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POWER QUALITY IMPROVEMENT IN A HARMONIC ENVIRONMENT

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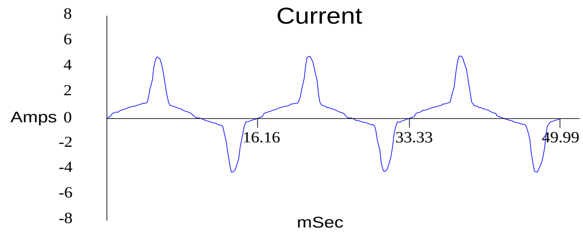
Abstract - *The effect of single-phase, non-linear loads, as sources of positive-, negative- and third-order, zero-sequence harmonic currents in low voltage electrical distribution systems, is discussed. Various traditional methods for dealing with these harmonic currents are outlined and their shortcomings identified. Alternative methods, which provide harmonic current reduction, and power quality improvement, are presented. Results of the application of alternative devices in typical environments are given.*

I. INTRODUCTION

Single-phase, full-wave, non-linear electronic loads, which are connected phase-to-neutral in a 120/208V, three-phase, four-wire distribution system, generate high levels of odd positive-, negative- and third-order, zero-sequence harmonic current. In office and data processing environments, these currents are principally the byproduct of switch-mode power supply technology.[1,2]

Electrically, the switch-mode power supply's AC voltage source is rectified to DC. The DC voltage is then applied to a large storage capacitor. In the first half-cycle, the capacitor is charged to the average value of the AC voltage. The electronic equipment then draws DC current from its power supply's charged capacitor, to a predetermined low voltage level. Before reaching the lower limit, he capacitor is again recharged to the average value of the AC voltage in the next half cycle.

This process, which is repeated twice in each cycle, causes AC current to flow only during that portion of the AC voltage sine wave when the rectified source voltage is above the capacitor's residual voltage. This sequence causes the 60Hz, AC current to flow in abrupt pulses as shown in *Figure 1*.[3]



Current Waveform - Switch-Mode Power Supply
Fig. 1

Almost all productivity equipment, used in office and data processing environments, contain switch-mode power supplies. These devices include personal computers, terminals, monitors, and peripheral devices, such as controllers, servers, printers, scanners, photocopiers and facsimile transmitters.

Low to medium levels of odd positive-, negative- and third-order, zero-sequence harmonic currents are also generated by fluorescent lamps. The power source for these devices may be either 120/208V or 277/480V three-phase, four-wire distribution system. The relationship between the voltage across, and the current through a fluorescent lamp is non-linear. This is due to the characteristic of the electric arc, which produces illumination.[4]

Although fluorescent lamps with magnetic ballasts draw non-sinusoidal currents, lamps fitted with electronic ballasts may generate even higher levels of harmonic current.

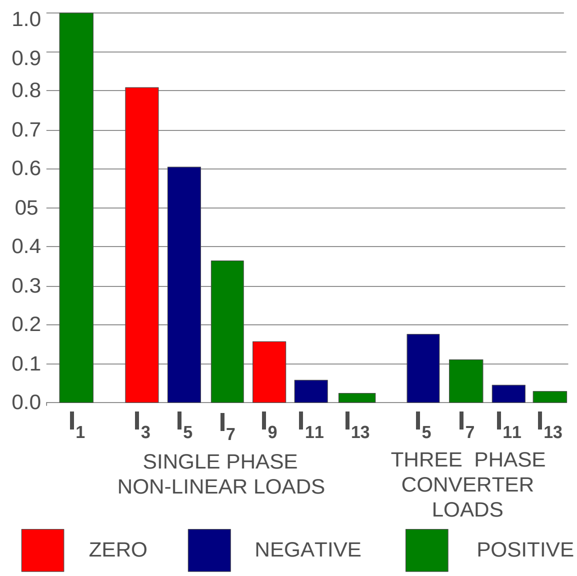
Medium to high levels of odd positive- and negative-sequence harmonic currents are generated by three-phase, full-wave, non-linear loads, which are connected to a 480V three-wire or 277/480V four-wire distribution system. These currents are principally the byproduct of three-phase, six-pulse, diode-bridge rectifiers.

In office and data processing environments, three-phase adjustable speed drives (ASD),[5] employed in heating, ventilating and air-conditioning systems, and three-phase uninterruptable power sources (UPS), typically use these electronic power converters.

Although harmonic mitigation and power quality improvement issues related to these three-phase loads are not fully discussed here, it should be understood that the ambient total harmonic distortion of voltage (THD_V) at the 480V level will be effected by these devices, and that these ambient levels will have an impact on THD_V at the 120/208V levels.

In order to keep the magnitude of harmonic currents generated by single-phase and three-phase loads in perspective, typical harmonic current profiles for an individual switch-mode power supply and a three-phase diode-bridge rectifier are displayed in *Figure 2*.[6]

Given the fact that the harmonic current profiles displayed in *Figure 2* are for individual devices and that some natural cancellation of these harmonic currents will occur within the power system,[7] significant levels of positive-, negative- and third-order, zero-sequence harmonic currents will remain to have a impact on the cost of power, the performance of the power distribution system, and the devices connected to it.



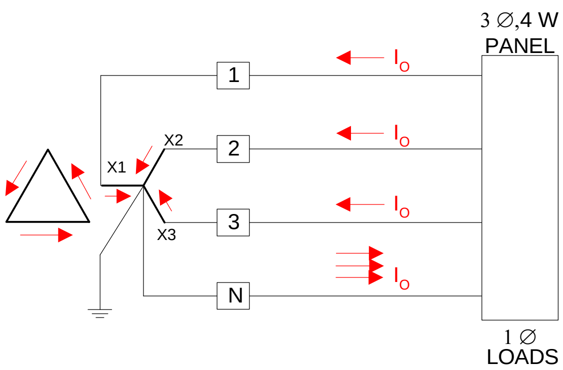
Harmonic Current Profiles for Non-linear Loads
Fig. 2

II. The Effect of Single-Phase, Non-Linear Loads

In isolation, switch-mode power supply loads may seem rather insignificant. However, when distribution transformers rather than power transformers supply these loads, they may represent 98% - 100% of the sub-system's total loads. The outcome may be costly and even hazardous.

To assess the effect of single-phase, non-linear loads, it is convenient to identify the switch-mode power supply (or any non-linear load) as a source of harmonic currents. An examination of *Figure 2* will reveal that, overall, single-phase, non-linear loads generate the highest harmonic current profiles. Of these, the 3rd harmonic current (I_3), which is the first third order, zero-sequence harmonic current in the series, is dominant.

Unlike balanced, three-phase positive- and negative-sequence harmonic currents, third-order, zero-sequence harmonic currents, flowing on each phase of the four-wire system, are 'in-phase'. As a result, zero-sequence currents, flowing through the 'wye' connected secondary windings of the source transformer, combine arithmetically at its neutral terminal ($I_0\varnothing_1 + I_0\varnothing_2 + I_0\varnothing_3 = I_0N$). These currents return to their source via the neutral conductor as shown in *Figure 3*.



Zero-Sequence Harmonic Currents
in a 3∅, 4W System
Fig. 3

Because most power and distribution transformers are configured with 'delta' connected primary windings, the transformed zero-sequence harmonic currents will circulate within the primary winding. As a result, these trapped currents do not normally propagate beyond the voltage level at which they are generated.

Positive-, negative- and third-order, zero-sequence harmonic currents, acting in an Ohm's Law relationship with their various system harmonic impedances, generate harmonic voltages ($E_h = I_h \times Z_h$).

The harmonic voltages, which appear on the three phases of the power system, will cause distortion of the fundamental voltage waveforms. Since the magnitude of any harmonic voltage is a function of its system impedance, the highest level of THD_V, in any circuit, will appear at its non-linear loads. For most applications, IEEE Std 519-1992 recommends a THD_V limit of 5%, and an IHD_V limit of 3% for an individual harmonic.

With the NEC (CEC in Canada) requirement to ground the system neutral at the X_0 terminal of the source transformer, and because the magnitude of any harmonic voltage is a function of its system impedance, the highest level of neutral-ground voltage in any radial circuit will appear at its non-linear loads. CBEMA recommends a limit of 5 volts at the connected loads. Office and data processing environments, with computer networks and audio/video studios, normally require much lower levels.

Depending on the capacity, configuration, and loading of the distribution system, the presence of positive-, negative- and third-order, zero-sequence currents will include any or all of the following symptoms:

- High Peak Phase Current
- High Average Phase Current
- High Total Harmonic Distortion of Current (THD_I)
- High Total Harmonic Distortion of Voltage (THD_V)
- High Apparatus and Circuit Losses
- Overheating
- Low True Power Factor
- Errors in Protective Device Performance
- Errors in Power Metering
- Increased Apparatus Vibration
- High Telephone Interference Factor

In addition to the above, the presence of third-order, zero sequence harmonic currents will normally include the following symptoms:

- High Neutral Current
- High Neutral-Ground Voltage

These symptoms will affect the performance and cost of maintaining the distribution system and its loads, the cost of power, and the cost of lost productivity should any of its components malfunction or fail.

Ironically, the very devices that generate these harmonic currents may be the most sensitive to the power quality problems they create. The performance of the switch-mode power supply, in particular the charging of its capacitor, is critically dependent on the magnitude of peak voltage. Zero sequence harmonic voltages will cause "flat-topping" of the voltage waveform or the reduction of peak voltage. In severe cases, data processing may be corrupted due to a momentary loss of power from the switch-mode power supply, or the power supply itself may fail.

III. Traditional Methods For Dealing With Harmonic Currents

Excessive levels of positive-, negative- and third order, zero-sequence harmonic currents, in three-phase, four-wire low voltage distribution systems, became obvious by the mid-1980s. Due to the rapid increase in the use of personal computers, switch-mode power supply densities were then sufficient to produce the symptoms described earlier. Of these symptoms, overheated distribution transformers and high neutral currents drew most attention.

By 1988, a number of solutions were being proposed. These solutions inevitably included a recommendation to de-rate the distribution transformer and double the neutral conductors. Unfortunately, the recommendation to de-rate the distribution transformer often led to its replacement with a higher kVA unit. This replacement often increased secondary fault levels to values which were beyond the protective device's short-circuit interrupting capability.

As an alternative to de-rating a conventional distribution transformer, the International Transformer Corporation developed the K-Rated distribution transformer. Standard K-Factor ratings were selected to approximate various harmonic current profiles, or load K-Ratings.

Since the level of THD_V at the non-linear loads is inversely proportional to the level of transformer loading, the de-rating of a conventional distribution transformer, or the application of a K-Rated transformer will reduce the level of power quality. In plain language, de-rated and K-Rated transformers increase THD_V.

As an example, measurements, taken by a NETA member company, recorded a THD_V of 5.1% at the secondary terminals of a conventional 112.5kVA distribution transformer. Because the transformer was overheating, the data center facility manager, on the advice of his consultant, replaced the unit with a K-13 transformer of the same rating and impedance. With the new unit supplying the same loads, THD_V increased to 11.8%.

The application of de-rated or K-Rated transformers can only mitigate the high operating temperature problem. K-Rated transformers are not a power quality solution. If K-Rated transformer manufacturers understand this reality, it is certainly not effectively communicated to end users, their consulting engineers, or electrical contractors.

IV. Harmonic Currents Reduction For Power Quality Improvement

If electrical distribution system survival were the only issue, the 'Band-Aid' approach outlined above might be adequate. However, if the total cost of operating the system [8] and the cost of lost productivity are considered, the reduction of power system harmonics and improvement of power quality must be the goal.

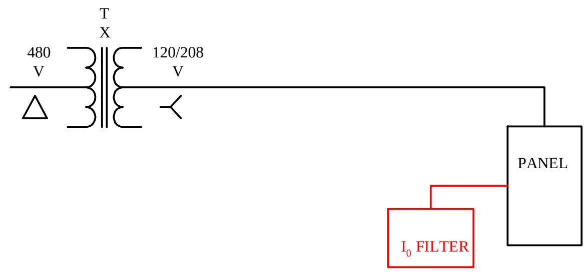
Since impeding harmonic currents will result in increased THD_V, the best tools at our disposal are the strategic reduction of zero-sequence impedances and the cancellation of positive- and negative-sequence harmonic currents.

ZERO-SEQUENCE HARMONIC FILTERS

As an alternative to the severe de-rating of conventional distribution transformers, the installation of K-Rated transformers and doubling the neutral conductor, the strategic application of a Zero-Sequence Harmonic Filter (I_0 Filter), as shown in *Figure 4*, will provide the following system benefits:

- Reduced Neutral Current
- Reduced Neutral-Ground Voltage (CMN)
- Reduced Peak Phase Current
- Reduced Average Phase Current
- Reduced Total Harmonic Distortion of Current (THD_I)
- Reduced Total Harmonic Distortion of Voltage (THD_V)
- Reduced Apparatus and Circuit Losses
- Reduced Overheating
- Increased True Power Factor
- Improved Protective Device Performance
- Reduced Errors in Power Metering
- Decreased Apparatus Vibration
- Improves Phase Current Balance
- Improves Phase Voltage Balance
- Carry Through Single-Phase Outage
- Decreased Telephone Interference Factor
- Normally, a Stand Alone Solution
- Cost Effective Solution

As shown in the *Figure 4* example, I_0 Filters are normally connected to a three-phase, four-wire panel that supplies single-phase, non-linear loads. As a parallel or shunt zero-sequence impedance of <0.005Ω (compared to ≤0.1Ω for a source transformer), the I_0 Filter will remove most of the zero sequence currents from the phase and neutral conductors.



The Application of a Zero Sequence Harmonic Filter
Fig. 4

The sizing of an I_0 Filter is ordinarily based on the capacity of the sub-system's ultimate level of non-linear loads to generate zero-sequence harmonic currents, rather than present levels or measured values. The formula for determining these ultimate values is as follows:

$$I_{0\ Max\ Neut} = I_{FL\ Max\ \varnothing} \times HF_0 \times LF \times 3$$

where:

- $I_{0\ Max\ Neut}$ - Maximum zero sequence harmonic current that could flow on the neutral conductor under the conditions defined by the Load Factor (LF).
- $I_{FL\ Max\ \varnothing}$ - Maximum fundamental current that will flow on the phase terminals at nameplate limits.
- HF_0 - Harmonic Factor for zero sequence harmonic current is the ratio of the root-sum-square (rss) value of all of the zero sequence harmonic currents to the root-means-square (rms) value of the fundamental [Note: Use HF_0 = 0.6 as a typical value rather than 0.8 which is the calculated value].
- LF - Load Factor is usually dictated by the requirements of the NEC (CEC in Canada). Since the source transformer is usually the load-limiting device, the LF is normally 80% of the transformers nameplate rating.
- 3 - This multiplier is required since the three maximum zero sequence harmonic phase currents ($I_{0\ Max\ \varnothing}$) add arithmetically at the X_0 Terminal of the distribution transformer and return to their source via the neutral conductor.

Multiple sub-system panels, supplying single-phase, non-linear loads, normally require the installation of an I_0Filter at each panel. The total required capacity of all filters is determined by the above formula ($I_{0\ Max\ Neut}$). The rating of each filter is normally based on the ratio of panel sizes or ultimate loads.

With reference to *Figure 4*, and using the formula, the calculated $I_{0\ Max\ Neut}$ values for standard transformer kVA ratings is given in *Figure 5*. These calculated values have been confirmed by numerous NETA members and power quality engineers.

TX kVA	$I_{0\ Max\ Neut}$ Amps
9	36
15	60
45	180
75	300
112.5	450
150	600
225	900
300	1200
500	2000

Maximum Zero Sequence Harmonic Currents
Fig. 5

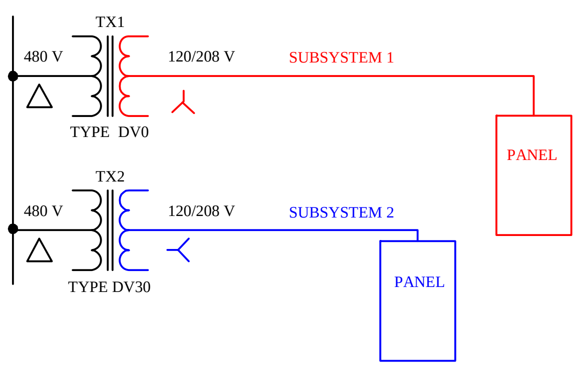
In addition to its capabilities as a third order, zero-sequence harmonic shunt, the I_0Filter also has the ability to balance three-phase positive- and negative-sequence harmonic currents in a four-wire sub-systems, including the fundamental currents. As a phase current balancer, it also functions to balance the phase voltages. These added benefits are of particular value when the I_0Filter is applied at a power distribution panel (PDU) that is supplied by an uninterruptable power supply (UPS). All benefits considered, I_0Filters normally add significant capacity to the UPS.

The application of an I_0 Filter(s) alone is normally sufficient to meet the recommendations of IEEE and CBEMA.

HARMONIC FILTERING TRANSFORMERS

As an alternative to the severe de-rating of conventional distribution transformers or the installation of K-Rated transformers, the application of Harmonic Filtering Transformers, as shown in *Figure 6*, will provide the following system benefits:

- Reduced Peak Phase Current
- Reduced Average Phase Current
- Reduced Total Harmonic Distortion of Current (THD_I)
- Reduced Total Harmonic Distortion of Voltage (THD_V)
- Reduced Apparatus and Circuit Losses
- Reduced Overheating
- Increased True Power Factor
- Improved Protective Device Performance
- Reduced Errors in Power Metering
- Decreased Apparatus Vibration
- Improved Phase Current Balance
- Improved Phase Voltage Balance
- Decreased Telephone Interference Factor
- Normally, a Stand Alone Solution
- Cost Effective Solution



The Application of Harmonic Filtering Transformers
Fig. 6

As shown in the Figure 6 example, multiple Harmonic Filtering Transformers (or a Harmonic Filtering Transformer in combination with an existing transformer and/or non-linear loads) can be connected to a common three-phase, three- or four-wire bus so that targeted positive- and negative-sequence harmonic currents are canceled.

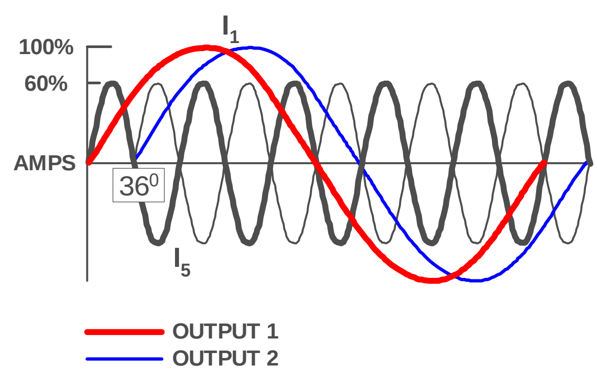
Targeted harmonic currents are canceled by phase-shifting one group of non-linear loads with reference to a second similar group of non-linear loads. The exact phase-shift angle, which is required to cause perfect cancellation of any particular harmonic current, under balanced conditions, is as follows:

$$\angle^{o} \text{ @ 60Hz} = \frac{180^{o} \text{ @ 60Hz}}{H}$$

where:

$\angle^{o}$ @ 60Hz - The angle in electrical degrees @ 60Hz which is required, between two separate sources of a particular harmonic current, in order to create a 180^{o} phase-shift at that harmonic frequency.

H - The harmonic number of the targeted harmonic frequency.



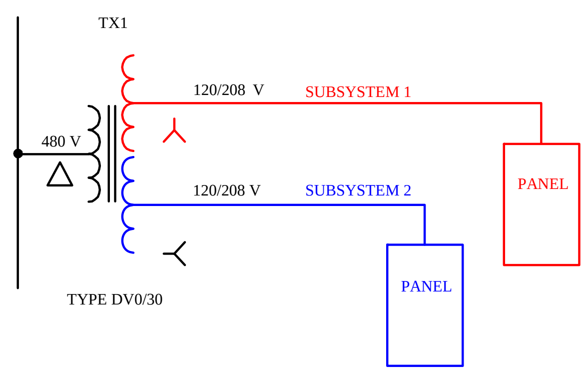
Two Sub-Systems Phase-Shifted by 36°
Fig. 7

The two fundamental (I_1) sinusoidal current waveforms, displayed in *Figure 7*, appear at the X_1 terminals of the two Harmonic Filtering Transformers which have a phase-shift angle of 36° between their secondary windings. The two 5th harmonic (I_5) sinusoidal current waveforms, in the same display, also appear at the X_1 terminals of same two Harmonic Filtering Transformers. The magnitudes of these current waveforms are as displayed in *Figure 2* for single-phase, non-linear loads.

With reference again to *Figure 7*, the two 5th harmonic (I_5) sinusoidal current waveforms are 180° out-of-phase at their frequency (300Hz). The I_5 currents will therefore cancel at a node that is equidistant from the harmonic sources (normally on the primary bus).

In order to achieve the maximum power quality benefit, it is normal practice to select the second-order, zero-sequence harmonic frequency that separates the pairs of positive- and negative-sequence harmonic currents to be cancellation. This method results in a very significant reduction of both targeted harmonic currents. For example, if the targeted frequencies were I_5 and I_7, the second-order, zero sequence harmonic frequency selected would be 6. The required angle is 30° (180°@ 60Hz / 6 = 30°). This angle equals 180°@300Hz.

With reference to *Figure 6*, the transformer designated as Type DZ has a primary-to-secondary phase-shift of 0° while the Type DV has a primary-to-secondary phase-shift of -30°.



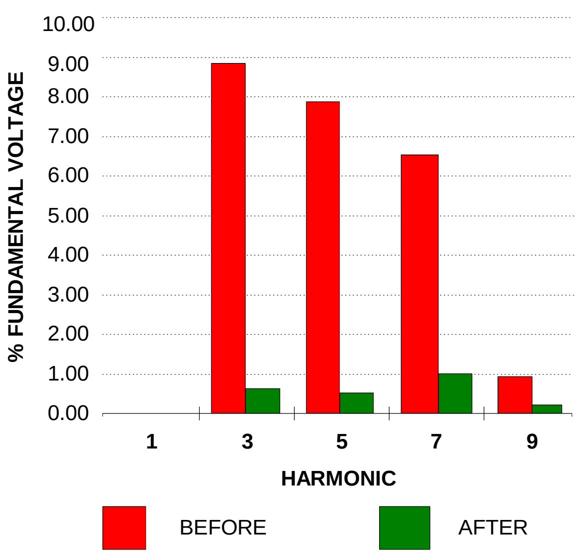
Application of Dual Output Transformer
Fig. 8

As shown in the *Figure 8* example, Dual Output Harmonic Filtering Transformers can be applied so that targeted positive- and negative-sequence harmonic currents are canceled.

Again, targeted harmonic currents are canceled by phase-shifting one group of non-linear loads with reference to a second similar group of non-linear loads. As before, it is normal practice to select the second-order, zero sequence harmonic frequency that separates the pairs of positive and negative sequence harmonic currents to be cancellation.

With reference to *Figure 8*, the Type DZV has a primary to secondary phase-shift of both 0° (Z) and -30° (V).

In addition to the phase-shifting techniques described in this section, all of the special transformers described in this section have zero-sequence impedances of <0.0005Ω (compared to ≤0.1Ω for a conventional distribution or K-Rated transformer). As a result, these Harmonic Filtering Transformers will not generate any significant amount of zero-sequence harmonic voltage. In addition, these transformers will act as phase current balancers at the primary bus.



Harmonic Voltage Profiles for Non-Linear Loads with Harmonic Filtering Transformers
Fig. 9

As a result of these harmonic current mitigating techniques, THD_V levels are significantly reduced in both the primary and secondary systems. The THD_V reductions displayed in *Figure 9* are typical when conventional or K-Rated distribution transformers are replaced with Harmonic Mitigating Transformers.

V. Conclusion

Power quality improvements, related to harmonics, can only be achieved by reducing harmonic currents in electrical power systems.

The application of ***I_0Filter***™ - Zero Sequence Harmonic Filters and ***Distribution TransFilter***™ are preferred alternatives to the 'band-aid' approach offered by conventional or K-Rated distribution transformers. These specialized harmonic mitigating transformers are high quality, passive electromagnetic devices, which provide an appropriate series or shunt impedance to targeted harmonic currents.

Unlike conventional and K-Rated transformers, PQI HarMitigators create an attractive payback by reducing power system losses and improving power factor.

References

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[2] R. Zavadil, et al, "*Analysis of Harmonic Distortion Levels in Commercial Buildings,*" Proceedings, First International Conference on Power Quality, PQA 1991.

[3] Personal Computer - Micron Pentium 75

$1.8A_{RMS}$	56.1% $THD_{I\ RMS}$
$4.5A_{Peak}$	67.9% $THD_{I\ Fund}$
2.5 Crest Factor	0.83 True PF
$1.0A_{h\ RMS}$	1.00 Disp PF

[4] IEEE P519A/D5-May 4, 1996 "*Guide for Applying Harmonic Limits on Power Systems*", Section 6.1 (p 59)

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