



## Modeling the Non-linear Load Contributions to Voltage Distortion at the Output of Three Different Types of 112.5 kVA Transformers

The harmonic currents generated by non-linear loads will produce voltage distortion as they interact with the impedance of an electrical distribution system. This voltage distortion can easily reach unacceptable levels unless Harmonic Mitigating Transformers (HMT) are used to produce cancellation of the offending harmonic currents. In the tables below, output voltage distortion has been calculated for 3 different types of transformers (K13, MIRUS Harmony-1™ and the dual output MIRUS Harmony-2™) under varying load conditions. They clearly show how K-rating alone is insufficient for treating non-linear load generated harmonics.

112.5 kVA, K13 Transformer						Voltage Distortion at Transformer Output, $V_h$ (%rms) <sup>3</sup>							
480-120/208V						100% non-linear load			50% non / 50% linear load				
h	Seq.	$I_h$ (%) <sup>1</sup>	$I_h$ (%rms)	$X_{Th}$ (%) <sup>4</sup>	$X_{Sh}$ (%) <sup>2</sup>	Full load	75% load	50% load	Full load	75% load	50% load		
1	+ve	100.0	77.5	3.5	0.7	n/a	n/a	n/a	n/a	n/a	n/a		
3	zero <sup>9</sup>	70.0	54.3	10.5	0.0	5.70	4.27	2.85	2.85	2.14	1.42		
5	-ve	35.0	27.1	17.5	3.5	5.70	4.27	2.85	2.85	2.14	1.42		
7	+ve	20.0	15.5	24.5	4.9	4.56	3.42	2.28	2.28	1.71	1.14		
9	zero	10.0	7.8	31.5	0.0	2.44	1.83	1.22	1.22	0.92	0.61		
11	-ve	3.0	2.3	38.5	7.7	1.07	0.81	0.54	0.54	0.40	0.27		
13	+ve	2.0	1.6	45.5	9.1	0.85	0.63	0.42	0.42	0.32	0.21		
15	zero	1.0	0.8	52.5	0.0	0.41	0.31	0.20	0.20	0.15	0.10		
<b>K factor =</b>		<b>6.3</b>				<b><sup>3</sup> V<sub>THD</sub> = 9.7%</b>			<b>7.3%</b>			<b>4.8%</b>	
<b><sup>6</sup> I<sub>THD</sub> =</b>		<b>81%</b>							<b>4.8%</b>		<b>3.6%</b>		
									<b>2.4%</b>				

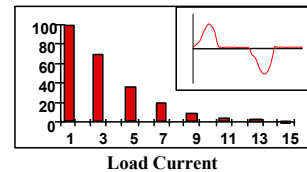
112.5 kVA, Harmony-1™ Transformer						Voltage Distortion at Transformer Output, $V_h$ (%rms)							
480-120/208V						100% non-linear load			50% non / 50% linear load				
h	Seq.	$I_h$ (%)	$I_h$ (%rms)	$X_{Th}$ (%)	$X_{Sh}$ (%)	Full load	75% load	50% load	Full load	75% load	50% load		
1	+ve	100.0	77.5	3.5	0.7	n/a	n/a	n/a	n/a	n/a	n/a		
3	zero <sup>10</sup>	70.0	54.3	1.1	0.0	0.57	0.43	0.28	0.28	0.21	0.14		
5	-ve	35.0	27.1	17.5	3.5	4.94	3.70	2.47	2.47	1.85	1.23		
7	+ve	20.0	15.5	24.5	4.9	3.95	2.96	1.98	1.98	1.48	0.99		
9	zero	10.0	7.8	3.2	0.0	0.24	0.18	0.12	0.12	0.09	0.06		
11	-ve	3.0	2.3	38.5	7.7	1.07	0.81	0.54	0.54	0.40	0.27		
13	+ve	2.0	1.6	45.5	9.1	0.85	0.63	0.42	0.42	0.32	0.21		
15	zero	1.0	0.8	5.3	0.0	0.04	0.03	0.02	0.02	0.02	0.01		
<b>K factor =</b>		<b>6.3</b>				<b>V<sub>THD</sub> = 6.5%</b>			<b>4.9%</b>			<b>3.2%</b>	
<b>I<sub>THD</sub> =</b>		<b>81%</b>							<b>3.2%</b>		<b>2.4%</b>		
									<b>1.6%</b>				

112.5 kVA, Harmony-2™ Transformer						Voltage Distortion at Transformer Output, $V_h$ (%rms)							
480-120/208V						100% non-linear load			50% non / 50% linear load				
h	Seq.	$I_h$ (%)	$I_h$ (%rms)	$X_{Th}$ (%)	$X_{Sh}$ (%)	Full load	75% load	50% load	Full load	75% load	50% load		
1	+ve	100.0	77.5	3.5	0.7	3.26	2.44	1.63	1.63	1.22	0.81		
3	zero <sup>10</sup>	70.0	54.3	1.1	0.0	0.57	0.43	0.28	0.28	0.21	0.14		
5	-ve	35.0	27.1	17.5	3.5	2.56	1.92	1.28	1.28	0.96	0.64		
7	+ve	20.0	15.5	24.5	4.9	2.05	1.54	1.03	1.03	0.77	0.51		
9	zero	10.0	7.8	3.2	0.0	0.24	0.18	0.12	0.12	0.09	0.06		
11	-ve	3.0	2.3	38.5	7.7	0.93	0.70	0.47	0.47	0.35	0.23		
13	+ve	2.0	1.6	45.5	9.1	0.73	0.55	0.37	0.37	0.28	0.18		
15	zero	1.0	0.8	5.3	0.0	0.04	0.03	0.02	0.02	0.02	0.01		
<b>K factor =</b>		<b>6.3</b>				<b>V<sub>THD</sub> = 3.5%</b>			<b>2.7%</b>			<b>1.8%</b>	
<b>I<sub>THD</sub> =</b>		<b>81%</b>							<b>1.8%</b>		<b>1.3%</b>		
									<b>0.9%</b>				

(For Notes and Assumptions see p. 2)

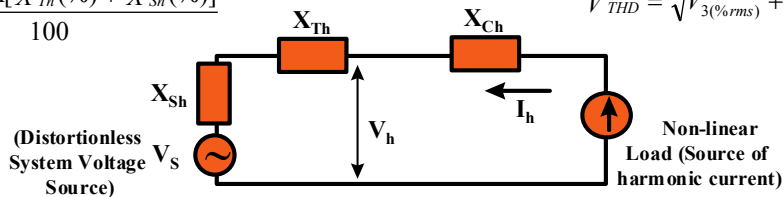
**Notes and Assumptions:**

1. The load harmonic spectrum used is that of a typical 120V, 1-ph., switch-mode power supply. Examples of such loads include personal computers, monitors, telecommunications and broadcasting equipment.
2. Each 112.5 kVA transformer is fed by a distortionless 3-ph., 480V source through a system source impedance  $Z_{Sh} = jX_{Sh} = j0.007pu$  (based on a 20kA fault level at transformer primary).  $X_{Sh}$ , the upstream supply reactance, does not enter into the calculations for voltage drop at 3<sup>rd</sup>, 9<sup>th</sup>, and 15<sup>th</sup> harmonics because the balanced portion of these currents (called the triplens) are either trapped in the delta primary, as in the K-factor transformer, or treated in the secondary windings, as in the Harmony™ transformers.
3. Voltage distortion calculation is as follows:



$$V_h(\%rms) = \frac{I_h(\%rms) \times [X_{Th}(\%) + X_{Sh}(\%)]}{100}$$

$$V_{THD} = \sqrt{V_{3(\%rms)}^2 + V_{5(\%rms)}^2 + \dots + V_{15(\%rms)}^2}$$



Where,

- $V_h(\%rms)$  = Voltage distortion, line-to-neutral, at harmonic h in %rms
- $I_h(\%rms)$  = Current at harmonic h in %rms
- $X_{Th}(\%)$  = Transformer reactance at harmonic h in %
- $X_{Sh}(\%)$  = Upstream system reactance at harmonic h in %
- $X_{Ch}(\%)$  = Downstream cable reactance at harmonic h in %
- $V_{THD}(\%)$  = Voltage total harmonic distortion in %.

4. 112.5 kVA transformer reactances used are as follows (resistance is considered negligible):
  - K-13:  $X^+ = X^- = X^0 = 3.5\%$
  - H-1:  $X^+ = X^- = 3.5\%$ ,  $X^0 = 0.35\%$
  - H-2:  $X^+ = X^- = 3.5\%$ ,  $X^0 = 0.35\%$
5. Voltage distortion at the output of a transformer will vary with respect to the following:
  - a. System source impedance
  - b. Transformer impedance
  - c. Non-linear load harmonic spectrum
  - d. % of linear vs non-linear load
6. Total Harmonic Current Distortion,  $I_{THD}$ , is calculated as follows:

$$I_{THD} = \sqrt{I_3^2(\%rms) + I_5^2(\%rms) + \dots + I_{15}^2(\%rms)}$$

7. K factor is calculated as follows:  $K_{factor} = \sum_{h=1}^{h=15} h^2 I_h^2$

Where,  $I_h$  = rms current at harmonic h, in per unit of rated rms load current

8. In the Harmony-2™ transformer, 5<sup>th</sup> and 7<sup>th</sup> load current harmonic fluxes cancel on the secondary side to reduce the voltage distortion at the 5<sup>th</sup> and 7<sup>th</sup> harmonics. For calculation purposes, it is assumed that unbalanced load currents leave a 20% residual and that half of the transformer impedance is on the primary side. For the Harmony-1™, it is assumed that pairs of Harmony-1™ transformers with 0° and 30° phase shifts are used to reduce the 5<sup>th</sup> and 7<sup>th</sup> harmonic voltage distortion by canceling these currents on the primary bus. Again, a 20% residual is used in the calculations.
9. Triplen harmonic voltage distortion is substantially lower in the Harmony™ transformers because they are designed to cancel the balanced portion of the triplen harmonic fluxes in their secondary windings.
10. Voltage distortion will be even higher at the loads due to the effect of downstream cable impedance. Also, distortion will be higher when sources, such as Diesel Generators or UPS units, are used, because of their high internal impedance.