ENERGY EFFICIENCY IMPROVEMENT IN ELECTRICAL DISTRIBUTION SYSTEMS AND THEIR LOADS

Abstract *– 'Penalty losses' are defined as consumed power that does not contribute directly to the intended work. Unavoidable circuit and transformer losses at 60Hz [50Hz] are excluded.*

Distribution system 'penalty losses' include losses due to reactive load currents, unbalanced load currents and nonlinear load-generated harmonic currents. 'Penalty losses' also include excessive excitation [no-load] losses in oversized power and distribution transformers and elevated impedance [load] losses due to nonlinear load-generated harmonic currents.

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.

1. INTRODUCTION

In the overwhelming majority of cases, the *'penalty losses',* which exist in medium and low voltage distribution systems and their loads, are self-inflicted. That is, they are generated within the facility. *'Penalty losses'* include losses due to the distribution of reactive load currents, unbalanced load currents and nonlinear load-generated harmonic currents.

In an Ohm's Law relationship with the distribution system's harmonic impedances, the imposition of harmonic currents will result in the generation of harmonic voltages and the distortion of the fundamental 60Hz [50Hz] sinusoidal voltage waveforms. Since an electrical circuit's harmonic impedances are dictated by source impedances and circuit geometry, harmonic voltage magnitudes and voltage distortion are normally highest at the load-end of the longest circuits that supply nonlinear loads.

Harmonic currents impose voltage distortion throughout the electrical distribution system. Supplying a load with distorted voltage will produce internal *'penalty losses'*. Since the published efficiency of any load is based on supplying it with undistorted sinusoidal voltage, its actual energy efficiency will be reduced. Further, applying distorted voltage to a linear load will result in equal distortion of the resulting load current. In this scenario, the linear load becomes a harmonic current generator, inflicting additional *'penalty losses'* in the distribution system.

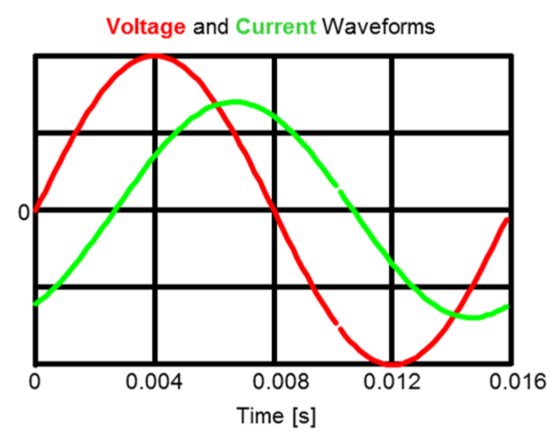
Similarly, in the overwhelming majority of cases, low voltage distribution systems are grossly underutilized. A Load Factor survey, undertaken by The Cadmus Group Inc.in 1999, found that the average loading of low voltage, dry-type distribution transformers in commercial, industrial and public buildings was in a range between 9% and 17% of their full load (FL) rating. More recent surveys have shown much lower Load Factors, the result of upgrading to more energy efficient loads.

Transformer oversizing is a typical outcome when meeting the requirements of national and local electrical codes in the US and Canada. To maximize energy conservation, the optimum transformer kVA rating can be determined by referring to CSA C802.4-2013 *(A Guide for kVA Sizing of Dry-Type Transformers).* Where there is a conflict between a code's requirements and the guide's recommendations, the designer should consider the lowest allowable kVA rating.

The motivation for replacing existing transformers is usually based on their questionable reliability and/or a need to reduce energy consumption and utility costs. Based on actual Load Factor measurements, the higher Excitation (no-load) Losses and lower Efficiencies of oversized pre-NEMA TP 1 transformers may provide an even greater opportunity to save energy and reduce utility costs. The code's requirements can allow 'rightsizing' when actual Load Factors can be established.

2. THE SOURCES OF 'PENALTY LOSSES' IN THE DISTRIBUTION SYSTEM'S CIRCUITRY

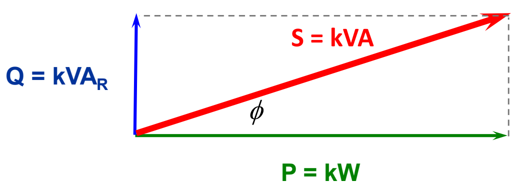
Background – In North America, electrical utilities generate and supply 60Hz sinusoidal alternating voltage to their customers. If this voltage is applied to a linear load (i.e. motors, resistive heating elements, incandescent lamps), the resulting current will also be sinusoidal. For all practical purposes, the 60Hz sinusoidal voltages and currents will be undistorted, as shown in *Figure 1.*



Linear Load
Figure 1

The Inductive Load Problems – If a linear load is inductive (i.e. transformer, motor), the current's sinusoidal waveform will lag the voltage's sinusoidal waveform in time, as shown in *Figure 1.* If current lags voltage, the inductive load has created a lagging Displacement Power Factor condition.

With reference to *Figure 2,* an inductive load consumes not only power (P), measured here in thousands of watts (kW), but Q, measured here in thousands of volt-amperes reactive (kVA_R). An inductive load imposes additional current on the electrical distribution system, between the source of power (the utility or in-house generation) and the inductive load.



Displacement Power Factor
under Linear Loading
Figure 2

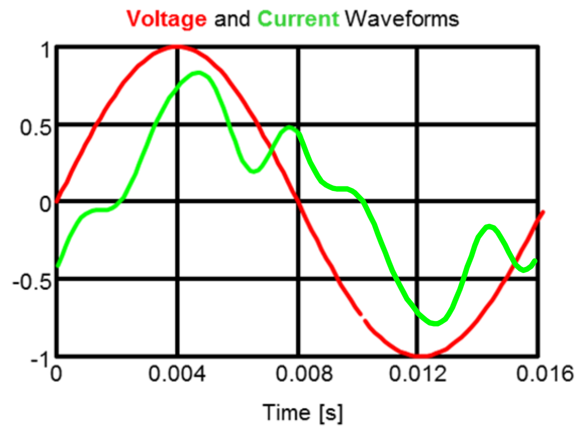
Since it is current that creates losses in an electrical distribution system, the losses produced by the current component of volt-amperes reactive must be considered as *'penalty losses'*.

The Inductive Load 'Penalty Loss' Solution – The best technical solution to this problem is the application of a suitably rated capacitor bank, an alternative source of kVA_R, at or near the inductive load. This approach will eliminate the *'penalty losses'* from its point of its application back to the source of power.

The Displacement Power Factor Solution – In addition to eliminating the *'penalty losses'* associated with inductive loads, this mitigation plan, if applied to sufficient inductive loads, will also contribute to the reduction or elimination of a utility imposed Power Factor penalty.

The Nonlinear Load Problems – If an alternating sinusoidal voltage is applied to a nonlinear electronic load (i.e. rectifier, variable frequency or direct current motor drive, switch-mode power supply), the resulting current waveform will be distorted, as shown in *Figure 3.* This distortion is produced by the imposition of nonlinear load-generated harmonic currents (integer multiples of the fundamental frequency). The addition of these sinusoidal harmonic currents to the fundamental sinusoidal current will result in the distortion of the fundamental current waveforms.

With reference to *Figure 3,* in most cases, the distorted current waveform will lag the voltage waveform in time. Again, if current lags voltage, the nonlinear load has created a lagging True Power Factor condition.

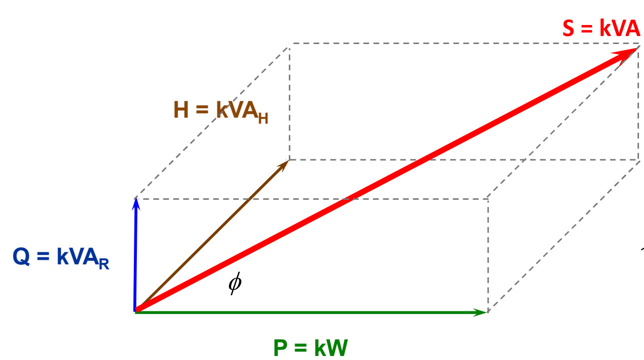


Nonlinear Load
Figure 3

The Nonlinear Load Penalty Loss Solution – The best technical solution to this condition is the application of a harmonic filter (i.e. tuned or detuned shunt filter, electro-magnetic zero-sequence shunt or zero-sequence phase-shifting filter, active harmonic filter, series reactor, phase-shifting reactor or phase-shifting harmonic mitigating transformer) at or near the nonlinear load(s). This approach will eliminate the *'penalty losses'* from its point of its application back to the power source.

The True Power Factor Solution – In addition to eliminating the *'penalty losses'* associated with nonlinear loads, this mitigation plan, if applied to sufficient nonlinear loads, will also contribute to the reduction or elimination of a utility imposed Power Factor penalty.

Unfortunately, capacitor banks alone are often used to correct True Power Factor problems in a nonlinear load environment. In reality, most facilities have both linear and nonlinear loads, each contributing to the True Power Factor problem, as measured by the utility's revenue meters. A vector diagram displaying this complex condition is shown in *Figure 4.*



True Power Factor
under combined Linear & Nonlinear Loading
Figure 4

With reference to *Figure 4*, it becomes clear that if one calculates True Power Factor, based on kW / kVA_R alone, while ignoring kVA_H, the resultant calculated kVA_R rating of the proposed capacitor bank would actually cause the angle Ø and kVA to increase and True Power Factor to decrease.

In a nonlinear environment, the application of a capacitor bank, without first implementing a harmonic mitigation plan that significantly reduces kVA_H and THD_V, will often result in any or all of the following undesirable outcomes:

1. Capacitor bank fuse interruptions or circuit breaker trip, removing the capacitor bank from service,
2. Failure of the capacitor bank before fuse interruption or circuit breaker trip,
3. Harmonic current and voltage amplification, due to resonance at a particular harmonic frequency(s) and
4. System apparatus and/or load insulation failures, due to high harmonic voltages and dV/dT stresses.

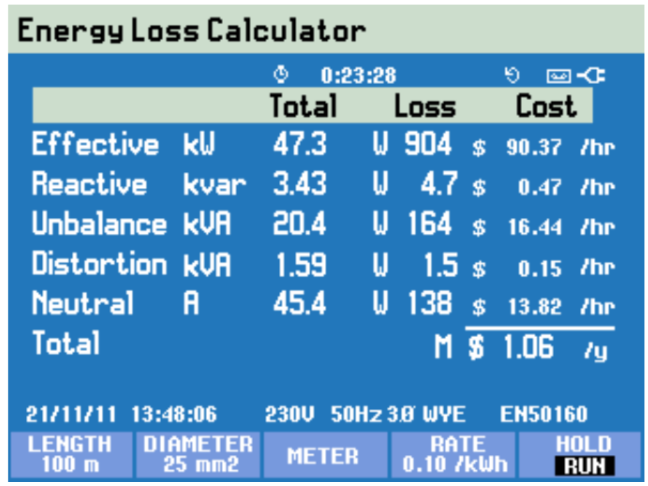
The Unbalanced Load Current Problem – Unbalanced currents in a three-phase distribution system produce *'penalty losses'* in its circuits. Unbalanced three-phase load currents may also be caused by voltage imbalance. In the case of three-phase motors, unbalance degrades their performance and shortens their life expectancy. Voltage imbalance at the motor's stator terminals causes phase current imbalance far out of proportion to the voltage imbalance. Unbalanced currents, in turn, lead to torque pulsations, increased vibration and mechanical stresses, increased losses, and motor overheating. Each one of these effects consumes energy, now quantifiable as 'penalty losses' in watts.

Unbalanced load currents in three-phase, four-wire systems, which supply phase-to-neutral connected single-phase loads, will produce neutral current. Whether balanced or unbalanced, systems that supply phase-to-neutral connected nonlinear loads will often produce neutral currents that exceed phase currents. This is due to the presence of third-order, zero-sequence harmonic phase currents that sum arithmetically at the distribution transformer's X_0 terminal and on the circuit's neutral conductor.

The Unbalanced Load Current Solution – As a first step, some effort should be made to balance three-phase feeder circuits at the design and commissioning of the distribution system. When current imbalance produce voltage imbalance, the application of a zero-sequence filter of sufficient kVA capacity may be appropriate.

The Measurement of the Distribution System's 'Penalty Losses' The Unified Power Measurement System uses a combination of classical methods (IEEE 1458-2010) and the University of Valencia's mathematical calculations to express power and energy measurements that directly quantify the *wasted energy* in electrical systems. Unified Power measures the *'penalty losses'* due to reactive load current, unbalanced load current, harmonic current and neutral current and, by factoring in circuit information and the cost per kilowatt hour, calculates the cost of waste energy over a week, a month, or a year. An example of a Unified Power measurement is detailed in *Figure 5.*

In this example, the most significant *'penalty losses'* are due to Unbalance and Neutral currents. This outcome is typical when the feeder circuit is somewhat underutilized.



Fluke® Unified Power Measurement System
Figure 5

The Unanticipated Problems – In addition to the various issues detailed above, unresolved power quality problems usually result in unanticipated and unexplained electrical failures, reduced productivity and higher operating costs.

3. The Source of 'Penalty Losses' in the Distribution System's Loads

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. 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.

The Voltage Distortion Solution – Implementation of a Penalty Loss Solution will resolve the linear and nonlinear load efficiency problems.

4. The Sources of 'Penalty Losses' and Inefficiency when Transformers are Oversized

The New Construction Problem – 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 in a range between 9% and 17% of FL. They also found that loading, for at least 12 hours a day, was only 10% on average. More recent surveys have shown much lower Load Factors, the result of upgrading to more energy efficient loads.

Transformer oversizing is a typical outcome when meeting the requirements of national and local electrical codes in the US and Canada. To maximize energy conservation, the optimum transformer kVA rating can be determined by referring to CSA C802.4-2013 *(A Guide for kVA Sizing of Dry-Type Transformers).* Where there is a conflict between a code's requirements and the guide's recommendations, we recommend the application of the lowest allowable kVA rating.

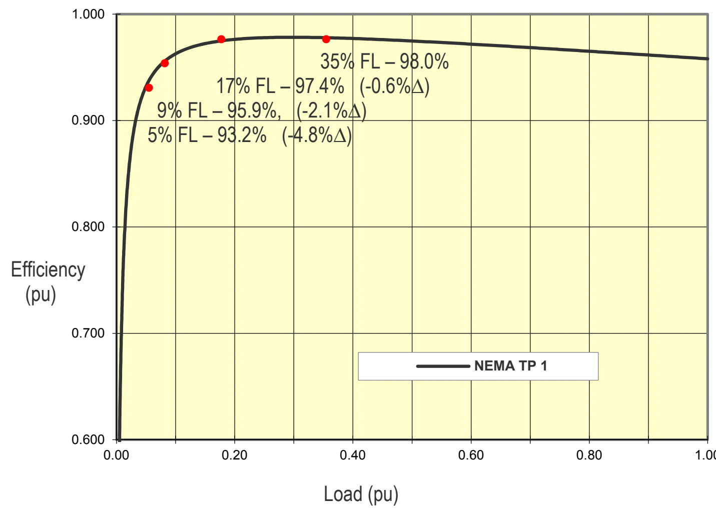
In addition to the higher capital cost of oversizing, the cost of operating a lightly loaded transformer is also higher. Using the Cadmus survey findings, *Figure 6* shows that the efficiency of a typical 75kVA, NEMA TP 1 transformer, with a required efficiency of 98.0% at 35% FL, is 97.4% at 17% FL, but only 95.9% at 9% FL. However, based on the more recent surveys, and our own experience, average loading is often much lower. For example, at 5% FL the transformer's efficiency is only 93.2%. Rightsizing a transformer, as recommended in CSA C802.4, can result in a substantial reduction in losses, an increase in efficiency and a reduction in energy costs.

Since the recommendations given in CSA C802.4 are for a transformer under linear loading, before proceeding with a final selection, its nonlinear efficiency, under anticipated loading and harmonic current profiles, should be determined by referring to CSA C802.5-2015 *(Guide for Selection of a Distribution Transformer for Nonlinear Applications.)*

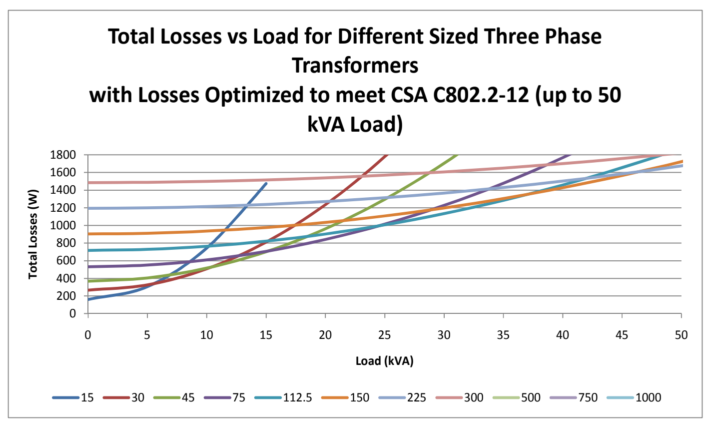
Based on these efficiency outcomes, one can then compare the energy savings, payback and return-on-investment (ROI) and EPA environmental outcomes for each alternative, some of which may include downsizing. A comparison of the total losses in a downsizing scenario, under linear loading, may be found in *Figure 7*.

With reference to *Figure 7*, using the 9% and 17% load levels described in *Figure 6,* one can examine the 'rightsizing' possibilities. For example, if a 75kVA transformer was initially considered, but the anticipated load was only 9% of FL or 6.75kVA, the best alternative may be a 30kVA transformer, with an average equivalent load of 22.5% FL. Based on the graph, a 15kVA unit at 45% FL may also qualify, since its calculated average Load Factor would not exceed 50% FL, a nationalgrid® Transformer Replacement Program recommendation for low voltage dry-type transformers (Implementation Manual, Version 2013.1, April 4, 2013). Before proceeding with this alternative, however, one must consider the possible addition of future loads, keeping in mind that existing loads may be replaced with more energy efficient loads over time.

Applying the same logic, if a 75kVA transformer was initially considered, but the anticipated load was only 17% FL or 12.75kVA, a 45kVA unit at 28.3% FL or a 30kVA unit at 42.5% FL could be considered.

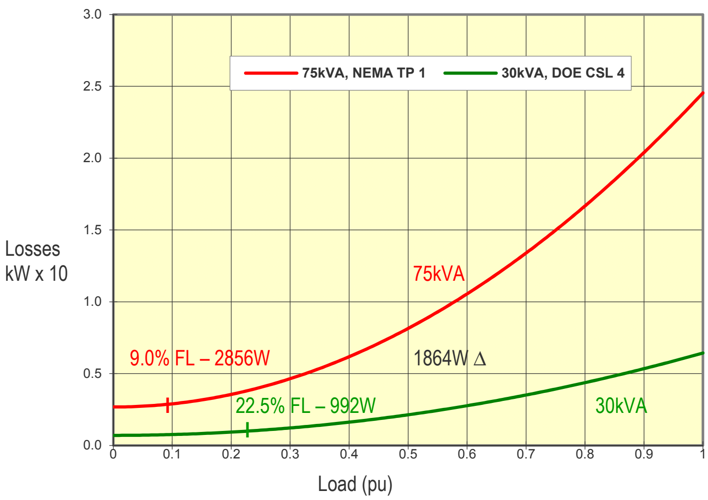


75kVA NEMA TP 1 Distribution Transformer
under Linear Loading
Figure 6

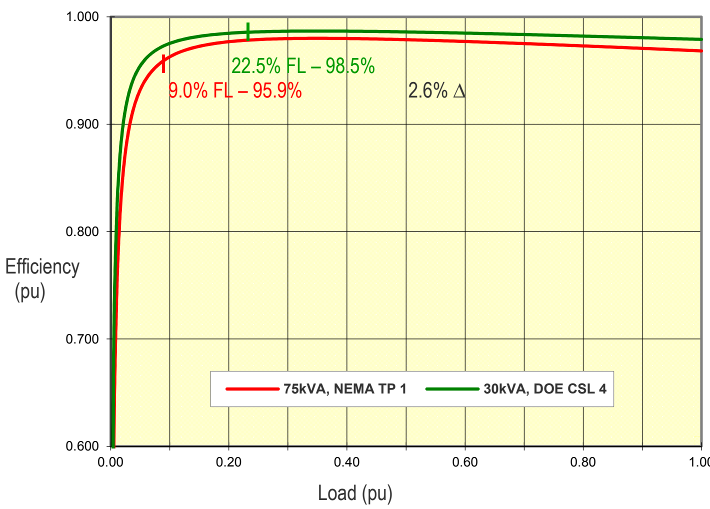


Graph taken from CSA C802.4
Standard for kVA Sizing of Dry-Type Transformers
Figure 7

Based on the 75kVA transformer at 9% FL example, *Figures 8 and 9* detail the difference in losses and efficiencies when comparing a 75kVA, NEMA TP 1 transformer and a 30kVA, DOE CSL 4 transformer. With 1864W lower losses and 2.6% higher efficiency, the 30kVA transformer will provide significant energy savings, payback and return-on-investment.



Distribution Transformers Losses
75kVA, NEMA TP 1 vs. 30kVA, DOE CSL 4, under 6.75kVA
Linear Loading
Figure 8



Distribution Transformers Efficiency
75kVA, NEMA TP 1 vs. 30kVA, DOE CSL 4, under 6.75kVA
Linear Loading
Figure 9

The Existing Facility Problem – The motivation to replacing an existing transformer is usually based on its questionable reliability and/or a need to reduce 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 pre-NEMA TP 1 transformers, particularly at low Load Factors, provides an even greater opportunity to save energy and reduce utility costs.

With reference to *Figure 10,* a typical pre-NEMA TP 1, 75kVA transformer has an efficiency of only 92.8% at 9.0% FL, whereas a DOE CSL 4, 30kVA transformer has an efficiency of 98.5% at a 22.5% FL equivalent, a 5.7% efficiency improvement and energy cost reduction.

Again, based on more recent surveys, average loading is often much lower. For example, at 5% FL, the efficiency of the 75kVA, pre-NEMA TP 1 unit is only 88.2%, whereas a DOE CSL 4, 15kVA transformer has an efficiency of 98.4% at a 25.0% FL equivalent, a 10.2% efficiency improvement.

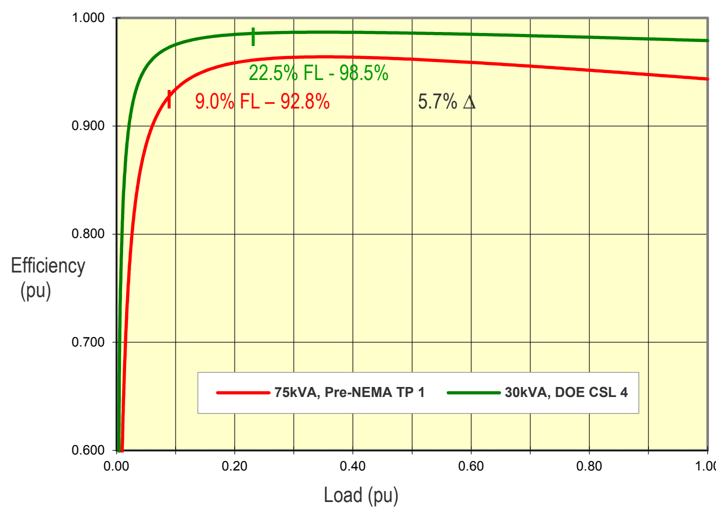
Rightsizing a transformer, as recommended in CSA C802.4 and by national**grid**® *(Transformer Replacement Program for Low-Voltage Dry-Type Transformers)* can result in a substantial reduction in operating costs.

The national**grid**® program recommends that downsizing should only be considered if:

1. The measured Load Factor of the existing transformer never exceeds 35% FL or
2. The calculated Load Factor of the replacement transformer never exceeds 50% FL.

Based on these criteria, the Load Factor (LF) for the replacement transformer can be calculated as follows:

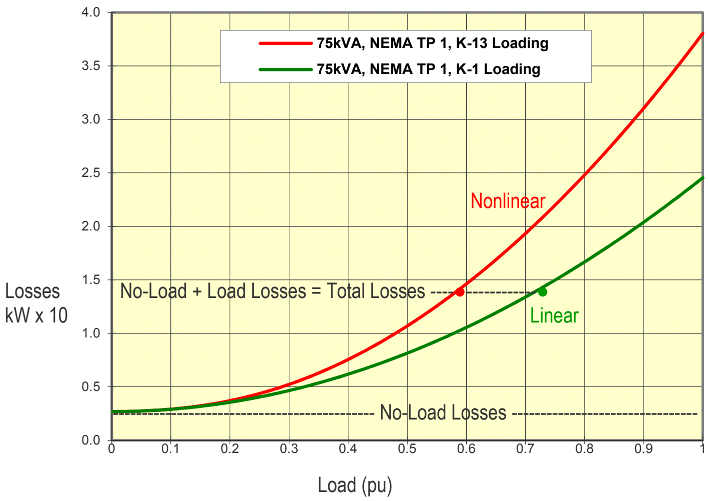
$$LF_{NEW} = LF_{OLD} \times (kVA_{OLD} / kVA_{NEW})$$



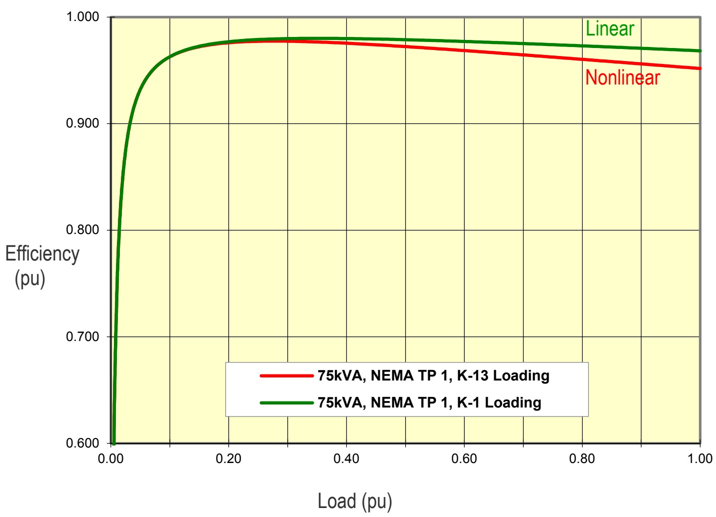
Distribution Transformers Efficiency
75kVA, Pre-NEMA TP 1 vs. 30kVA, DOE CSL 4, under 6.75kVA
Linear Loading
Figure 10

5. The Sources of 'Penalty Losses' and Inefficiencies when a Transformer's Loads are Nonlinear

To determine the replacement transformer's potential energy savings, payback, ROI and EPA environmental outcomes, the new CSA C802.5 Calculator must first be used to calculate the losses and efficiencies of the existing and proposed replacement transformers under their measured or calculated Load Factors and harmonic current profiles. At low Load Factors, the national electrical codes are somewhat more flexible regarding downsizing, if the Load Factors can be verified. Since a transformer's efficiency begins to fall off below 15% FL, downsizing to a smaller, more efficient transformer saves energy and also provides an attractive capital cost reduction.



Distribution Transformer Losses
75kVA, NEMA TP 1 under K-1 Linear and K-13 Nonlinear Loading
Figure 11



Distribution Transformer Efficiency
75kVA, NEMA TP 1 under K-1 Linear and K-13 Nonlinear Loading
Figure 12

With reference to *Figure 11,* it becomes obvious that Load Losses begin to contribute to a transformer's Total Losses at approximately 10% FL (0.10 pu). On closer examination, the unit's nonlinear Load Losses begin to exceed its linear Load Losses at approximately 15% FL. The increase in nonlinear Load Losses is harmonic current profile dependent. That is, as the load K-Factor increases the nonlinear Load Losses increase. Since the transformer's Total Losses determine its efficiency, *Figure 12* shows a decrease in the transformer's nonlinear efficiency as we exceed 15% FL. When determining potential transformer replacement benefits, the proposed or existing and alternative or replacement transformers' nonlinear performances must be determined.

With reference to Appendix A, given any two transformers' 'kVA Ratings', 'No-Load Losses' and 'Load Losses' or 'Efficiencies', 'Capital Costs', 'Power Costs', 'AC Requirements' and 'Transformer Loading' profile, The PQI (or equivalent FES) Calculator™ will detail each transformer's 'Penalty Losses', 'Calculation of Annual Savings', 'Calculation of Financial Benefits' (i.e. payback & ROI on substitution or replacement scenarios, annual reduction in kWh & %kWh) and produce an 'EPA Summary of Environmental Benefits'. With respect to Total Losses and Efficiencies, these proprietary calculators are IEEE Std C57.110 and CSA C802.5 compliant.

The Power Quality Solution – Given a facility's proposed or 'as built' electrical distribution system drawings and panel schedules, PQI engineers can develop (and execute) a power and harmonic measurement plan. The FES power system analysis software can be used to simulate the anticipated or 'as found' system conditions and identify the potential or actual root cause of all undesirable anticipated or measured outcomes. Our engineers can then simulate the proposed system revisions and confirm the desired outcomes. Based on these simulations and with the implementation of our proposed system revisions, Power Quality International will guarantee compliance with IEEE Std. 519-1992 recommendations.

The Energy Optimization Solution – Harmonic current reduction in the distribution system and voltage distortion improvement at the loads will reduce energy consumption (Refer Appendix B for several mitigation methods). IEEE 519-1992 compliance is the first step in reducing energy consumption. Having solved the power quality issues, FES engineers will then identify other potential energy saving opportunities and simulate their performance. Again, if our proposals are fully implemented, we may also guarantee a range of savings.

Author – Gregory Ferguson was born in Toronto, Ontario, Canada in 1937. He received a B.Sc. Degree in Electrical Engineering from Ryerson University, Toronto.

Before incorporating FES International in 1968, his experience included employment with the Ontario Hydro Electric Power Commission as a Protection & Control Engineer and the Scarborough Public Utilities Commission, Canada, as the Protection & Control Department Manager. Greg is also the founder and past president of Power Quality International, Inc. (1993). He was also the founding partner of Electrical Testing Instruments Ltd., Canada (1973).

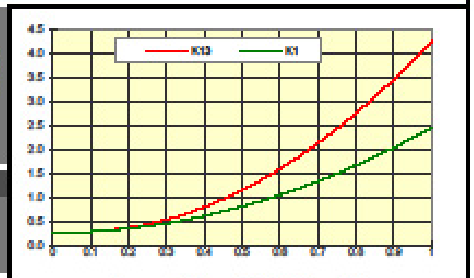
In 1991 Greg emigrated to the US where he became a citizen in 2000. With over 50 years' experience in power system engineering, he became a Life Member of IEEE in 2008.

APPENDIX A

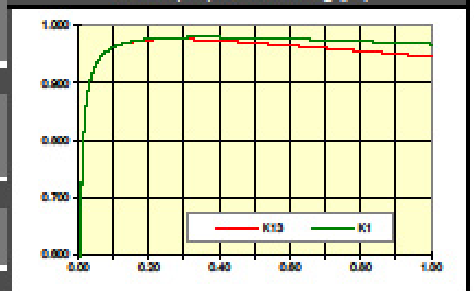
The PQI Calculator ™

TRANSFORMER LOAD

Project	Sample
Description	To compare the performance of a 75 kVA Distribution Transformer, with NEMA TP 1 Efficiency, under both Linear (K1) Loading and Nonlinear (K13) Loading.
Date	May 1, 2015



Losses (kW) vs. kVA Rating (pu)



Efficiency (pu) vs. kVA Rating (pu)

Rating & Efficiency

K13		kVA Rating	75.0
Zero-Sequence Harmonic Flux Cancellation		Yes/No	No
Linear Eff. at	35%	of TX Rated kVA	98.00%
K1		kVA Rating	75.0
Zero-Sequence Harmonic Flux Cancellation		Yes/No	No
Linear Eff. at	35%	of TX Rated kVA	98.00%

Capital Costs

K13	
K1	
Installation [if replaced before end-of-life]	

Power Costs

Average kWh Rate ($/kWh)	
Average Demand Rate ($/kW/month)	

Air Conditioning Requirement

Months/Year [direct or indirect]	

Transformer Load		Daytime	Evening	Weekend	Total
% of Nameplate kVA Rating for	K13	0%	0%	0%	0.0%
% of Nameplate kVA Rating for	K1	0%	0%	0%	0.0%
Hours/Day for Segment		14	10	24	
Days/Year for Segment		261	261	104	

Calculation of Penalty Losses		Daytime	Evening	Weekend	Average
Actual kW Losses for	K13	0.268	0.268	0.268	0.268
Actual kW Losses for	K1	0.268	0.268	0.268	0.268
Difference in kW	K13 K1	0.000	0.000	0.000	0.000

Calculation of Annual Savings		Daytime	Evening	Weekend	Total
Cost of Penalty Losses for	K13	$0.00	$0.00	$0.00	$0.00
Cost of Penalty Losses for	K1	$0.00	$0.00	$0.00	$0.00
Annual Energy Savings, Including A/C Costs		$0.00	$0.00	$0.00	$0.00

Calculation of Financial Benefits

Annual Savings, Including A/C Costs, when using	K1	$0.00 / year
Payback on Incremental Cost [substitution]		0.0 months
Return-on-Investment (ROI) on Incremental Cost [substitution]		0.0 %
Payback on Installed Cost [before end-of-life replacement]		0.0 years
Return-on-Investment (ROI) on Installed Cost [before end-of-life replacement]		0.0 %
Annual Reduction in kWh		0 kWh saved
Annual Energy Savings (% kWh)		#DIV/0! %

Summary of Environmental Benefits

Annual Reductions per EPA Formula	0.00 tons of CO2	0 kgs of SO2
	0.00 kgs of coal	0 kgs of Nox
	0 acres of trees	0 homes heated
	0 fewer cars on the road each year	

With the exception of project *'Description'*, *'Date'* and the transformers' *'Rating & Efficiency'*, The PQI Calculator's *'Capital Costs'*, *'Power Costs'*, *'Air Conditioning Requirement'*, *'Transformer Loading' and 'Harmonic Profile'* entries have been left unpopulated. Adding this additional information would allow all calculation (green blocks).

APPENDIX B

POWER QUALITY IMPROVEMENT IN A HARMONIC ENVIRONMENT

A paper reprint from the InterNational Electrical Testing Association (NETA) Annual Technical Conference, St. Louis, MO, March 19, 1997

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POWER QUALITY IMPROVEMENT IN A HARMONIC ENVIRONMENT

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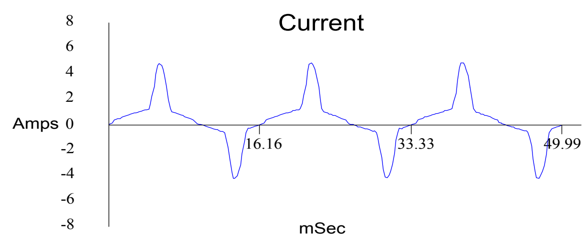
Abstract - *The effect of single-phase, non-linear loads, as sources of positive-, negative- and third-order, zero-sequence harmonic currents in low voltage electrical distribution systems, is discussed. Various traditional methods for dealing with these harmonic currents are outlined and their shortcomings 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.

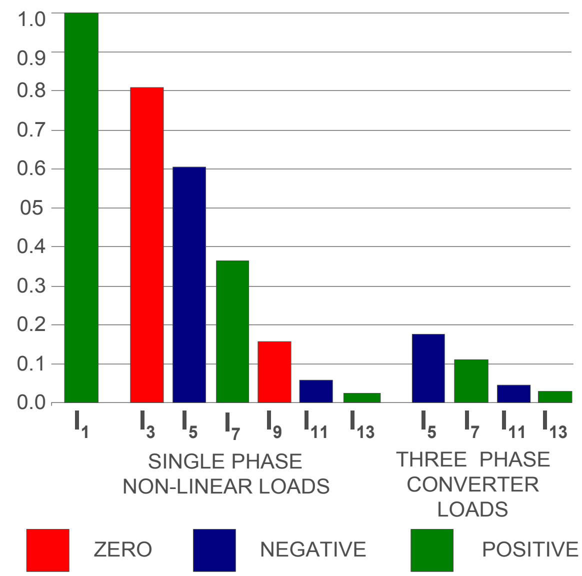
Medium to high levels of odd positive- and negative-sequence harmonic currents are generated by three-phase, full-wave, non-linear loads, which are connected to a 480V three-wire or 277/480V four-wire distribution system. These currents are principally the byproduct of three-phase, six-pulse, diode-bridge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



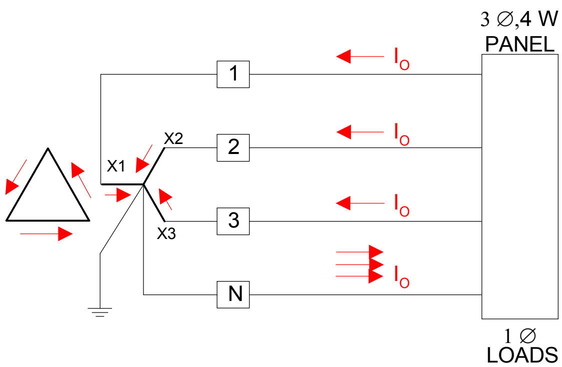
Harmonic Current Profiles for Non-linear Loads
Fig. 2

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.

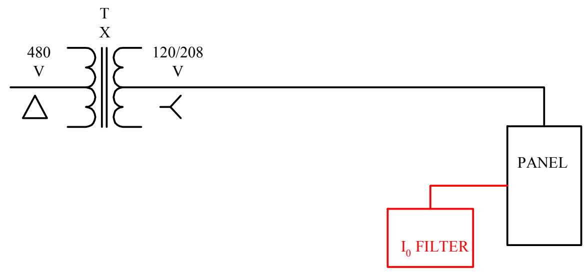
Since impeding harmonic currents will result in increased THD_V, the best tools at our disposal are the strategic reduction of zero-sequence impedances and the cancellation of positive- and negative-sequence harmonic currents.

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

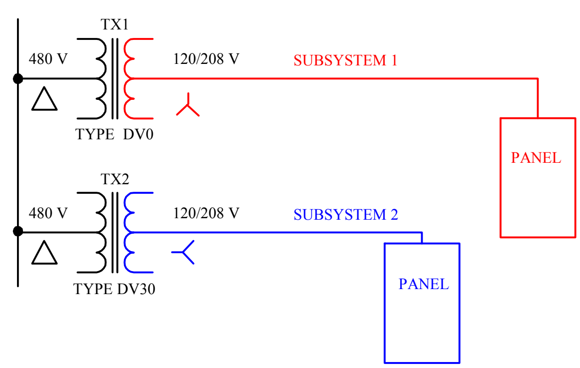
In addition to its capabilities as a third order, zero-sequence harmonic shunt, the I_0Filter also has the ability to balance three-phase positive- and negative-sequence harmonic currents in a four-wire sub-systems, including the fundamental currents. As a phase current balancer, it also functions to 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

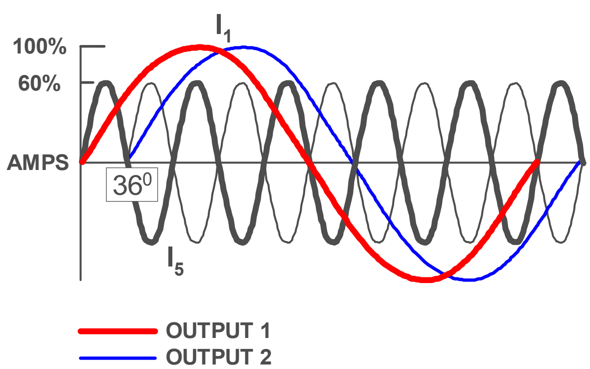
As shown in the Figure 6 example, multiple Harmonic Filtering Transformers (or a Harmonic Filtering Transformer in combination with an existing transformer and/or non-linear loads) can be connected to a common three-phase, three- or four-wire bus so that targeted positive- and negative-sequence harmonic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

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

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° phase-shift at that harmonic frequency.
H	-	The harmonic number of the targeted harmonic frequency.



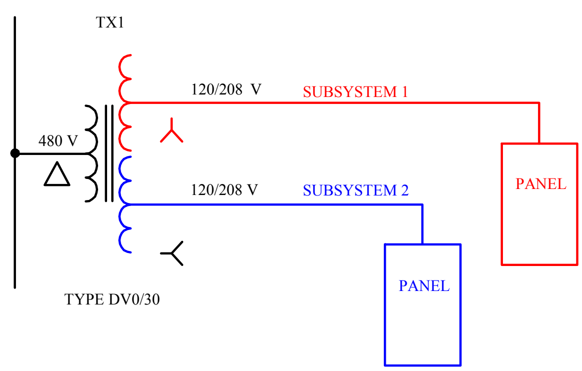
Two Sub-Systems Phase-Shifted by 36°
Fig. 7

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°.



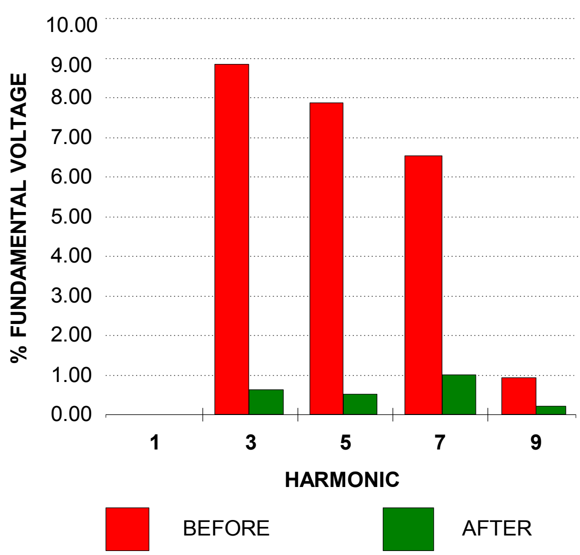
Application of Dual Output Transformer
Fig. 8

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

[1] Freund, "*Double the Neutral and Derate the Transformer or Else*", Electrical Construction and Maintenance, December 1988.

[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)

[5] D. E. Rice, "*Adjustable Speed Drive and Power Rectifier Harmonics - their Effect on Power Systems Components*," IEEE Trans. On Ind. Appl., Vol. IA-22, No. 1, Jan./Feb. 1986, pp. 161-177.

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[7] A. Mansoor, et al, "*Predicting the Net Harmonic Currents produced by large numbers of Distributed Single-Phase Computer Loads*." Conference Record IEEE PES Winter Power Conference, Jan. 1995, #95 WM 260-0 PWRD.

[8] T. Key & J-S. Lai, "*Costs and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in Commercial Office Buildings*." A paper preprint from IEEE IAS Annual Meeting, October 1995, Orlando, Florida.

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