ENERGY EFFICIENCY IMPROVEMENT
IN ELECTRICAL DISTRIBUTION SYSTEMS AND THEIR LOADS
Gregory Ferguson, Life Member IEEE

Abstract – ‘Penalty losses’ \cite{1} are defined as consumed power that does not contribute directly to the intended work. 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.\cite{1} 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 (EH = IH * ZH) and the distortion of the fundamental 60Hz [50Hz] sinusoidal voltage waveforms.\cite{2} Since an electrical circuit’s harmonic impedances are dictated by the source’s harmonic 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,\cite{3} 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.
**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 (kVAR). 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.

\[
\begin{align*}
Q &= \text{kVAR} \\
P &= \text{kW} \\
S &= \text{kVA}
\end{align*}
\]

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 kVAR, 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.

\[
\begin{align*}
Q &= \text{kVAR}_R \\
S &= \text{kVA} \\
H &= \text{kVAR}_H
\end{align*}
\]

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** [5] – 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.

\[
\begin{align*}
Q &= \text{kVAR}_R \\
P &= \text{kW} \\
S &= \text{kVA} \\
H &= \text{kVAR}_H
\end{align*}
\]

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 alone, while ignoring kVAR, the resultant calculated kVAR rating of the proposed
The capacitor bank would actually cause the angle $\phi$ 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 kVAH and THDV, 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)\(^6\) 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 phases of the distribution system. When current imbalance produce voltage imbalance in a three-phase, four-wire circuit, the application of a shunt connected zigzag autotransformer,\(^{[6]}\) of sufficient capacity (kVA) to redistribute the source phase currents, may provide a solution.

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 an hour or year. An example of a Unified Power measurement is detailed in Figure 5.

In this example, the most significant ‘penalty losses’ are due to harmonic current ‘Distortion’ and ‘Neutral’ currents. This outcome is typical when the feeder circuit is supplying phase-to-neutral connected nonlinear loads.

<table>
<thead>
<tr>
<th>ENERGY LOSS CALCULATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effective</strong> 3.92 kJ</td>
</tr>
<tr>
<td><strong>Reactive</strong> -0.52 kvar</td>
</tr>
<tr>
<td><strong>Unbalance</strong> 0.18 kVA</td>
</tr>
<tr>
<td><strong>Distortion</strong> 2.48 kVA</td>
</tr>
<tr>
<td><strong>Neutral</strong> 21.1 A</td>
</tr>
<tr>
<td><strong>Total</strong>           533.5 $/yr</td>
</tr>
</tbody>
</table>

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 (THDV) 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.\(^{[1, 2, 7]}\) 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 (%THDI = %THDV). 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.

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.

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 nationalgrid® (Transformer Replacement Program for Low-Voltage Dry-Type Transformers) can result in a substantial reduction in operating costs.

The nationalgrid® 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:

\[ \text{LF}_{\text{NEW}} = \text{LF}_{\text{OLD}} \times \left( \frac{\text{kVA}_{\text{OLD}}}{\text{kVA}_{\text{NEW}}} \right) \]

5. THE SOURCES OF ‘PENALTY LOSSES’ AND INEFFECTIVENESS 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.

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.

The Application of Harmonic Mitigating Transformers – Figure 13 & 14 detail the performance of the same 75kVA, Pre-NEMA TP 1 transformer shown in Figure 10, but under K-30, phase-to-neutral connected nonlinear loading. In this example however, the 30kVA transformer, shown in Figure 10, has been replaced with a DOE CSL 4 harmonic mitigating transformer (HMT), with zero-sequence flux cancellation secondary windings. This design feature provides several important benefits:
1. Zero-sequence flux is virtually eliminated in the magnetic core. As a result, the core’s flux density is reduced and zero-sequence current is virtually eliminated in the delta-connected primary winding.

2. The cancellation of zero-sequence flux and primary winding current reduces the transformer’s impedance losses and increases its energy efficiency.

3. The cancellation of zero-sequence flux substantially reduces the transformer’s zero-sequence impedances (i.e. >100 times less). As a result, the HMTs contribution to voltage distortion at the loads is virtually eliminated ($E_0 = I_0 \times Z_0$).

4. The secondary windings can also be phase-shifted to cancel targeted positive- and negative-sequence harmonic currents.

The motivation to replacing a proposed or existing transformer with an HMT is usually based on a need to reduce energy consumption and utility costs. With reference to Figure 13, a typical pre-NEMA TP 1, 75kVA transformer has an efficiency of only 96.3% at 18% FL under K-30 nonlinear loading, whereas a DOE CSL 4, 30kVA HMT has an efficiency of 98.1% at a 45% FL, 13.5kVA equivalent load. This results in a 2.8% efficiency improvement and energy cost reduction.

When comparing the performance of the 75kVA, Pre-NEMA TP 1 transformer under both linear and K-30 nonlinear loading, as detailed in Figures 10 and 13, the differences in its efficiency above 20% FL is very significant.

Switch-mode power supplies, the front-end of virtually all 120V loads in an office environment, respond poorly with higher ‘penalty losses’ and lower efficiencies as voltage distortion rises above 5% THDv. It may be difficult to justify the additional cost of an HMT under light loading, based on reduced transformer losses. However, its significantly lower zero-sequence impedances can dramatically reduce voltage distortion at its loads. Based on replacement outcomes to date, the reduction of voltage distortion at the loads produces significant savings that often exceed those produced by just using more efficient ‘right sized’ transformers. When high voltage distortion is predicted or measured, low zero-sequence impedance HMTs should be considered.

The Calculation of Transformer Losses and Efficiency – With reference to Appendix A, Figure 15, given any two transformers’ kVA Ratings’, ‘No-Load Losses’ and ‘Load Losses’ or ‘Efficiencies’, and ‘Capital Costs’, ‘Power Costs’, ‘AC Requirements’ and ‘Transformer Loading’ profile, the 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, annual reduction in kWh & %kWh) and produce an ‘EPA Summary of Environmental Benefits’. In this example the calculator is comparing a conventional 75kVA transformer with a 30kVA HMT under K-30 nonlinear loading.

With respect to Total Losses and Efficiencies, the FES Calculator™ is IEEE Std. C57.110 and CSA C802.5 compliant. As an alternative, the CSA C802.5 Calculator could be used to calculate each transformer’s nonlinear losses and efficiencies. With this information, all other values could be calculated manually.

The Power Quality Solution – Given a plant’s ‘as built’ electrical distribution system drawings and panel schedules, FES engineers can develop and execute a power and harmonic measurement plan. Power system analysis software can then be used to simulate the ‘as found’ system conditions and identify the root cause of all undesirable measured outcomes. Our engineers can then simulate their proposed system revisions and confirm the desired outcomes. Based on these simulations and with the implementation of the proposed system revisions, FES 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. 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. The reduction of reactive load currents, unbalanced load currents, excessive excitation losses due to oversized transformers and losses due to undervoltage conditions, when the loads are electronic, should also be considered as part of the energy optimization study. Again, if the proposed revisions are fully implemented, we may also guarantee a range of savings.

5. REFERENCES


[3] Surveys conducted at four Johns Hopkins University School of Medicine facilities, Baltimore, MD, US Capital Building, Washington, DC, Horizon Blue Cross Blue Shield, Newark, NJ, Clark County School District, Las Vegas, NV, and Bank of America Office, Charlotte, NC.


The three-phase, four-wire, zigzag autotransformer, referenced in this paper, has a three-phase core with two windings per core leg. All windings are wound in the same direction and have the same number of turns, with one coil being positioned inside the other. Each phase-to-neutral connected pair of series coils includes a coil located on two different core legs. As a result, each phase-to-neutral connected pair (i.e. H1 – H0) are in a one-to-one ratio with one of the coils in the other two phases (i.e. H2 – H0, H3 – H0). As a result, a heavily loaded phase will receive power from the other two phases.


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). 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**

<table>
<thead>
<tr>
<th>Project</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>To compare the performance of a 75 kVA, K-13 Distribution Transformer and a 75 kVA, Type DY0 Distribution Filter, under K-13 loading.</td>
</tr>
<tr>
<td>Date</td>
<td>August 20, 2008</td>
</tr>
</tbody>
</table>

**Rating & Efficiency**

<table>
<thead>
<tr>
<th>K13</th>
<th>KVA Rating</th>
<th>75.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-Sequence Harmonic Flux Cancellation</td>
<td>Yes/No</td>
<td>No</td>
</tr>
<tr>
<td>Linear Eff. at 35% of TX Rated kVA</td>
<td>95.00%</td>
<td></td>
</tr>
<tr>
<td>DY0</td>
<td>KVA Rating</td>
<td>75.0</td>
</tr>
<tr>
<td>Zero-Sequence Harmonic Flux Cancellation</td>
<td>Yes/No</td>
<td>Yes</td>
</tr>
<tr>
<td>Linear Eff. at 35% of TX Rated kVA</td>
<td>98.65%</td>
<td></td>
</tr>
</tbody>
</table>

**Capital Costs**

| K13 | $4,350.00 |
| DY0 | $5,605.00 |
| Installation (if replaced before end-of-life) | $1,000.00 |

**Power Costs**

| Average KWh Rate ($/kWh) | $0.1200 |
| Average Demand Rate ($/kW/month) | $8.0000 |

**Air Conditioning Requirement**

| Months/Year (direct or indirect) | 12 |
| Transformer Load | | |
| % of Nameplate kVA Rating for K13 | Daytime | Evening | Weekend | Total |
| 50% | 35% | 25% | -- |
| % of Nameplate kVA Rating for DY0 | 50% | 35% | 25% | -- |
| Hours/Day for Segment | 12 | 12 | 24 | 24 |
| Days/Year for Segment | 261 | 261 | 104 | 365 |

**Calculation of Penalty Losses**

| Actual kW Losses for K13 | 3.577 |
| Actual kW Losses for DY0 | 0.823 |
| Difference in kW | 2.753 |

**Calculation of Annual Savings**

| Cost of Penalty Losses for K13 | $1,687.65 |
| Cost of Penalty Losses for DY0 | $388.48 |
| Annual Energy Savings, including A/C Costs | $1,753.88 |

**Calculation of Financial Benefits**

| Annual Savings, including A/C Costs, when using DY0 | $3,176.68 / year |
| Payback on Incremental Cost [substitution] | 4.7 months |
| Return-on-Investment (ROI) on Incremental Cost [substitution] | 253.1 % |
| Payback on Installed Cost [before end-of-life replacement] | 2.1 years |
| Return-on-Investment (ROI) on Installed Cost [before end-of-life replacement] | 48.1 % |
| Reduction in kWh over 25 years of operation | 387,298.12 kWh saved |

**Summary of Environmental Benefits**

| Annual Reductions per EPA Formula | 11.44 tons of CO2 |
| 33,695.74 kgs of coal | 90 kgs of SO2 |
| 2 acres of trees | 39 kgs of Nox |
| 2 fewer cars on the road each year | 2 homes heated |

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The PQI Calculator™

**Figure 15**

POWER QUALITY INTERNATIONAL, LLC
The K-30 nonlinear load supplied by each transformer, compared in Figure 15, has an identical harmonic current profile. The current profile includes high levels or positive-, negative- and zero-sequence harmonic currents, which are produced by randomly switched, phase-to-neutral connected, switch-mode power supplies. This harmonic current profile produced a THDi = 101.66%, a K-Factor = 29.65 and a FHL = 14.58.

The nonlinear losses shown in Figures 15 & 16 are identical. To demonstrate the effect of K-30 nonlinear loading, each transformer’s linear losses are superimposed in Figure 16. In addition to the obvious difference in nonlinear losses, when comparing the two transformers, there is a substantial difference in the effect the K-30 load has, when comparing each transformer’s linear and nonlinear losses. The 30kVA HMT has much better performance because of its zero-sequence flux cancellation secondary windings. As a result, its magnetic core is not subjected to zero-sequence flux and its delta connected primary winding is not subjected to the induced zero-sequence currents. The resulting reduction in core, winding and eddy current losses is significant.