Transformers Efficiency: Unwinding the Technical Potential

David Korn, The Cadmus Group
Adam Hinge, Sustainable Energy Partnerships
Fouad Dagher, NEES Companies
Charles Partridge, Boston Edison

ABSTRACT

Dry type distribution transformers are located in many commercial and industrial buildings, and consume energy 24 hours each day. One study has calculated losses from dry type transformers at almost 1,700 GWh per year. Because of the potential for reduction in their energy loss, transformers have been identified as a potential energy efficiency technology for market transformation.

Energy losses in transformers occur in both their core (independent of the transformer's load), and in the windings, where losses are proportional to the square of the load. A key issue in determining the most cost effective and energy efficient transformer option in buildings is the average load on the transformer in typical buildings.

In 1996, the National Electrical Manufacturers Association (NEMA) adopted a voluntary energy efficiency standard for transformers, which became the basis for a legislated Massachusetts transformer minimum efficiency standard. The standard sets minimum efficiency levels at a 35 percent load fraction. EPA has also used the NEMA standard as the basis for its Energy Star designation for transformers, and other states have or are considering adopting the standard for their energy codes. Questions were raised by a number of interested parties regarding the actual loading of transformers, which led to concerns that depending on a transformer's load, the legislated Massachusetts requirement may actually cause greater energy use or not be cost effective. If loads proved to be high, then transformers with efficient cores such as low temperature rise models might be more applicable.

To address the technical and economic concerns raised, a study was done on over 40 buildings with about 90 transformers to measure actual transformer loads and determine the energy efficiency potential. The study found that average loads were low, averaging 16 percent, far below the 35 percent used as a basis for TP 1. This paper discusses the results of the study, and the ramifications for transformer efficiency activities.

Background

Industrial and commercial facilities that are served by 3-phase power from the utility typically use low-voltage, dry-type transformers to distribute power internally at 208/120 volts. Loads commonly served by such transformers include wall plugs, lights, fans, and equipment such as computers, printers, and small industrial machinery. However, the extent of the typical load that these types of equipment place on the transformers was not well understood prior to the study.

Transformers are generally sold in three categories distinguished by the expected temperature rise of the winding surface over ambient conditions at their design load. Models specified as 80°C or 115°C temperature rise typically are manufactured with more efficient (more conductive) windings that heat up less than standard 150°C units. The vast majority of the transformers specified and in place are standard 150°C temperature-rise models.

In 1996 the National Electrical Manufacturers Association (NEMA), in its TP 1 standard, specified minimum recommended efficiencies for various sizes of transformers, including low-voltage ones (NEMA 1996). The TP 1 standard calls for efficiencies of around 98 percent (depending on transformer size) at a load factor of 35 percent.[1] At that load factor, such efficiencies are achieved by reducing core losses, which as a percentage of total losses are highest at low load factors. The U.S. Environmental Protection Agency adopted this standard as a criterion for the ENERGY STAR® label for low-voltage transformers. In 1997, the Commonwealth of Massachusetts passed Act 164, Section 313 of which requires that all distribution transformers sold in the Commonwealth after December 31, 1999 meet the TP 1 standard.

As shown in Figure 1, standard-model (150°C) transformers reach peak efficiencies of roughly 96 to 97 percent when the transformers are loaded at 30 to 50 percent of their nameplate capacity (depending on the model). This contrasts with the efficiency of roughly 98 percent achieved by TP 1 transformers at a 35 percent load factor. Also shown are the losses for conventional (non-TP 1) transformers rated at an 80°C temperature rise; these are more efficient than both TP 1 and 150°C transformers at high load factors, but not at low ones.

Figure 1
Efficiency versus Load for Three Representative 75kVA Transformer Models[2]

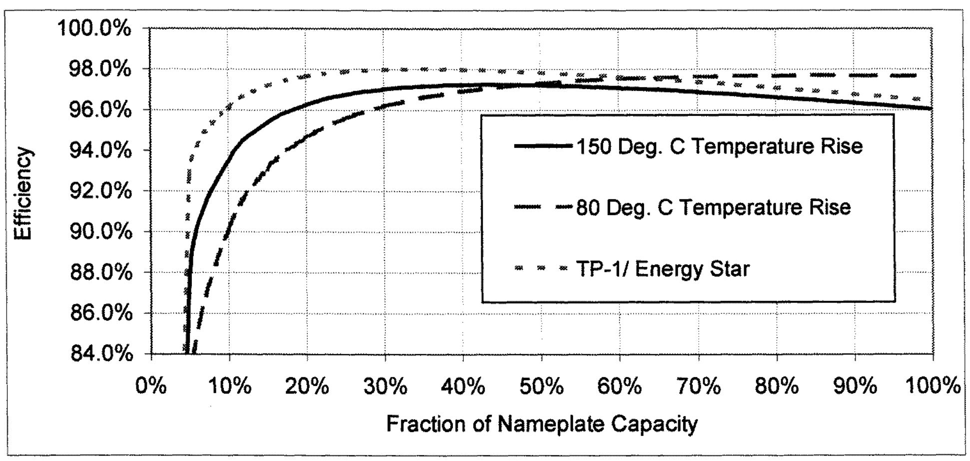


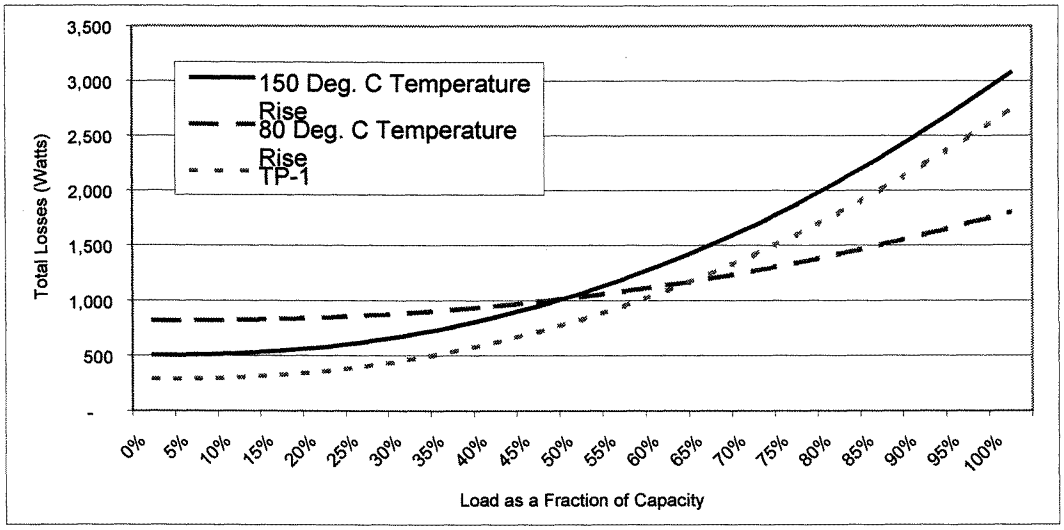
Figure 2 displays the same information as the preceding figure but in a different form. It shows that TP 1 models have lower losses than conventional (150°C) models at all loads, but higher losses than low-temperature-rise (e.g., 80°C) models at loads greater than 65 percent. The savings from using TP 1 transformers are thus sensitive to the transformer load factor. Determining the load factor at which low-voltage transformers

[1] A load factor of 35 percent means that the transformer is transforming electricity at a rate equal to 35 percent of its nameplate capacity. For example a 75-kVA transformer operating at 35 percent load factor is transforming 26.25 kVA (26,250 volt-amperes).

[2] Graph produced by the Transformer Efficiency Calculator (TEC) developed by The Cadmus Group, Inc. under contract to U.S. EPA, August 1999.

actually operate thus was a primary motivation for this study.

Figure 2
Total Losses versus Load for Three Representative 75kVA Transformer Models



Purpose of the Study: the Need for Data on Transformer Loading

The higher efficiency of TP 1/ ENERGY STAR transformers is an opportunity for substantial savings, particularly if loads on dry-type transformers are 50 percent of their capacity or lower. Energy savings would not be as large as those available from low-temperature rise transformers loaded at 65 percent or more.

The primary purpose of the study was to better understand the loads on transformers and the resulting effect on transformer losses. This study complements work done by the U.S. EPA[3] and Cadmus to examine the impact of energy-efficient transformers. Field work performed during this study focused on determining the average transformer load for the service territories of the two participating utilities at a resolution that would allow differentiation between three load regimes: (1) low loads (0 to 30 percent), where core losses would be dominant; (2) moderate loads (30 to 65 percent), where core and winding losses would be important but where TP 1 transformers would still be a logical choice; and (3) high loads (65 to 100 percent), where winding losses would be increasingly important and where low-temperature-rise transformers would be advantageous choices. The study was designed so that results could reasonably be extrapolated to other regions.

The study monitored electrical circuit loads in commercial and industrial buildings to determine, with a reasonable level of statistical confidence; the load factors experienced by dry-type, low-voltage distribution transformers (which are typically rated at or below 600 kVA). This information was sought primarily to predict the average efficiencies of standard transformers in use and to assess the usefulness of the TP 1 standard. It is expected that this information will give utilities, specifiers, and designers a better basis for projecting the

[3] Information on EPA's commercial and industrial ENERGY STAR program can be viewed at www.energystar.gov. The web site contains lists of models with an ENERGY STAR label and has several transformer evaluation tools available for downloading.

savings expected to accrue from the use of TP 1 transformers. Secondary benefits of this study will be to gain information on how transformer capacities relate to the expected and actual load, and include answering questions related to the type of transformer best suited for actual commercial and industrial loads.

This report shows the characteristics of the 353 transformers reviewed in the study and reports detailed findings from monitoring 89 of these transformers. Because the facilities and the transformers studied were chosen at random, the results can be extrapolated to the service territories of the New England Electric System Companies and Boston Edison Company. Although other service territories were not sampled, the results are representative of southern New England and New York State because climate, and therefore the mix of heating and cooling, is similar. To the extent that circuit design practices are similar nationally, many of the results are applicable because the bulk of the loads carried by the transformers are plug loads such as computers and task lighting, which are used in a similar manner throughout the country.

Study Methodology

The primary purpose of the study was to determine the average transformer load factor for the service territories of the participating utilities at a resolution that would allow differentiation between three load regimes: 0 to 30 percent, 30 to 65 percent, and 65 to 100 percent.

A second goal was to examine several building types and determine whether loads vary appreciably among them. If loads were found to vary greatly between the building types, then the information would be important to designers specifying the type of transformer to be installed. Sample sizes were designed to provide a resolution of ±5 percent, at a 95-percent confidence level, based on initial estimates of population variation.

The study was intended to monitor circuits that were installed or modified in the last 10 years so that the results would represent recent design practices and so be useful to engineers now specifying transformers.

To accomplish the goals described above, buildings considered for the study were screened to meet each of the following conditions:

- Buildings had to be within the service areas of the participating utilities.
- Buildings had to be in one of five categories:
    - Universities
    - Health care facilities
    - Manufacturing facilities
    - Office buildings
    - Retail facilities
- Buildings had to be built or have had their electrical distribution system modified or renovated within the past 10 years.

Facility and Circuit Selection

The participating utilities supplied Cadmus with lists of large customers that had either renovated or built their facilities in the last 10 years. Between the utilities, roughly 250 facilities were identified in the 5 building types listed above. Cadmus organized the lists provided by the utilities into the 5 building types and used a random-number generator to select 12 buildings of each type; a total of 60. For each building type, Cadmus and the utilities made initial contacts and requested participation. Building managers refusing to cooperate and buildings that did not have 480-volt service were removed from consideration. After initial contacts, 43 buildings were qualified for participation in the study.

At each facility, the study field team first surveyed all dry-type transformers and noted the following information:

- Transformer make, type (temperature rise), and model.
- Transformer capacity.
- Transformer impedance.
- Primary and secondary voltages and, where listed, amperages.
- Type of primary and secondary circuits (e.g., typically delta primary/wye secondary).

The field team then listed the transformers as candidates for measurement. They removed from consideration a few transformers that did not meet these requirements:

- They could not be accessed safely, or the load they served could not be at least generally determined.
- They were known to be older than 10 years. In developing their initial list of buildings, the participating utilities first screened buildings to include those that were either built or modified in the last 10 years. Cadmus then interviewed building operators in the field to determine the approximate ages of the transformers. In some cases the building operators did not precisely know transformer ages, and several transformers probably up to 15 years old were monitored.

Transformers remaining on the candidate list were randomly selected for monitoring using a random-number generator. This selection method was used for several reasons:

- It helped ensure that a representative selection of transformer sizes would be monitored. This was important because the ratio of core to winding losses varies by size and thus the relationship between load and efficiency also varies.
- It avoided a bias toward monitoring transformers that the field teams or the facility electricians found interesting. This avoided focusing on problem transformers or on particular brands or types.

Results of Transformer Metering

Loads for All Monitored Transformers

The average load factors of the 89 transformers monitored were calculated using a root-mean-square (RMS) method to properly weight periods of high loads. By using this method, the average can be used to directly calculate transformer losses. On average, the load was 15.9 percent of the transformers' nameplate capacity in volt-amperes. Summary statistics for the 89 transformer loads are presented in Table 1. Based on the observed standard deviation, the estimated average load of dry-type transformers over the utility service areas was 13 to18 percent at a 95-percent confidence level.

The median load factor is well below the mean, reflecting the effect of using RMS averaging rather than a simple arithmetic mean, and the fact that several transformers loaded in 30 to 60 percent range will pull up the average load without appreciably raising the median. The minimum load of 0.0 percent reflects a single transformer serving an unused circuit. The fact that it was not used was not known prior to installing metering equipment. It was retained in the study because it was chosen randomly and metered and will reflect a portion of the larger transformer population. Removing the transformer from the study would have minimal effect on the statistics in Table 1 because of the large number of transformers metered.

Table 1
Summary Statistics for the 89 Transformer Loads Measured
(Percent of transformer capacity)

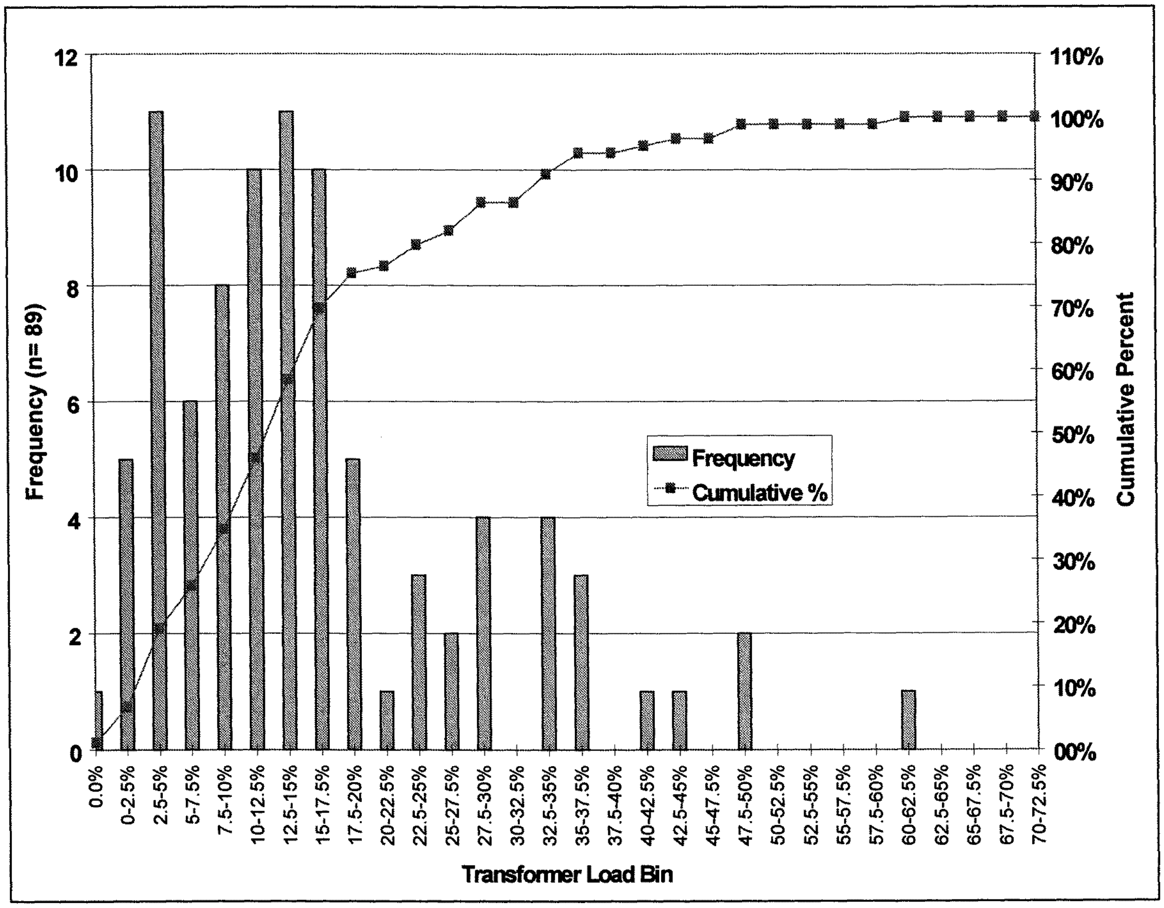
RMS average load	15.9%
Upper estimate @ 95 percent confidence	18.5%
Lower estimate @ 95 percent confidence	13.3%
Median RMS load	12.7%
Observed maximum RMS load	62.4%
Observed minimum RMS load	0.0%
Standard deviation of average loads	12.4%
Number of transformers	89

Not only was the average RMS load on transformers low, fewer than 4 percent of transformers monitored had average loads greater than 50 percent (see Figure 3). Only 14 percent had average loads greater than the 35-percent target load of the TP 1 standard.

The reason for the average load to be well below the transformer's capacity is two-fold. First, the average load is naturally lower than the peak load because of variations in loads that the transformer serves and the schedule of those loads. Advances in power management allow office equipment to "sleep" when not in use, effectively decreasing the average load relative to peak loads. Second, the peak load is below the transformer's capacity because transformers are specified based on their expected peak load plus some margin of safety and room for future expansion in demand. Considering the two ratios together, the peak relative to transformer capacity and the ratio of the peak to average load, it is understandable that the average load on a transformer is low.

The *peak* load of each transformer as measured by logged current readings collected every 10 minutes was determined for each of the 89 transformers, then averaged. The average peak load was 33 percent. This does not necessarily mean that the average margin of safety was precisely 3.0. Other considerations, including the balance of loads across the transformer's three phases, may reduce the margin somewhat, but the margin of safety is, nonetheless, substantial. The average ratio of average to peak loads for the monitored transformers was 52 percent, reflecting varying load schedules and the fact that modern office equipment draws little current when not in use.

Figure 3
Histogram of RMS Average Transformer Loads



Loads by Building Type

To determine whether there was variation in transformer loads between building types, 17 or 18 transformers were monitored in each of the following five building types:

- Universities.
- Health care facilities.
- Manufacturing facilities.
- Office buildings.
- Retail facilities.

Summary statistics are presented in Table 2 for each building type. The average loads were consistent across building types, varying from only 14.1 to 17.6 percent. Figure 4 shows the average RMS loads and the range of the 95-percent confidence limits of the average load for each building type. The confidence interval is larger for each building type than for all building types together because fewer samples were collected for each building type. Even the upper bounds, however, are well below the 35-percent load at which transformer efficiencies are listed in TP 1 and in the ENERGY STAR label.

Table 2
Transformer RMS Average Load Factors by Building Type
(Percent of transformer capacity)

	Building Category				
RMS average load factor:	Universities	Health Care	Manufacturing	Office	Retail
Average	16.3%	17.6%	14.1%	14.6%	17.0%
Upper estimate @ 95 percent confidence level	23.4%	24.9%	20.2%	19.7%	22.6%
Lower estimate @ 95 percent confidence level	9.1%	10.4%	8.0%	9.5%	11.3%
Median	14.3%	12.7%	10.8%	13.6%	14.3%
Maximum	62.4%	50.0%	47.5%	33.7%	42.5%
Minimum	1.3%	1.3%	0.9%	0.0%	1.1%
Standard deviation of average loads	14.5%	14.2%	12.3%	10.2%	11.4%
Quantity	18	17	18	18	18

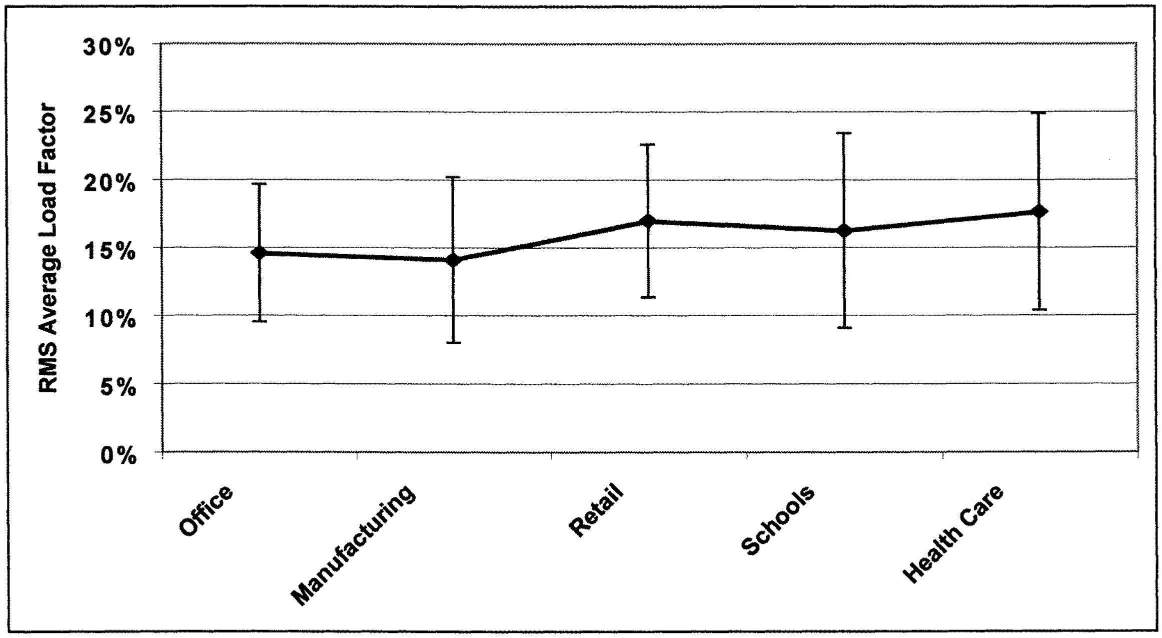
Prior to the study, it was expected that average loads would differ among building types because of varying schedules, varying equipment, and the possibility of different design practices. As measured, however, the average loading varied little in part because the transformers serve similar equipment, typically computers and lighting, across building categories. Loads particular to a building type, manufacturing equipment for example, are often served by 480-volt power upstream, on the primary side of the studied transformers.

Load by Building Schedule, Transformer Size

There was little statistical difference between circuits in buildings with three-shift schedules and those with single-shift schedules. The primary reason is that transformers often serve a mixture of circuits with varying schedules, which do not necessarily correspond well with overall building schedules. For example, transformers in a single-shift office building may serve refrigerators and other loads that are not shut off at night. A portion of the loads in three-shift buildings may cycle off repeatedly and result in low average loads or, like task lighting, may be shut off during second and third shifts. This result is for the study-wide population of transformers. For an individual transformer, however, there are certainly cases where a three-shift building's transformer carries a higher average RMS load than one in a single shift building.

We examined loading by transformer size to see whether the size of a transformer was correlated with a high or low load. While the average loads varied, the variation was not statistically significant because of the large standard deviation and small sample size. While the load of 15 and 30 kVA transformers was relatively high, these transformers account for only 7 percent of the capacity of the dry-type transformer market.

Figure 4
RMS Average Transformer Load Factors by Building Type



(Bars indicate 95 percent confidence interval of each average load)

Loads Observed in the Monitored Transformers

Figure 5 combines the 179,000 10-minute load measurements of all 89 transformers to illustrate the portion of time that the transformer population occupies a particular load regime. Not only are the average loads low, but the loads for all periods are relatively low. Loads exceeded 50 percent of design capacity during only about 3 percent of all measured time periods.

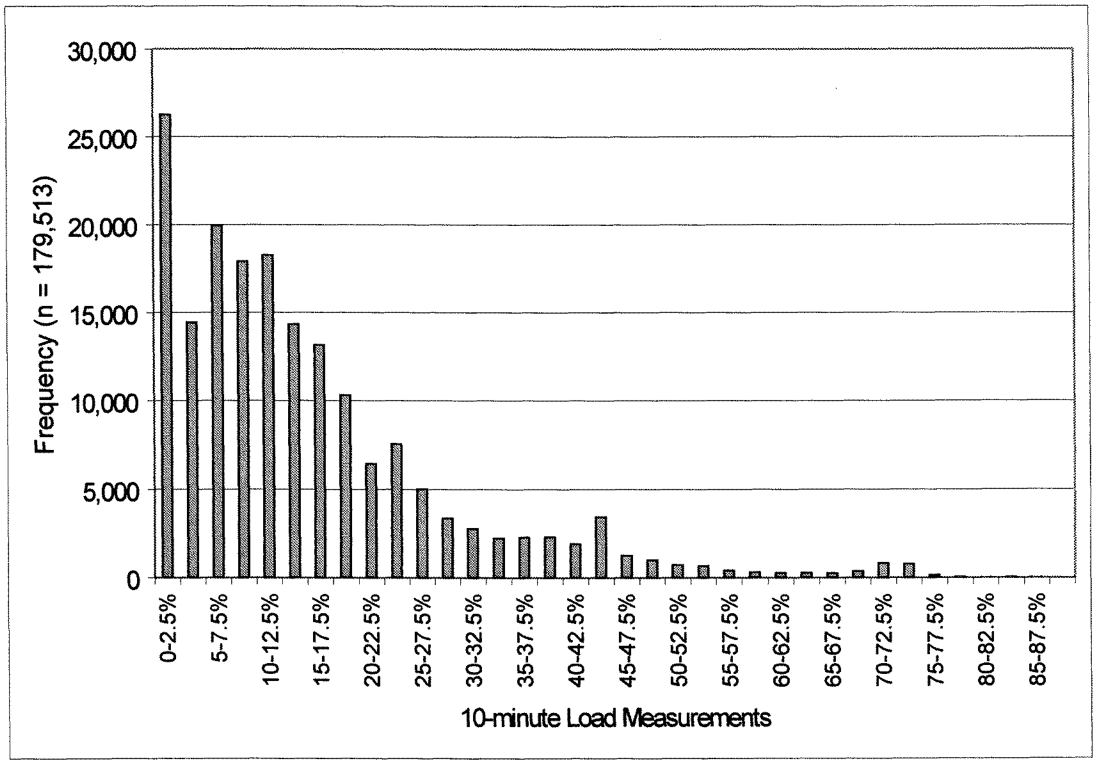
If all of the transformers metered in the study were reduced an average of one-third in size (equivalent to installing a 30-kVA model instead of a 45-kVA unit), roughly 1 percent of measurements would have been at or slightly above capacity, with most transformers well within their capacity for all time periods.

Implications toward Energy Savings Potential

As shown in Figure 1, the efficiency of a 75 kVA TP 1/ ENERGY STAR transformer peaks at 98 percent at 35 percent load while the efficiency of a conventional transformer peaks at a load of 40 to 50 percent. At the average RMS study load of 16 percent, a TP 1 transformer is roughly 1.7 percent more efficient than a conventional model, or stated another way, uses roughly 40 percent less energy than a conventional model.

A 75-kVA TP 1 transformer has a core loss of less than 300 watts, a saving of 200 to 250 watts over a standard unit (Table 3). Through the use of more-efficient core materials, lower core losses ultimately may be economically feasible. An amorphous core dry-type transformer with a core loss of 70 watts, an order of magnitude improvement over standard models, was released in spring 2000. The winding losses for a typical 75-kVA transformer at 16-percent load are roughly 50 watts (roughly 2 percent of their full load losses). The winding losses are only slightly lower for other high-efficiency models, primarily because at low loads the winding losses are low and thus little improvement is possible.

Figure 5
Histogram of Transformer Load Factor Measurements
For All Study Time Periods and All Transformers



As shown in Figure 1, a typical 80°C model is designed to reach peak efficiency at a load of roughly 75 to 80 percent. In this graph using the RMS average load yields the average transformer efficiency. The 80°C model transformer would be a poor choice at the RMS load shown in this study. In fact, this model would have roughly 2.5 times the losses of a TP 1/ ENERGY STAR transformer. There may, however, be other reasons for specifying an 80°C model including the large margin of capacity it provides, and the lower heat rise which may be desired in confined spaces where heat buildup is a concern.

For the 321[4] three-phase transformers surveyed (26.5 MVA) for which full information was available and verifiable, roughly 790,000 kWh would have been saved annually had TP 1/ ENERGY STAR transformers been installed instead.[5] These savings of roughly 18,600 kWh per facility per year could be achieved by a new building specifying ENERGY STAR transformers. For context, the study buildings were large commercial and

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[4] Of the 353 transformers surveyed, 321 had information on both size and type available.

[5] Energy savings were calculated using a major manufacturer's TP 1 line and the average energy use of major manufacturers' standard transformer models. Savings were calculated for the sizes of the 321 transformers surveyed. The study average load of 15.9 percent RMS load was used to calculate losses.

industrial buildings with an average area of roughly 100,000 square feet.

Table 3
Losses in Various Types of 75 kVA Transformers

		Winding Loss (watts)		
75kVA Transformer Models	Core Loss (watts)	@ 100% Load	@16% *RMS* Average Load	Total Loss @16% *RMS* Average Load
Standard Model	500-550	2,500-3000	45-54	545-604
Major Manufacturer's TP 1	288	2,480	45	333
Major Manufacturer's 80°C	819	984	18	837
Custom model	190	910	16	208
Amorphous core (predicted)[6]	70	2600	47	117

Extrapolating to the annual dry-type transformer market of roughly 12,000 MVA (Barnes et. al. 1997) and using the size distribution found in this study, roughly 350 million kWh would be saved per year nationally assuming 20 percent market penetration for five years of sales.[7] Interpolating this figure based on commercial and industrial electrical sales U.S. Census Department 1998) this converts to savings of 5.5 million kWh in Massachusetts. Interpolating based on population yields a savings figure of 8 million kWh.

If an ultra-low-loss transformer were rapidly brought to market, the possible savings would be on the order of 620 million kWh, assuming the same level of market penetration. Massachusetts' savings would range from 10 to 14 million kWh.

Conclusions

This study found that dry-type low-voltage transformers are lightly loaded across building types, building schedules, and transformer sizes, with an RMS average load factor of 16 percent. This load is in the range in which most losses are attributable to the transformer core and where an efficient-core transformer design such as TP 1/ ENERGY STAR is advantageous. The study also found that loads on the monitored transformers were low for most time periods, exceeding 50 percent of capacity for only 3 percent of measurements. This means that most transformers do not approach 50-percent loading even during their peak load.

Transformers are lightly loaded: peak loads even at the individual phase level averaged 33 percent of capacity for transformers monitored. The low peak loads in the transformers indicate that sizing procedures for these types of transformers may be worth examining. While not all transformers are over-sized, the majority of those metered were lightly loaded during the study even at their peak loads. If it were possible to reduce the size of a portion of the transformers installed, the incremental cost of the smaller TP 1 transformer over the larger standard unit would be much lower then buying a TP 1 model of equal size.

At the loads measured in this study, nearly all of the transformer losses are from the core; losses from windings are minor. Because the windings are operating at such low loads,

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6 Conversation with Allied Signal, Amorphous metals division, October 1999.

7 Savings were calculated by extrapolating study savings to the annual sales of transformers.

even major improvements in their efficiency would produce a relatively small benefit, not just on average but for nearly every transformer measured. Therefore, TP 1/ ENERGY STAR transformers and other models with high-efficiency cores are good choices for the loads measured in this study. For the transformers metered, an 80°C temperature rise model would have been a poor choice. In general because the types of transformers metered are lightly loaded, low temperature rise transformers would cost more *and* require more energy than standard models.[8] Similarly 115°C temperature rise models would use more energy than TP 1 models for nearly all of the average RMS loads measured.

For the transformers surveyed in 43 facilities, nearly 800,000 kWh would have been saved annually had TP 1/ ENERGY STAR transformers been installed instead.[9] Extrapolating to the annual dry-type transformer market of roughly 12,000 MVA, roughly 350 million kWh would be saved per year nationally, assuming 20 percent market penetration of TP 1/ ENERGY STAR for five years of transformer sales, and 620 million kWh could be saved annually if an ultra-low-loss transformer were rapidly brought to market.

The pending TP 1 standard will provide energy savings over the traditional use of standard models for any load fraction that transformers experience. Transformers with an 80°C temperature rise were rarely encountered in this study and nationally are not commonly used for dry-type, low-voltage applications. While they can provide higher energy efficiency than even TP 1 models at very high loads, such loads were not observed in metered transformers and are anticipated to occur rarely, if ever, in the transformer population. Thus, energy consumption per facility and in the aggregate will decrease through adoption of the TP 1 standard.

The study's findings have ramifications beyond Massachusetts however:

- Metered load fractions were low illustrating the importance of efficient transformer cores. At the metered average load fraction of 16 percent, a typical transformer winding losses roughly 2 percent of its rated full load loss. For a standard 75-kVA transformer this is only 50 watts. Because a standard core losses over 500 watts, energy efficiency investment is best directed towards an efficient core.
- Amorphous core transformers recently introduced have ultra low loss cores (e.g. 75 watts for a 75-kVA transformer) and reach peak efficiencies of 99% at load fractions of 15 to 20%. In contrast a standard TP 1 transformer reaches a peak efficiency of 98% at 35 % load but delivers roughly 97% efficiency at 15% load. Where low loads are suspected, a transformer with a very efficient core should be installed.
- The 16% low fraction may lead to revision of some loss and savings estimates. Some researchers have used an installed capacity figure multiplied by an average load of 35% of higher to calculate the amount of electricity transformed in low voltage, dry-type transformers. A load fraction of 16% would cut such an estimate in half.
- The findings show that low temperature rise transformers are rarely the optimum choice from an efficiency standpoint unless they also have a high efficiency core.
- The findings may illustrate the need to revisit transformer-sizing procedures. While the

[8] There are some models available that combine low temperature windings with an energy efficient core that would be efficient at both low and high loads. The problem with these models is that the purchaser pays a premium for high efficiency windings but receives little benefit from them.

[9] Energy savings were calculated using a major manufacturer's TP 1 line and the average energy use of major manufacturers' standard transformer models. Savings were calculated for the sizes of the 321 transformers surveyed. The study average load of 15.9 percent RMS load was used to calculate losses.

study focused on average loading, 10 minute metering data for individual transformer legs rarely showed loading above 50 percent.

- In light of this study's findings, assumed loading to medium voltage transformers should be revisited. Several research efforts assumed loading as high as 50 percent. TP 1 bases efficiency standards at 50% load. Several leading brands of medium voltage transformers are designed for peak efficiency at 50 percent. The factors that lead to low loads in low voltage transformers may also play a role in loads to medium-voltage transformers.

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