BONNEVILLE POWER ADMINISTRATION

Emerging Technologies

Dry-Type Transformer New Construction and Retrofit Energy Savings Potential

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A Report for the BPA Emerging Technologies Initiative

Bonneville Power Administration (BPA) funds the assessment of emerging technology opportunities that have the potential to increase energy efficiency. BPA is committed to identify, assess and develop emerging opportunities with significant potential for energy savings in the Pacific Northwest.

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Abstract

Significant annual energy savings in the Pacific Northwest may be achieved through a decrease in no-load losses of low-voltage dry-type transformers. These reduced losses may be realized by replacing older inefficient transformers with new efficient ones, downsizing, and right-sizing new installations and retrofits. Bonneville Power Administration currently offers incentives for retrofit and new construction applications of lower loss transformers, and supports education and market research to further the opportunities for purchasers to select transformers with the lowest available no-load losses for their applications.

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Acronyms

ACEEE – American Council for an Energy-Efficient Economy
A&E – Architectural and Engineering
aMW – Average megawatt
BPA – Bonneville Power Administration
C&I – Commercial and industrial
CEE – Consortium for Energy Efficiency
DOE – US Department of Energy
EPA – US Environmental Protection Agency
ET – Emerging technologies
FCRPS – Federal Columbia River Power System
HMT – Harmonic Mitigating Transformer
HVAC – Heating, ventilation, and air conditioning
kVA – Kilovolt-ampere
LBNL – Lawrence Berkeley National Laboratory
LEED – Leadership in Energy and Environmental Design
NEEP – Northeast Energy Efficiency Partnership
NEMA – National Electrical Manufacturers Association
OPAL – Optimized performance for the application load
RMS – Root-mean-square
THD – Total harmonic distortion
USD – United States dollars
WE – Weekends
WD – Weekdays
WSU – Washington State University Energy Program

Executive Summary

Low-voltage dry-type transformers are a proven technology. Air-cooled low-voltage dry-type transformers rely on natural ventilation to remove heat. They are widely used in commercial, industrial, and institutional buildings to step down alternating current distribution voltages (typically 480/277 V) to those required by HVAC systems, lighting, and process loads (220, 208 V) or voltages required for office equipment (120 V). Dry-type transformers are typically owned, operated and maintained by the end-use facility owner, not the servicing utility. “Dry-type” refers to the fact they are not immersed in oil (used to help cool the transformer) and thus are allowed for indoor applications; oil filled transformers must reside outdoors, per US fire protection code.

Dry-type transformers lose energy through both no-load and load losses. While no-load losses are small compared to load losses, a decrease in no-load losses can lead to significant annual energy savings because no-load losses occur continuously when a transformer is energized. While transformer energy efficiency is given assuming sinusoidal current and voltage waveforms and is taken at the 35% load point, previous studies have found that dry-type transformers in various building types are generally loaded to about 16% of the full capacity.

This report examines the changes in both voluntary and mandatory minimum low-voltage dry-type transformer efficiency over time. The performance and energy efficiency of new dry-type transformers varies. While all transformers must meet or exceed the current US Department of Energy (DOE) 2016 mandatory minimum efficiency standards, transformer manufacturers try to produce a least cost design while trading off no-load or core losses against load or resistance losses in the winding or coil material. That trade-off means that some transformer designs are superior and have reduced losses when lightly loaded.

There is a need for awareness building and education programs so low-voltage dry-type transformer purchasers can begin to selectively acquire and install transformers with the lowest available no-load losses. The report also examines the energy savings associated with the replacement of older dry-type transformers both with and without downsizing. Energy savings can also be obtained through right-sizing of new transformer applications in the future and during transformer retrofits and upgrades.

Purchase of a new dry-type transformer that is optimized for operation over the end-users specified load range can result in energy savings at a minimal incremental cost. Although more information is desired about the loading on, sizing practices, or performance of the existing Pacific Northwest low-voltage dry-type transformer stock, BPA stands ready with existing custom project incentives. Bonneville Power Administration (BPA) encourages utilities’ engagement to further the practice of purchasing more efficient, better sized new transformers and exploring early retirement of existing units. If you seek further information or have questions, please contact Tony Koch (jakoch@bpa.gov), with Bonneville Power Administration.

Background and Technology Overview

Bonneville Power Administration

Bonneville Power Administration (BPA) is a federal power marketing agency within the Department of Energy. BPA markets wholesale electrical power from 31 federal hydroelectric projects in the Northwest, one nonfederal nuclear plant and several small nonfederal power plants. Although BPA is part of the U.S. Department of Energy, it is self-funded and covers its costs by selling its products and services.

In 1980 Congress authorized the Pacific Northwest Power Act (Power Act). The act creates a NW Power Planning Council (Council) and mandates the Council create a regional conservation and electric power plan that establishes a 20 year demand forecast of BPA's load service obligation. This plan is also known as the Council's Power Plan and must be updated at least once every five years. In serving the region's load obligations, the administrator is directed to meet all load growth through conservation resources first.

Since its inception, the BPA's Energy Efficiency program has delivered 5,050 average megawatts (aMWs) to the region, which is equivalent to the annual output from five of the largest hydro projects in the Federal Columbia River Power System (FCRPS). BPA works in concert with its 114 public power customer utilities to deliver about 40% of the regional efficiency targets. The Council's Power Plan requires the region to:

- Aggressively pursue energy conservation
- Aggressively pursue various institutional and business-practice changes to reduce the demand for flexibility and to use the existing system more fully, and
- Look broadly at the cost effectiveness and reliability of possible sources of new capacity and flexibility [1]

BPA launched its Resource Program shortly after passage of the Northwest Power Act. The purpose of the program is to assess BPA's need for power and reserves and develop an acquisition strategy to meet those needs. The Resource Program identified an energy deficit particularly with the largest deficits in the winter.[2] Prioritizing conservation measures that address system peaks is most beneficial.

[1] https://www.nwcouncil.org/sites/default/files/7thplanfinal_chap03_resstrategy_3.pdf
[2] https://www.bpa.gov/p/Power-Contracts/Resource-Program/Documents/BPA%202020%20Resource%20Program%20Refresh%20Summary.pdf

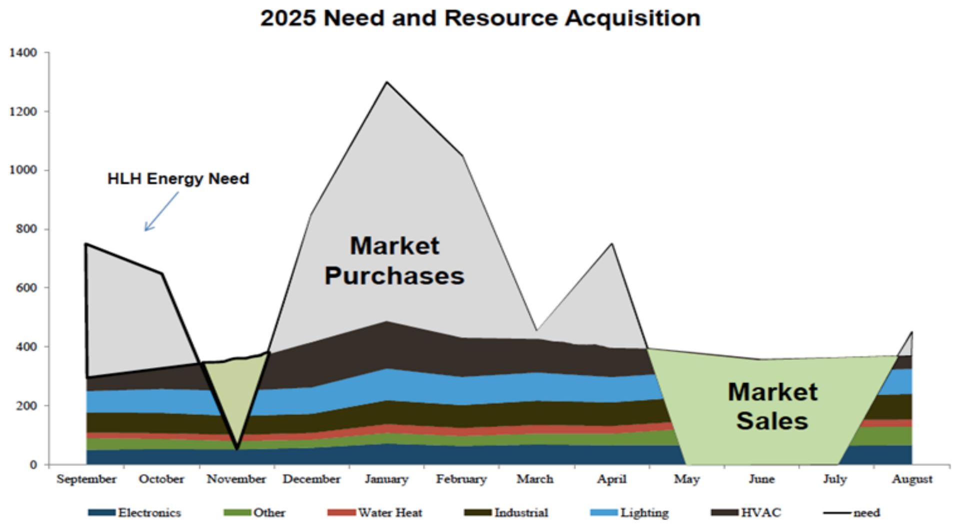


Figure 1. BPA Resource Program Requirements

Technology Description

Dry-type transformers are not a new technology. They are widely used in commercial, industrial, and institutional buildings to step down alternating current distribution voltages (typically 480/277 V) to those required by HVAC systems, lighting, and process loads (220, 208 V) or voltages required for office equipment (120 V) (PG&E). Commercial buildings often have one or more low voltage distribution transformers on each floor to supply power for HVAC equipment, building systems, and plug loads (CEE). Loads typically served by dry-type transformers include wall plugs, lights, fans, and office equipment such as computers, printers, copiers, and small industrial machinery (National Grid).

Figure 2. Low-Voltage Dry-Type Transformer and Sample Transformer Nameplate

Figure 2 shows a typical low-voltage dry-type transformer along with a sample transformer nameplate (National Grid). The nameplate provides information about the transformer type, rating or size (in kVA), temperature rise (typically 80, 115, or 150^{o}C) and provides connection guidance. Unfortunately, transformer nameplate data does not show the no-load or load loss values. These are documented as part of the manufacturing process and are provided to the purchaser of the transformer.

Dry-type transformers have no moving parts; they consist of a steel core wrapped with high conductance copper or aluminum primary and secondary windings. The ratio of the number of turns or times each wire is wrapped around the core in the primary versus secondary windings dictates the level that the input voltage is stepped down (PG&E).

Transformers lose energy through both no-load and load losses. Dry-type transformers are air-cooled and rely on natural ventilation to remove heat. A liquid-immersed or oil-cooled transformer is generally more efficient that a dry-type unit, but such units are not generally placed inside buildings due to leakage and flammability concerns. Utilities purchase liquid immersed transformers for mounting on poles, or outdoor pads or vaults. Commercial, institutional, and industrial users install dry-type transformers almost exclusively.

Low-voltage dry-type transformers are differentiated by input voltage and secondary voltage (they generally take building power at 600 V or less and reduce it to 208/120 V), temperature rise (80^{O}C, 115^{O}C, or 150^{O}C), and ability to withstand waveforms with harmonic distortion (K-factor rating).

Dry-type transformer's lifetimes typically exceed 30 years, require little to no maintenance, and have low failure rates because they have no moving parts (PG&E). They are generally installed or replaced only during new construction, major renovations when load increases significantly, at the end of an in-service transformer lifetime, or when a utility retrofit incentive program is available.

Like many kinds of electrical equipment, dry-type transformer performance and efficiency has significantly improved over time. Many old, inefficient units remain in service and energy savings are available through a retrofit program that results in replacement with an upgraded and perhaps downsized unit.

Performance of new dry-type transformers also varies. While all transformers must meet or exceed the current mandatory minimum DOE-2016 efficiency standard at the 35% load point, transformer manufacturers try to produce a least cost design while trading off no-load or core losses versus load or resistance losses in the winding or coil material. That trade-off means that some transformer designs are superior and have reduced losses when lightly loaded while others have reduced losses when operating at close to full-load. Purchase of a dry-type transformer that is optimized for operation over the end-users specified load range can result in energy savings at a minimal incremental cost.

Evolution of Transformer Efficiency Standards

National Electrical Manufacturers Association Voluntary Efficiency Standards

The National Electrical Manufacturers Association (NEMA) published its NEMA Standards Publication TP-1-1996 Guide for Determining Energy Efficiency for Distribution Transformers in 1996 to establish voluntary NEMA transformer minimum efficiency levels (NEMA). This is the first time a national level of efficiency was suggested and thus marks the start of increased efficiency. Later in the report it will be used as a time frame reference in consideration of replacing working transformers. Single-phase low-voltage dry-type units rated from 15 to 333 kVA are covered by this standard along with three-phase units rated from 15 to 1000 kVA. (The original TP-1 efficiency standards were later modified with the publication of NEMA TP-1 – 2002.)

Even with the NEMA published voluntary efficiency standards, sales of energy efficient transformers languished due to high prices and limited availability. In 1998, the Consortium for Energy Efficiency (CEE) through its Commercial and Industrial (C&I) Distribution Transformer Initiative, and the US Environmental Protection Agency (EPA) through its Energy Star C&I Transformer Program, launched voluntary initiatives to stimulate energy efficient dry-type transformer purchases (CEE). Both programs encouraged the purchase of transformers that equaled or exceeded the voluntary NEMA TP-1 minimum efficiency levels which reduced transformer losses by about 50% relative to pre TP-1 performance.

In 2010, NEMA released a new set of voluntary efficiency levels for distribution transformers sold under its NEMA Premium label. NEMA Premium transformers provided a minimum of 30% fewer total load losses than those specified by the TP-1 minimum standard level.

Department of Energy Mandatory Minimum Efficiency Standards

Under the Energy Act of 2005, the DOE established mandatory transformer efficiency standards equivalent to the NEMA TP-1 levels for liquid-immersed and dry-type transformers. These standards went into effect in January of 2007. The efficiency of liquid-immersed transformers is taken at a reference temperature at 50% of nameplate transformer loading while the efficiency for dry-type units is measured at 35% of the transformer's full nameplate load.

In 2013, the DOE updated the Energy Policy Act of 2005 to raise the efficiency levels for liquid-immersed and dry-type distribution transformers. Due to small sales volumes, single-phase dry-type transformer efficiency standards remained at the NEMA TP-1 levels. The new mandatory minimum efficiency levels for low-voltage dry-type distribution transformers, referred to as the DOE 2016 transformer standards, came into effect as of January 1, 2016. These standards roughly corresponded with the NEMA Premium requirements and are summarized in Table 1. The 2016 standards were fairly rigorous as DOE estimated that 82.2% of the low-voltage dry-type transformer sales market performed below their new mandatory minimum efficiency requirement.

Table 1. DOE-2016 Mandatory Minimum Efficiency Standards for Low Voltage Dry-Type Distribution Transformers

Single-phase		Three-phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
15	97.70	15	97.89
25	98.00	30	98.23
37.5	98.20	45	98.40
50	98.30	75	98.60
75	98.50	112.5	98.74
100	98.60	150	98.83
167	98.70	225	98.94
250	98.80	300	99.02
333	98.90	500	99.14
		750	99.23
		1000	99.28

Note: All efficiency values are at 35 percent of nameplate-rated load, determined according to the DOE Test Method for Measuring the Energy Consumption of Distribution Transformers (see Appendix A to Subpart K of 10 CFR part 431). Low-voltage dry-type distribution transformers with kVA ratings not appearing in the table shall have their minimum efficiency level determined by linear interpolation of the kVA and efficiency values immediately above and below that kVA rating.

The Energy Independence and Security Act requires that the Secretary of Energy periodically determine whether product standards require amendments, and issue a Notice of Proposed Rulemaking for new proposed standards. On June 13, 2019, the DOE Building Technologies Office issued a Request for Information pertaining to amending the standards for liquid-immersed and dry-type distribution transformers. The Secretary must make a determination on transformer standard modifications by 2021. To date, there has been no activity to amend the standard. The 2016 DOE mandatory minimum efficiency standard is now the baseline against which the performance of more efficient transformers are compared.

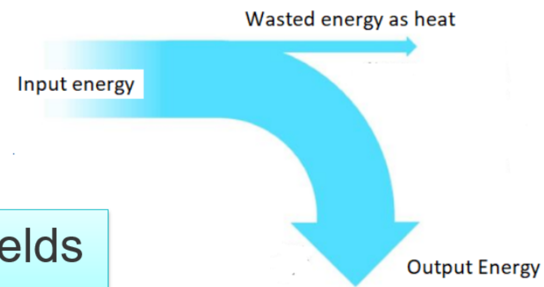
Transformer Efficiency: No-Load Losses and Load Losses

The efficiency of a distribution transformer is simply the power output at the secondary side divided by the input power on the supply side. Efficiency can also be expressed as “Efficiency = (Input – Losses)/Input”. A decrease in losses thus results in an increase in efficiency. DOE has developed mandatory minimum efficiency standards for single and three-phase distribution transformers for a range of kVA ratings. The dry-type transformer standards are based upon performance at a designated load or capacity point – 35%. One disappointing consequence of the DOE 2016 standards is that manufacturers stopped marketing transformers based upon performance or efficiency.

Equation 1. Determining Transformer Efficiency

Transformer efficiency =
Power output at the secondary side divided by the input power on the supply or primary side

Or, (Input – Losses) / Input



A decrease in losses yields an increase in efficiency

Transformers suffer both fixed no-load losses plus load-dependent losses in the windings of the transformer, often referred to as conductor, coil or copper losses. The no-load losses occur whenever the transformer is energized, thus they occur even when the transformer is not loaded. In contrast, load losses vary as the square of the current passing through the transformer coils. To obtain available transformer-related energy savings, purchasers must be aware that long-term energy savings opportunities exist (a typical dry-type transformer life exceeds 30 years) and purchasers should consider selecting transformers using life cycle or “Total Cost of Ownership” methodologies (Hitachi) (Siemens).

Figure 3 illustrates the efficiency of a transformer’s no-load, load, and total losses as a function of load. Efficiency is close to its peak in the 35% to 50% load range. At loadings less than 30% of a transformers rated load (see oval on Figure 3) total losses are dominated by the no-load loss component.

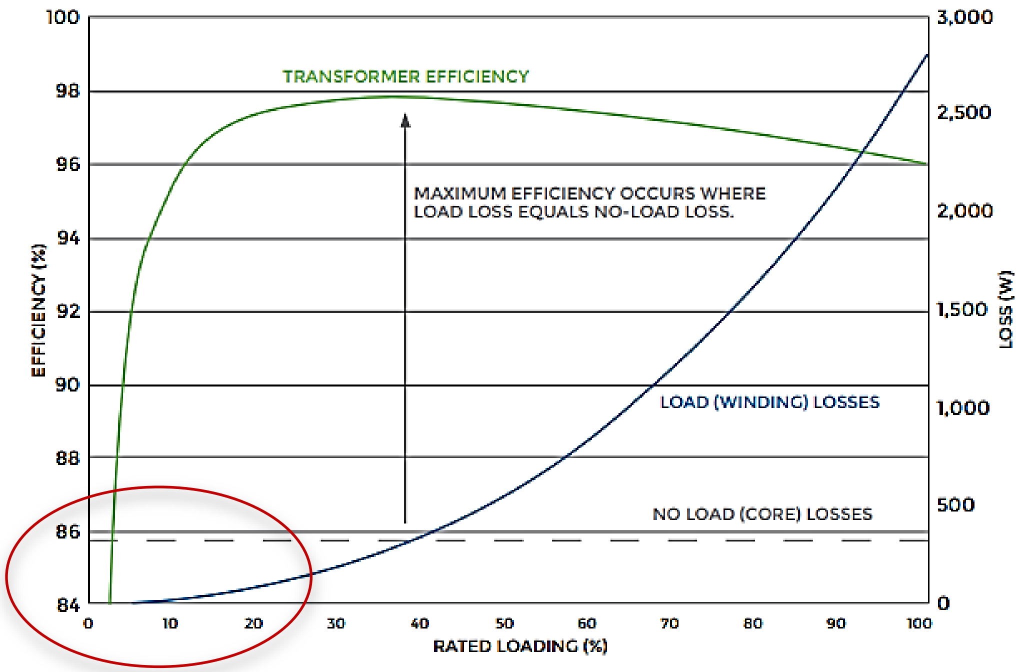


Figure 3. Impact of Load on Transformer Losses and Efficiency

Dry-Type Transformer Loading

While no-load losses are small compared to load losses, a decrease in no-load losses can lead to significant annual energy savings because no-load losses occur 24/7 and transformers are generally not loaded close to their full-load rating. A typical commercial sector transformer average weekday (WD) and average weekend (WE) load profile is shown in Figure 4 (National Grid). This transformer operates unloaded during weekends and in the early morning and late evening hours during weekdays with peak weekday loads approaching 40% of the transformers rated capacity. Transformers operating with average loads of 10-20% of nameplate and with peak loading less than 50% can be considered to be “lightly loaded” and offer good energy savings based on improved no-load loss. Conversely, the load loss component becomes small compared to the annual energy losses from core losses.

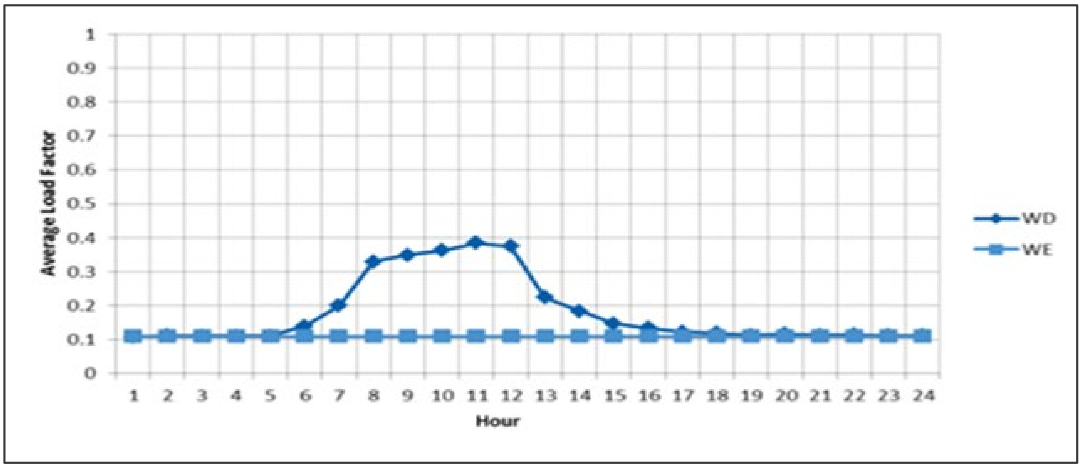


Figure 4. Typical Load Profile for a Commercial Sector Transformer on Weekdays (WD) and Weekends (WE)

While low-voltage dry-type transformers are tested for efficiency at their 35% load point, loadings for in-service units can be considerably lower. In 1999, the Northeast Energy Efficiency Partnerships (NEEP) directed a study conducted by the Cadmus Group to determine how distribution transformers in the region were loaded (Cadmus). Their study *Low-Voltage Transformer Loads in Commercial, Industrial, and Public Buildings* found that dry-type low-voltage transformers are relatively lightly loaded across building types, building schedules, and transformer sizes. The average root-mean-square load factor was found to be 16% (see Figure 5), meaning that no-load losses are the dominating loss component.

The Cadmus Group examined the loading on dry-type transformers in a number of building types including offices, manufacturing plants, retail stores, schools, and healthcare facilities (see Figure 6). Average loading is low because many of the buildings operate for only a single-shift five days per week and transformer losses approach no-load loss values during late evening hours and on weekends. The study concluded that nearly 90% of the monitored transformers were loaded below the 35% target load used by both the NEMA and DOE efficiency standards. It was concluded that low temperature rise transformers with designs that reduce winding losses do not save energy unless they also have an efficient core that minimizes no-load losses.

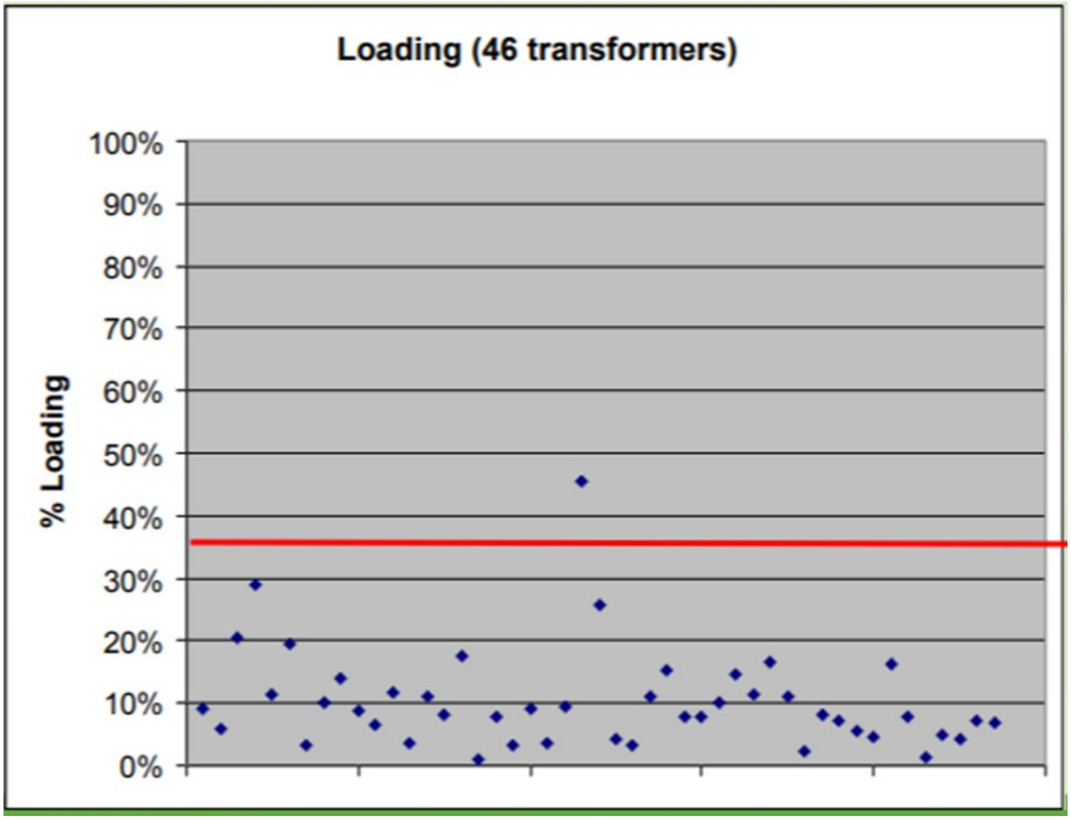
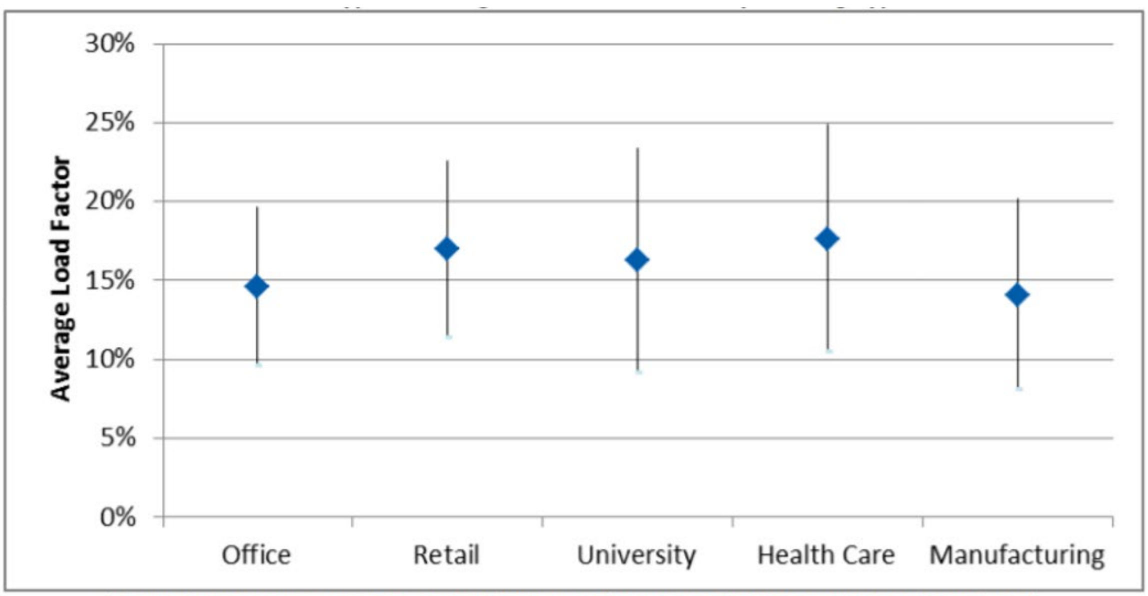


Figure 5. RMS Average Dry-Type Transformer Loading for Commercial Building Applications



*The Cadmus Group, Inc. 1999. *Low-Voltage Transformer Loads in Commercial, Industrial, and Public Buildings. Prepared for Northeast Energy Efficiency Partnerships.*

Figure 6. RMS Average Transformer Loads for Various Building Types

High Efficiency Dry Transformer Availability

Incremental Energy Savings Analysis Process

While transformer efficiency standards are expressed as efficiency at a stated transformer load point (35%), annual energy savings are determined from reductions in transformer energy losses when subject to an annual load profile. Therefore, the total values indicated in the DOE 2016 standards are not readily useful for calculating annual energy savings because they only measure losses at a constant transformer load. In contrast, utilities must apply an average of loadings because each transformer experiences different loadings. Energy savings from the purchase of a high efficiency transformer can be determined through calculating the annual kWh losses from the baseline transformer for a given average load or load profile and then comparing losses with those from the higher efficiency alternative when operating under identical loads. Total annual electrical energy losses (kWh/year) from a transformer are often expressed using the "equivalent hours" methodology, seen in Equation 2.

Equation 2

$$Annual\ Transformer\ Energy\ Losses\ (kWh/yr) = (No\text{-}Load\ Loss + Loss\ Factor\ \times\ Load\ Loss\ at\ peak)\ \times\ 8760\ hr/yr\ \times kW/1000\ W$$

Annual Load Factor	= average power in kW/peak power in kW
Loss Factor	= 0.85 x (annual load factor)^2 + 0.15 x (annual load factor)
Load Loss (W)	= Watts loss when transformer is fully loaded to its nameplate kVA rating
Load Loss at peak	= Nameplate load loss (W) x (kVA at peak transformer load / nameplate kVA rating)^2

The transformer annual load factor is often expressed as the ratio of the average load (in kW) for a transformer to the peak input power (kW) during a typical operational year. Annual energy savings are equal to the difference in annual energy losses between any two units, as shown below in Equation 3.

Equation 3

$$\boldsymbol{Energy\ Savings\left(\frac{kWh}{yr}\right) = Losses\ from\ Baseline - Losses\ from\ Higher\ Efficiency\ Unit}$$

For lightly loaded dry-type transformers in commercial and institutional settings, annual energy consumption closely tracks the no-load losses (in Watts) times 8,760 hours per year (the hours that the transformer is energized). Thus, energy savings from purchase of a dry-type transformer with low no-load losses are given in Equation 4:

Equation 4

$$Energy\ Savings\ \left(\frac{kWh}{yr}\right) = (NLL_{Std} - NLL_{EE}\ in\ Watts)/1000)\ x\ 8{,}760\ hours/year$$

Transformer energy savings are passive; they are not dependent upon controls or changes in occupant behavior. There is no efficiency degradation over the installed life of the dry-type transformer.

Variations in Transformer Performance

Many manufacturers produce low-voltage dry-type transformers (see Table 2). Some produce transformers that offer superior performance while lightly loaded; other transformers are optimized for heavily-loaded applications, while other designs attempt to provide efficient service across a range of loading conditions.

Table 2. Manufacturers of Dry-Type Transformers

ABB	Hubbell Inc.
Cooper Power Systems (Eaton)	Jinpan International USA
Emerson	MGM Transformer Co.
Schneider Electric (Square D)	Milbank Manufacturing
Federal Pacific	Powersmiths
Hammond Power Solutions	Siemens
PDI	

Differences in low-voltage dry-type transformer performance are illustrated in Table 3. The Powersmiths and Square D products have low no-load losses ranging between 54 and 57 W for the 30 kVA transformer highlighted. In contrast, the Hammond Power Solutions and the Siemens Series H transformers have no-load losses between 96 W and 109 W. The transformers with reduced no-load losses would perform best under lightly loaded conditions.

The Hammond Power Solutions and Siemens transformers, however, are designed with full-load losses between 760 W and 853 W which are far below the range of 1050 W to 1332 W available with the Powersmiths and Square D units. These products would perform more efficiently when put into use under conditions of heavy loading.

Table 3. Differences in Transformer Performance

3-Phase Dry Type Low Voltage Distribution Transformers 480 to 208Y/120

kVA Rating	Winding	Powersmiths E-Saver 80R 130°C		Square D EX 150°C	
		N.L., Watts	Load, Watts	N.L., Watts	Load, Watts
15	Al	35	775	46	521
30	Al	57	1332	54	1050
45	Al	78	1725	90	1242
75	Al	111	2537	135	2219
112.5	Al	164	3313	180	2938
150	Al	203	3945	210	3192

kVA Rating	Winding	Hammond Power Solutions, 150°C Rise Sentinel G (Cu)		Siemens Series H 150°C	
		N.L., Watts	Load, Watts	N.L., Watts	Load, Watts
15	Cu/Al	64	400	63	537
30	Cu/Al	96	760	109	853
45	Cu/Al	135	990	143	1200
75	Cu/Al	194	1470	188	1950
112.5	Cu/Al	275	1850	240	2760
150	Cu/Al	335	2335	350	2800

A software tool was developed to compare energy savings available from the selective purchase of new dry-type transformer models with reduced no-load losses. The model uses the “Equivalent Hours” methodology highlighted in Equation 2 when a lightly loaded transformer is placed into service with a root-mean-square (RMS) annual average load of 16%. When lightly loaded, annual energy savings can be determined by using Equation 4. Under lightly loaded conditions, the energy consumption reduction benefits of using larger diameter windings to reduce load losses are minimal.

Potential energy savings due to selective purchase of a dry-type transformer with low no-load losses are summarized in Table 4. Table 4 shows the annual energy savings for a 16% loaded transformer due to purchase of the design with the lowest available no-load losses versus a design that is optimized for a higher load range. Purchase and installation of the unit with the lowest no-load losses will provide attractive energy savings, ranging from 329 kWh/year for the 15 kVA unit up to 1,271 kWh/year for the 150 kVA unit. Note that both of the example transformers comply with the DOE’s 2016 mandatory minimum efficiency standards. The energy savings occur simply due to purchase of a unit that performs best given the transformer sizing and loading conditions encountered under current practices.

Table 4. Potential "New Purchase" Annual Energy Savings

	Eaton DT-3, 150°C Rise, Cu Windings			Powersmiths E-Saver 80R Losses, Al, K-7, 130°C rise			
kVA	**NLL, W**	**FLL, W**	**Losses, kWh/year**	**NLL, W**	**FLL, W**	**Losses, kWh/year**	**Savings, kWh/year**
15	73	401	644	35	775	315	**329**
30	114	732	1006	57	1332	513	**493**
45	118	1271	1047	78	1725	701	**346**
75	206	1615	1821	111	2537	998	**823**
112.5	251	2223	2222	164	3313	1471	**751**
150	350	2351	3090	203	3945	1819	**1271**

Note: Transformers are assumed to be loaded to 16% of their rated capacity.

Dry-Type Transformer Energy Savings

Energy losses and efficiency values for stock or off-the-shelf three-phase Square D Brand EX low-voltage dry-type transformers (480 V primary and 120/240 or 208Y/120 secondary) are given in Table 5. Stock transformers are generally designed to just exceed the DOE mandatory minimum efficiency standards when 35% loaded. The Square D transformers do significantly exceed the DOE standard in the small kVA ratings.

Table 5. Square D Low-Voltage Distribution Transformer Losses and Efficiency

kVA	No-Load Loss, W	Conductor Loss, W	Efficiency, 35% Load (75°C), %	DOE 2016 Minimum Efficiency Standard, %
15	46	521	98.17	97.89
30	54	1050	98.38	98.23
45	90	1242	98.60	98.40
75	135	2219	98.68	98.60
112.5	180	2938	98.83	98.74
150	210	3192	99.00	98.83
225	328	4198	99.06	98.94
300	601	4397	99.13	99.02
500	902	6617	99.24	99.14

No-load and load losses for 3-phase dry-type transformers of various kVA ratings that are supplied by various manufacturers are given in Table 6 through Table 11. Energy savings are again determined at the 16% transformer load point and vary widely based upon transformer no-load losses. The Powersmiths design has the lowest no-load losses that were found in a market assessment and may be considered as the baseline or “Best Available” dry-type transformers for determination of the maximum energy savings potential under lightly loaded conditions.

Energy savings could be obtained through simply incentivizing or specifying the purchase of transformers with no-load losses below a critical value for each kVA rating. Transformers can be constructed with various allowable temperature rises with copper windings, aluminum windings, or with a copper primary with an aluminum secondary. Specification of a low temperature rise transformer or one with copper windings does not necessarily result in energy savings. Note that, in the first energy savings example, the Powersmiths transformer provides little energy savings relative to the Square D transformer up to rating of 225 kVA as the Square D transformer also has extremely low no-load losses.

Table 6. Annual Energy Savings using BPA 'Equivalent Hours' Methodology (Powersmiths) versus Square D Brand EX

Dry Transformer at 16% Load Point

Square D Brand EX Losses 150°C Rise				Powersmiths E-Saver 80R Losses			
KVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
15	46	521	403	35	775	311	92
30	54	1050	474	57	1332	507	-33
45	90	1242	790	78	1725	693	96
75	135	2219	1185	111	2537	987	198
112.5	180	2938	1580	164	3313	1456	124
150	210	3192	1843	203	3945	1801	41
225	328	4198	2878	319	4317	2820	58
300	601	4397	5269	371	6229	3287	1983
500	902	6617	7908	558	8419	4938	2971
750	900	8391	7893	770	11377	6812	1081

Table 7. Annual Energy Savings using BPA 'Equivalent Hours' Methodology (Powersmiths) versus Eaton DT-3 150°

3-Phase Dry Transformer at 16% Load Point

Eaton DT-3 150°C Rise Cu Windings				Powersmiths E-Saver 80R Losses			
KVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
15	73	401	640	35	775	311	329
30	114	732	999	57	1332	507	492
45	118	1271	1035	78	1725	693	342
75	206	1615	1806	111	2537	987	819
112.5	251	2223	2201	164	3313	1456	745
150	350	2351	3068	203	3945	1801	1267
225	418	4103	3666	319	4317	2820	846
300	561	4491	4919	371	6229	3287	1632

480 V Delta Primary and 208Y / 120 V Secondary

Table 8. Annual Energy Savings using BPA 'Equivalent Hours' Methodology (Powersmiths) versus Eaton DT-3 80°

3-Phase Dry Transformer at 16% Load Point

Eaton DT-3 80°C Rise Cu Windings				Powersmiths E-Saver 80R Losses			
KVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
15	60	352	526	35	775	311	215
30	118	473	1034	57	1332	507	527
45	206	489	1805	78	1725	693	1112
75	251	838	2200	111	2537	987	1212
112.5	350	1125	3067	164	3313	1456	1611
150	418	1559	3663	203	3945	1801	1862
225	561	2178	4917	319	4317	2820	2097

480 V Delta Primary and 208Y / 120 V Secondary

Table 9. Annual Energy Savings using BPA 'Equivalent Hours' Methodology (Powersmiths) versus Siemens Series H 150°C

Dry Transformer at 16% Load Point

Siemens Series H 150°C Rise Losses				Powersmiths E-Saver 80R Losses			
KVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
15	63	537	552	35	775	311	241
30	109	853	956	57	1332	507	449
45	143	1200	1254	78	1725	693	561
75	188	1950	1649	111	2537	987	662
112.5	240	2760	2105	164	3313	1456	649
150	350	2800	3069	203	3945	1801	1267
225	420	4320	3684	319	4317	2820	864
300	500	5570	4386	371	6229	3287	1099
500	790	5910	6926	558	8419	4938	1989
750	970	8800	8506	770	11377	6812	1694

Copper, 480 V Primary and 208Y / 120 V Secondary

Table 10. Annual Energy Savings using BPA 'Equivalent Hours'

Methodology (Powersmiths) versus
Siemens 150°C Al Windings

Dry Transformer at 16% Load Point

Siemens 150°C Rise Al Winding Losses				Powersmiths E-Saver 80R Losses			
KVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
15	51	669	447	35	775	311	136
30	90	1060	789	57	1332	507	282
45	120	1440	1053	78	1725	693	359
75	190	1930	1666	111	2537	987	679
112.5	253	2620	2219	164	3313	1456	763
150	305	3300	2675	203	3945	1801	874
225	440	4040	3859	319	4317	2820	1039
300	508	5630	4456	371	6229	3287	1169
500	780	6060	6839	558	8419	4938	1902
750	900	9380	7894	770	11377	6812	1082

Aluminum, 480 V Primary and 208Y / 120 V Secondary

Table 11. Annual Energy Savings using BPA 'Equivalent Hours' Methodology (Powersmiths) versus
Siemens Series H 80°C

Dry Transformer at 16% Load Point

Siemens Series H 80°C Rise Losses				Powersmiths E-Saver 80R Losses			
KVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
15	71	375	622	35	775	311	311
30	125	570	1096	57	1332	507	588
45	158	870	1385	78	1725	693	692
75	230	1260	2016	111	2537	987	1029
112.5	322	1600	2822	164	3313	1456	1366
150	405	1910	3550	203	3945	1801	1748
225	465	3350	4077	319	4317	2820	1257
300	525	4550	4604	371	6229	3287	1317
500	860	5420	7539	558	8419	4938	2602
750	1310	6010	11482	770	11377	6812	4670

Copper, 480 V Primary and 208Y / 120 V Secondary

Market Transformation for High Efficiency Dry-Type Transformer

The 2000 paper *Market Transformation for Dry-Type Distribution Transformers: The Opportunity and the Challenges* by authors from Sustainable Energy Partnerships, ACEEE, CEE, the Cadmus Group, and ICF Consulting notes that dry-type transformer efficiency improvement is a largely untapped building energy saving measure. Despite DOE later establishing mandatory minimum efficiency standards for dry-type transformers, challenges and barriers to gaining additional efficiency improvements still exist, including:

- Lack of awareness and knowledge,
- Lack of incentives. Engineers and contractors specifying transformers have no incentive to reduce operating costs for the building owner. Building owners who lease space have no incentive to reduce costs for their tenants,
- Lack of availability (or perceived availability). Stocking practices and availability are dependent upon demand for improved performance units,
- Lack of identifiers or markings for low-loss transformers (in the past, both Energy Star and NEMA Premium provided product differentiation), and
- Higher cost. If not stocked, a special order item would tend to be more expensive.

CEE notes that low voltage dry-type transformers at and below 300 kVA are typically stock items. Transformers larger than 300 kVA or those with higher than the federal minimum efficiency are typically built-to-order. Within the three-phase low-voltage dry-type transformer market, the most common sizes sold are 45 kVA, 75 kVA, and 112.5 kVA. When combined, these ratings historically accounted for 60% of sales by volume and 55% of sales by capacity.

CEE maintains that the market for low voltage dry-type transformers is driven primarily by new construction and facility expansions. The delivery channel for these transformers consists of stocking distributors, with electrical contractors or customer agents (architectural & engineering (A&E) firms, general contractors) responsible for preparing specifications and making purchasing decisions.

Retrofit of Pre-TP-1-1996 Transformers

Cost effective energy and demand reduction savings can be captured through replacing existing Pre-TP-1-1996 transformers with new, more efficient transformers. Information on TP-1-1996 is provided on page 5 of this report. Pre-TP-1-1996 represent the least efficient working transformers in the field. Further, by downsizing, the replacement transformers can provide additional reductions in core losses, and at a reduced purchase price, which further increases the cost effectiveness. Downsizing should be considered in most applications as utility efficiency programs have produced large reductions in energy delivered by transformers serving lighting loads, plug loads, and HVAC systems. Smart controls that modify HVAC operation based upon zone occupancy, occupancy sensors, CO_2 sensors, daylighting controls, and advanced sleep mode for computers and monitors also result in electrical loads being reduced. Another benefit of downsizing is the reduced cost of the smaller transformer – resulting in increased cost-effectiveness and a more rapid simple payback period. National Grid notes that, due to their light loading, many dry transformers can be expected to last for 50 years. National Grid recommends replacement and downsizing of Pre-TP-1 transformers when the load on the existing transformer never exceeds 35%. To be conservative, they do not allow the load profile on the replacement transformer to exceed 50%.

A dry-type transformer retrofit or upgrade action would be initiated by having a utility representative or consultant visit a site and record:

- the transformer primary and secondary voltages, and
- transformer nameplate data, including manufacturer and model number.

In addition, measuring 15 min average current on the 120 V secondary can be used for possibly downsizing the transformer.

Some utilities have developed and access a default transformer performance database when documenting baseline transformer performance. Transformer performance such as pre TP-1 or not, are often estimated through identifying the date of facility construction. After no-load losses are determined, annual energy savings are expressed as the difference in the existing transformer and new high efficiency transformer no-load losses, which occur 24/7/365. One dry-type transformer manufacturer (Hammond Power Solutions) has made a pre-2007 transformer replacement calculator available on-line – www.hammondpowersolutions.com/en/Resources/categories/hps-toolbox<http://www.hammondpowersolutions.com/en/Resources/categories/hps-toolbox

Benefits of a transformer retrofit and upgrade include:

- Significant reduction in transformer losses, which can be >75%;
- Removal of end-of-life failure risks;
- Installation of a transformer optimized for modern electronic equipment and for non-linear loads;
- Decades of future energy savings without the need for upgrades, control systems or building occupant behavior change;
- Reduction in air-conditioning loads due to less heat rejected into building spaces; and
- Carbon footprint benefits.

Annual Energy Savings from Retrofit of Pre-TP-1-1996 Transformers

Pre-TP-1 transformer no-load and load losses are extracted from Table 12 "Expected Losses (Watts) for Pre-TP-1 transformers" contained in NationalGrid's 2013 *Transformer Replacement Program for Low-Voltage Dry-Type Transformers: Implementation Manual*. Older transformers are expected to be replaced by a conventional DOE 2016 compliant transformer.

Table 12. Annual Energy Savings Due to Retrofit of Pre-TP-1 Dry-Type Transformers

Dry Transformer at 16% Load Point

	Pre-NEMA TP-1 Transformers (Nationalgrid)			Hammond Power Solutions, Sentinel G Al, 150°C			
kVA	NLL, W	FLL, W	Losses, kWh/year	NLL, W	FLL, W	Losses, kWh/year	**Savings, kWh/year**
15	162	712	1426	62	420	547	**879**
30	256	1274	2256	86	840	762	**1494**
45	322	1655	2838	120	1110	1063	**1775**
75	462	2542	4073	190	1490	1680	**2394**
112.5	604	3457	5327	226	2260	2003	**3324**
150	661	4690	5838	315	2500	2785	**3053**
225	862	6242	7615	405	3580	3585	**4031**
300	1087	7397	9598	540	4040	4772	**4826**
500	1648	11166	14551	840	5590	7416	**7135**
750	2189	14830	19328	1020	8370	9021	**10307**

Table 13. Annual Energy Savings Due to Retrofit and Downsizing of Pre-TP-1 Dry-Type Transformers

Dry Transformer at 16% Load Point with Downsizing by one kVA Rating

Pre-NEMA TP-1 Transformers (Nationalgrid)				Hammond Power Solutions, Sentinel G Al, 150°C				
kVA	NLL, W	FLL, W	Losses, kWh/year	kVA	NLL, W	FLL, W	Losses, kWh/year	Savings, kWh/year
30	256	1274	2256	**15**	62	420	594	**1662**
45	322	1655	2838	**30**	86	840	789	**2048**
75	462	2542	4073	**45**	120	1110	1121	**2953**
112.5	604	3457	5327	**75**	190	1490	1728	**3598**
150	661	4690	5838	**112.5**	226	2260	2043	**3795**
225	862	6242	7615	**150**	315	2500	2867	**4749**
300	1087	7397	9598	**225**	405	3580	3649	**5949**
500	1648	11166	14551	**300**	540	4040	4983	**9568**
750	2189	14830	19328	**500**	840	5590	7598	**11730**
				750	1020	8370		

The Tables above show that annual energy savings greatly increase over those shown in the “New Purchase” scenario as the no-load losses of the older Pre-TP-1 transformers are very high. Energy savings increase even more when the replacement transformer is downsized – even as the loading increases and conductor losses increase – as the no-load losses of the smaller replacement transformer are significantly reduced.

Sizing Transformers for Cost Effectiveness

Dry-type transformers can overheat if they are undersized and overloaded or if they are exposed to non-linear loads due to harmonic distortions from electronics such as variable speed drives. The rated heat output of a transformer can be reached at 50% load even if only 50% of the load actually imposed on the transformer is non-linear due to a switched-mode power supply (Ling). Transformer de-rating or the purchase of K-Factor rated transformers is recommended to avoid overheating risks when serving such electronic loads.

Hammond Power Solutions provided estimated end-user purchase prices for their Sentinel G dry-type distribution transformers. The prices shown are for transformers with Aluminum winding; a 25% price adder would be typical for copper wound transformers. The annual energy savings are determined through assuming a 16% average transformer load; a 25% installation cost multiplier; and that the existing pre-TP-1 transformer is replaced with a “Best Practices” or lowest no-load loss transformer.

Table 14. Simple Payback Due to Retrofit and Retrofit with downsizing of Pre-TP-1 Dry-Type Transformer

Dry-Type Transformer Replacement Cost-Effectiveness (with a like-size transformer)

kVA	Contractor Cost	Annual Savings, kWh	Value of Savings, @$0.06/kWh	Simple Payback, years (with 25% markup)
15	$1,194	**1112**	$66.71	22.4
30	1609	**1743**	104.56	19.2
45	1654	**2137**	128.20	16.1
75	2663	**3075**	184.49	18.0
112.5	3659	**3856**	231.35	19.8
150	4071	**4020**	241.18	21.1
225	6699	**4776**	286.59	29.2
300	9326	**6284**	377.05	30.9
500	14508	**9577**	574.60	31.6

Dry-Type Transformer Replacement Cost-Effectiveness (with a downsized transformer)

kVA	Contractor Cost	Annual Savings, kWh	Value of Savings, @$0.06/kWh	Simple Payback, years (with 25% markup)
30 to 15	$1,194	**1855**	$111.31	13.4
45 to 30	1609	**2281**	136.88	14.7
75 to 45	1654	**3282**	196.92	10.5
112.5 to 75	2663	**4245**	254.72	13.1
150 to 112.5	3659	**4308**	258.51	17.7
225 to 150	4071	**5668**	340.07	15.0
300 to 225	6699	**6682**	400.92	20.9
500 to 300	9326	**10911**	654.68	17.8
750 to 500	14508	**14079**	844.73	21.5

Table 14 indicates that replacement of a pre-TP-1 transformer is a costly undertaking and replacement of a lightly loaded transformer with a similar sized unit results in simple paybacks in the range of 16 to 20 years. However, rightsizing the transformer at the time of replacement improves the cost-effectiveness and results in simple paybacks that are often below 15 years. Assuming energy cost of $0.06/kWh and utility incentive of $0.25 per kWh (of first year savings), and correctly sizing the transformer for the load, the simple payback period can be reduced further down to 6-10 years

Utility Transformer Retrofit Programs

Austin Energy

Austin Energy includes a transformer efficiency incentive along with its suite of Commercial Rebate Offerings. Their program targets dry-type transformers in new construction or when end-of-life replacements must be made. Some larger liquid-immersed transformers have been upgraded through participating in the program when customers purchase energy on a Large Primary Voltage rate schedule and thus own and maintain the transformer. The utility incentive level is $300/kW as Austin Energy is interested in demand reductions. The savings are based on kW draw at the 35% transformer load point, thus no transformer load profiles are needed or collected.

Incentives are generally paid to the end-user although for larger incentives, payment could be made to a transformer distributor. Marketing of the program is to all involved parties; end users, electrical contractors, architect/engineering firms, and transformer distributors.

The DOE standard establishes the baseline level against which transformer demand reductions are compared. Transformers that qualify for the program must offer a higher efficiency than the DOE's mandatory minimum values. There have been no problems with finding transformer distributors that stock and can supply units that exceed the DOE's 2016 transformer efficiency standards – higher efficiency dry-type units are readily available. Incentives are on the order of $50 for a 75 kVA transformer, with applications often submitted for multiple transformers at a single site. Customers make use of this incentive program with several hundred applications for transformer rebates in the past year. (Personal communication with Manny Garza, Customer Energy Solutions, Austin Energy).

Hawaii Electric

Hawaii Energy is not part of the utility serving Hawaii (Hawaiian Electric) but is charged by the Public Utilities Commission with providing information, education, and rebates to all electricity using sectors. The goal of their transformer program is to retrofit or replace old pre TP-1 dry-type units with new transformers that exceed the DOE's 2016 minimum efficiency standards. A lightly loaded pre TP-1 transformer may have a useful operating life up to 50 years and an early replacement can thus result in many years of energy savings.

Hawaii Energy set up their transformer retrofit program with assistance from vendors, particularly Powersmiths which is a transformer manufacturer located in Ontario, Canada (Hawaii does not have any domestic transformer manufacturers). Powersmiths offers their E-Saver line of dry-type transformers and has an extensive database of pre-TP-1 transformer performance. A program representative goes out, records the primary and secondary voltage, transformer nameplate data, including manufacturer, and model number; then uses the database to document baseline transformer no-load and load losses. Sometimes, transformer efficiency level such as pre TP-1 or not, is estimated through identifying the date of facility construction.

No-load losses are then obtained for the replacement unit (from field measurements or manufacturer's test data). Energy savings are expressed as the difference in the existing transformer and new high efficiency transformer no-load losses which occur continuously. The incentive offered by Hawaii Energy is $125/kW and $0.12/kWh. The revamped program has been in operation for only a short time with a handful of applications to date. The program will be offered in the future with an expanded marketing effort focused on transformer distributors, A&E firms, and those doing commercial or industrial energy audits. Hawaii Energy recommends that transformer upgrades be examined as part of lighting energy audits. Hawaii Energy indicates that health care facilities and schools with campuses may have as many as 5 to 30 transformers that can be upgraded. Hawaiian Electric commercial energy rates are between $0.19/kWh and $0.28/kWh. (Person communication with Hoang Tran, Hawaii Energy).

National Grid

National Grid has long offered incentives for the replacement of pre NEMA TP-1 25 kVA to 300 kVA low-voltage dry-type transformers with transformers that meet or exceed the minimum efficiency required by federal standards. The rated size of the replacement transformer must be equal to or less than the existing transformer. Failed transformers do not qualify for incentives. (Personal communication with Dinesh Patel, Principal Engineer, Technical Policy and Strategy, National Grid).

National Grid has prepared a table that shows the typical annual kWh losses and energy savings due to replacement of a pre-TP-1 transformer with a NEMA Premium Efficiency unit (Table 15). USDOE 2016 standards equal or slightly exceed the NEMA Premium minimum efficiency requirements.

Table 15. Expected Energy Savings Due to Retrofit of Pre-NEMA TP-1 and NEMA TP-1 Transformers

Size (kVA)	Expected Annual Losses, kWh (pre-TP-1)	Expected Annual Losses, kWh (TP-1)	Expected Annual Losses, kWh (NEMA Premium)	Expected Annual Savings, kWh (NEMA Premium)
15	1,600	1,300	900	700
30	2,500	2,000	1,400	1,100
45	3,200	2,500	1,800	1,400
75	4,600	3,200	2,300	2,300
112.5	6,000	4,800	3,400	2,600
150	6,800	5,400	3,800	3,000
225	8,900	7,100	5,000	3,900
300	11,100	8,900	6,200	4,900
500	16,800	13,400	9,400	7,400
750	22,300	17,800	12,500	9,800
1000	27,300	21,800	15,300	12,000

National Grid also has developed a table (Table 16) that shows the no-load and full-load Watts for typical Pre-TP-1 transformers. These values are used to baseline the performance of all transformers to be replaced and were used in the transformer retrofit and downsizing analyses presented in this report (National Grid).

Table 16. Estimate of Pre-NEMA TP-1 Transformer No-Load and Load Losses, and Total Loss at various Load Factors

Size (kVA)	NLL	FLL	Load Factor																				
			0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
15	162	712	200	200	200	200	200	200	200	200	300	300	300	300	400	400	500	500	600	700	700	800	900
30	256	1,274	300	300	300	300	300	300	300	400	400	500	500	600	700	700	800	900	1,000	1,100	1,300	1,400	1,500
45	322	1,655	300	300	300	400	400	400	400	500	500	600	700	800	800	900	1,100	1,200	1,300	1,500	1,600	1,800	2,000
75	462	2,542	500	500	500	500	500	600	600	700	800	900	1,000	1,100	1,300	1,400	1,600	1,800	2,000	2,200	2,500	2,700	3,000
112.5	604	3,457	600	600	600	700	700	800	800	900	1,100	1,200	1,300	1,500	1,700	1,900	2,100	2,400	2,700	3,000	3,300	3,700	4,100
150	661	4,690	700	700	700	700	800	900	1,000	1,100	1,300	1,500	1,700	1,900	2,100	2,400	2,800	3,100	3,500	3,900	4,400	4,800	5,400
225	862	6,242	900	900	900	1,000	1,100	1,200	1,300	1,500	1,700	1,900	2,200	2,500	2,800	3,200	3,700	4,100	4,600	5,200	5,800	6,400	7,100
300	1,087	7,397	1,100	1,100	1,100	1,200	1,300	1,400	1,600	1,800	2,100	2,300	2,700	3,000	3,400	3,900	4,400	4,900	5,500	6,200	6,900	7,700	8,500
500	1,648	11,166	1,600	1,700	1,700	1,800	2,000	2,200	2,400	2,700	3,100	3,500	4,000	4,600	5,200	5,900	6,600	7,500	8,400	9,400	10,500	11,600	12,900
750	2,189	14,830	2,200	2,200	2,300	2,400	2,600	2,900	3,200	3,600	4,100	4,700	5,300	6,100	6,900	7,800	8,800	9,900	11,100	12,500	13,900	15,400	17,100
1000	2,677	18,139	2,700	2,700	2,800	3,000	3,200	3,600	4,000	4,500	5,100	5,700	6,500	7,400	8,400	9,500	10,800	12,100	13,600	15,200	17,000	18,900	20,900

Improving Transformer Sizing Practices

While no-load losses are fixed and occur whenever a transformer is energized, load losses vary as the square of the current passing through the transformer windings. Losses are also dependent upon the resistivity of the winding material (aluminum or copper), the total length of the conductors, temperature rise, and the cross sectional area of the winding (use of larger diameter wire and cooler operation reduce winding losses). This means that transformer efficiency is load dependent and decreases at higher loads (see Figure 7) (Burgess).

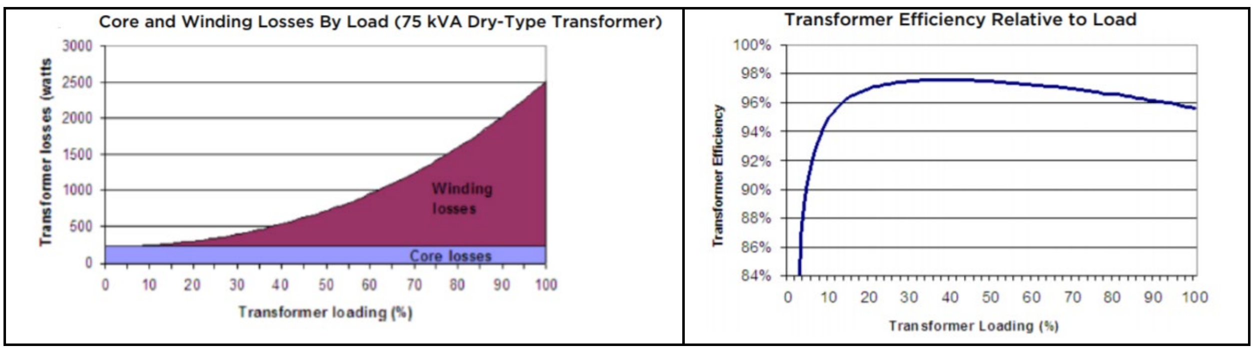


Figure 7. Transformer Losses and Efficiency Relative to Loading

Load losses represent the greatest portion of the total losses when a transformer is heavily loaded (Fairhead). Most of the dry-type transformer efficiency gains in the past have come from reducing core or no-load losses. To achieve additional gains, cores must be made bigger, which results in trade-offs as winding lengths become longer.

The biggest efficiency gains possible in the low-voltage dry transformer arena are due to replacement or retrofit of pre-TP-1 and pre-2007 transformers, which was before efficiency levels became mandatory under federal law. It is easy to identify these units as their nameplate would indicate compliance under the federal standard.

Early replacement results in immediate energy savings and avoids an end of life failure event. Rightsizing transformers is the second biggest area of potential energy savings, since transformers have been historically greatly oversized. As buildings become more efficient, advances in controls, lighting, and plug loads require even less transformer capacity.

Right-sizing of a transformer is easy when an entire small building or office is served by a single transformer. Simply determine peak kVA from the monthly billing statements. If lighting is the only load served, a spot measurement with all lighting energized will suffice for transformer resizing. Longer metering periods are necessary to develop a load profile that represents HVAC-related heating and cooling loads**. Right-sizing of a transformer saves energy as the no-load losses of the smaller transformer are greatly reduced**. Downsizing also involves the re-sizing of breakers or other thermal protective equipment. When downsizing, ensure that the new design is code-compliant.

Methods for determining the loading on commercial sector transformer applications include the use of engineering models or Watts per square foot tables. When an expected load is determined, designers tend to conservatively specify the next largest transformer kVA rating. Standard NEMA transformer ratings include 15, 30, 45, 75, and 112.5 kVA. If an average 40% load is expected on a 15 kVA transformer, the designer may specify a 30 kVA unit – which would result in an application with a 20% loaded transformer under typical operating conditions. To reduce dramatic oversizing, at least one transformer manufacturer makes transformers rated at intermediate kVA values. For the example cited above, installation of a 20 kVA transformer would result in a reduced no-load loss value with a transformer loaded at an average of 30% of the nameplate rated load. Available intermediate transformer ratings are given in Table 17.

Table 17. Intermediate Size Transformer Ratings Offered by Powersmiths

Standard kVA	Additional kVA	Standard kVA	Additional kVA
15		150	
	20		175
	25		200
30		225	
45			250
	50	300	
	63		400
75			450
	100	500	
112.5			600
	125		

Right-sizing of transformers can result in a win-win situation as the first costs of the transformer, breakers, panelboard, conductors, and conduit are decreased. The infrastructure footprint is also reduced. Right-sizing must be done with care, however, as the decrease in no-load losses due to downsizing can be offset by an increase in load losses.

Considerations for Dry-Type Transformer Selection

Key factors to consider when selecting a transformer include the expected transformer loading, winding material specification, allowable temperature rise, the presence of system harmonics, and K-factor or harmonic mitigation requirements (Zega). All are important with respect to both efficiency and transformer costs.

Copper versus Aluminum Windings

Load losses include winding losses (I^2R losses), stray losses due to stray fluxes in the windings and core clamps, and circulating currents in parallel windings (Fairhead). These losses vary with the square of the current passing through the windings. Windings are typically made up of either copper or aluminum (Zega). Copper conductors have superior current-carrying properties, but aluminum conductors can match the current-carrying capacity of copper when the conductors are sized properly. The density of copper is over three times greater than for aluminum, but when comparing the two winding materials strictly on a weight basis, aluminum has better current carrying abilities (Zega). Most manufacturers offer transformers of the same efficiency rating when using either copper or aluminum windings (Zega). Copper transformers are more expensive due to the higher comparative cost of copper.

Some have held the belief that energy savings are maximized through simply selecting high conductivity copper versus aluminum windings or through specifying a transformer with a lower allowable temperature rise.

For lightly-loaded transformers in commercial and institutional applications, annual energy consumption closely tracks the no-load losses times 8,760 hours per year. As shown in Table 18, for Square D transformers, specification of copper windings does not necessarily result in any improvement in energy efficiency or reduction in annual energy losses when the transformer is lightly loaded. No-load or core losses are not reduced by winding material selection and in a lightly-loaded application, no-load losses account for the greatest portion of total losses.

Table 18. Low Voltage Dry Type Transformer Performance versus Coil Material and Allowable Temperature Rise

Square D 3-Phase Dry Type Low Voltage Distribution Transformers 480 to 208Y/120					
kVA Rating	Winding	150°C Rise		80°C Rise	
		N.L.,Watts	Load, Watts	N.L.,Watts	Load, Watts
15	Al	46	521	69	214
30	Al	54	1050	100	449
45	Al	90	1242	128	650
75	Al	135	2219	171	1062
112.5	Al	180	2938	210	1460
150	Al	210	3192	328	1518

3-Phase Dry Type					
kVA Rating	Winding	**150ºC Rise**		**80ºC Rise**	
		N.L.,Watts	Load, Watts	N.L.,Watts	Load, Watts
15	Cu	43	580	72	186
30	Cu	72	907	96	476
45	Cu	96	1310	139	602
75	Cu	139	2044	167	921
112.5	Cu	167	2534	259	1098
150	Cu	259	2386	333	1549

Low Allowable Temperature Rise Transformers

Most ventilated transformers use a Class 220˚C insulation system. This temperature rating is the sum of the allowable winding temperature rise which is normally 150ºC, the maximum ambient temperature at 40ºC, and an allowance of 30ºC to account for hot spots inside the coils (Fairhead). Common low temperature rise transformer ratings for dry-type or ventilated transformers include 80ºC and 115ºC.

Low-temperature rise transformers are designed to have lower load losses than conventional 150ºC rise transformers. As losses are reflected as generated heat, a low-temperature rise transformer would run cooler and reject less heat to the surroundings when compared to their conventional counterparts. Low heat generation is achieved through increasing conductor diameter or reducing conductor length, which is enabled through providing a smaller core. The low temperature rise transformer might also be larger to allow for more effective natural ventilation. Until the establishment of the voluntary NEMA and mandatory federal minimum efficiency standards, an "energy efficient" transformer was considered to be a low temperature rise transformer (Fairhead). Low temperature rise transformers do provide superior energy efficiency, but only when the transformer is loaded to more than half of its full load capacity.

Specification of a low-temperature rise transformer actually can increase overall losses in a lightly-loaded transformer. Table 18 indicates that, for both aluminum and copper winding designs, no-load losses tend to increase when the transformer manufacturer minimizes load losses. The biggest performance change in a low temperature rise transformer is a significant decrease in full-load losses which are negligible for a lightly-loaded transformer.

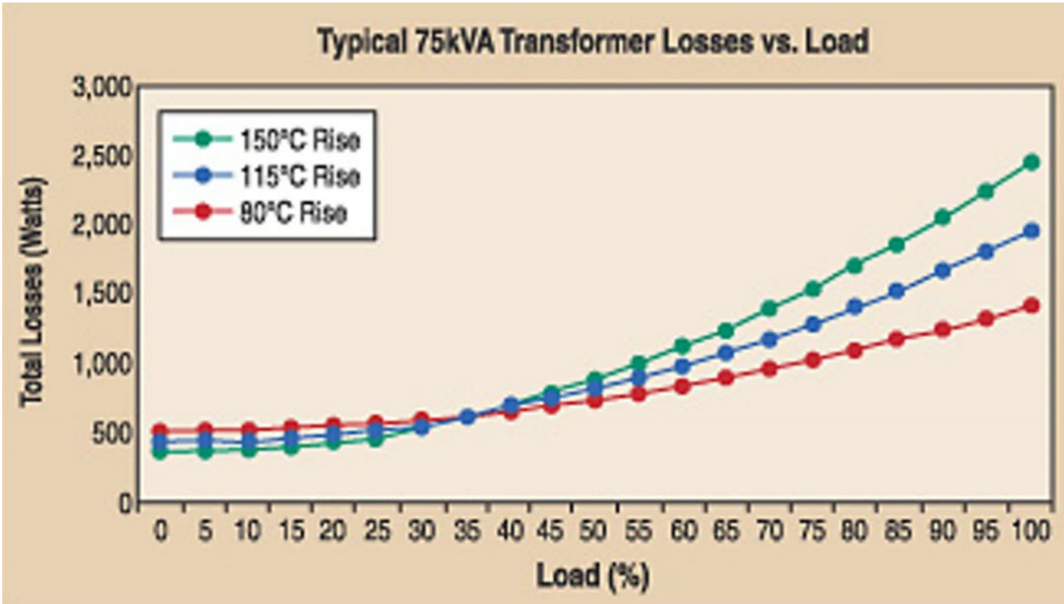


Figure 8. Losses versus Load for Transformers with Different Temperature Rise Designs

Figure 8 shows the losses for transformers with different allowable temperature rise ratings as a function of the transformer loading (Fairchild). All of the transformers compared have the same total losses and efficiency at the 35% load point. It is readily seen, however, that the losses of the low-temperature rise transformer are much lower than the conventional designs under conditions of high loading. On the other hand, the standard 150ºC allowable temperature rise transformer shows superior performance under lightly-loaded conditions.

K-Factor Rating

Harmonics are currents or voltages with frequencies that are integral multiples of the fundamental power frequency (Eaton). Harmonic currents that are generated by nonlinear loads can contribute to efficiency losses in transformers (Zega, Eaton). Non-linear loads include switch-mode power supplies, pulse-width-modulated variable speed drives for motors, photocopiers, personal computers, laser printers, fax machines, battery chargers, and universal power supplies. When converting utility-supplied AC power to DC power, a switched mode power supply draws current in high-amplitude short pulses that creates significant distortion in both electrical current and voltage waveforms. This distortion, measured as total harmonic distortion (THD), can travel back to the power source and affect other equipment connected to the same source (Eaton). THD can cause overheating of electrical distribution equipment and transformers, high voltage and circulating currents caused by harmonic resonance, high neutral currents, and equipment malfunctions and false tripping of circuit breakers (Eaton).

A standard transformer is not designed for the high harmonic currents produced by non-linear loads and can overheat and prematurely fail (Eaton). K-rated transformers do not eliminate harmonics, but are designed to withstand the excess heat generated by harmonic currents (Eaton). A standard transformer designed for linear loads has a K-factor of 1. K-factors range from 1 to 50 with the higher K-factor transformers being typically larger than standard units. The higher the K-factor, the more heat tolerance or heating from harmonic currents the transformer is able to withstand (Eaton).

A K-4 transformer is generally adequate due to improvements in modern power supplies; non-linear loads rarely exceed K-9 in the field and a K-13 transformer is "bullet proof." (Personal communication with Mike Van Gheem, U.S. Marketing Manager, Hammond Power Solutions). Note that a higher K value extends transformer life, but does not produce efficiency gains. Table 19 gives the appropriate K-factor ratings to select for different percentages of non-linear current in an electrical system (Eaton).

ANSI/IEEE recommended practices state that a transformer subject to nonsinusoidal load current having more than 5% total harmonic distortion needs to be derated. When current THD exceeds 15%, the transformer capability should be evaluated by professionals using IEEE recommendations (MGM). The IEEE recommendations do not apply to K-factor rated transformers as they are designed to withstand excess heat generation from distorted current waveforms (MGM).

One low-voltage dry-type transformer manufacturer states that less than 15% of purchase specifications call for K-rated transformers (Van Gheem). It is likely that dry-type transformer oversizing has a beneficial aspect in that the non-K-factor rated transformers have excess cooling capacity and are thus able to accommodate the excess heat generation from current THD without exceeding allowable temperature rises or shortening of equipment life.

Table 19. Transformer K-factor Selection versus Non-Linear Current in Electrical System

Non-linear Load	K-rating
Incidental electronic equipment representing <5 percent	K1
Harmonic-producing equipment representing <35 percent	K4
Harmonic-producing equipment representing <50 percent	K7
Harmonic-producing equipment representing <75 percent	K13
Harmonic-producing equipment representing <100 percent	K20

A second transformer K-factor selection guide is shown in Table 20 (Zega). Again, an increased presence of nonlinear loads indicates the need for a transformer that is designed to withstand the heat buildup that harmonics can create.

Table 20. Transformer K-factor Selection versus Type of Load Served

Transformer K-factor ratings	
K-factor	Load type
K-1	Linear loading
K-4	Solid-state electronics
K-9	Medium-density solid-state electronics
K-13	Heavy-density solid-state electronics
K-20	Switching loads and variable frequency drives
K-40	High-order harmonics switching loads

Harmonic Mitigation Transformers

Harmonic Mitigating Transformers (HMTs) are specifically designed to minimize the voltage distortion and power losses that result from harmonics generated by non-linear loads (MGM). K-rated transformers are simply designed to prevent overheating when subject to heavy non-linear loads but do nothing to reduce the harmonic currents and associated losses or voltage distortion themselves (MGM).

HMTs use electromagnetic mitigation to deal specifically with triplen (3^{rd}, 9^{th}, 15^{th}) harmonics. Secondary windings of the transformer are arranged to cancel zero sequence fluxes and eliminate circulating currents in the primary windings. Phase shifting is used to address 5^{th} and 7^{th} harmonics (Eaton). HMT transformers reduce upstream harmonic currents while saving energy and eliminating overheating through reducing harmonic losses. Both K-factor rated and HMTs are designed to the same DOE-2016 efficiency standards as conventional transformers but do carry a significant price premium.

A Design Philosophy to Maximize Transformer Efficiency

Canadian transformer manufacturer Powersmiths recognized that low-voltage dry-type distribution transformers could be "optimized" for light-load or heavy load applications. They offer transformers that are optimized for conditions of light loading through providing exceptionally low no-load losses. Powersmiths has focused on the production of "ultra-efficient" dry-type transformers, with their market niche being purchasers wanting to meet LEED requirements, obtain net-zero building performance, or in meeting carbon footprint reduction goals.

Powersmiths claim that their performance optimized transformers deliver 20% to 50% lower losses than those designed to just meet the DOE 2016 efficiency standards. Their OPAL (Optimized Performance for the Application Load) model lines are designed for maximum performance over a specified load range. A transformer optimized for light loading conditions should not be used in an application where higher than anticipated loading occurs. Their transformers are "K-rated" i.e. K=7, and thus carry a significant price premium.

Powersmiths achieves superior performance through using the best core steel available along with attention to efficient design and construction. Design best practices also address such critical issues as impedance, inrush, fault levels, and arc flash. As shown in Figure 9, different transformer models are optimized for different load ranges – 0 to 25%; 50% to 100%; and 75% to 100% of rated load. The E-Saver 33-L model is designed to offer significant energy savings under conditions of light loading.

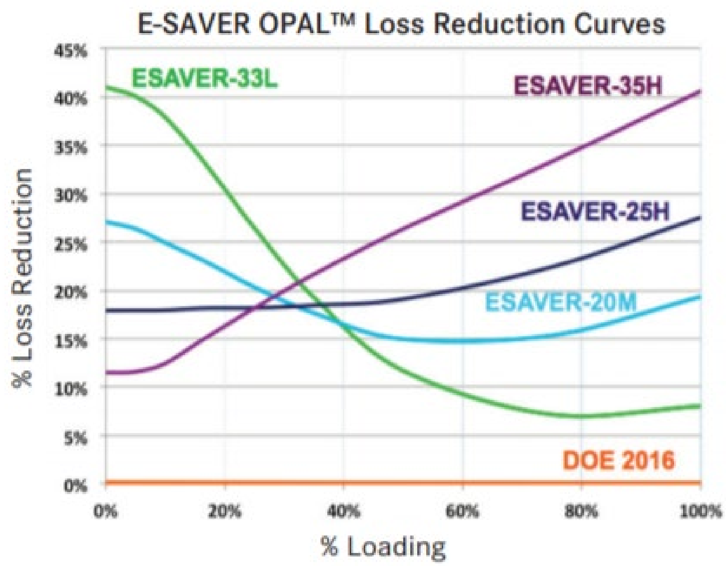


Figure 9. Loss Reduction Curves for Powersmith's Load-Optimized Transformer Models

Powersmiths also recognizes that transformer sizing is important when trying to maximize efficiency and addresses transformer oversizing issues through manufacturing kVA ratings that are "in between" the typical ratings that are specified by NEMA or IEEE. (Personal communications with Camilo Arango, Regional Sales and Business Development Manager, and Rick Howard, Engineering Manager, Powersmiths International).

No-load and load loss data is given in Table 21 for the Powersmiths E-Saver-80R (Al) and their E-Saver-81R (Cu windings) low-voltage dry type transformer models.

Table 21. No-Load and Load Losses for Transformers Optimized Light-Loading Conditions

E-Saver-80R			
Aluminum, K-7, 130C Rise			
kVA	No Load Losses (W)	Full Load Losses (W)	
10	34	434	3-Ph
15	35	775	3-Ph
20	48	1157	3-Ph
25	57	674	1-Ph
30	57	1332	3-Ph
37.5	65	1025	1-Ph
45	78	1725	3-Ph
50	79	1309	1-Ph
63	100	2130	3-Ph
75	111	2537	3-Ph
100	125	2227	1-Ph
112.5	164	3313	3-Ph
125	186	3470	3-Ph
150	203	3945	3-Ph
167	167	4010	1-Ph
200	288	4462	3-Ph
225	319	4317	3-Ph
250	356	4853	3-Ph
300	371	6229	3-Ph
400	465	7324	
500	558	8419	3-Ph
750	770	11377	3-Ph

E-Saver-81R			
Copper, K-7, 130C Rise			
kVA	No Load Losses (W)	Full Load Losses (W)	
10			
15	33	703	3-Ph
20	40	800	
25	42	668	1-Ph
30	55	995	3-Ph
37.5	66	1181	
45	77	1367	3-Ph
50	88	1469	3-Ph
63	96	1835	
75	109	2147	3-Ph
100	139	2530	
112.5	154	2722	3-Ph
125	169	2967	
150	198	3458	3-Ph
167	216	3645	
200	251	4007	
225	277	4282	3-Ph
250	300	4699	
300	346	5533	3-Ph
400	420	6939	3-Ph
500	504	8187	3-Ph
750	697	10796	3-Ph

Northwest Market Channels, Annual Shipments, and Estimate of Potential Annual Energy Savings

Large manufacturers of low-voltage transformers compete with each other to deliver the lowest first cost by manufacturing high volume transformers that comply only with the minimum efficiency requirements of DOE 2016. The lowest first cost wins over low lifecycle cost in the majority of transformer purchase decisions (Powersmiths).

Standard low-voltage dry-type transformers at and below 300 kVA are typically stock items that are held in distributor warehouses (CEE). Transformers larger than 300 kVA are typically built-to-order. All medium-voltage dry transformers are built-to-order.

The delivery channels for commercial and industrial purchasers of low-voltage dry-type transformers (shown in Figure 10) include the stocking distributor, electrical contractor, or customer representative which is typically a general contractor or an architecture and engineering firm (CEE). Manufacturer representatives are a key source for technical information regarding dry-type transformer products. Electrical contractors purchase transformers either from a stocking distributor or directly from a manufacturer (CEE). They are responsible for electrical system installation, but are not involved in payment of energy bills (CEE). Customer agents such as architecture and engineering firms or general contractors generally prepare specifications for the electrical contractor, who actually procures the equipment. Depending upon end user or customer awareness and goals, the most energy-efficient or high-performance transformer for a given application may or may not be acquired.

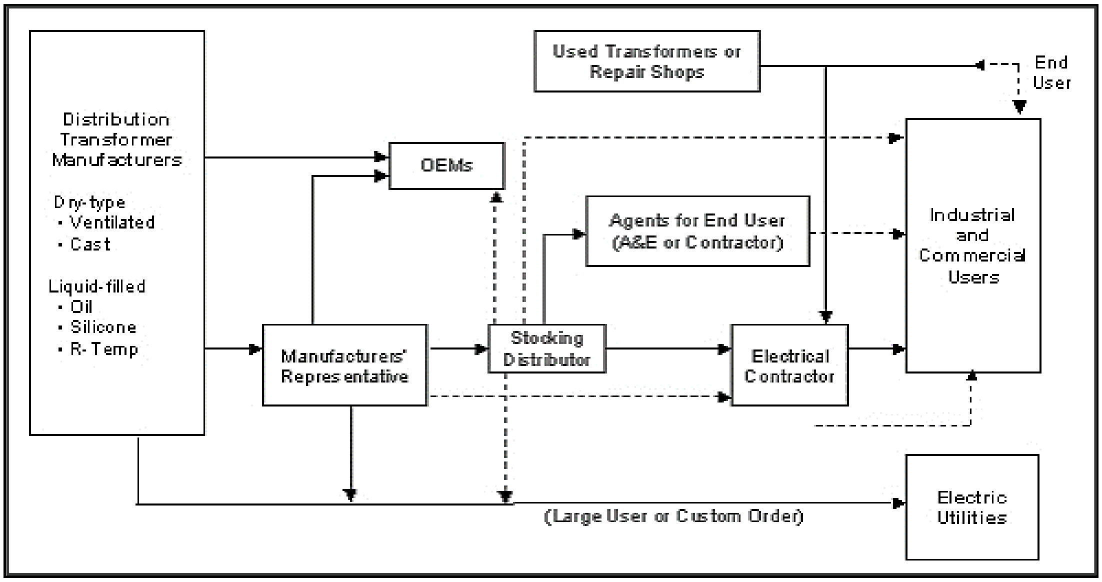


Figure 10. Transformer Stocking, Distribution, and Delivery Channels

Estimate of Dry-Type Distribution Transformer Annual Shipments to the Northwest

NEMA provided transformer shipment data to DOE that was used to establish the costs and savings for adopting the 2016 standards. The 2009 data (see Table 22) indicates that 17,749 dry-type single-phase low-voltage distribution transformers were shipped nationwide along with 206,929 three-phase dry-type units (US DOE).

More recent shipment data is not available. If shipments are prorated by northwest to national electrical energy consumption, it could be assumed that 1.56% of the low-voltage three-phase dry-type units would be shipped to the Northwest each year, meaning a total of at least 3,228 transformers would be purchased and installed annually. If the average energy savings per transformer is about 1,095 kWh/year due to selectively acquiring those with the lowest no-load losses, potential savings are on the order of 3.53 million kWh/year. Note that these energy savings may be obtained at little or no additional or incremental cost through education of end users and those involved in the transformer procurement process. The energy savings potential from conducting a transformer retrofit/downsizing program could be much greater, but it is impossible to determine the magnitude of the potential annual energy savings without knowledge regarding the existing pre TP-1 transformer stock remaining in operation in commercial, institutional and industrial facilities.

Table 22. Estimate of National Transformer Shipments (2009)

Distribution Transformer Equipment Class	Units Shipped (nationwide)	MVA Capacity Shipped
Low-Voltage, Dry-Type, single-phase	17,740	647
Low-voltage, Dry-Type, three-phase	206,929	15,778
Totals	**224,669**	**16,425**

Dry-Type Transformer Costs

Equipment costs for conventional, K-factor rated (K=9) and Powersmiths ultra-efficient K-rated transformers are given in Table 23 (Van Gheem, Powersmiths). Both the K-rated and the Ultra-efficient transformers are shown to carry a significant price premium.

Table 23. Comparative Costs for Conventional, K-Rated, and Ultra-Efficient Low-Voltage Dry-Type Transformers

kVA Rating	HPS Sentinel G, K=0, 150°C	Eaton K-9, Al, 115°C	MGM K-9, Al, 115°C	Powersmiths OPAL 80-R, K-7, 130°C
75	$2,663	$3,570	$3,393	$5,413
112.5	$3,659	$4,817	$4,220	$7,768
150	$4,071	$6,176	$5,355	$9,455
225	$6,699	$8,841	$7,560	$12,399

Recommendations and Conclusions

Market transformation of dry-type transformers requires education and increased awareness. Market actors that make transformer purchase decisions need to understand appropriate transformer sizing and minimizing low-load losses. Manufacturers indicate that higher efficiency products could be offered, such as an extremely low no-load loss amorphous core dry-type transformer, but absent market demand they do not perceive that there is a market for them.

At the same time, very little is known about the loading on, sizing practices, or performance of the existing northwest low-voltage dry-type transformer stock. Even less is known regarding load types, voltage and current total harmonic distortion (THD) typically encountered by dry-type transformers in the field. More information is needed so that BPA and their customer utilities can improve the offering of low-voltage dry-type transformer retrofit and upgrade incentive programs.

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