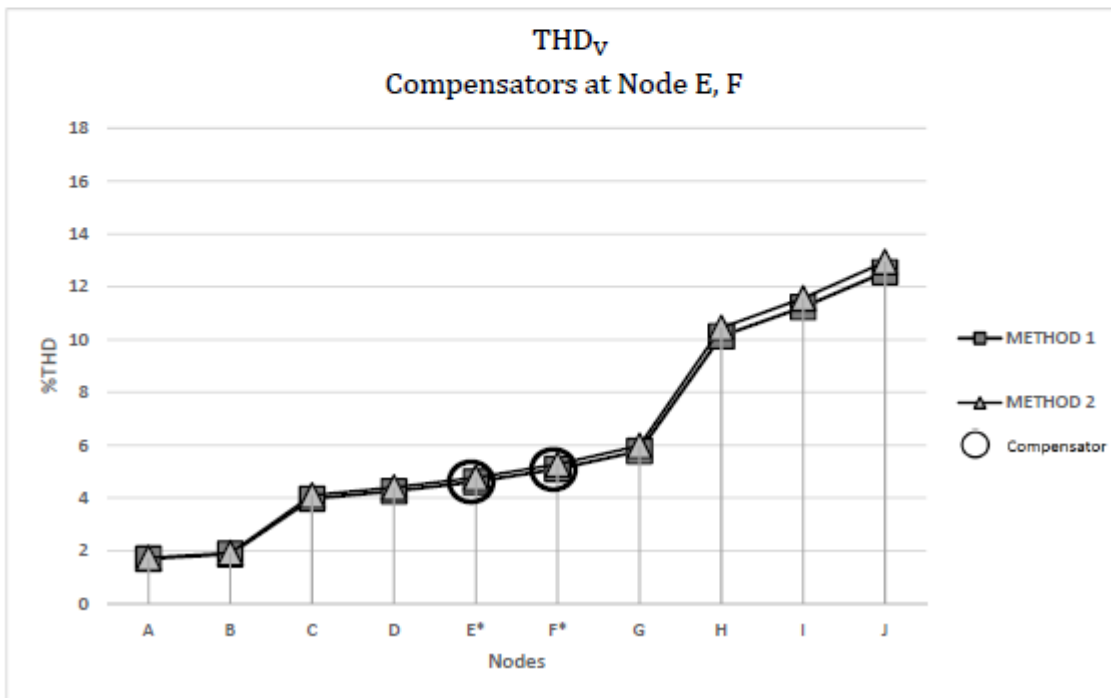
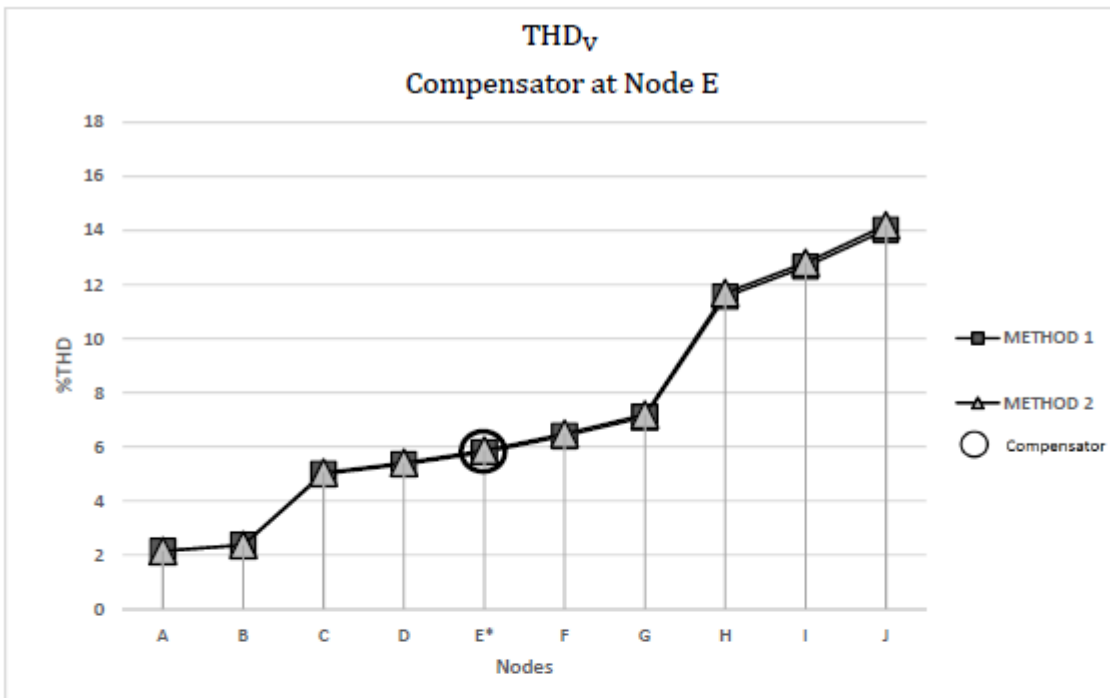
Comp @ E		
Node	METHOD 1	METHOD 2
A	2.142	2.139
B	2.362	2.362
C	4.987	5.039
D	5.343	5.403
E*	5.79	5.86
F	6.396	6.477
G	7.095	7.185
H	11.547	11.684
I	12.658	12.803
J	14.019	14.188

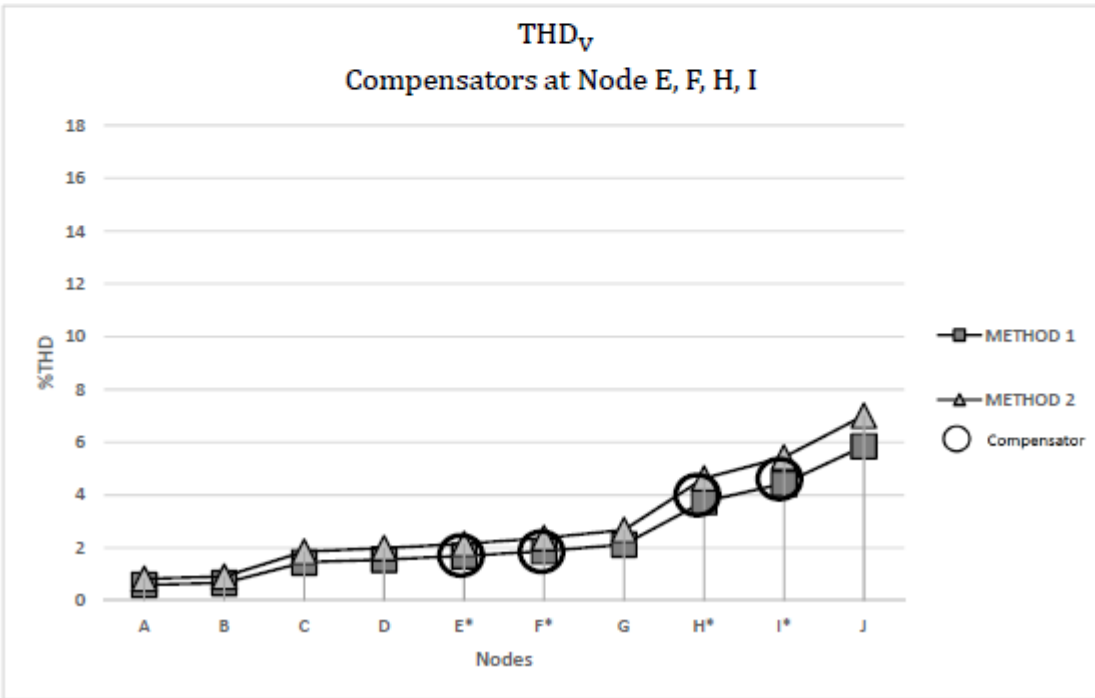
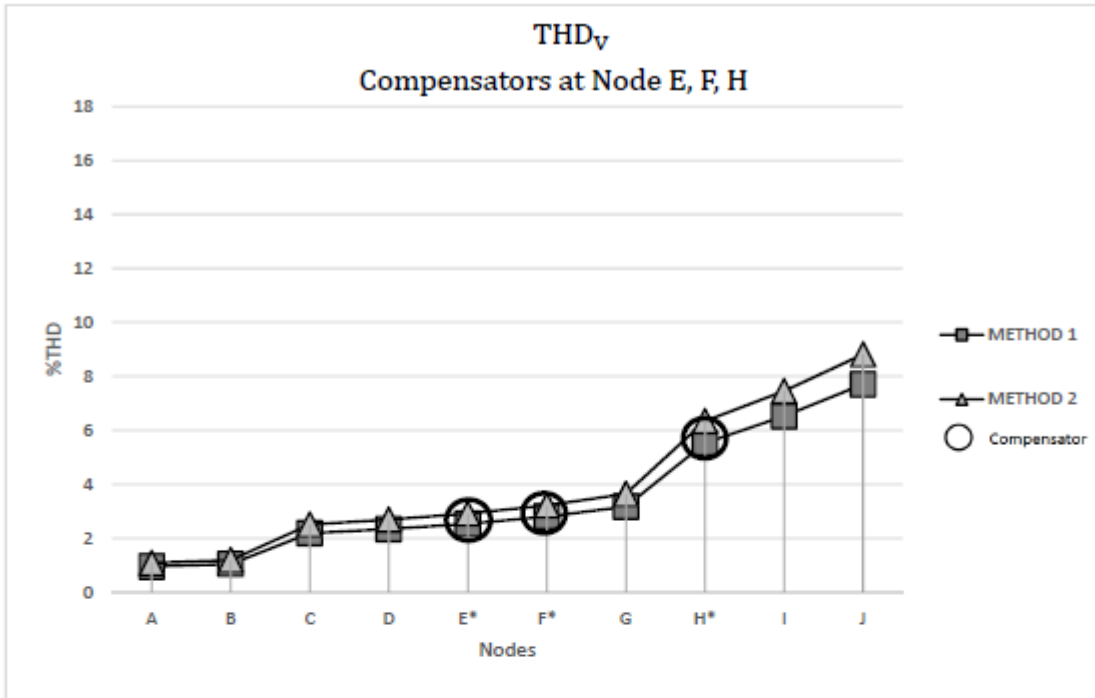
Comp @ E,F		
Node	METHOD 1	METHOD 2
A	1.703	1.73
B	1.877	1.913
C	3.974	4.103
D	4.259	4.401
E*	4.617	4.775
F*	5.102	5.279
G	5.779	5.982
H	10.133	10.451
I	11.23	11.567
J	12.56	12.944

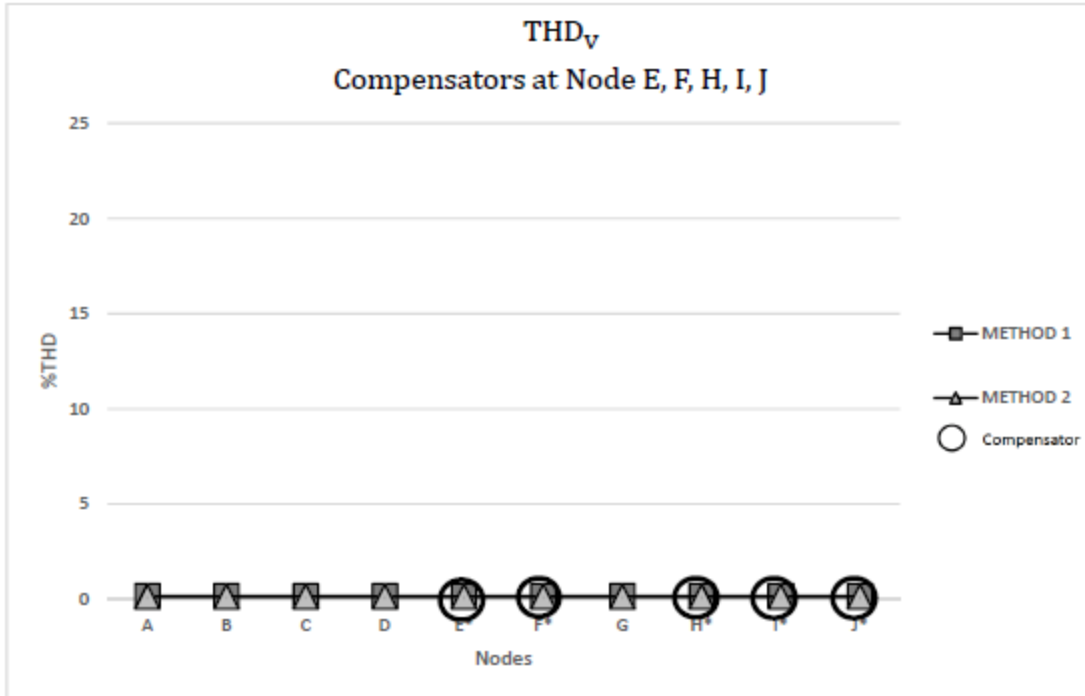
Comp @ E,F,H		
Node	METHOD 1	METHOD 2
A	0.9464	1.078
B	1.04	1.187
C	2.182	2.506
D	2.337	2.686
E*	2.532	2.912
F*	2.797	3.217
G	3.167	3.641
H*	5.525	6.342
I	6.524	7.451
J	7.704	8.814

Comp @ E,F,H,I		
Node	METHOD 1	METHOD 2
A	0.6015	0.83
B	0.6662	0.909
C	1.45	1.86
D	1.557	1.99
E*	1.691	2.153
F*	1.874	2.373
G	2.128	2.679
H*	3.75	4.631
I*	4.439	5.433
J	5.851	7.009

Comp @ E,F,H,I,J		
Node	METHOD 1	METHOD 2
A	0.17395	0.1424
B	0.17395	0.1424
C	0.17395	0.1424
D	0.17395	0.1424
E*	0.17395	0.1424
F*	0.17395	0.1424
G	0.17395	0.1424
H*	0.17395	0.1424
I*	0.17395	0.1424
J*	0.17395	0.1425







## Appendix I - Method Comparison of THD<sub>v</sub> for J to A Input Order

**J to A of VOLTAGE:** This page is a comparison of the two methods by which we measured voltage THD. The compensators were added from the farthest point in the network to the generator; J, I, H, F, E to compensate harmonics at the locations of non-linear loads.

Comp @ J		
Node	METHOD 1	METHOD 2
A	1.888	1.929
B	2.085	2.13
C	4.45	4.545
D	4.771	4.873
E	5.175	5.285
F	5.567	5.688
G	5.971	6.106
H	8.569	8.78
I	8.97	9.195
J*	8.955	9.2

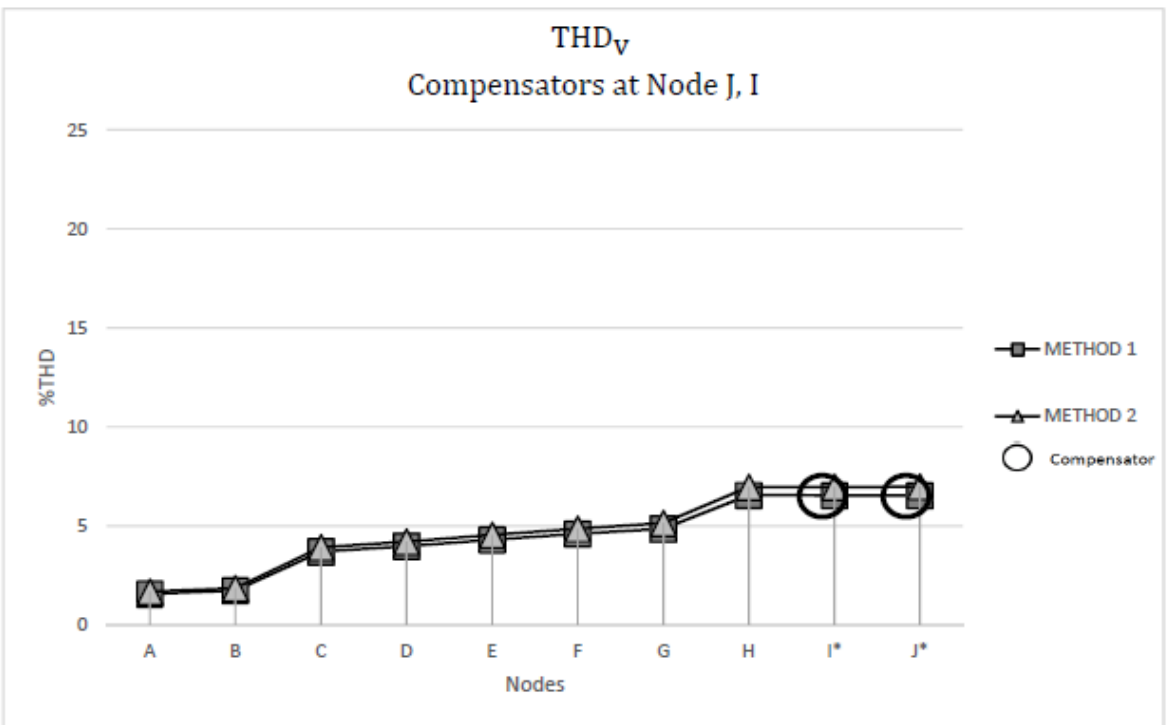
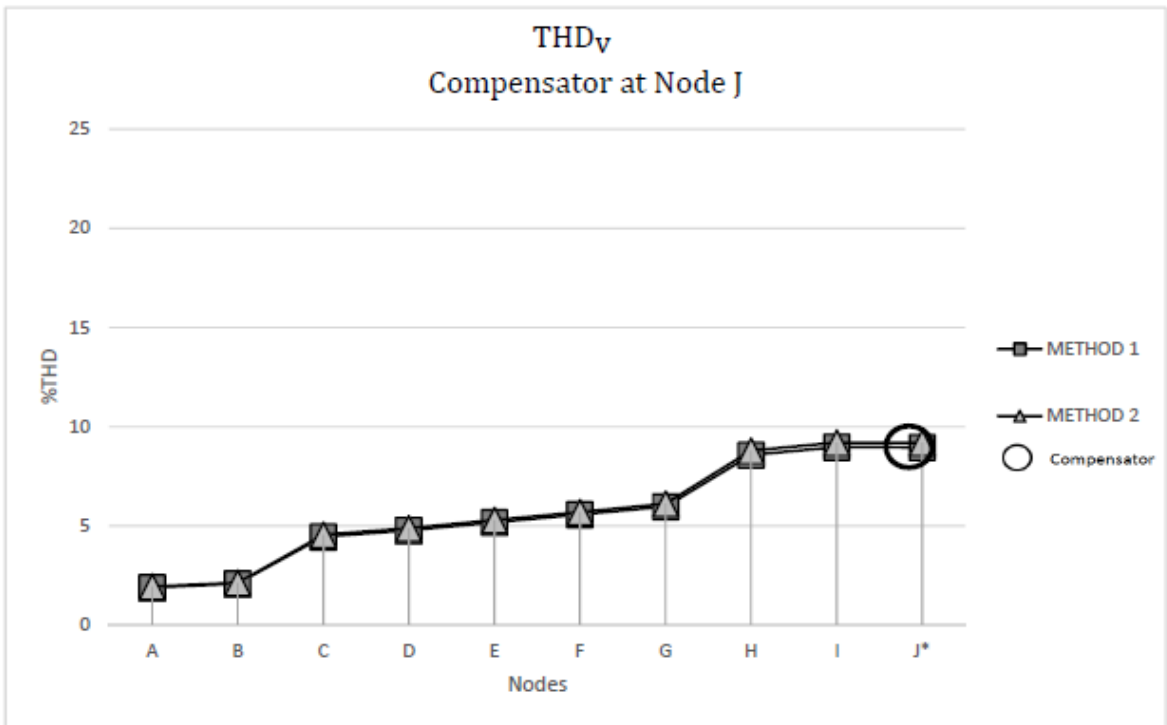
Comp @ J, I		
Node	METHOD 1	METHOD 2
A	1.558	1.674
B	1.723	1.846
C	3.698	3.911
D	3.966	4.192
E	4.302	4.544
F	4.594	4.856
G	4.858	5.141
H	6.55	6.964
I*	6.534	6.967
J*	6.527	6.97

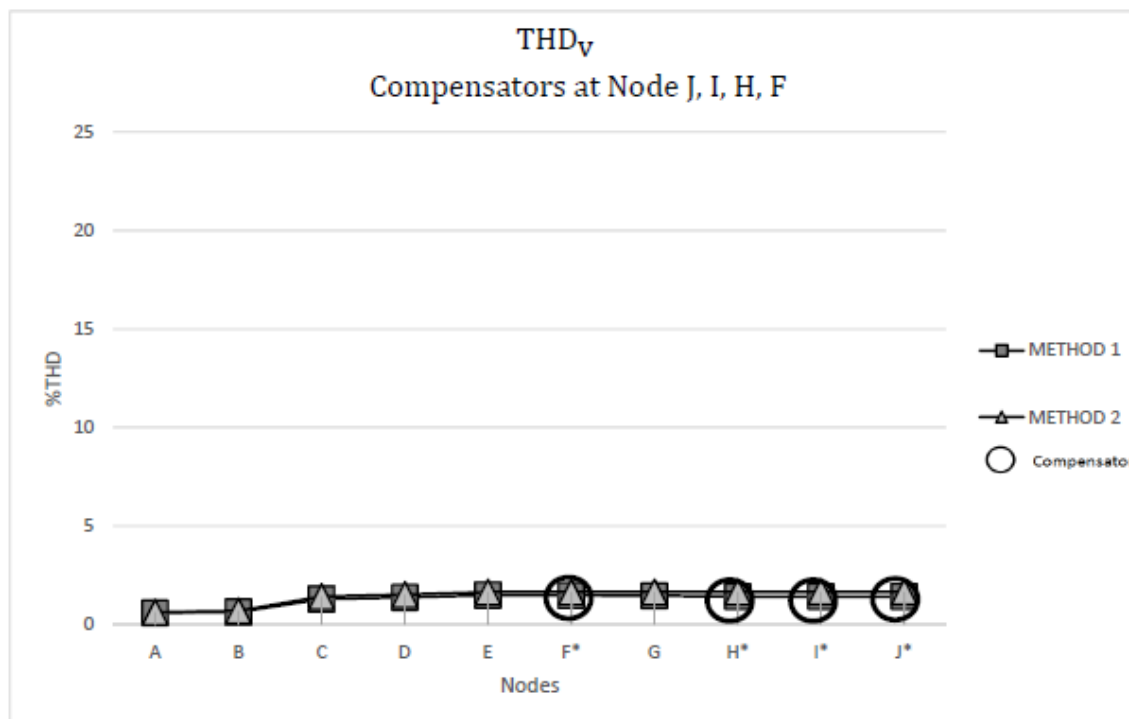
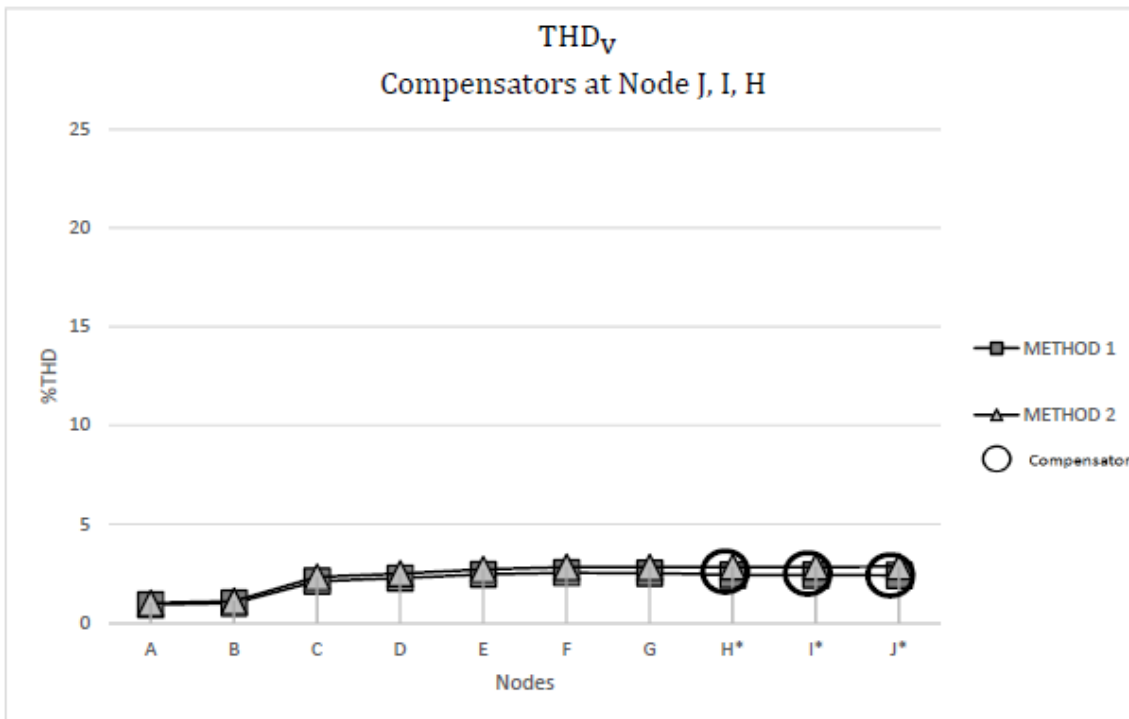
Comp @ J, I, H		
Node	METHOD 1	METHOD 2
A	0.9029	0.989
B	0.9953	1.09
C	2.106	2.32
D	2.257	2.49
E	2.447	2.701
F	2.536	2.817
G	2.511	2.818
H*	2.421	2.831
I*	2.414	2.834
J*	2.41	2.838

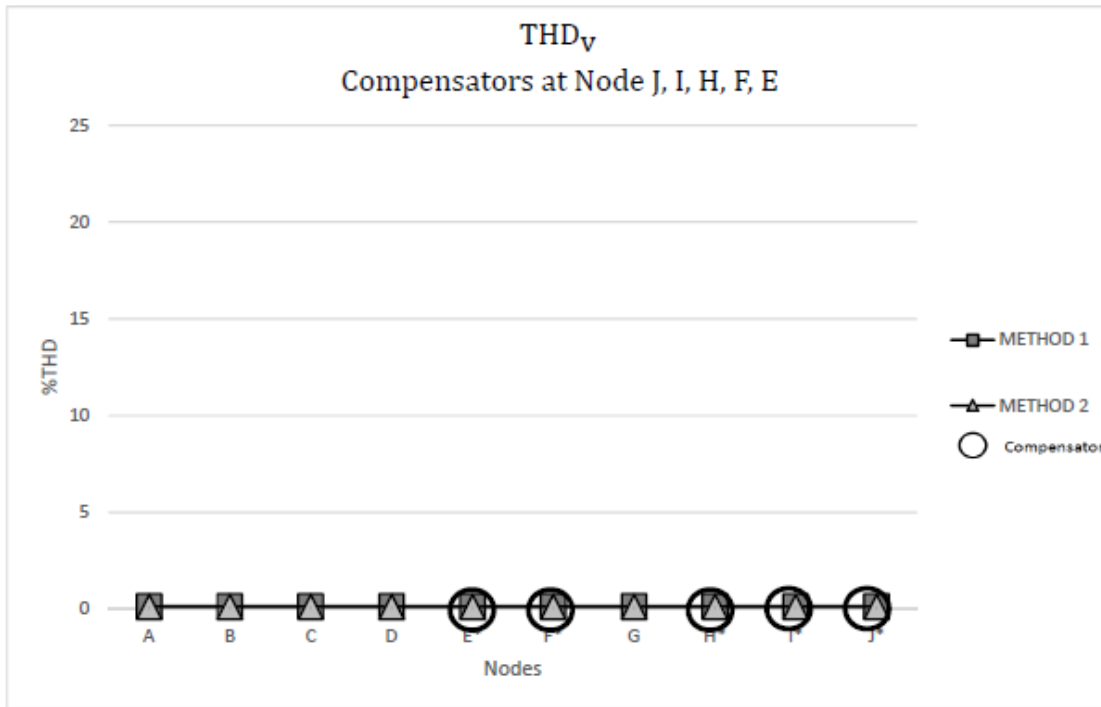
Comp @ J, I, H, F		
Node	METHOD 1	METHOD 2
A	0.5931	0.6319
B	0.6462	0.6924
C	1.294	1.427
D	1.382	1.528
E	1.494	1.654
F*	1.483	1.653
G	1.469	1.653
H*	1.423	1.658
I*	1.42	1.659
J*	1.418	1.661

Comp @ J, I, H, F, E		
Node	METHOD 1	METHOD 2
A	0.16909	0.1424
B	0.169	0.1424
C	0.169	0.1424
D	0.169	0.1424
E*	0.169	0.1424
F*	0.169	0.1424
G	0.169	0.1424
H*	0.169	0.1424
I*	0.169	0.1424
J*	0.169	0.1425









## Appendix J - Method Comparison of THD<sub>v</sub> for Random Input Order

**RANDOM of VOLTAGE:** This page is a comparison of the two methods by which we measured voltage THD. The compensators were added in the random order of J, H, E, F, I to compensate harmonics at the locations of non-linear loads.

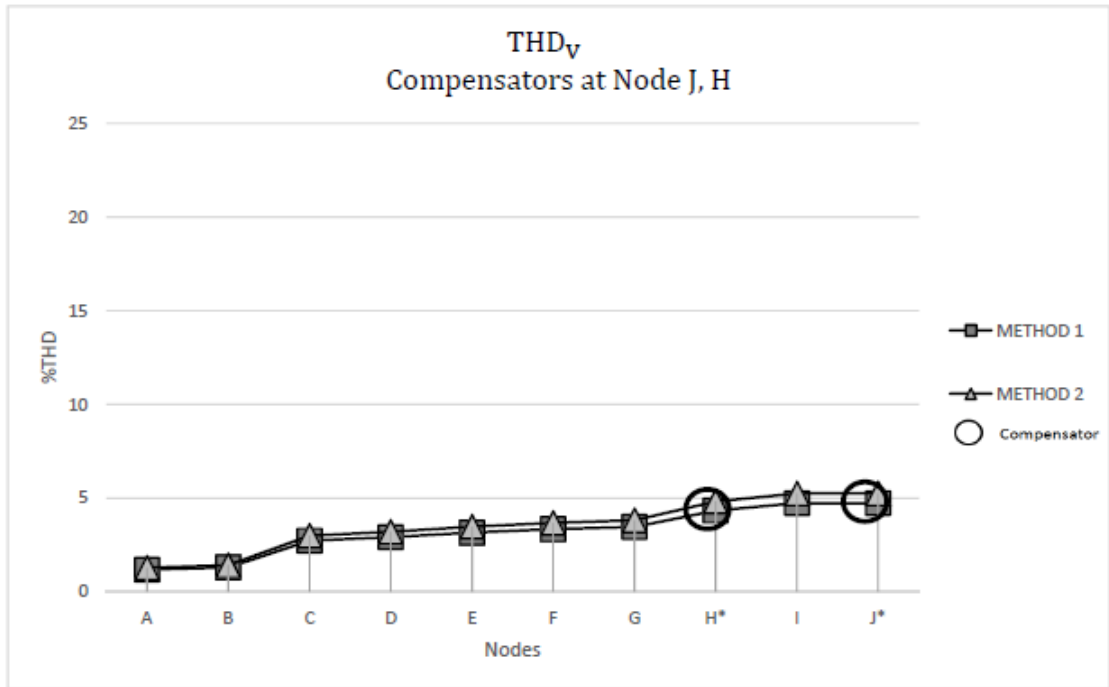
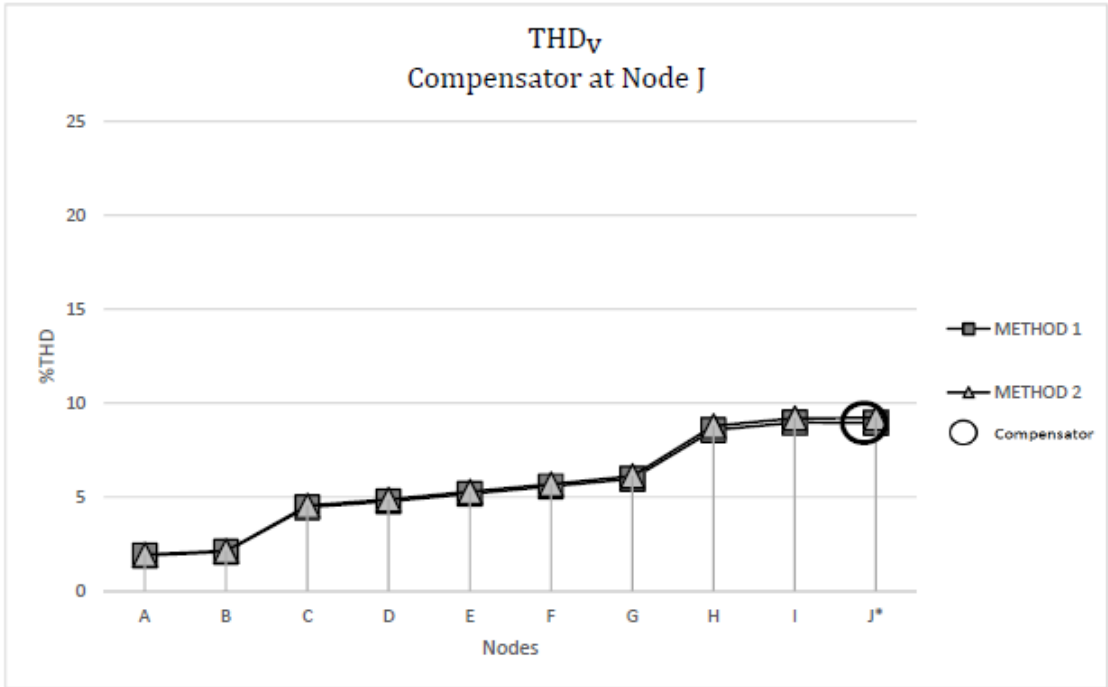
Node	COMP @ J	
	METHOD 1	METHOD 2
A	1.888	1.929
B	2.085	2.13
C	4.45	4.545
D	4.771	4.873
E	5.175	5.285
F	5.567	5.688
G	5.971	6.106
H	8.569	8.78
I	8.97	9.195
J*	8.955	9.2

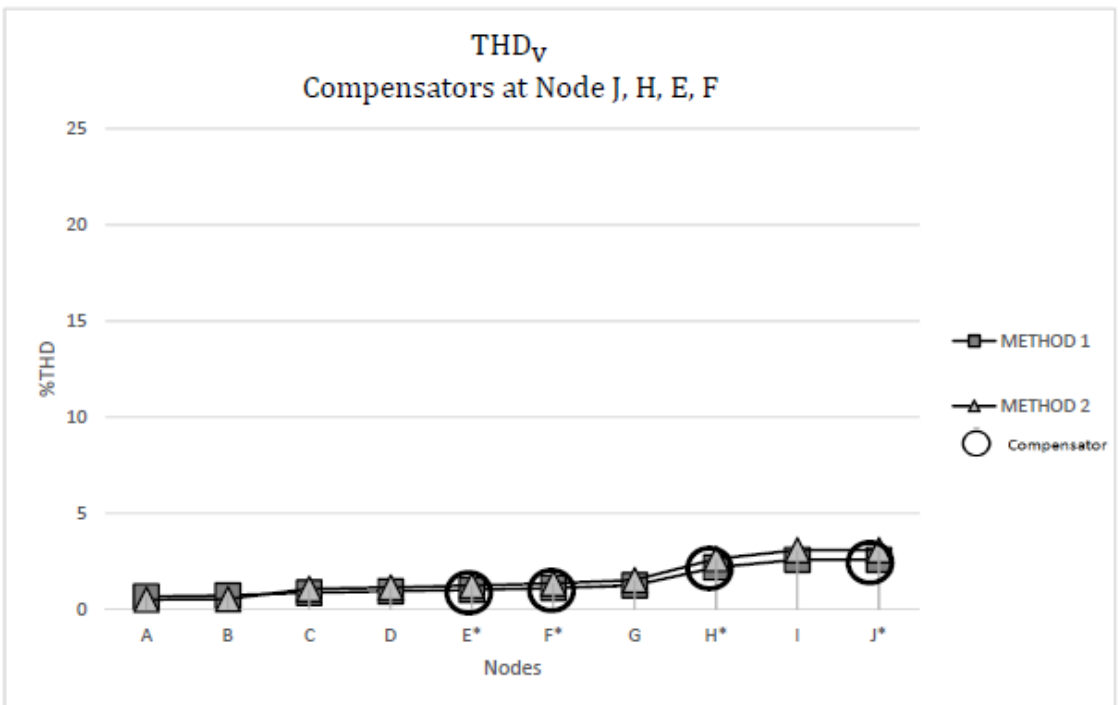
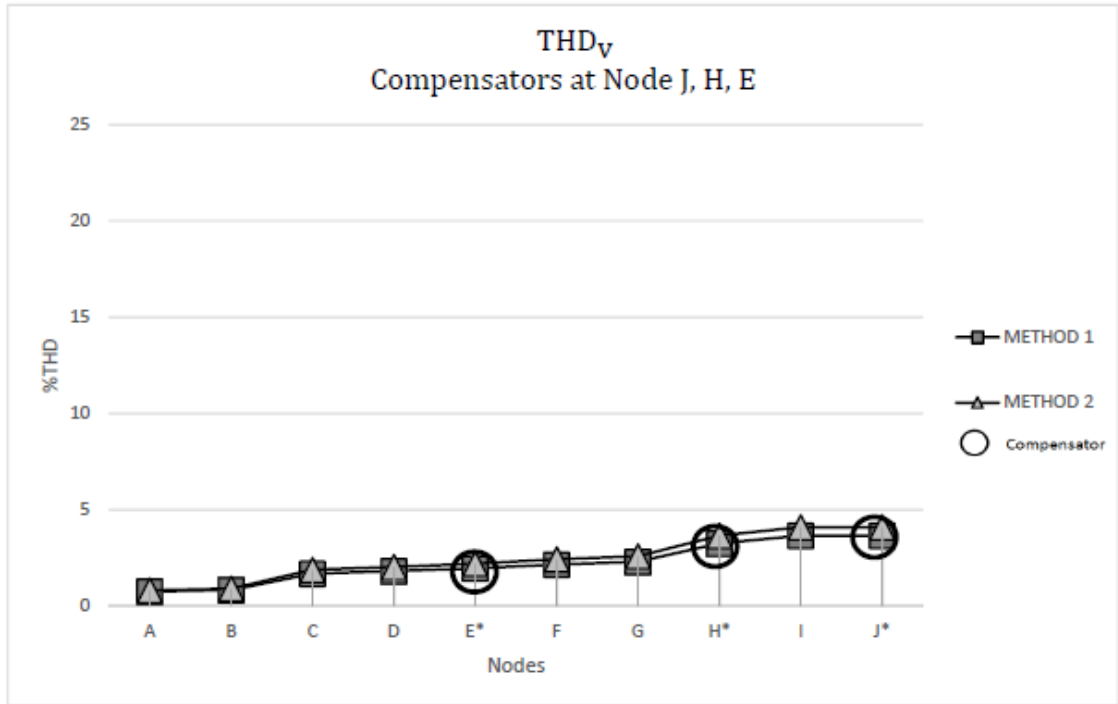
Node	Comp @ J,H	
	METHOD 1	METHOD 2
A	1.19	1.292
B	1.309	1.423
C	2.731	2.992
D	2.924	3.205
E	3.166	3.474
F	3.347	3.685
G	3.464	3.829
H*	4.339	4.827
I	4.742	5.258
J*	4.734	5.259

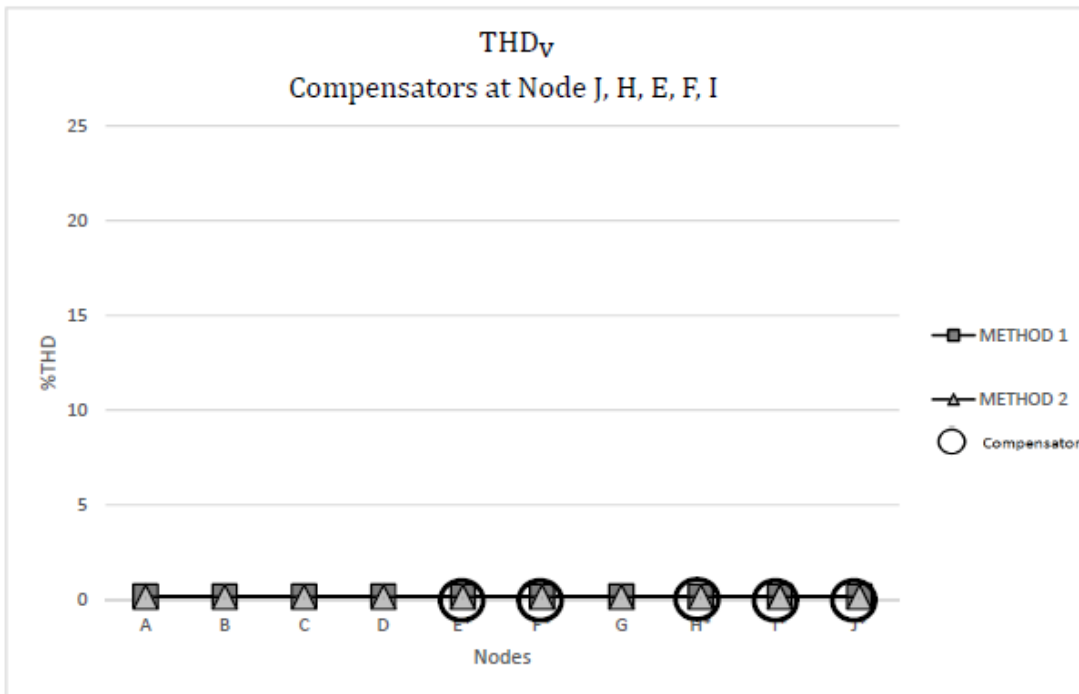
Node	Comp @ J,H,E	
	METHOD 1	METHOD 2
A	0.7572	0.8195
B	0.8289	0.9011
C	1.693	1.89
D	1.811	2.025
E*	1.958	2.195
F	2.158	2.424
G	2.298	2.583
H*	3.251	3.652
I	3.663	4.102
J*	3.657	4.102

Node	Comp @ J,H,E,F	
	METHOD 1	METHOD 2
A	0.6584	0.4994
B	0.718	0.542
C	0.8705	1.067
D	0.9315	1.14
E*	1.008	1.231
F*	1.111	1.354
G	1.256	1.525
H*	2.183	2.621
I	2.575	3.072
J*	2.573	3.074

Node	Comp @ J,H,E,F,I	
	METHOD 1	METHOD 2
A	0.172	0.1424
B	0.172	0.1424
C	0.172	0.1424
D	0.172	0.1424
E*	0.172	0.1424
F*	0.172	0.1424
G	0.172	0.1424
H*	0.172	0.1424
I*	0.172	0.1424
J*	0.172	0.1425







## Appendix K - Method Comparison for THD<sub>I</sub> for A to J Input Order

A to J of CURRENT: This page is a comparison of the two methods by which we measured current THD. The compensators were added from closer to the generator to the farthest point in the network; E, F, H, I, J to compensate harmonics at the locations of non-linear loads.

Node	Comp @ E	
	METHOD 1	METHOD 2
A	8.263	8.294
B	8.597	8.619
C	9.189	9.192
D	10.046	10.016
E*	11.673	11.594
F	14.676	14.915
G	13.024	13.246
H	13.428	13.646
I	18.53	18.826
J	18.80	19.084

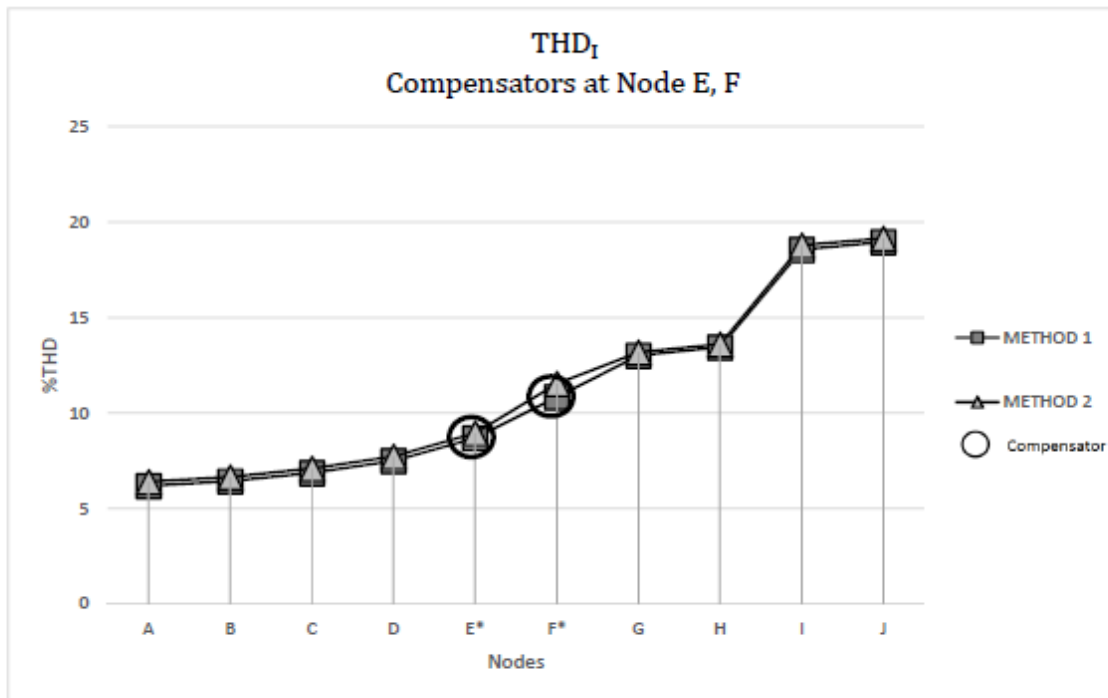
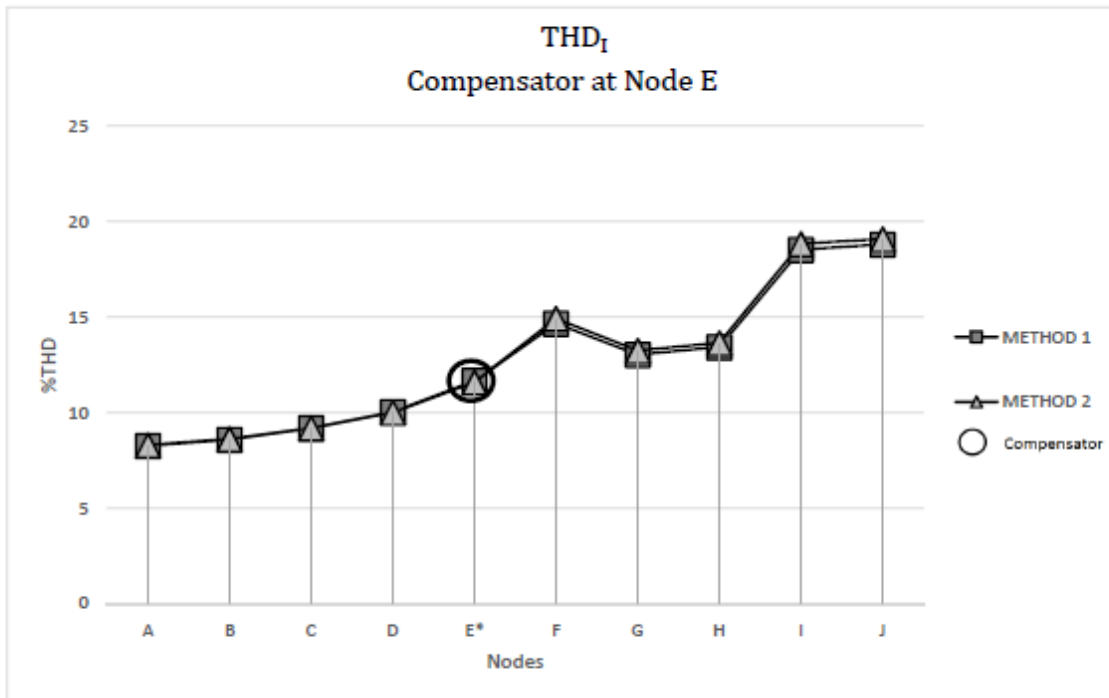
Node	Comp @ E,F	
	METHOD 1	METHOD 2
A	6.18	6.385
B	6.426	6.637
C	6.86	7.083
D	7.486	7.724
E*	8.681	8.952
F*	10.831	11.538
G	13.015	13.181
H	13.436	13.593
I	18.563	18.786
J	18.963	19.154

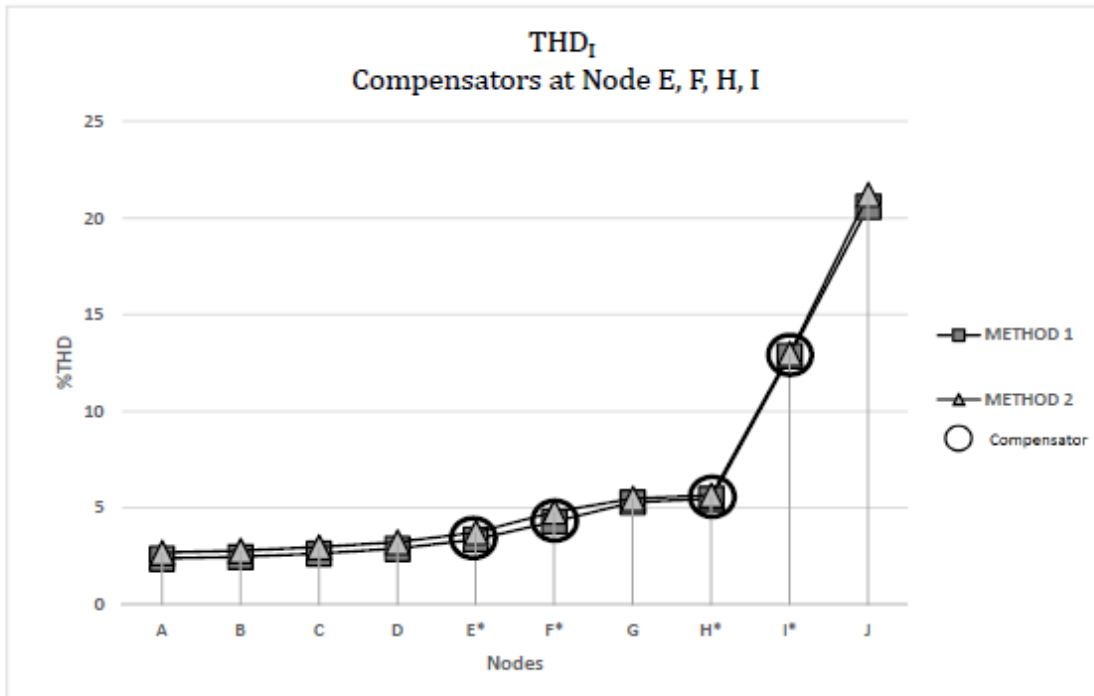
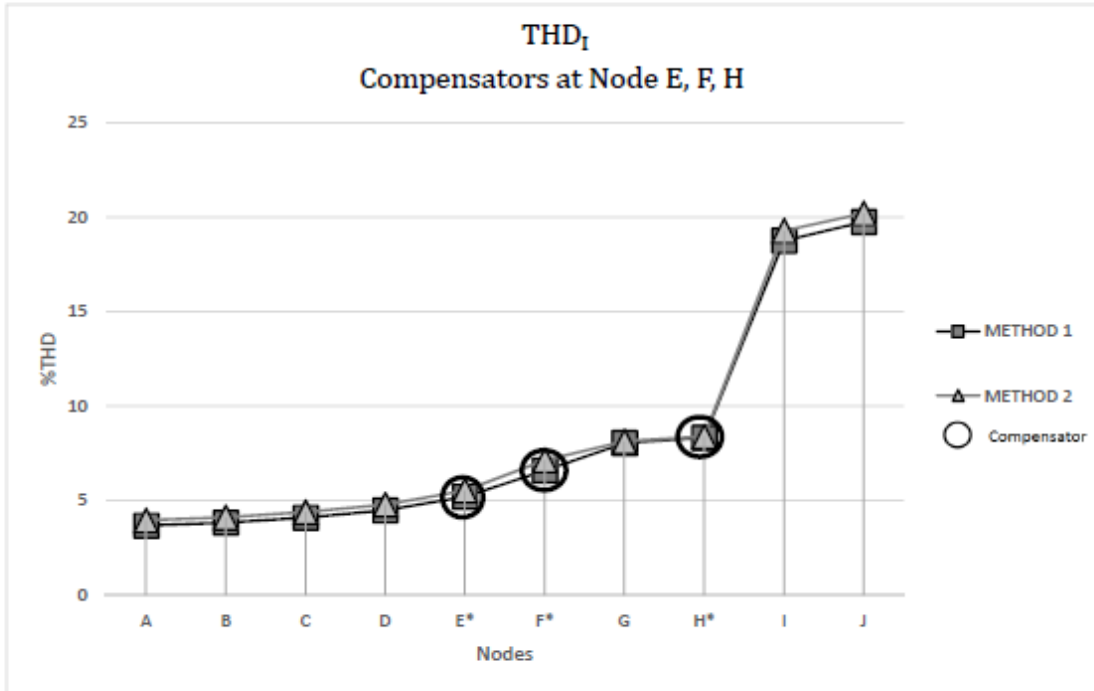
Node	Comp @ E,F,H	
	METHOD 1	METHOD 2
A	3.675	3.952
B	3.824	4.108
C	4.089	4.382
D	4.476	4.777
E*	5.203	5.534
F*	6.584	7.128
G	8.048	8.139
H*	8.327	8.393
I	18.757	19.292
J	19.753	20.203

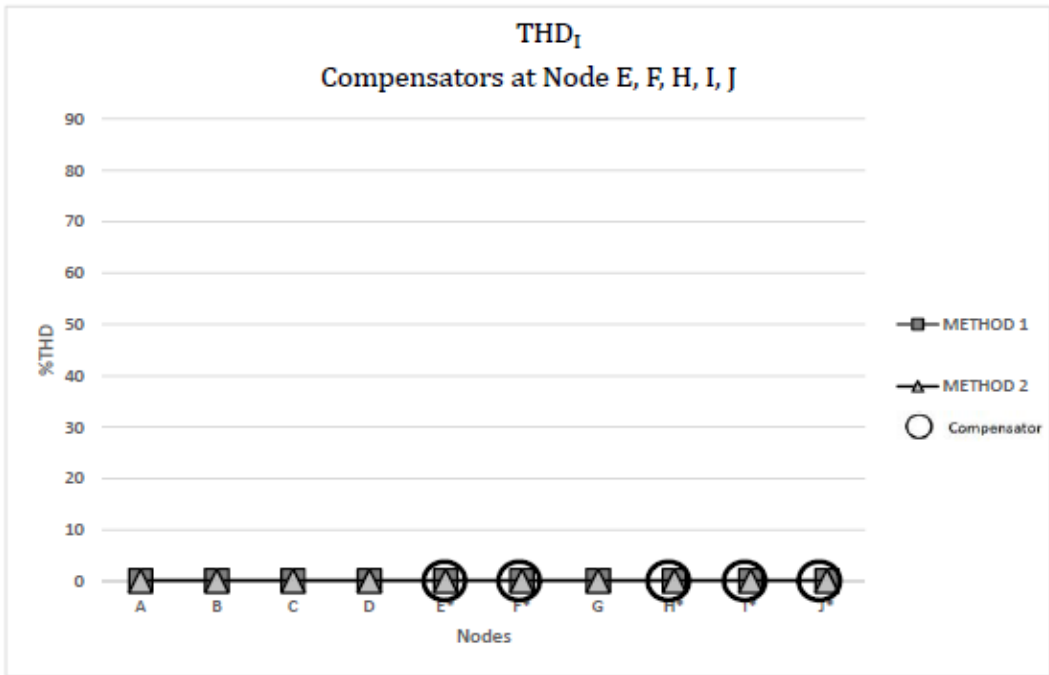
Node	Comp @ E,F,H,I	
	METHOD 1	METHOD 2
A	2.369	2.677
B	2.466	2.781
C	2.64	2.965
D	2.895	3.229
E*	3.374	3.734
F*	4.298	4.804
G	5.293	5.49
H*	5.483	5.661
I*	12.872	12.995
J	20.593	21.221

Node	Comp @ E,F,H,I,J	
	METHOD 1	METHOD 2
A	0.17395	0.1492
B	0.17395	0.1492
C	0.17395	0.1494
D	0.17395	0.1497
E*	0.17395	0.1494
F*	0.17395	0.1497
G	0.17395	0.1524
H*	0.17395	0.1525
I*	0.17395	0.1524
J*	0.17395	0.1535









## Appendix L – Method Comparison of THD<sub>i</sub> for J to A Input Order

J to A of CURRENT: This page is a comparison of the two methods by which we measured current THD. The compensators were added from the farthest point in the network to the generator; J, I, H, F, E to compensate harmonics at the locations of non-linear loads.

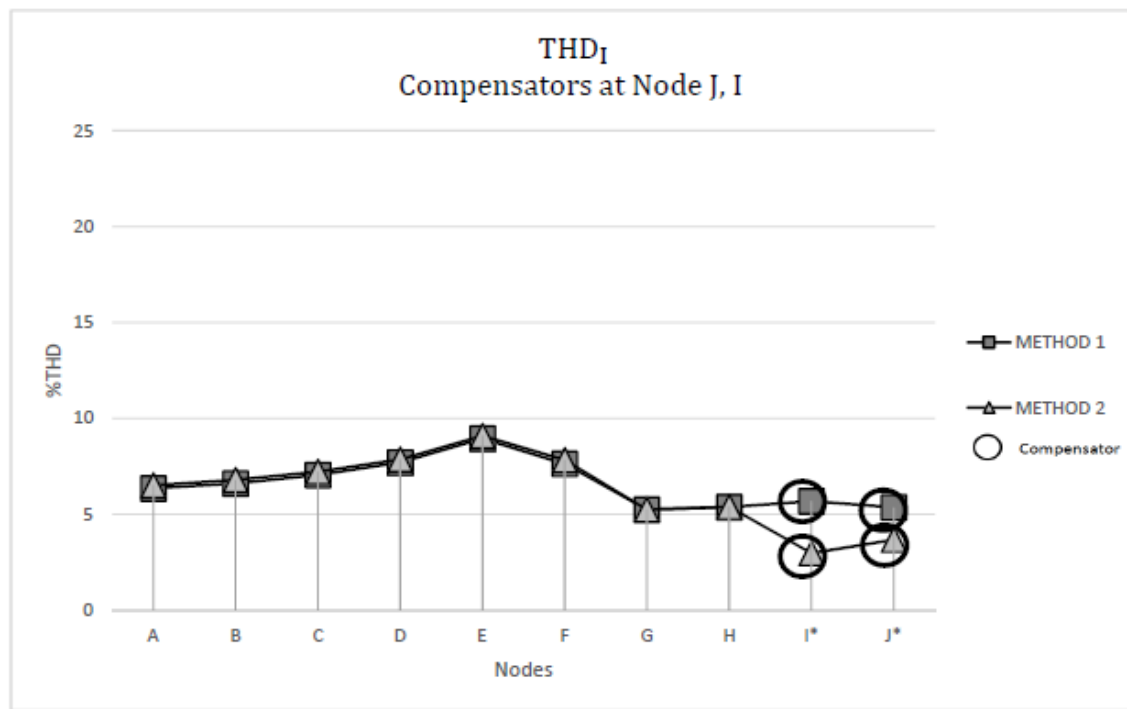
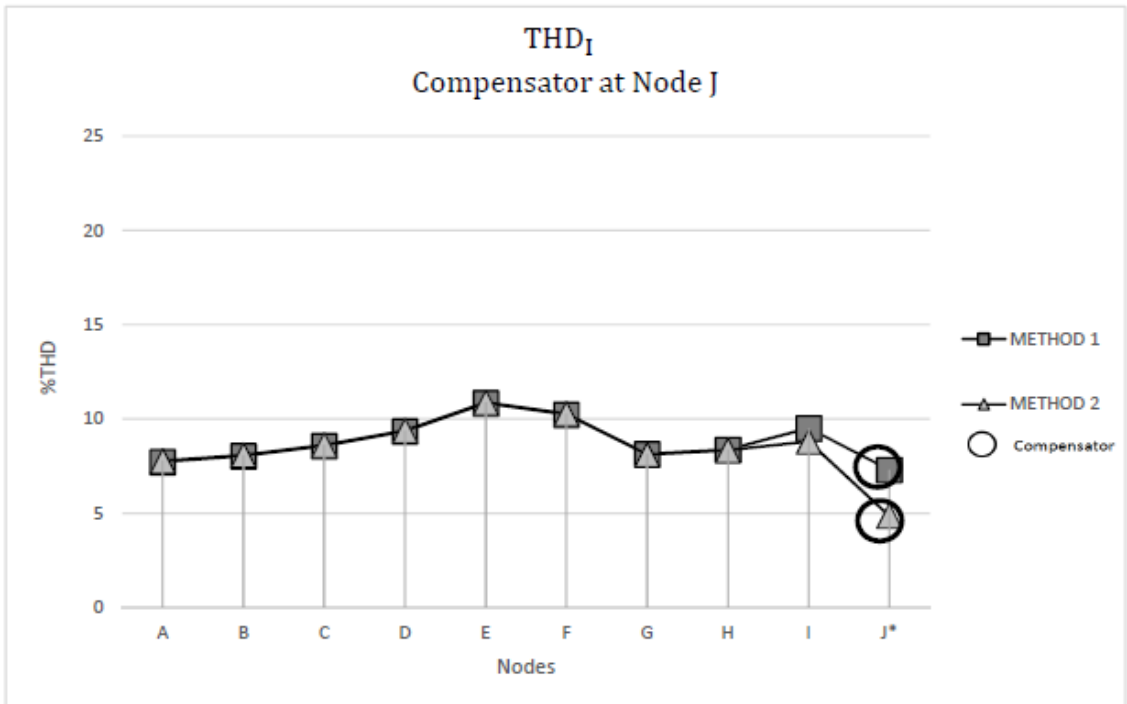
Comp @ J		
Node	METHOD 1	METHOD 2
A	7.729	7.777
B	8.035	8.082
C	8.575	8.62
D	9.354	9.392
E	10.839	10.869
F	10.241	10.284
G	8.147	8.111
H	8.381	8.343
I	9.514	8.804
J*	7.298	4.857

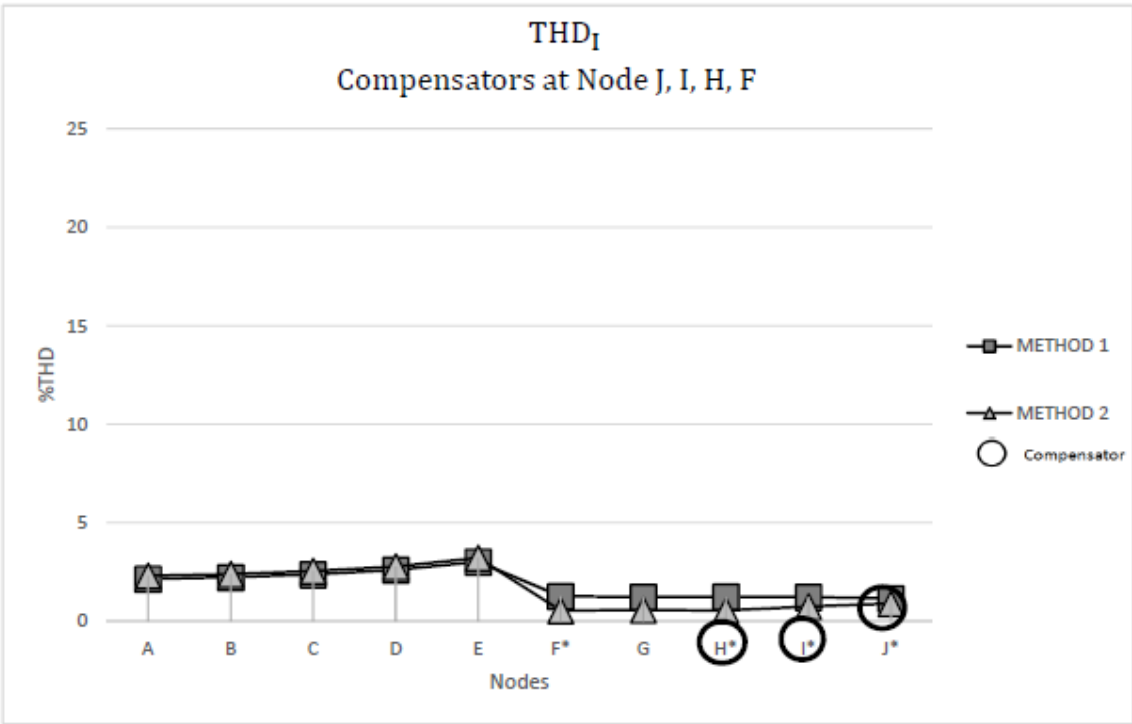
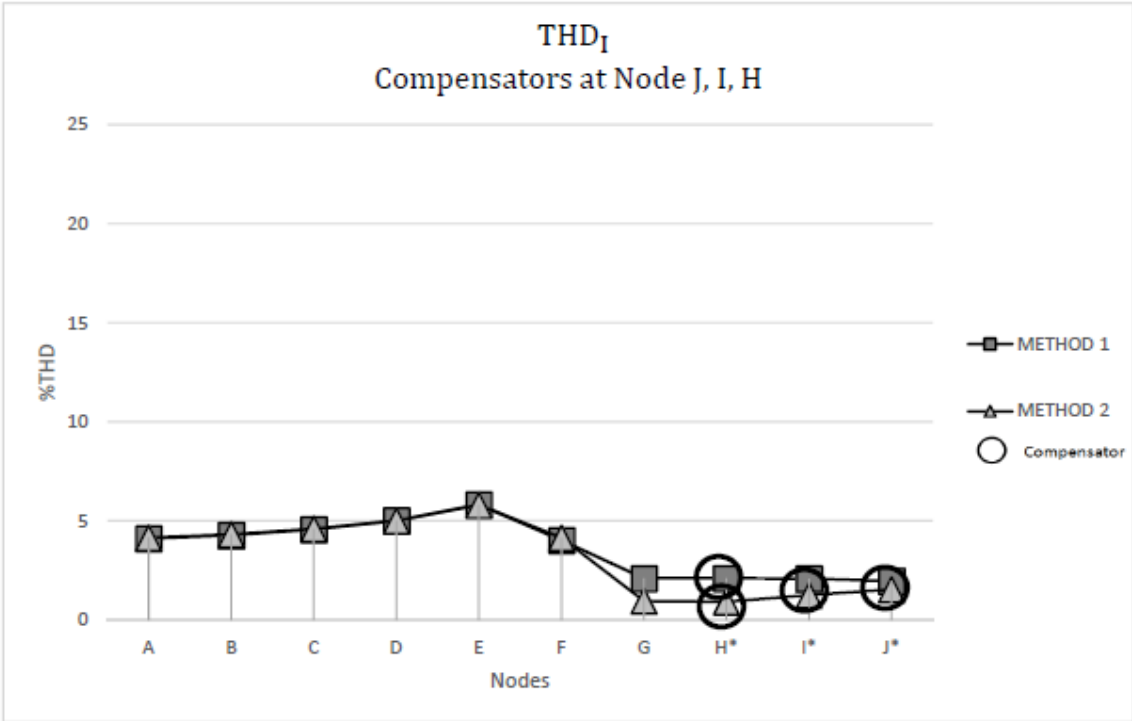
Comp @ J, I		
Node	METHOD 1	METHOD 2
A	6.348	6.509
B	6.603	6.794
C	7.054	7.213
D	7.708	7.858
E	8.95	9.093
F	7.63	7.834
G	5.241	5.24
H	5.38	5.382
I*	5.683	2.98
J*	5.354	3.669

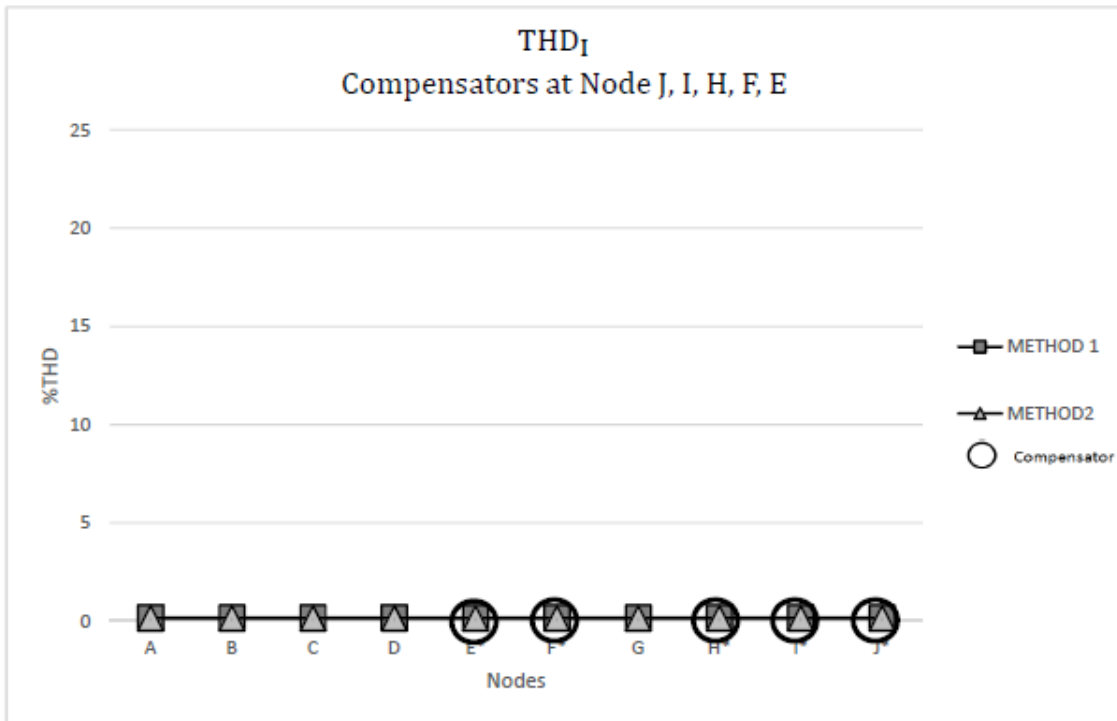
Comp @ J, I, H		
Node	METHOD 1	METHOD 2
A	4.105	4.144
B	4.272	4.308
C	4.572	4.596
D	5.009	5.009
E	5.824	5.797
F	4.017	4.143
G	2.097	0.9569
H*	2.1	0.9183
I*	2.085	1.253
J*	1.962	1.535

Comp @ J, I, H, F		
Node	METHOD 1	METHOD 2
A	2.147	2.303
B	2.233	2.393
C	2.386	2.551
D	2.608	2.779
E	3.025	3.213
F*	1.272	0.5515
G	1.237	0.5738
H*	1.239	0.5517
I*	1.23	0.742
J*	1.158	0.9009

Comp @ J, I, H, F, E		
Node	METHOD 1	METHOD 2
A	0.1691	0.1492
B	0.1691	0.1492
C	0.1691	0.1494
D	0.1691	0.1497
E*	0.1691	0.1494
F*	0.1691	0.1497
G	0.1691	0.1524
H*	0.1691	0.1525
I*	0.1691	0.1524
J*	0.1691	0.1535







## Appendix M – Method Comparison of THD<sub>i</sub> for Random Input Order

**RANDOM of CURRENT:** This page is a comparison of the two methods by which we measured current THD. The compensators were added in the random order of J, H, E, F, I to compensate harmonics at the locations of non-linear loads.

COMP @ J		
Node	METHOD 1	METHOD 2
A	7.729	7.777
B	8.035	8.082
C	8.575	8.62
D	9.354	9.392
E	10.839	10.869
F	10.241	10.284
G	8.147	8.111
H	8.381	8.343
I	9.514	8.804
J*	7.298	4.857

Comp @ J,H		
Node	METHOD 1	METHOD 2
A	5.282	5.456
B	5.496	5.669
C	5.878	6.044
D	6.432	6.582
E	7.471	7.608
F	6.264	6.463
G	4.148	3.623
H*	4.234	3.701
I	8.123	8.271
J*	7.097	2.771

Comp @ J,H,E		
Node	METHOD 1	METHOD 2
A	3.63	3.735
B	3.78	3.88
C	4.047	4.137
D	4.4397	4.503
E*	5.161	5.202
F	6.577	6.68
G	3.808	3.591
H*	3.912	3.682
I	8.161	8.3
J*	5.49	2.158

Comp @ J,H,E,F		
Node	METHOD 1	METHOD 2
A	1.513	1.691
B	1.577	1.757
C	1.69	1.872
D	1.856	2.037
E*	2.167	2.351
F*	2.762	3.022
G	3.398	3.453
H*	3.519	3.559
I	8.142	8.1517
J*	2.098	1.655

Comp @ J,H,E,F,I		
Node	METHOD 1	METHOD 2
A	0.172	0.1492
B	0.172	0.1492
C	0.172	0.1494
D	0.172	0.1497
E*	0.172	0.1494
F*	0.172	0.1497
G	0.172	0.1524
H*	0.172	0.1525
I*	0.172	0.1524
J*	0.172	0.1535



