

Transformers and Associated Losses - The Opportunity for Savings

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Low voltage distribution transformers have historically been considered as one of the more efficient parts of the electrical infrastructure. However, published data shows that real world transformer losses are much higher than published manufacturers' data suggests. This paper tracks the origin of the higher losses to the increasingly electronic nature of connected equipment, and looks at the impact on different transformer types including low temperature rise, Energy Star and K-rated. This paper explains the different approaches and compares them to Powersmiths transformers, which have been 3rd party validated at Oak Ridge National Lab, a US DOE test facility, to hold 98% efficiency under electronic equipment load profile and dramatically reduce unwanted system voltage distortion.

Author's Note

In addition to extra losses, consequences of feeding electronic equipment include unwanted distortion of the voltage waveform that reduces operating reliability of both the electrical system and connected equipment.

While the concept of energy savings is much easier to relate to, many consider the negative impacts of voltage distortion to far outweigh the cost of increased system losses. More information on the power quality benefits of Powersmiths products, including other papers, is available at our web site www.powersmiths.com

Published Transformer Loss Data Can Dramatically Underestimate Measured Losses

Today's transformer losses are being increasingly driven by electronic equipment like computers whose load profile drives both additional losses and unwanted distortion [1,2]. Since transformer manufacturers test only under ideal (linear) conditions, as called for in present construction standards, there is a substantial gap between published loss data and actual losses incurred after installation, as illustrated in figure 1.

Testing at Oak Ridge National Lab [3], a US DOE test facility, documented substantial increases in core and coil losses - almost **triple** what was expected - when a 112.5kVA transformer was feeding 60kW of 120V computer load.

Years ago, equipment used to be predominately linear in nature, where current flows continuously, following the supply voltage, such as

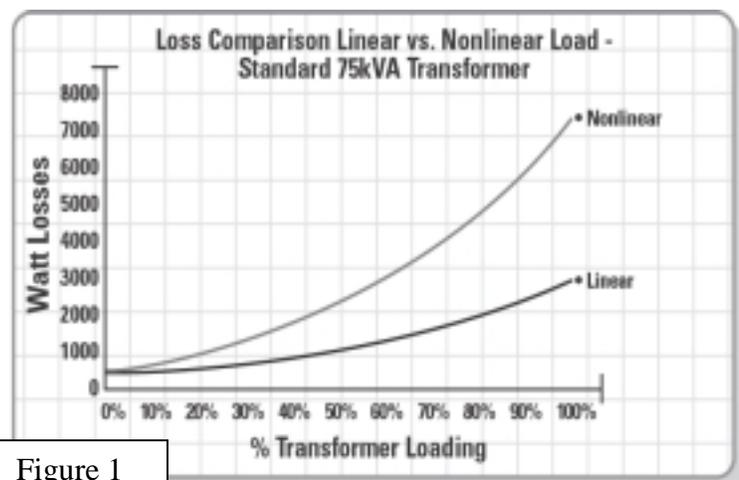


Figure 1

in motors and incandescent lighting. Today, with the influx of electronic equipment from the computer in the office to the variable speed drive in the factory and in our HVAC systems, our electrical systems feed a growing portion of this type of load, which is nonlinear, drawing current in pulses rather than continuously. Figure 2 illustrates the dramatic difference in load profiles. Electronic equipment and other nonlinear loads now make up most of the load on transformers in many facilities. Even in the average office, aren't we plugging in mostly computers, printers, scanners and other electronics to our 120V receptacles?

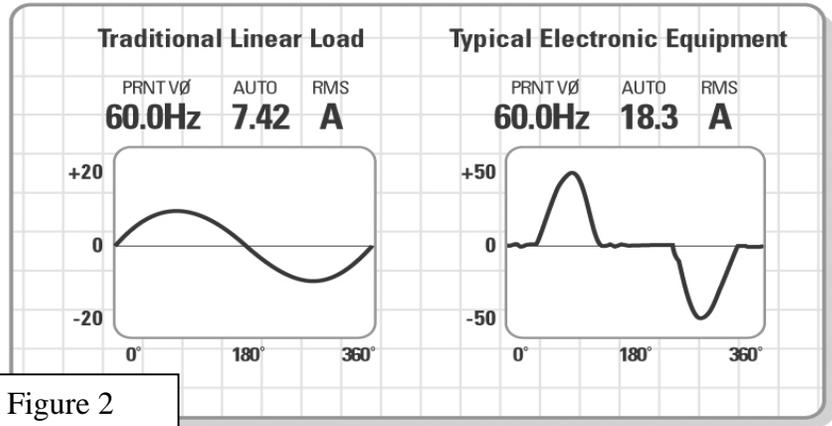


Figure 2

Transformer Losses

Transformers have two major components that drive losses: the core and the coils (see figure 3). The typical core is an assembly of laminated steel, and core losses are mostly related to magnetizing (energizing) the core. These losses, also known as no-load losses, are present all the time the transformer is powered on – regardless of whether there is any load or not. Core losses are roughly constant from no-load to full-load when feeding linear loads. They represent a continuous cost, 24 hours/day, *for the 25-year or more life of the transformer*. The cost is substantial. A common 75kVA commercial transformer has in the range of 400 Watts in no-load losses (like leaving four 100 Watt light bulbs turned on). At \$0.10/kWh, this represents a continuous cost of \$350/yr or \$8,750 over the 25 year expected life span of the transformer, eclipsing the purchase cost many times over. And this is just the cost of being turned on. This is just the base cost. The cost of powering the load itself is much more than this. Yes, it costs real money to run a transformer.

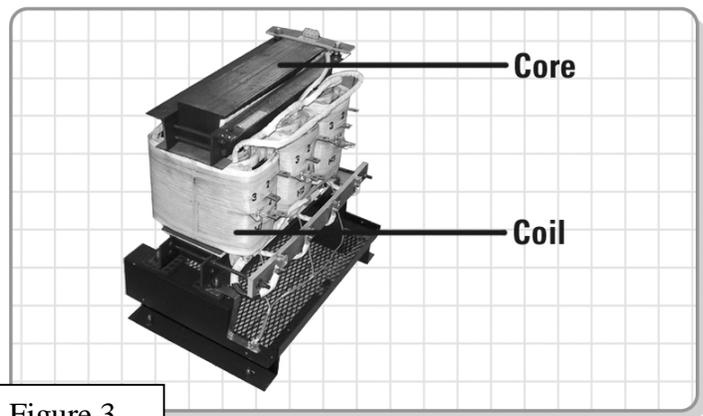


Figure 3

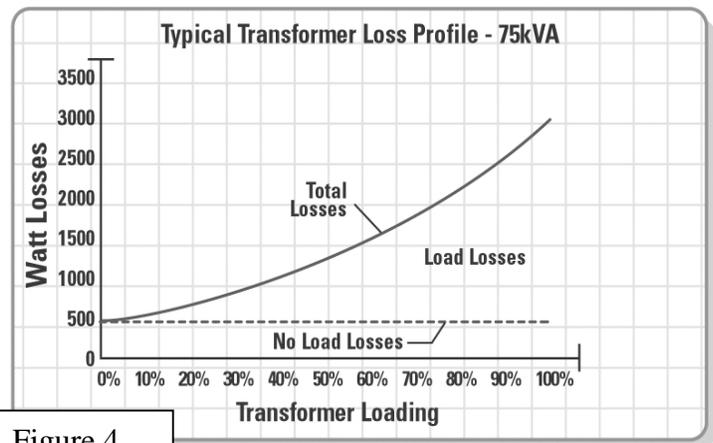


Figure 4

The coil losses, commonly referred to as load losses, are associated with feeding power to the connected load. For linear loads, these losses are predominately I^2R , in other words load losses increase by the square of current from no-load to full-load, driven by the resistance of the coil. Figure 4 shows a graphical representation of how transformer losses increase with loading.

To calculate the cost of these losses, one must refer to the billing structure of the electric utility. This varies across the country and may involve kWh, kW peak demand, and kVA charges. Taking a simple example from figure 4, at 60% load the transformer has roughly 1500 Watts of losses (or 1.5kW) – equivalent to running fifteen 100W light bulbs. If the user is being billed only on kilowatt-hour consumption at a rate of \$0.10/kWh, the operating cost would be 1.5kW x \$0.10/kWh, which equals \$0.15/hr or roughly \$1,300/year – the same order of magnitude as the purchase price of the transformer. Most utilities charge a combination of a kWh rate and a peak demand charge, some charge by kVA or kW only. Other charges may also apply.

Transformer Purchasing – Tendency to Buy Based on First Cost

Electric utilities have traditionally purchased their distribution transformers based on life cycle costing, or Total Ownership Cost (TOC), where the cost of losses is factored into the buying process – after all, as regulated industries they could plan for the long haul. Commercially this is not the case, and with the uncertainty surrounding deregulation, utilities are looking more at first cost, despite the commitment to a higher long-term cost.

The standard low voltage step-down transformer is widely considered a commodity and as such the only perceived differentiator in this case is price – lowest purchase cost wins. Commercial transformer specifications rarely require a minimum efficiency. As you would expect, building a less efficient transformer is cheaper than building a more efficient one, so a typical low-first-cost transformer will have a low up-front cost but high operating cost, with the lifetime cost of the operating losses exceeding the purchase cost many times over.

Transformer Losses – Impact on our Health and the Environment

The EPA estimates that 60-80 billion kilowatt hours annually are attributed to transformer losses, at a cost of \$3-4 Billion dollars, and tying up 9 days of U.S. generating capacity annually. Apart from the cost and the wasted power distribution infrastructure, there are the environmental and health consequences - burning coal or other fossil fuels to produce this wasted power creates additional greenhouse gas emissions – including smog – something we see and feel every day. Reducing transformer losses clearly has many benefits.

Comparing Transformer Losses

Several variables contribute to transformer losses, the most important of which include load level, load profile, and core and coil construction. Since there are a wide variety of transformers on the market serving different purposes, and available from different manufacturers, actual losses incurred in the field will vary substantially from installation to installation.

Load level varies widely, with some installations running very heavily loaded and others more lightly loaded. This difference substantially impacts actual losses incurred. Unfortunately, there is a small body of field data available, driven by the factors such as a lack of awareness of the cost of the losses, and the cost of gathering detailed data from a reasonable number of individual transformers. Faced with the lack of comprehensive field data, this paper pools our years of field experience with a combination of published efficiency data under linear and nonlinear load,

independent testing, as well as before/after field measurements to build a series of representative loss curves for different transformers as accurately as possible with the data available.

It would be easy to walk away given the difficulty of the task, except that the energy savings from the use of more efficient transformers pays for itself many times over its 25-year expected life.

Standard Transformer

The standard transformer is built to deliver its nameplate kVA rating under *linear* load only and is UL listed on this basis. As it has the lower purchase price on the market, it represents the majority of transformer purchases across the country. When feeding electronic equipment, substantial derating is required, on the order of 50% or more, to prevent overheating and premature failure [4]. Along with the high operating cost goes substantial lost capacity, and distortion of the voltage to connected equipment.

Low Temperature Rise Transformer

Transformers with a low operating temperature rise have often been purchased with energy savings in mind, as published full load losses are substantially lower than those of many other transformers. These transformers are traditionally available in either 80°C or 115°C operating temperature rise, as opposed to the standard 150°C rise that represents the majority of low voltage 3-phase low voltage dry-type transformer sales.

The low temperature rise transformer is designed to run cooler than a standard transformer when fully loaded. To meet this objective, manufacturers typically use a larger core and winding set, having the result of higher no-load losses (more core), but lower load losses (more coil). Since total losses are the sum of both core and coil losses, the low rise transformer will have higher losses than other transformers at low load levels where core losses predominate, but lower losses when heavily loaded, since coil losses predominate at high load levels.

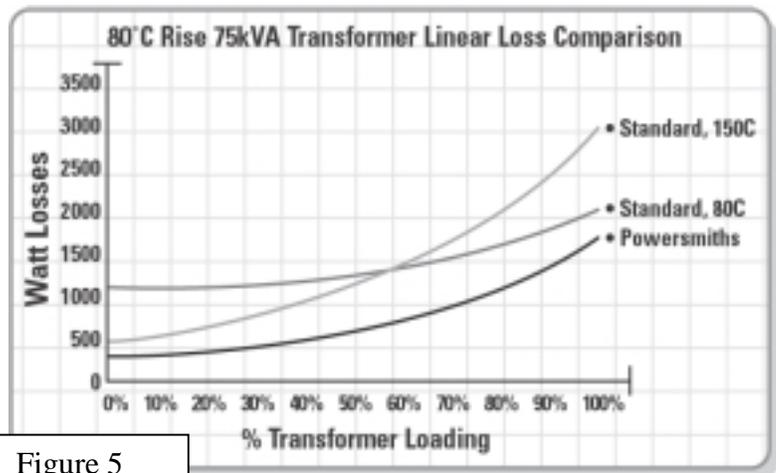


Figure 5

From Figure 5, it is evident that at less than 60% load, it actually costs MORE to operate the 80°C rise transformer than the standard 150°C rise transformer. Depending on the size and manufacturer, the break-even point can be as high as 80%. Since the many transformers are less than 50% loaded, use of an 80°C rise transformer is often a commitment to HIGHER energy costs – the exact opposite of what was intended.

Note that the Powersmiths transformer (curve representative of both the K-Star and T1000 models) has a lower operating cost than either of these transformers at ALL load levels. For example at 40% load, the 80°C unit has about 1300W losses, the 150°C rise has about 1050W losses, and the Powersmiths transformer has about 600W losses, meaning that this 80°C rise

transformer costs 24% more to operate than the standard transformer, and over double the Powersmiths under *linear* load, with none of the power quality or efficiency benefits under nonlinear load deliver by Powersmiths. Another limitation with the low temperature rise transformer is that its UL listing applies when feeding linear loads only.

ENERGY STAR Transformer

In 1998, the EPA included a high efficiency transformer program under the ENERGY STAR banner. As a reference document, the EPA settled on NEMA TP-1 “Guide for Determining Energy Efficiency for Distribution Transformers” [5]. The NEMA TP-1 standard establishes required efficiencies at 35% load for low voltage dry-type transformers, and at 50% load for liquid-filled and medium voltage dry-type transformers. The required efficiency rises with kVA. In a bid to move the first-cost driven market to higher efficiency transformers, Minnesota and Massachusetts both adopted NEMA TP-1 into law, with other states poised to follow suit.

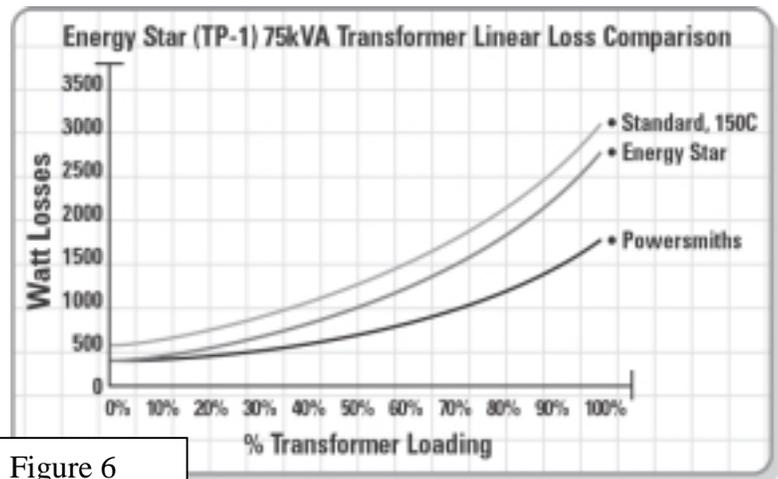


Figure 6

Unfortunately, NEMA TP-1 / Energy Star transformer efficiencies reference test data under linear load, resulting in published efficiencies that are much higher than experienced in the real world due to the additional losses associated with the widespread use of electronic equipment. Ironically, transformers feeding harmonic-rich loads (electronic equipment like PCs) are exempt from meeting NEMA TP-1 benchmark efficiencies. Like the standard transformer, the Energy Star transformer is built to deliver its nameplate kVA rating under *linear* load and is UL listed on this basis. Like standard transformers, Energy Star transformers exhibit increased losses, loss of capacity and increased voltage distortion when feeding electronic equipment.

As shown in figure 6 (linear loading), while the Energy Star compliant transformer is more efficient than the standard transformer, it is not as efficient as the Powersmiths transformer, and delivers none of the power quality benefits that the Powersmiths transformer does.

K-Rated Transformer

Unlike standard transformers, which are designed to feed linear load only and lose capacity when feeding nonlinear loads, k-rated transformers have been designed to feed nonlinear loads with harmonic content up to their nameplate rating. The UL listing is maintained as long as the load profile has a k-factor lower than the k-rating of the transformer. Industry standard ratings include K4, K13 and K20, with K4 and K13 being the most frequently specified. A higher k-rating represents the capability to withstand higher harmonic content.

K-rating is a heat survival rating, not a treatment of associated power quality issues like voltage distortion, and efficiency is not typically discussed. Surviving the extra heat means using more core and coil material, and sometimes use of different construction techniques. Depending on the

manufacturer's design, harmonic losses may be reduced to varying degrees. Ironically, even though the designated use of the k-rated transformer is to feed nonlinear load, manufacturers publish their loss data under linear load conditions. Again, Powersmiths transformers have substantially lower losses and deliver cleaner voltage to the connected equipment than k-rated transformers.

Powersmiths Transformers

Understanding that efficiency and power quality are complimentary goals, Powersmiths designed its transformers with both in mind. Furthermore, they have been independently validated at Oak Ridge National Lab, a US DOE test facility, to run at 98% efficiency under single-phase nonlinear load profile, a dramatic improvement over traditional transformers.

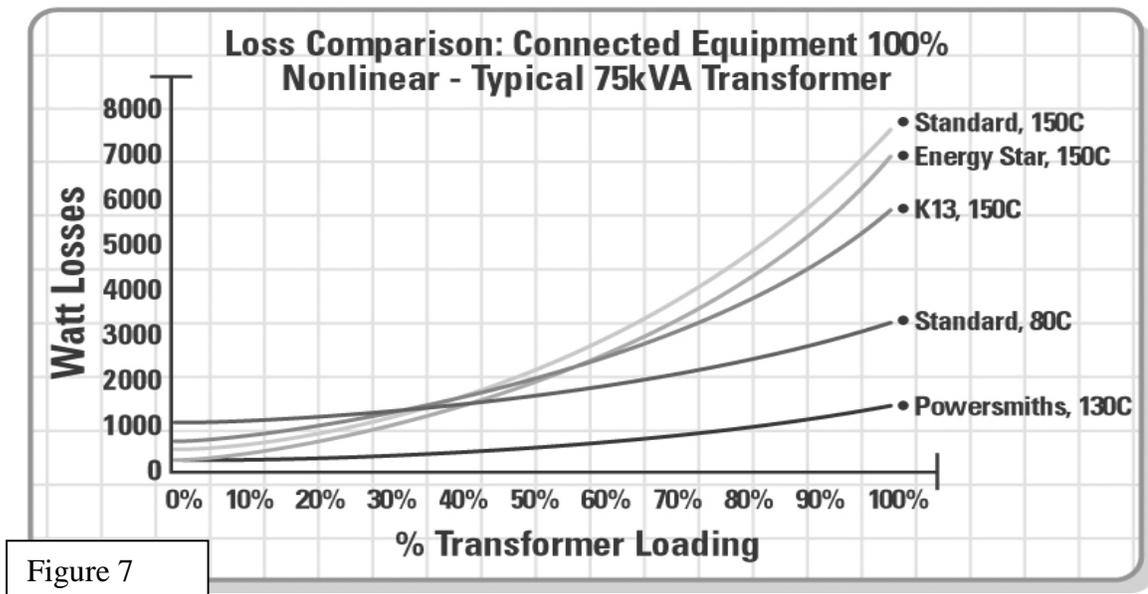


Figure 7

As noted at the outset, losses will vary as a function of load level and load profile and transformer design. Figure 7 compares projected losses of 100% computer-type nonlinear load, and figure 8 looks at projected losses when the load mix is 50% nonlinear equipment. Of course the losses are lower if there is less harmonic content, but as shown in figure 8, even with only half the load being nonlinear at 50% transformer load (37.5kVA), Powersmiths still delivers substantial projected savings of roughly 1600W-700W = 900W over the closest alternative, for an over 50% reduction in losses. The higher the load and the nonlinear content, the greater the energy savings and the greater the power quality benefits.

The Powersmiths product line includes products that are more oriented towards energy and others that are more oriented towards Power Quality. For example, the Powersmiths K-Star transformer is geared to k-rated transformer replacements and projects where the emphasis is on energy savings with the added Power Quality benefit of treating the 3rd harmonic. The Powersmiths T1000 provides comprehensive (3rd, 5th, 7th) harmonic treatment on a system basis, while delivering the same high efficiency but geared to an expectation of heavier transformer loading and higher harmonic content. Both of the T1000 and the K-Star were performance validated at Oak Ridge National Lab.

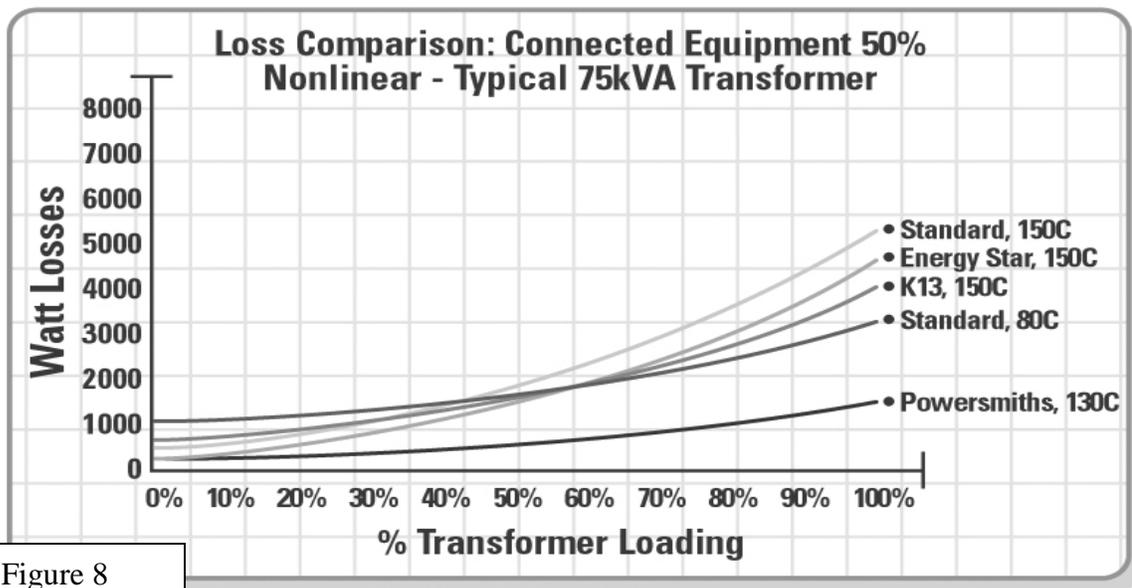


Figure 8

Transformer Losses and Air Conditioning Load

The losses produced by a transformer typically require ventilation/cooling. The higher the transformer losses, the higher the associated cooling cost. The cooling system has both an infrastructure and ongoing operation costs to be considered. It is a simple calculation to translate Watt losses into Btu/hr (1 Btu/hr = 3.3 Watts) for use in calculating the burden on the cooling system. Most manufacturers publish their Btu/hr at full load, which traditionally puts the 80°C rise transformer in a good light since it has lower full load losses than the standard 150°C rise transformer. For example, where a standard transformer is less than 50% loaded, which is quite common, replacing it with an 80°C rise transformer will typically result in higher Watt losses – not less, translating into more Btu cooling requirement – exactly opposite to what was intended. For example, referring to figure 8, with a mixed linear/nonlinear load, the 80°C rise transformer at 50% load will produce roughly 100W more losses than the 150°C rise transformer standard resulting in higher Btu/hr output of about 100/3.3 = 30Btu/hr. By comparison under the same load, the Powersmiths transformer has lower losses by about 1000W or 1000/3.3 = 300Btu/hr than the 80°C rise transformer, and 900W or 900/3.3 = 272Btu/hr less than the 150°C rise transformer. Across the full load range Powersmiths produces less losses and therefore requires less associated cooling than all the other transformers.

Case Study – Powersmiths Transformer Delivers Savings

The tenant of a commercial building on the U.S. west coast had a 75kVA transformer that was hot, even though it was lightly loaded – about 30% of the transformer nameplate rating. A fan was installed and directed at the transformer. The load profile was a mix of linear and nonlinear load as shown in figure 9. The local utility had a rebate program in effect, subject to proof of performance. To fulfill this

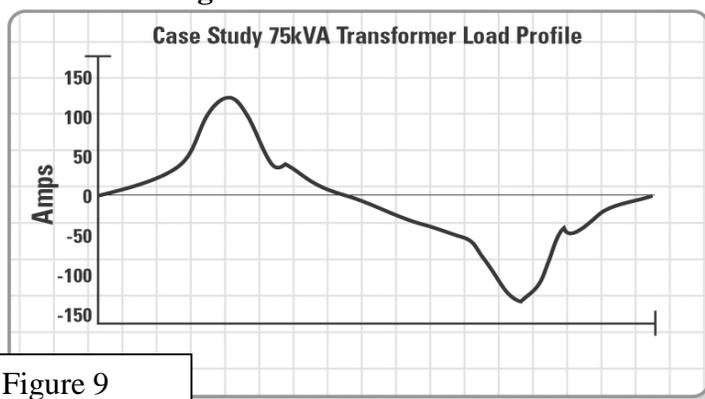


Figure 9

requirement, a 3rd party was contracted to perform revenue class metering before and after the replacement of the existing transformer with a Powersmiths T1000 transformer having the same nameplate rating.

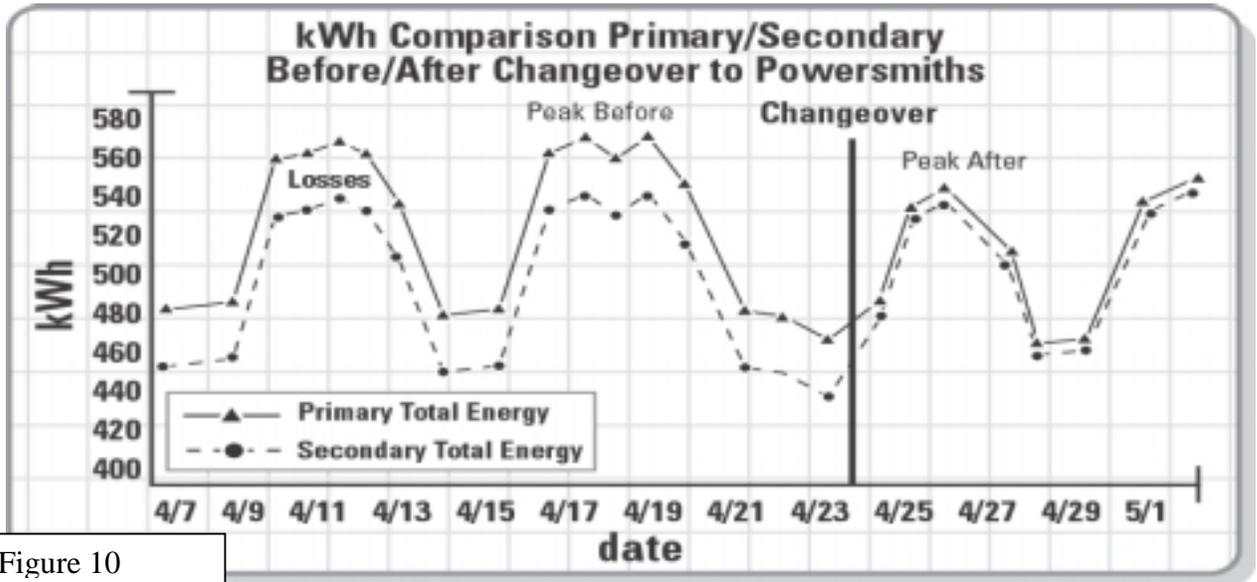


Figure 10

After the changeover, when the standard transformer was replaced with the Powersmiths transformer, the most physically noticeable difference was the reduction in the electrical room temperature due to the lower heat output from the new Powersmiths transformer. Of course, reduced heat means reduced transformer losses, translating into energy savings. Furthermore, power quality improvement was evident as the voltage distortion in the system was reduced. Figure 10 tracks the energy consumption two weeks prior to the transformer replacement and one week after. Losses are the difference between the primary and secondary total energy graphs. Notice that this difference (losses) is much lower with the Powersmiths transformer than with the standard transformer. Figure 11 translates this difference into daily cost to operate the transformer. The results prove that substantial savings are to be had even at lower load levels and

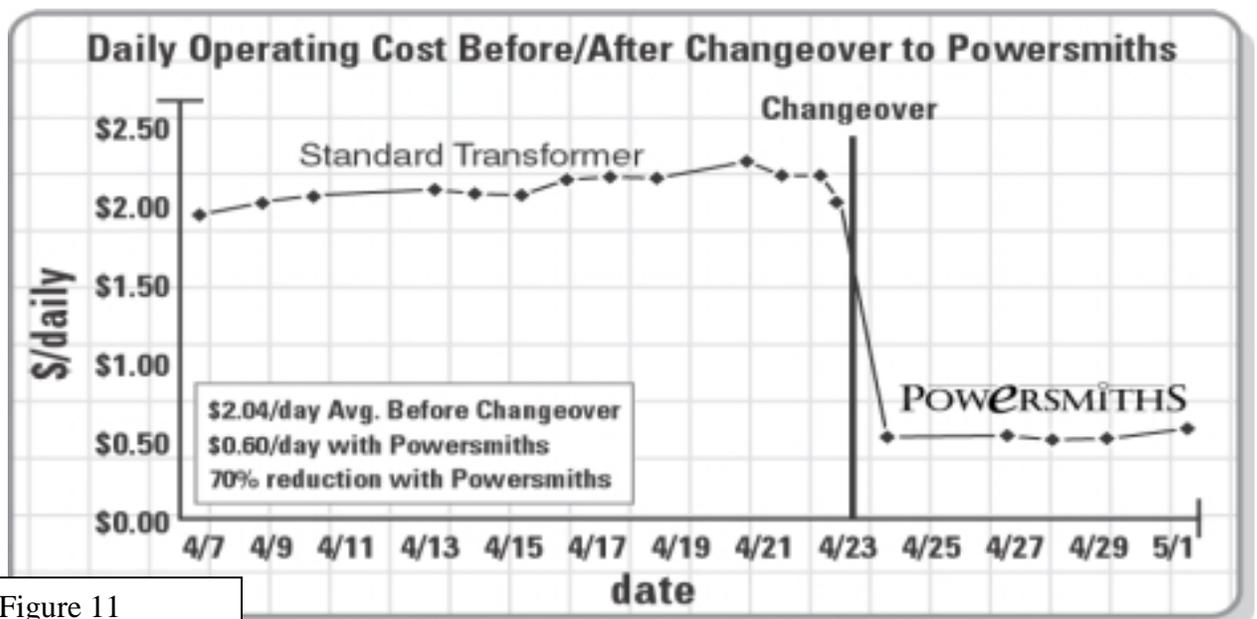


Figure 11

lower nonlinear load concentrations. Qualification for a utility rebate program, as was the case here, makes the return on investment even more attractive.

Energy Savings and Payback Calculator

In order to facilitate the evaluation of potential savings, Powersmiths has developed an Energy Savings and Payback (ESP) calculator. It is a one-page spreadsheet (figure 12) where the user enters data such as the quantity and size of transformers on the project, load level and profile, kWh and demand rates, as well as product costs. The program then calculates the annual energy savings, payback period, and environmental benefits associated with a particular scenario. This tool allows the user to evaluate what to expect under a variety of system conditions such as different load levels, load profiles and utility cost structures. Contact Powersmiths or their local representative for a copy of this tool.

Summary Remarks

As electronic equipment has become more integrated into our daily lives, transformers losses have added a substantial hidden energy cost to operating our buildings. Powersmiths transformers, such as the K-Star and the T1000, have been demonstrated to deliver substantial energy savings and Power Quality improvements, whether the transformer is lightly or heavily loaded, and whether it feeds a dedicated computer equipment load or a mix of linear and nonlinear load. Powersmiths transformers provide improved operating reliability and a proven payback in energy savings.

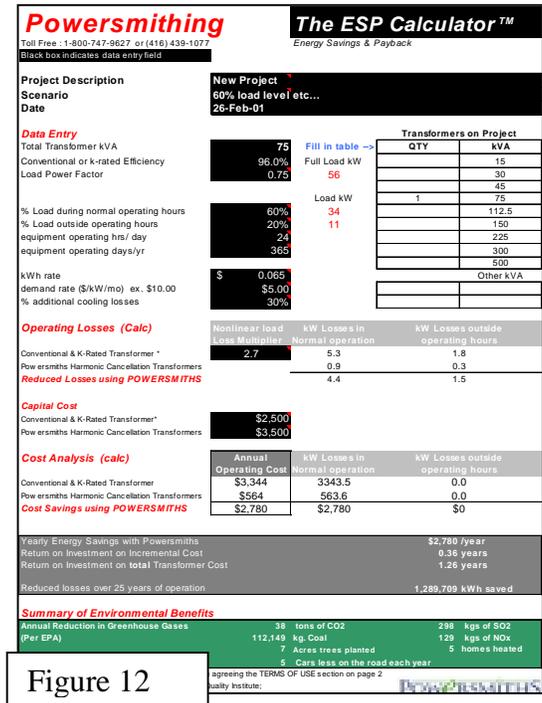


Figure 12

The author would like to thank Jim Tubbesing for his feedback during the preparation of this paper.

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