

Improving the Efficiency of an Electrical Distribution System and its Loads Reduces Energy Costs

Much has already been done to save electrical energy and reduce utility costs. Early on, inefficient load replacement and load management were seen as 'low hanging fruit'. The question is, are there any unclaimed 'gold nuggets' remaining?

Energy Services Companies provide the expertise to bring building and industrial systems to peak efficiency. This often includes the replacement of inefficient low voltage distribution transformers and occasionally the replacement of customer-owned medium voltage power transformers.

Beyond the savings typically achieved, PQI has succeeded in further reducing utility costs by reducing the Penalty Losses in the electrical distribution system and their loads. This is the wasted energy you may not have thought about – the valuable unclaimed 'gold nuggets'.

What are Penalty Losses? – Penalty Losses are defined as consumed power that does not contribute directly to the intended work. (Unavoidable distribution system and load losses at 60Hz are not considered as Penalty Losses.)

PENALTY LOSSES IN THE DISTRIBUTION SYSTEM'S CIRCUITS

What causes Penalty Losses in Distribution System Circuits? – A distribution system's circuit Penalty Losses include losses due to reactive load currents, unbalanced load currents, nonlinear load-generated harmonic currents and neutral currents.

More than ten years ago, the IEEE Power Quality Standards Committee began an assessment of the academic work necessary to accurately segment and quantify Penalty Losses in electrical distribution systems. They knew that there were gaps in the mathematical models underlying classical three-phase power measurement and calculations. In particular, the effects of reactive, load unbalance, harmonic and neutral currents were never considered.

Harmonic distortion and load unbalance were viewed as imperfections in the purity of power that caused equipment performance issues, and that power factor diminished the capacity of the distribution system. Quantifying the wasted power had never been considered. Harmonics and unbalance were troubleshooting concerns, not energy consumption issues. That is, until energy became a premium commodity.

Now we can measure Penalty Losses in a circuit. The Fluke Model 435, Series 2 Analyzer's Unified Power Measurement System uses a combination of classical IEEE 1458 and the University of Valencia's mathematical equations to express power and energy measurements that directly quantify the wasted energy in electrical circuits.

This system measures Penalty Losses due to reactive load currents, unbalanced load currents, load-generated harmonic currents and neutral currents. By factoring in circuit information and utility rates, it also estimates the cost of this wasted energy.

Although it would be impractical to simultaneously or randomly measure every circuit in a distribution system, sample measurements offer an insight into the magnitude of Penalty Losses in circuits under any loading scenarios.

The magnitude of energy savings becomes obvious after completing a third-party measurement and verification on an energy efficiency improvement project that mitigates these Penalty Losses.

Energy Loss Calculator				
	Total	Loss	Cost	
Effective kW	47.3	W 904	\$ 90.37	/hr
Reactive kvar	3.43	W 4.7	\$ 0.47	/hr
Unbalance kVA	20.4	W 164	\$ 16.44	/hr
Distortion kVA	1.59	W 1.5	\$ 0.15	/hr
Neutral A	45.4	W 138	\$ 13.82	/hr
Total		M	\$ 1.06	/y

21/11/11	13:48:06	230V	50Hz	3Ø	WYE	EN50160
LENGTH	DIAMETER	METER	RATE	HOLD		
100 m	25 mm ²		0.10 /kWh	RUN		

Fluke Model 435, Series 2 Measurements
Figure 1

With reference to *Figure 1*, the most significant Penalty Losses in this example are those assigned to the Unbalance and Neutral currents. However, the Total Penalty Losses in the circuit equal 308.2 watts (= 4.7W + 164W + 1.5W + 138W). This outcome is not unusual when an unbalanced feeder circuit is supplying phase-to-neutral connected nonlinear loads.

Please note that the 47.3kW Effective load, has circuit losses of 904W. These losses, which equal 1.9% $([904 \times 100] / 47,300)$ of the Effective load, are unavoidable 60Hz circuit losses, which, by definition, do not qualify as Penalty Losses. The annual cost of this circuit's Penalty Losses is \$270,508.80 (= \$1,062,150.00 – $[\$90.37 \times 24\text{hr}/\text{day} \times 365\text{days}/\text{year}]$).

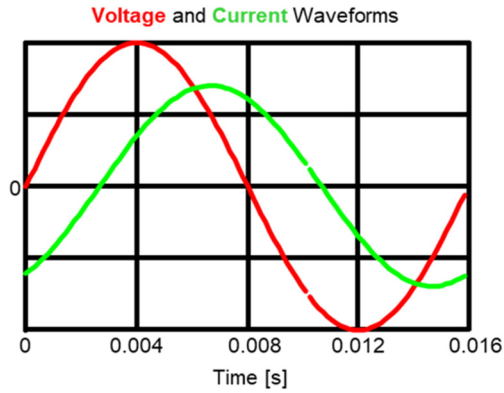
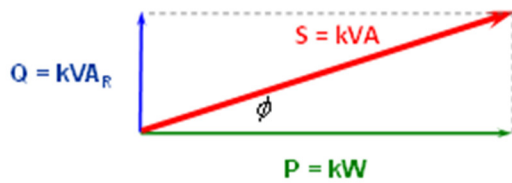


Figure 2

What is the Inductive Load Problem? – With reference to Figure 2, if a linear load is inductive, such as a motor, the current's sinusoidal waveform will lag the voltage's sinusoidal waveform in time. If current lags voltage, the inductive load has created a lagging Displacement Power Factor condition.



Displacement Power Factor under Linear Loading
Figure 3

With reference to the Power Triangle found in Figure 3, an inductive load not only consumes Power in watts, but Q or volt-amperes reactive. Since it is current that creates I²R losses, the losses produced by the current component of volt-amperes reactive must be considered as Penalty Losses.

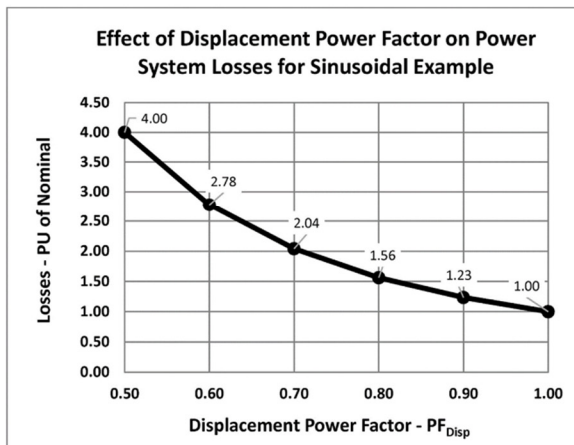


Figure 4^[1]

To further demonstrate the relationship between Displacement Power Factor and distribution system Penalty Losses, the graph found in Figure 4 shows us that at Unity PF (1.00) the system is free of Penalty Losses. That is, the 1.00 pu losses represents the unavoidable I²R 60Hz losses. However, as PF_{DISP} increases, so do Penalty Losses. For example, with a Displacement Power Factor (PF_{DISP}) of 0.70, the Penalty Losses have more than doubled to 2.04 the unavoidable 60Hz losses.

What is the Inductive Load Solution? – The best technical solution to this problem is the application of a suitably rated capacitor bank, an alternative source of volt-amperes reactive, at or near the inductive load. This approach will eliminate the Penalty Losses between its point of application and the source of power.

In addition to eliminating Penalty Losses, this mitigation plan, if applied to sufficient inductive loads, will also contribute to the reduction or elimination of a utility-imposed Power Factor penalty.

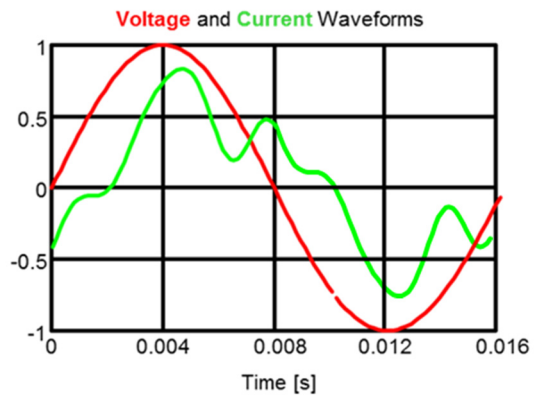


Figure 5

What is the nonlinear load problem? – With reference to Figure 5, if an alternating sinusoidal voltage is applied to a nonlinear electronic load, such as a rectifier, motor drive or switch-mode power supply, the resulting current waveform will be distorted. This distortion is produced by the imposition of load-generated harmonic currents, which are integer multiples of the fundamental frequency. In virtually all cases, the distorted current waveform will lag the voltage waveform in time. If current lags voltage, the nonlinear load has created a lagging Distortion Power Factor (PF_{DIST}) condition.

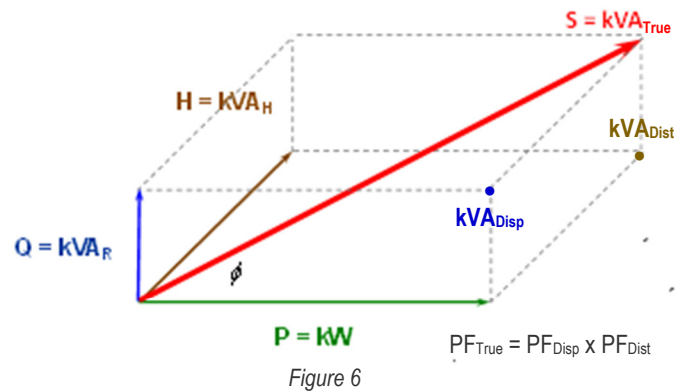


Figure 6

With reference to Figure 6 and the three-dimensional vector diagram, a nonlinear electronic load consumes not only Power in watts, but H or volt-amperes harmonic. A nonlinear load imposes harmonic currents on the electrical distribution system. Again, since it is current that creates I²R losses, the losses produced by the current component of volt-amperes harmonic must be considered as Penalty Losses. This vector diagram displays a more complex condition where both inductive and nonlinear loads contribute to the reduction of True PF and an increase in Penalty Losses.

To further demonstrate the relationship between Displacement, Distortion and True Power Factors, and Distribution System Penalty Losses, please refer to the graphs found in Figure 7.

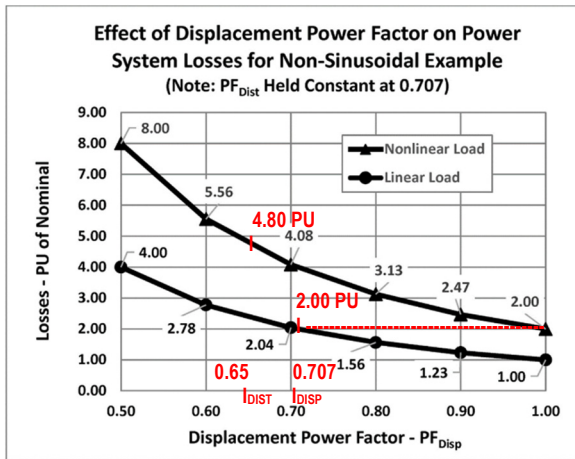


Figure 7 [1]

As in Figure 4, the lower Linear Load curve shown here represents the relationship between PF_{DISP} and Penalty Losses in PU of Normal (being the unavoidable 60Hz losses), whereas the upper Nonlinear Load curve represents the relationship between PF_{DISP} and Penalty Losses. In this example PF_{DISP} is 0.707 and PF_{DIST} is 0.65. To determine the combined inductive and harmonic Penalty Losses PU multiplier, the upper Nonlinear Load curve must be raised from a multiplier of 1.00 at unity PF, which would be its position in the absence of inductive loading, to 2.00 at unity PF. This point is derived from the 0.707 PF_{DISP} intersection with the lower Linear Load curve. The intersection of 0.65 PF_{DIST} and the Nonlinear Load curve gives us the combined Losses in PU of Normal multiplies of 4.80 PU. The 'penalty losses' are therefore 4.8 times higher than the unavoidable 60Hz losses. Under this rather extreme loading condition, PF_{TRUE} is only 0.4596 lagging ($TP_{TRUE} = PF_{DISP} \times PF_{DIST}$).

It is important to understand that the Nonlinear Load curve shown in this example is harmonic current profile dependent. That is, any variation in the magnitude of positive-, negative- and/or zero-sequence harmonic currents will adjust its shape and Losses – PU multiplier outcome.

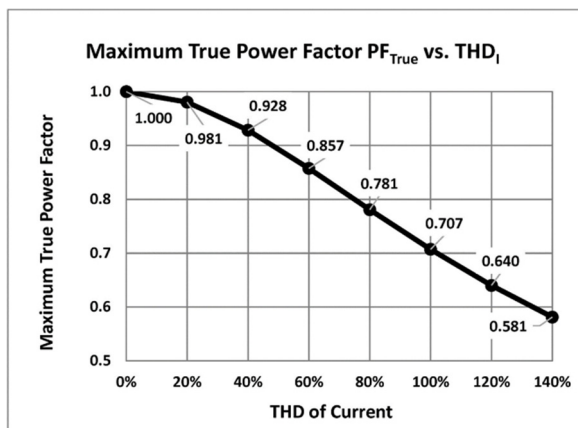


Figure 8 [1]

With reference to Figure 8, it is useful to see how Total Harmonic Distortion of Current effects Power Factor. Again, the curve is harmonic current profile dependent.

What is the nonlinear load solution? – The best technical solution for this condition is the application of a harmonic mitigating device, such as a series reactor, passive or active harmonic filter, or harmonic mitigating transformer (HMT), at or near the nonlinear load(s). This approach will

reduce or eliminate the Penalty Losses from its point of its application back to the power source. In addition to eliminating the Penalty Losses, this mitigation plan, if applied to sufficient nonlinear loads, will also contribute to the reduction or elimination of a utility-imposed Power Factor penalty.

The wrong nonlinear load solution – Unfortunately, capacitor banks are often used to correct True Power Factor problems in a nonlinear load environment. In reality, most facilities have both linear inductive and nonlinear harmonic current-generating loads, each contributing to the True Power Factor problem. However, in modern public buildings, the effect of nonlinear electronic loads is usually far greater than inductive loads. That is, kVA_H is typically greater than kVA_R . The vector diagram found in Figure 6 displays this complex condition.

On examination it becomes clear that if one calculates True Power Factor based on P kW divided by S kVA, while ignoring kVA_H , the resultant calculated rating of the proposed capacitor bank(s) would be far larger than required by the vector's kVA_R value. The oversized capacitor would actually cause the angle ϕ and S kVA to increase and True Power Factor to decrease.

In addition, in a nonlinear environment, the application of a capacitor bank, without first implementing a harmonic mitigation plan that significantly reduces kVA_H and voltage distortion (THD_V), will often result in several of the following undesirable outcomes:

- The overloaded capacitor bank's protective device may remove the capacitor bank from service
- The overloaded capacitor bank may fail before its protective device can remove it from service
- Harmonic current and voltage amplification may occur, due to resonance at a particular harmonic frequency
- System apparatus and/or load insulation systems may fail, due to high harmonic voltages and dV/dT stresses.

PENALTY LOSSES IN THE DISTRIBUTION SYSTEM'S LOADS

What causes Penalty Losses in the Loads? – Load Penalty Losses include losses due to distortion of the supply voltages' sinusoidal waveforms. Load Penalty Losses also include losses due to low voltage, when the loads are electronic.

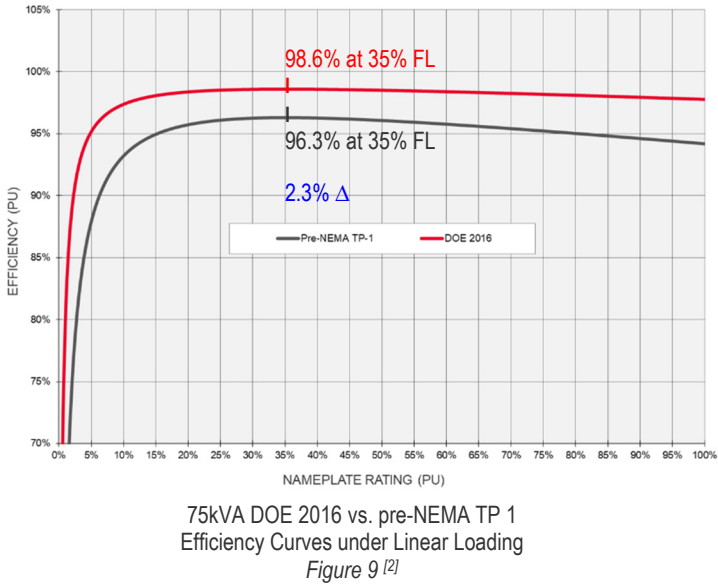
In an Ohms Law relationship with the distribution system's harmonic impedances, harmonic currents generate harmonic voltages that distort the fundamental voltage. IEEE Standard 519-1992 recommends a 5% total harmonic distortion of voltage (THD_V) limit at the distribution system's loads. It is important to understand that an electrical or electronic load manufacturer's published energy efficiency is based on supplying their device with an undistorted sinusoidal voltage waveform(s).

Supplying a nonlinear electronic load with distorted voltage will increase the load's internal losses and decrease its energy efficiency.^[3, 4, 5] However, supplying a linear load with distorted voltage(s) will not only increase its Penalty Losses and decrease its efficiency, but will cause the linear load to also impose harmonic currents on the distribution system. In this scenario, its current distortion must equal the voltage distortion ($\%THD_I = \%THD_V$). In either case, energy efficiency and performance are diminished as voltage distortion increases.

What is The Voltage Distortion Solution? – Implementation of a Penalty Loss Solution will resolve the load efficiency problems.

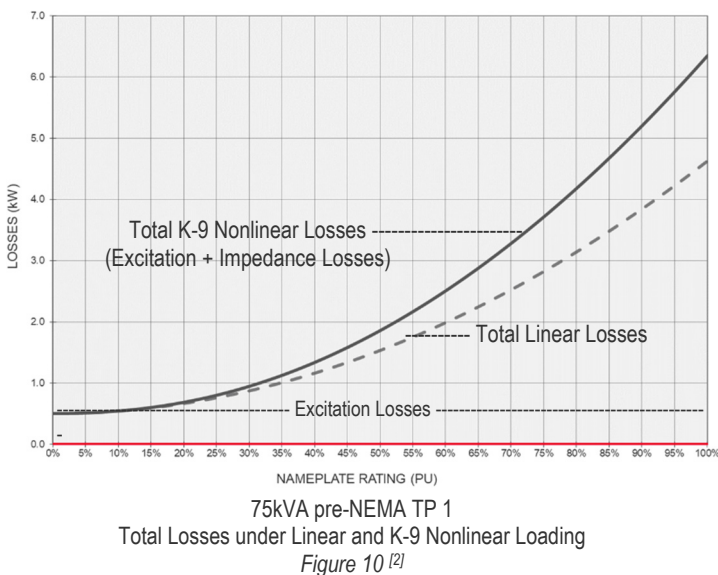
PENALTY LOSSES IN THE TRANSFORMER

What is a Transformer's Base-Line Efficiency Problem? – Most distribution transformers found in existing buildings were installed before the US Department of Energy implemented NEMA TP 1 as a national minimum efficiency standard in 2007. Before 2007, without a mandate to do otherwise, most transformer selections were based on 'first cost', not high energy efficiency. The lowest cost transformers were typically less efficient.



The efficiency curves shown in *Figure 9* represent two 75kVA distribution transformers, one with DOE 2016 efficiency, the other with typical pre-NEMA TP1 efficiency. The pre-NEMA TP1 curve shown is based on typical Excitation and Impedance Losses found in CSA C802.5, Annex A, Historical (pre-NEMA TP 1) Losses.

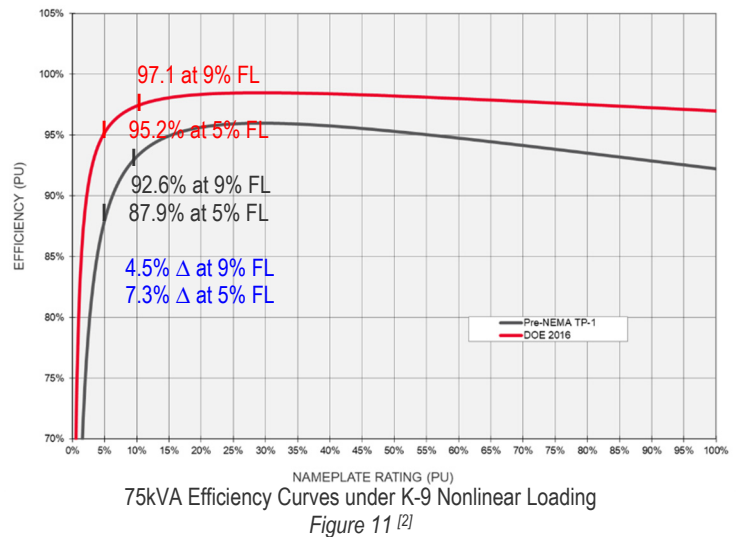
Based on a 35% linear load, which is the standards' required efficiency determination load, the DOE 2016 efficiency is 98.6% while the pre-NEMA TP 1 is only 96.3%, a 2.3% difference.



What is a Transformer's Harmonic Related Energy Efficiency Problem? – The efficiency of a distribution transformer is based on the

measurement of Total Losses (Excitation Losses plus Impedance Losses) at 35% of the transformer's full load rating. These measurements determine the Linear Load efficiency at 35% FL. However, the 'real world' loads supplied by distribution transformers are almost exclusively nonlinear. The Total Losses curves shown in *Figure 10* represent a 75kVA pre-NEMA TP 1 distribution transformer under both linear and K-9 nonlinear loading. As the K-Factor increases, the Total Nonlinear Losses increase. These curves are based on typical pre-NEMA TP 1 No-Load and linear Load Losses found in CSA C802.5, Annex A, Historical Losses.

Please note that the Excitation Losses are uniform from no-load to full load and are unaffected by the transformer's nonlinear loads. Excitation losses can only be affected by severe voltage distortion at its line-side primary terminals (which rarely happens).



The motivation to replace an existing transformer is usually based on its questionable reliability and/or a need to reduce energy consumption and utility costs.

A Load Factor survey, undertaken by The Cadmus Group Inc. in 1999, found that the average loading of low voltage, dry-type distribution transformers in commercial, industrial and public buildings was 17% of their full load ratings. More recent surveys have shown much lower Load Factors, the result of upgrading to more energy efficient loads.

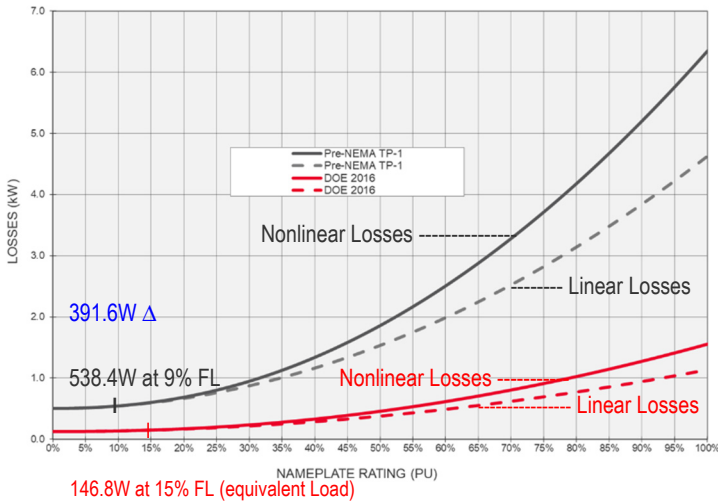
The efficiency curves shown in *Figure 11* represent a 75kVA Harmonic Mitigating Transformer, with DOE 2016 efficiency and zero-sequence flux cancellation, and a conventional 75kVA distribution transformer with typical pre-NEMA TP 1 efficiency. In this case, however, the transformers have been subjected to a K-9 nonlinear load.

Based on a 9% FL nonlinear load, the DOE 2016 transformer's efficiency is 97.1%, while the pre-NEMA TP 1 is only 92.6%, a 4.5% difference. Similarly, at a 5% FL nonlinear load, the DOE 2016 efficiency is 95.2%, while the pre-NEMA TP 1 is only 87.9%, a 7.3% difference.

By simply replacing the pre-NEMA TP 1 transformer with a DOE 2016 HMT with the same kVA rating, the reduction in energy cost would be 4.5% at 9% FL and 7.3% at 5% FL. At any other load, the savings would also be significant.

The motivation to replace existing transformers may also include a need to improve power quality and optimize the reduction of energy consumption and utility costs.

Based again on the Load Factor survey undertaken by The Cadmus Group, the higher Excitation Losses and lower Efficiencies of a 75kVA pre-NEMA TP 1 transformer, compared to a 45kVA DOE 2016 HMT, particularly at low Load Factors, provides an even greater opportunity to save energy and reduce utility costs.

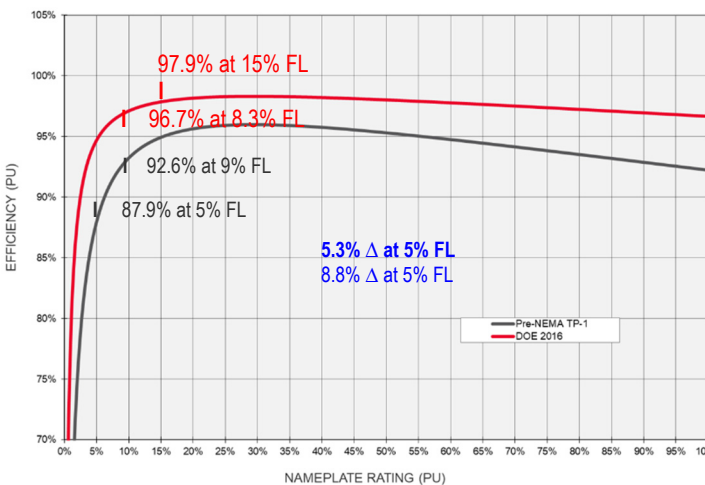


75kVA Pre-NEMA TP 1 vs. 45kVA DOE 2016 Total Losses under K-9 Nonlinear Loading
Figure 12 [2]

To maximize energy conservation, the optimum transformer kVA rating can be determined by referring to the CSA C802.4 guide for kVA sizing of dry-type transformers or the nationalgrid® transformer replacement program recommendation for low voltage dry-type transformers.

The examples given in Figure 11 show Total Losses at 5%FL and 9%FL. At these load levels the CSA C802.4 guide or nationalgrid®'s recommendations could be used to downsize several standard kVA ratings. However, to avoid the high cost of replacing protective devices and cables, reducing the rating by only one size, from 75kVA to 45kVA, would probably yield the most attractive financial outcome.

With this in mind, the Total Losses Curves shown in Figure 12 represent the 75kVA pre-NEMA TP 1 distribution transformer and a 45kVA Distribution TransFilter (PQI's HMT with base DOE 2016 efficiency). At 9% FL, the 75kVA transformer's Total Losses are 538.4W compared to the 45kVA unit's Total Losses of only 146.8W, a reduction of 72.7%.



75kVA Pre-NEMA TP 1 vs. 45kVA DOE 2016 Efficiencies under K-9 Nonlinear Loading
Figure 13 [2]

The Total Losses given in Figure 12 produce the nonlinear load efficiency outcomes shown in Figure 13. With an energy efficiency differential of 5.3%, the kWh cost of supporting this 6.75kVA (0.09 x 75kVA or 0.015 x 45kVA) load would be reduced by 5.3%.

Alternatively, if the load on the 75kVA transformer was only 5%, the equivalent load on the 45kVA unit would be 8.3%. The kWh cost of supporting this 3.75kVA (0.5 x 75kVA or 0.083 x 45kVA) load would be reduced by 8.3%.

A CLOSER LOOK AT HARMONIC CURRENTS

Single-Phase Nonlinear Load Problems – Let's take a closer look at the harmonic problem when single-phase nonlinear loads are connected phase-to-neutral in three-phase four-wire systems.

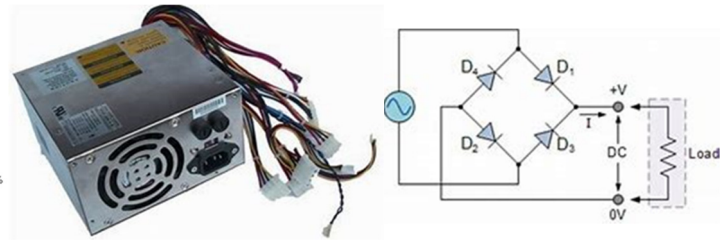


Figure 14

The overwhelming majority of 120-volt loads, supplied by 208/120-volt three-phase, four-wire distribution systems, are switch-mode power supplies, as shown in Figure 14. These small power supplies are the front-ends of almost all 120-volt loads in modern public buildings. These loads include communications systems, computers, monitors, printers, scanners, facsimile machines and virtually all lighting systems, including LEDs. Except for the refrigerator in the cafeteria (which may also include a switch-mode power supply for its control logic) and the water cooler, virtually all loads supplied by a distribution transformer are nonlinear.

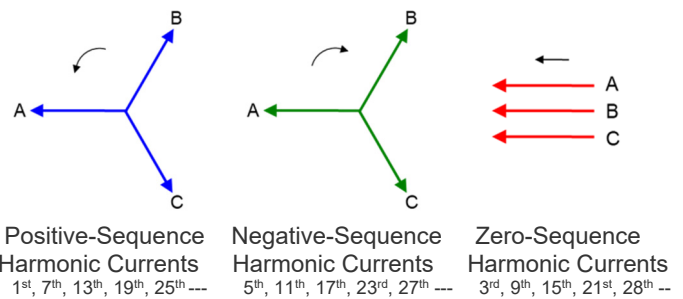


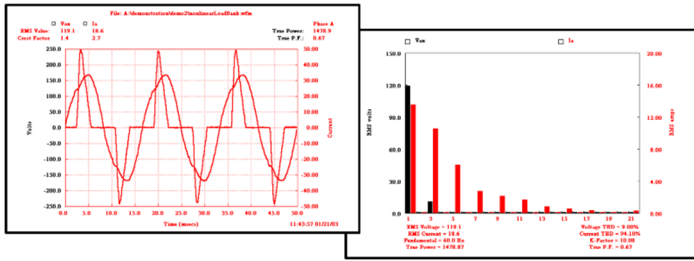
Figure 15

With reference to the vector diagrams shown in Figure 15, harmonic currents produced by switch-mode power supplies divide into three groups; positive-sequence, with the same rotational sequence as the fundamental 60Hz frequency, and negative-sequence, with a reversed rotational sequence.

The rotational speed of each positive- or negative-sequence harmonic is governed by its harmonic number. For example, the 5th harmonic rotates five times faster than the fundamental frequency but in the reverse direction.

Unlike the first two groups, the third-order zero-sequence harmonic phase currents are in-phase. As a result, they add

arithmetically on the system's neutral. Zero-sequence currents can only occur when the nonlinear loads are connected phase-to-neutral in a three-phase, four-wire distribution system.

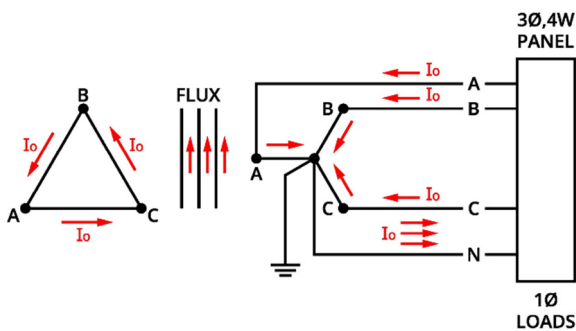


Phase-to-Neutral Connected Switch-Mode Power Supply's Harmonic Current Profile
Figure 16

The site measurement values in Figure 16 are for an individual switch-mode power supply. In this sample the total harmonic distortion of current is 94.1%. The 3rd zero-sequence harmonic current is approximately 83% of the fundamental current magnitude. Its True Power Factor is 0.67 lagging. The grossly distorted current waveform shown here is typical for a modern switch-mode power supply. This can be confirmed by measuring the harmonic current profile of your notebook computer with a harmonic analyzer or plugging it into PQI's Type TPM Demonstration Meter.

The Total Harmonic Distortion of Current measured at the secondary terminals of a distribution transformer will be reduced, since the individual switch-mode power supplies are not synchronized; that is, their currents will not begin to flow in each half-cycle at exactly the same instant in time. Nevertheless, zero-sequence phase currents will add arithmetically on the system's neutral conductor to create significant Penalty Losses.

IEEE 519-1992, Table 4.3 Spectrum of Typical Switch Mode Power Supply			
Harmonic	Magnitude	Harmonic	Magnitude
1	1.000	9	0.157
3	0.810	11	0.024
5	0.810	13	0.063
7	0.370	15	0.079



A Conventional Delta-Wye Connected Transformer
Figure 17

Load-generated zero-sequence harmonic currents create a number of serious safety, power quality, energy efficiency and operational problems.

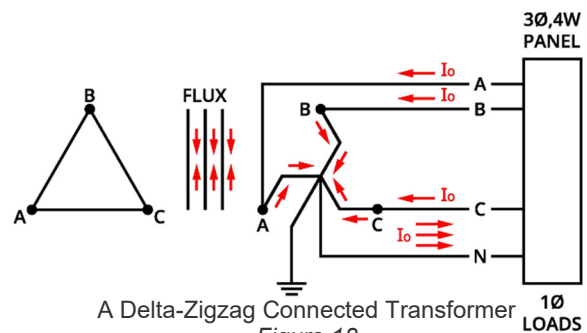
With reference to Figure 17:

Problem #1 – Because zero-sequence currents on the three phases of the distribution system are in-phase, they add up arithmetically at the distribution transformer's neutral. As a result, neutral currents may exceed phase currents, a possible fire and safety issue in older distribution systems with undersized neutral conductors.

Problem #2 – The high value zero-sequence currents imposed on the secondary windings of the distribution transformer will generate zero-sequence flux in the three-phase magnetic core and zero-sequence currents in the delta-connected primary windings. Zero-sequence harmonic currents increase the transformer's Impedance (Load) Losses and reduce its energy efficiency.

Problem #3 – In an Ohms Law relationship with the load-generated zero-sequence currents, the zero-sequence impedance of a delta-wye connected transformer will produce high levels of zero-sequence voltage and voltage distortion at the transformer's loads. 'Flat topping' of the voltage waveform is common. This outcome will elevate the loads' internal Penalty Losses and reduce their efficiencies.

Problem #4 – Because the system neutral is grounded at the distribution transformer's neutral (X_0) terminal (an NEC requirement), in an Ohms Law relationship with the neutral circuit's harmonic impedances, zero-sequence currents produce zero-sequence voltages between neutral and ground at the nonlinear loads. The Information Technology Industrial Council (ITIC) recommends a 5-volt limit. International Gaming Technology (IGT), the largest manufacturer of gaming machines in the world, requires a 4-volt limit. Without harmonic mitigation, these levels are normally exceeded.



A Delta-Zigzag Connected Transformer
Figure 18

The Zero-Sequence Harmonic Solution – Unlike the power quality and energy efficiency problems inherent in a conventional delta-wye winding configuration, PQI's Type DV delta-zigzag winding configuration, shown in Figure 18, has several significant advantages. The load-generated, zero-sequence currents in the secondary windings will not produce zero-sequence flux in the magnetic core or zero-sequence currents in the primary delta-connected winding.

This achievement can be confirmed by tracing the path and direction of the zero-sequence currents flowing through the pairs of secondary windings on each core leg. Because the zero-sequence currents flow in each core leg pair are 180° out-of-phase, the zero-sequence flux generated by each pair of coils will be 180° out-of-phase. The result is zero-sequence flux cancellation.

For clarity, *Figure 19* details the Type DV transformer's three-legged magnetic core and zigzag connected secondary windings, as shown in *Figure 18*. Each of the six coils has the same number of turns and is wound in the same direction.

Unlike the three 60Hz phase currents, which are progressively 120° out-of-phase, the zero-sequence currents imposed on the three phases at A, B & C are 'in phase'.

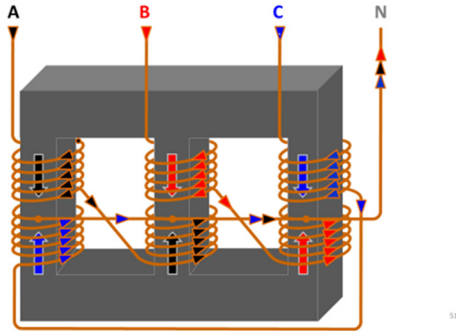


Figure 19

If we consider the first positive half-cycle of any zero-sequence harmonic current, the direction of the magnetic flux it produces in the upper coils will be in the downward direction. Since the bottom of each upper coil is connected to the bottom of each lower coil on an adjacent core leg, the zero-sequence flux generated by each pair of coils on the same core leg will be 180° out-of-phase. As a result, the zero-sequence currents will not produce zero-sequence magnetic flux in their core leg and zero-sequence current will not be induced in the primary delta-connected windings.

In addition, the zigzag winding will act as an ultra-low impedance short-circuit for all zero-sequence harmonic currents. The zero-sequence impedance of this winding configuration is approximately 20 – 50 times lower than a conventional delta-wye transformer.

What are the benefits?

1. The zigzag winding configuration eliminates zero-sequence flux in the magnetic core. This design feature reduces core losses.
2. The elimination of zero-sequence magnetic flux in the core will eliminate zero-sequence currents in the primary delta-connected winding. These benefits reduce the transformer's load losses.

3. With the reduction of zero-sequence impedance, zero-sequence voltage and voltage distortion at the loads will be substantially reduced to less than 5%, an IEEE 519 recommendation. This outcome will reduce the loads' Penalty Losses, making them significantly more energy efficient.

As stated, PQI's other proprietary secondary winding designs also provide complete zero-sequence flux cancellation at any required primary-to-secondary phase-shift, while preserving the delta-connected primary winding.

The Positive- & Negative-Sequence Harmonic Solution

– Targeted positive- and negative-sequence harmonic currents can be cancelled by phase-shifting one group of nonlinear loads against a similar group of nonlinear loads, which are supplied by the same primary bus. The exact phase-shift that is required to cause perfect cancellation of a particular harmonic current, under balanced harmonic loading conditions, is shown in this simple formula:

$$\text{Required Phase-Shift @ 60Hz} = 180^\circ @ 60\text{Hz} / H$$

$$\text{Example: } 180^\circ @ 60\text{Hz} / 5\text{th} = 36^\circ @ 60\text{Hz} = 180^\circ @ 300\text{Hz}$$

where:

H is the number of the targeted harmonic frequency (i.e. the 5th)

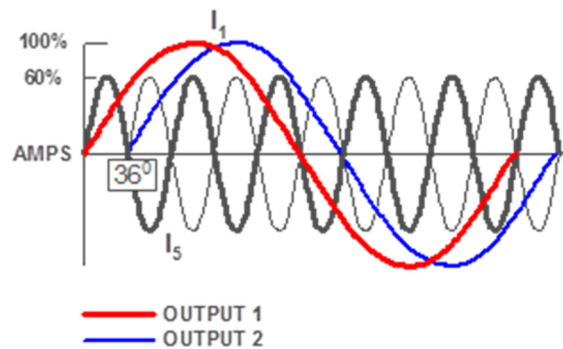


Figure 20

With reference to *Figure 20*, to display this concept visually, the two 60Hz sinusoidal current waveforms (red & blue) appear at the X1 terminals of two Harmonic Mitigating Transformers, which have a phase-shift difference of 36° between their secondary windings. The two 5th harmonic sinusoidal current waveforms (dark & light grey) also appear at the X1 terminals. Notice that these waveforms are 180° out-of-phase and, as a result, will cancel at a node on the transformers' common primary bus.

Since positive- and negative-sequence harmonic currents appear in pairs (i.e. 5/7, 11/13, 17/19, ---), it is common practice to substitute the even harmonic that separates a targeted negative- and positive-sequence pair. For example, if the 5th and 7th are the targeted harmonic currents, then 'H', in the formula would be the 6th and the required phase-shift would be 30°.

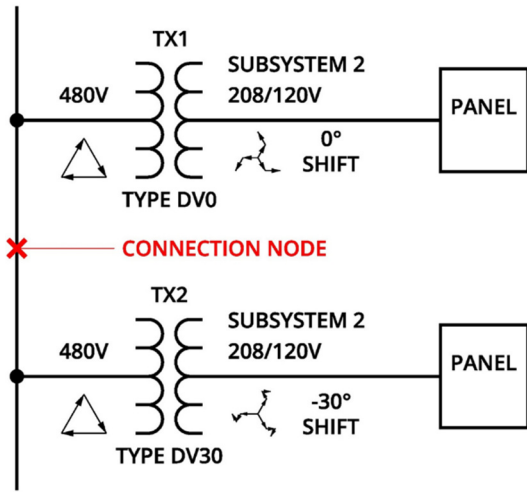


Figure 21

With reference to *Figure 21*, the required phase-shift can be accomplished using two Type DV harmonic mitigating transformers with appropriate primary-to-secondary phase-shifts. In this example, the upper transformer has a primary-to-secondary phase-shift of 0° .

The lower transformer has a primary-to-secondary phase-shift of -30° . This transformer's more complex proprietary zero-sequence flux cancellation winding requires a coil on all three core legs to create the -30° phase-shift. PQI's proprietary flux cancellation designs allow it to create any delta primary-to-secondary phase-shift with full zero-sequence flux cancellation.

As you may know, all PQI competitors offer only two options, a delta-zigzag configuration, which produces a 0° shift, and a wye-zigzag configuration, which produces a $+30^\circ$ shift. There are two significant issues with the wye-zigzag configuration. Without the benefit of the delta primary winding, when the load-generated zero-sequence phase currents are unbalanced, the transformer's zero-sequence impedance increases proportionately.

Unlike PQI's competitors' products that can only create twelve-pulse outcomes, PQI's standard products can also be used to create eighteen-, twenty-four-, thirty-six- and forty-eight-pulse systems. For example, if a four-story building had a transformer on each floor, one could select four phase shifts; 0° , -15° , -30° & -45° . This would create a twenty-four-pulse rather than a six-pulse riser, significantly reducing current distortion, I^2R Penalty Losses and improving power factor.

As an alternative to the two-transformer solution, a transformer with probably less than twice the kVA rating and two phase-shifted secondary windings could be used. This alternative creates three additional benefits:

1. The cost of the dual output transformer is lower than the cost of two single output transformers.
2. This alternative eliminates one primary protective device.
3. The dual output transformer's cancellation node is within the auto-connected secondary winding, rather

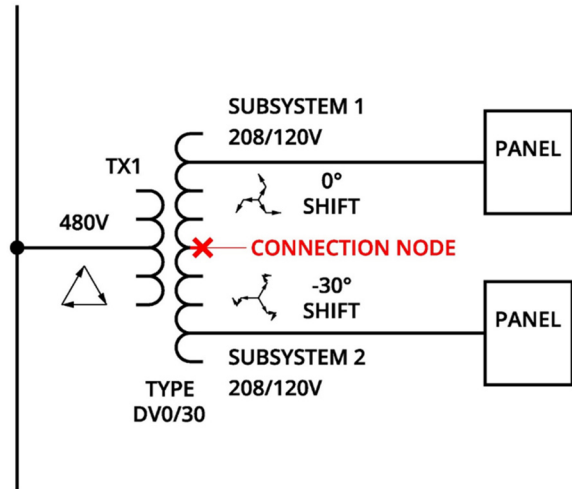


Figure 22

than at the common primary bus. This method substantially lowers the impedance of the cancellation node, resulting in lower voltage distortion at the loads.



Type DV Distribution TransFilter™
Figure 23

Type DV Distribution TransFilters™ are ultra-efficient, low voltage, dry-type, harmonic mitigating isolation transformers that have been specifically designed to mitigate the energy efficiency and power quality problems produced by phase-to-neutral connected switch-mode power supply loads.

The Type DV Distribution TransFilter shown here is equipped with PQI's Type TPM Transformer Performance Meter. This powerful system analyzer is available at little or no additional cost.

Product Sheets and Application Guides for the Type DV Distribution TransFilter and the Type TPM Transformer Performance Meter are available upon request.

Three-Phase Nonlinear Load Problem – Let's take a closer look at the harmonic problem when three-phase nonlinear loads are connected to a three-phase, three- or four-wire system.



Figure 24

The majority of motors in commercial, industrial and public buildings are now controlled by motor drives, supplied by three- or four-wire distribution systems.

With reference to the vector diagrams shown in Figure 25, harmonic currents, produced by AC or DC motor drives or any other type of three-phase nonlinear load, divide into two groups; positive- and negative-sequence. Their rotational sequences and rotational speeds are as given earlier.

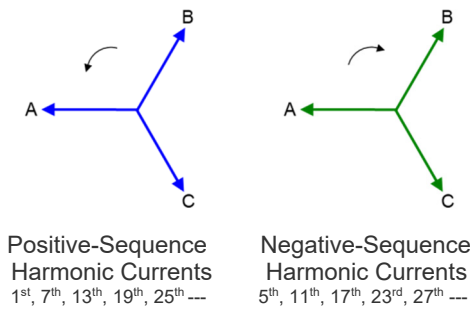


Figure 25

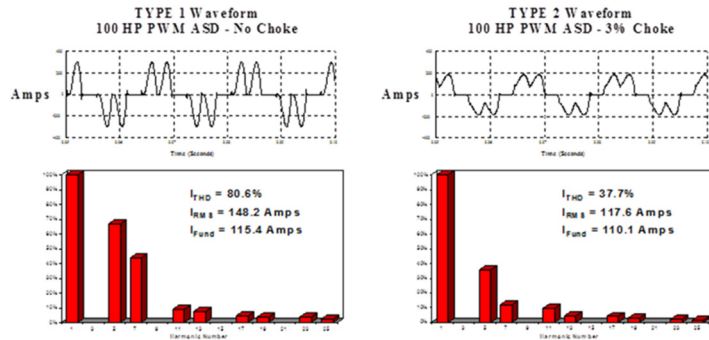


Figure 26

The measurement values shown in Figure 26 are for a 100HP six-pulse AC motor drive. The current waveform and measurements on the left side exclude any harmonic mitigation. As a result, $THD_I = 80.6\%$, $I_{RMS} = 148.2A$ and $I_{60Hz} = 115.4A$.

The current waveform and measurements on the right side represent the same motor drive that now includes a 3% choke or reactor. In this case $THD_I = 37.7\%$, $I_{RMS} = 117.6A$ and $I_{60Hz} = 110.1A$. As a result, the harmonic current has been reduced by more than 50% while RMS current has been reduced by more than 20%.

The harmonic current profile shown on Figure 26, for the drive without mitigation, is similar to the values found in IEEE Std 519-1992, as shown in the six-pulse rectifier table

IEEE 519-1992, Table 4.3 Spectrum of Typical Switch Mode Power Supply			
Harmonic	Magnitude	Harmonic	Magnitude
1	1.000	9	0.000
3	0.000	11	0.045
5	0.175	13	0.029
7	0.110	15	0.000

The photograph shown Figure 27 is of an industrial electro-chemical plant's 30MW cell line, which operates at up to 150,000 amps DC. The connection diagram details its six-pulse rectifier. Modern electro-chemical plants are typically designed with two or more cell lines, so the harmonic currents produced by each can be used to mitigate the other(s).

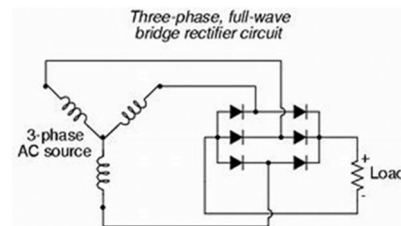


Figure 27

The Positive- & Negative Harmonic Solution – As detailed in Figures 21 & 22, Type DY harmonic mitigating transformers, with appropriate primary-to-secondary phase-shifts, can also be used to mitigate positive- and negative sequence harmonic currents. However, unlike Type DV transformers, Type DY transformers do not require flux cancellation windings, since zero-sequence harmonic currents are not generated by three-phase nonlinear loads.

Type PY & PV Medium Voltage Class Power TransFilters™ are available.



Reference

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