B O N N E V I L L E   P O W E R   A D M I N I S T R A T I O N

Emerging Technologies

Low-Voltage Liquid Immersed Amorphous Core Distribution Transformers

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Amorphous Core Liquid Immersed Distribution Transformers

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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

Bonneville's Energy Efficiency Engineering team collaborated with Washington State University Energy Program to perform a national level review of low-voltage liquid immersed distribution transformer purchasing practices. Amorphous core transformers are not commonly purchased in the Pacific Northwest, yet they have the potential of providing substantial annual energy savings. Amorphous core transformers reduce no-load losses by 50 to 70 percent compared to traditional baseline U.S. Department of Energy 2016 grain-oriented silicon-steel transformers. Additional energy savings may be realized under certain conditions, such as when lightly loaded and when operating under conditions of high harmonic distortion.

See additional insights regarding the purchasing of high efficiency liquid-filled transformers in EPA's report entitled: ENERGY STAR Guide to Buying Energy Efficient Distribution Transformers.

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Acronyms

ACEEE – American Council for an Energy-Efficient Economy
ACT – liquid-immersed amorphous core metal transformer
BC – British Columbia
Bil – basic insulation level
BPA – Bonneville Power Administration
C&I – commercial and industrial
CAD – Canadian dollars
CEE – Consortium for Energy Efficiency
DOE – U.S. Department of Energy
EPA – U.S. Environmental Protection Agency
ET – Emerging technologies
GE – General Electric
GO – grain oriented
HVAC – Heating, ventilation, and air conditioning
LADWP – Los Angeles Department of Water and Power
LBNL – Lawrence Berkeley National Laboratory
LEED – Leadership in Energy and Environmental Design
NEEP – Northeast Energy Efficiency Partnership
NEMA – National Electrical Manufacturers Association
NES – Nashville Electric Service
OPAL – optimized performance for the application load
PUD – Public Utility District
PUL – Percent Unit Loading
RMS – root-mean-square
TCO – Total Cost of Ownership
TOC – Total ownership cost
TVA – Tennessee Valley Authority
UN – United Nations
USD – United States dollars
WE – Weekends
WS - Weekdays
WSU – Washington State University

Executive Summary

Changing market conditions are diminishing the amount of energy savings that Bonneville Power Administration (BPA) claims from its largest conservation measures. Namely, energy savings from lighting and residential HVAC are diminishing as these products are either fully embraced by the market or the incentives are no longer cost effective. BPA is looking to the utility distribution sector for new cost effective energy efficiency incentives and energy savings.

Although amorphous core transformers (ACT) have been available for decades, they are not commonly purchased in the Pacific Northwest (PNW). The current U.S. Department of Energy (DOE) 2016 mandatory transformer minimum efficiency standards do not require the use of amorphous core transformers. Yet the potential annual energy savings from the purchase of single and three-phase low-voltage liquid-immersed amorphous core transformers are substantial. Because of their design and the materials used in their manufacturer, ACT reduce no-load losses by 50 to 70 percent as compared to baseline transformers manufactured with conventional grain-oriented Silicon-steel materials. Over time, advances in materials annealing practices and transformer design and fabrication have greatly reduced the incremental cost and weight penalties that were characteristic of early ACT designs. While transformer no-load losses appear relatively small compared to load or winding losses, a decrease in no-load losses can lead to significant energy savings because they occur whenever the transformer is energized, which is 24/7 (8,760 hours/year).

It is estimated that over 18,000 liquid-immersed distribution transformers are shipped to the Northwest each year. These shipments serve BPA customer utility needs for both transformer end-of-life replacements and to serve new loads. Regional energy savings would be about 2,066 MWh per year or 0.24 aMW annually if enhanced efficiency ACT were to account for 30% of all BPA customer utility low-voltage transformer purchases. Over a ten-year period, cumulative energy savings could amount to 20,660 MWh annually or 2.4 aMW per year.

ACT are shown to provide superior performance over conventional grain-oriented silicon steel transformers (i.e. provide additional energy savings) when operating under conditions of high harmonic distortion. A BPA contractor completed modeling that indicates that ACT transformers do not significantly increase the probability or severity of ferroresonance incidents.

High efficiency ACT are demonstrated energy savers, especially when the distribution transformers are lightly loaded, 20% of nameplate capacity or less. Several US utilities and most Canadian utilities selectively purchase these transformers. BPA currently offers incentives to encourage their customer utilities to acquire energy savings via the purchase of higher efficiency distribution transformers. BPA recommends that utilities include ACT manufacturers in their bid pool and obtain equipment cost quotations, weight estimates, and transformer performance data so that informed energy efficient product procurement decisions are made, prior to actual purchase.

Background

BPA

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 has delivered 5,050 aMWs to the region, which is equivalent to the annual output from five of the largest hydro projects in the 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.

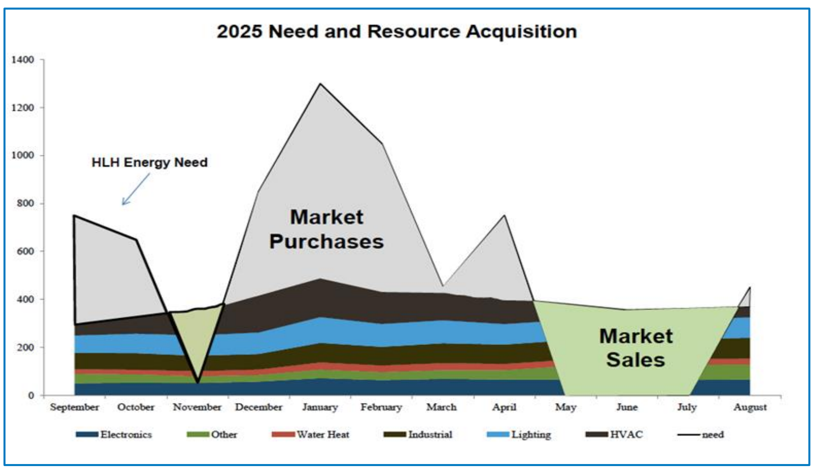

Figure 1. BPA Resource Program Requirements

[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

Transformer Standards

National Electrical Manufacturers Association

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). NEMA TP-1 applies to distribution transformers with a supply voltage of 34.5 kV and below and a low voltage secondary (i.e. less than or equal to 600 Volts); single-phase units rated at 10 to 833 kVA are covered by this standard along with three-phase units rated from 15 to 2500 kVA. (The TP-1 efficiency levels 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 EPA – through its Energy Star C&I Transformer Program – launched **voluntary** initiatives to stimulate energy efficient transformer purchases (CEE). Both programs recognized the NEMA TP-1 minimum efficiency levels – which reduced transformer losses by about 50% relative to pre TP-1 performance.

Department of Energy 2016 Standard

Under the Energy Act of 2005, the U.S. DOE established **mandatory** transformer efficiency standards – again equivalent to the NEMA TP-1 levels for liquid-immersed. These standards went into effect in January of 2007. In 2010, NEMA released a new set of **voluntary** efficiency levels for distribution transformers sold under its NEMA Premium label. NEMA Premium transformers must provide a minimum of 30% fewer total load losses than those specified by the TP-1 minimum standard level.

In 2013, the U.S. DOE updated the Energy Policy Act of 2005 to raise the efficiency levels for liquid-immersed transformers. Single-phase transformer efficiency standards remained at the NEMA TP-1 levels. The new mandatory minimum efficiency levels, referred to as the DOE 2016 transformer standards, came into effect as of January 1, 2016. These standards roughly correspond with the NEMA Premium requirements and are summarized in Appendix 1 (US DOE) (MGM Transformer Company).

The efficiency of a liquid-immersed distribution transformer is determined at 50% of its rated capacity (or 50% load point). No-load losses are determined at a temperature of 20ºC while load losses are determined at a temperature of 75ºC. The DOE 2016 standards were recognized to be fairly rigorous as they estimated that 72.7% of the liquid-immersed distribution transformers sold in 2009 would not be in compliance with the new mandatory minimum efficiency requirements (US DOE).

In its technical support document, DOE recognized that higher efficiency liquid-immersed distribution transformers are commercially available that use an amorphous metal core material. Amorphous core transformer (ACT) performance was not used to set the national standard as Hitachi Metals is the only global supplier of the amorphous material and they operate a single wholly-owned subsidiary in the U.S. (the Metglas factory in South Carolina)[3].

The Energy Independence and Security Act requires that the Secretary of Energy determine whether product standards require amendments, and issue a Notice of Proposed Rulemaking for the 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 distribution transformers. The Secretary must make a determination on transformer standard modifications by 2020 (DOE) (U.S. DOE). To date, there has been no activity to amend the standard. The 2016 DOE standard is the ACT transformer baseline for measuring efficiency.

Liquid Immersed Amorphous Core (ACT) Distribution Transformers

This research examines both single and three-phase liquid-immersed amorphous metal core distribution transformers between 10 kVA and 2500 kVA with a secondary voltage of 600V or less. Liquid-immersed transformers are filled with oil and are purchased mostly by utilities to reduce supply voltages to levels suitable for customer use. These transformers are primarily used outdoors on poles, pad-mounts, or in vaults as distribution transformers.[4] Hereafter, this paper will refer to these transformers as ACT distribution transformers.

Potential annual energy savings from the purchase of single and three-phase high efficiency ACT are substantial. It is estimated that over 18,000 units are shipped to the Northwest each year[5]. These shipments serve BPA customer utility needs for load growth plus account for end-of-life transformer replacements. If customer utilities procure ACT transformers that just meet the DOE minimum efficiency standards at a 30% penetration or adoption rate, the region could save about 2,066 MWh/year or 0.24 aMW per year. Over a 10 year period, cumulative regional energy savings could be 2.4 aMW. However, assuming Northwest utilities purchase the higher efficiency ACT transformers the region could save even more – 2,852 MWh per year or 0.34 aMW. Since the amount of energy savings are proportional to number of transformers purchased, doubling the purchasing quantity would double the annual energy savings.

Generally, high efficiency ACT transformers do not exhibit a significant price or weight premium. Above 100 kVA, pole-mounted ACTs designed to the 2016 DOE Standard are actually less expensive than conventional baseline transformers with silicon grain-oriented steel cores. For the more efficient ACT transformers, the incremental cost or price premium is less than 13% above that of a comparable baseline unit. Above 500 kVA, ACTs are actually significantly less expensive.

> *Transformer purchase decisions must appropriately value a transformers' no-load and load losses*

Utilities must ensure that ACT manufacturers are included in their bidder lists to realize the cost and efficiency advantages when making transformer purchasing decisions. In addition,

[3] Personal Communication with Bene Martinez, Sales Manager, Metglas, Inc. 5/17/2019.

[4] There are also dry-type transformers that are mostly used inside buildings that are not discussed in this report.

[5] See Section 11 for derivation.

these transformers are “custom-designed” for each utility based on specific no-load and load loss valuation factors. These values are used to optimize transformer design using the Total Cost of Ownership (TCO) life cycle methodology. Without accurately determining these loss valuation factors, utilities may purchase “least cost” transformers with reduced efficiency. When TCO is not taken into account at the time of purchase, the utility may suffer unnecessary distribution system losses over the 30+ year life of the acquired transformer.

Findings

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 standards are based upon performance at a designated load or capacity point – 50%. One disappointing consequence of the DOE 2016 standards is that manufacturers stopped marketing transformers based upon performance or efficiency. All transformers sold in the U.S. or imported into the U.S. must meet the DOE 2016 standards so efficiency is no longer a selling point. Thus, efficiency ratings for no-load losses are often not provided by transformer manufacturers. An examination of technical specification sheets indicates that many manufacturers no longer provide the no-load and load losses. As a result, many utility procurement officials simply purchase the lowest cost unit.

Equation 1

$$Efficiency = \frac{Input - Losses}{Input}$$

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 liquid-immersed transformer life exceeds 30 years) and should select transformers using life cycle or "Total Cost of Ownership" methodologies (Hitachi) (Siemens).

Figure 2 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 2) total losses are dominated by the no-load loss component. DOE's Smart Grid program is investigating load control as one way of reducing transformer load losses (UN Environment).

Lower no-load losses in ACTs are a direct result of the properties of the base **amorphous metal core**. The ACT core's higher resistivity and reduced material thickness leads to lower eddy current losses. A reduction in resistance of the amorphous metal to changes in magnetization (or coercivity) is due to the absence of a crystalline structure (anisotropy) and leads to lower hysteresis losses[6] (Hitachi).

[6] Hysteresis losses are due to the energy required to magnetize and demagnetize the transformer core as current flows in the forward and reverse directions.

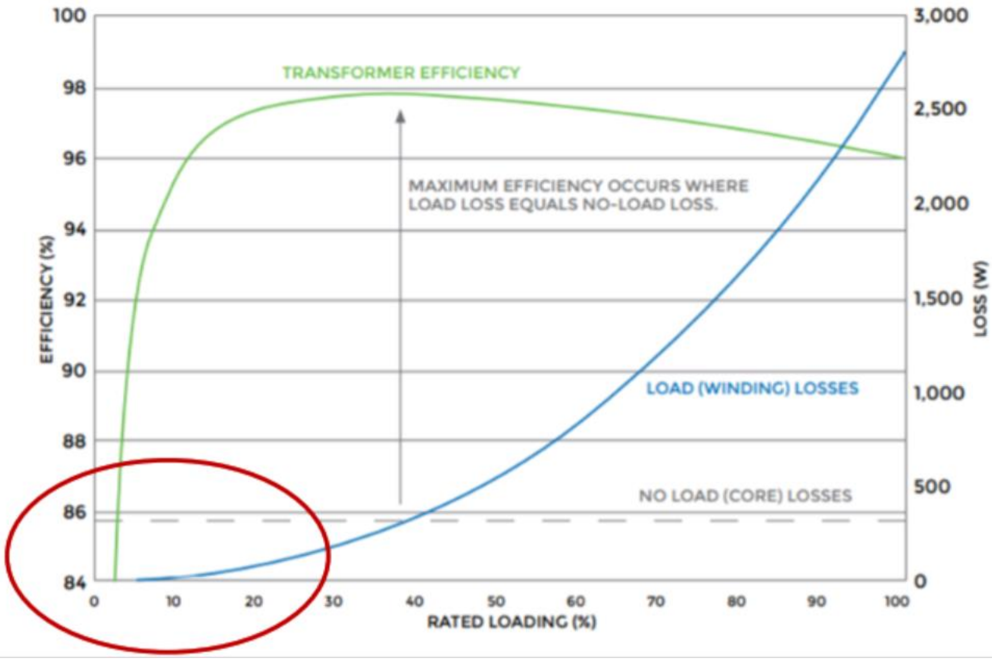

Figure 2. Impact of Load on Losses and Efficiency

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 load profile is shown in Figure 3 (National Grid). Operating experience from the European Union suggests that the ratio of no-load to load losses is close to three (Kefalas).

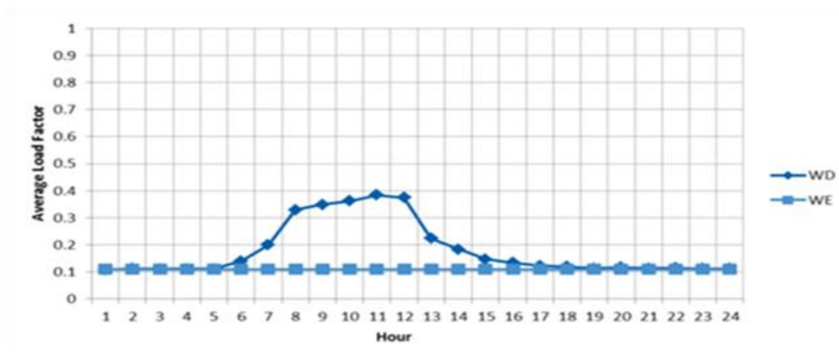

Figure 3. Typical Load Profile for a Commercial Sector Transformer on Weekdays (WD) and Weekends (WE)

While low-voltage liquid immersed transformers are tested for efficiency at their 50% load point, loadings for in-service units can be considerably lower. The IEEE transformer committee has obtained data from various utilities that indicates that transformer per units loads often fall below 25%--- much less than the load point at which they are tested (see Table 1). Utilities purchase 90% of ACT liquid-immersed transformers for outdoor use. Liquid-immersed transformers are not specified for indoor applications due to the potential for oil leaks and subsequent fire hazards.

Table 1. Average Transformer Loading for Various Utilities

Utility	Per Unit Transformer Load
Dominion	10%
Duke Energy	15%
ConEd	26%
Toronto Hydro	24%
Clallam County PUD	13.9%

Sources: Metglas, "Distribution Transformers RFI" and John Purvis at Clallam County PUD

While transformer efficiency standards are generally expressed as efficiency at a stated transformer load point (50%), 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

Equation 2

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

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

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 expressed using the "equivalent hours" methodology, seen in Equation 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. ACTs tend to produce annual energy savings because no-load losses are reduced by 50% to 70% (Energy Star) (National Grid). Annual energy savings are equal to the difference in annual energy losses between any two units, as shown below in Equation 3.

Equation 3

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

High Efficiency Transformers

ACT were developed in 1960 and field-tested by the Electric Power Research Institute (EPRI) in the mid-1980s. They are now a mature and proven technology. These transformers are widely used in Canada, India, China, the European Union, and the United Kingdom. ABB notes that over three million units are in operation worldwide and that over 40 manufacturers of ACT transformers exist and are readily available and used in the U.S. (ABB). However, a utility must include these ACT transformer manufacturers in its bid pool to be offered a high efficiency unit. ACT transformer manufacturers that sell into the North American market are listed in Table 2.

Table 2. Manufacturers Selling ACT in North America

ABB	Central Maloney
Cooper Power Systems (Eaton)	Sanil (Korea)
Schneider Electric	CHERYONG (Korea)
Siemens	ERMCO
Howard Power Solutions	CAMTRAN (Canada)
GE Prolec	Hitachi (Japan)

DOE examined efficiency and cost relationships for several classes of distribution transformers. Its analysis indicates that using ACTs are the best way to obtain additional transformer efficiency benefits at a reasonable cost. DOE did not establish national efficiency standards calling for this specification and design however, because there is not enough domestically available material to serve increased demand and additional low-loss core material would have to be sourced from overseas. (US DOE).

ACT Transformer Performance Characteristics

Grain-Oriented (GO) Silicon steel versus ACT Designs

Amorphous metal has a non-crystalline structure (amorphous is more of a glassy structure), so energy losses due to hysteresis (or due to magnetic domains rotating when subject to magnetic induction) are small when magnetic fluxes pass through the core. As the thickness of the amorphous metal "ribbon" is about 1/10th that of silicon steel transformer material, eddy current losses are also reduced. The result is that no load losses (hysteresis losses and eddy current) are reduced by 50% to 70% as compared to conventional materials (Hitachi) (Ramanan).

Table 3. Properties of Transformer Core Lamination Steel

Thickness (mm)	Grade	Core Losses (W/kg) 50 Hz
0.23	M3	0.090
0.27	M4	1.12
0.30	M5	1.30
0.35	M6	1.45

Traditional transformers have core laminations that are cut from a special steel called cold rolled grain oriented (GO) electrical silicon steel. This specialty steel has a special grain surface and comes in thicknesses of 0.23 mm, 0.27 mm, 0.30 mm, or 0.35 mm (referred to as M3, M4, M5, and M6) grade lamination steel. Core losses are expressed in Watts per kg. Core losses for popular grades of GO electrical steel are given in the Table 3 (World of Steel).[7]

[7] https://www.worldofsteel.com/learning_det.php?type=electrical_steel&name=Electrical%20Steel%20-%20Grades%20and%20Standards.

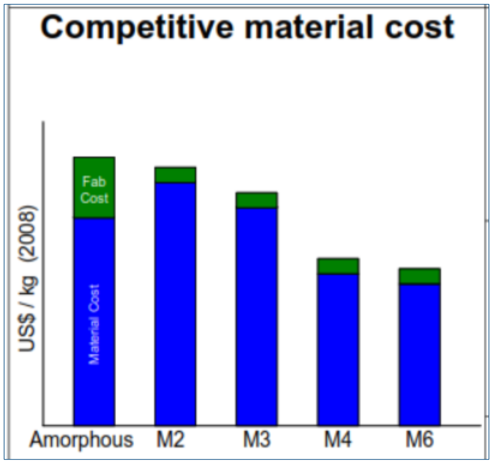

Figure 4. Relative Cost of Amorphous and Other Transformer Core Lamination Steels

Over time, increasing transformer efficiency standards have led to the use of higher quality and higher cost transformer lamination steel. Transformers that meet the 2016 DOE Standard might use M3 lamination steel instead of M6 electrical steel.[8] Use of a higher quality steel to meet the more stringent efficiency standards results in a decrease in the difference in no-load Watts between the baseline and ACT transformers but also results in a diminishing difference in first cost and weight between the amorphous metal and GO silicon steel transformers. See Figure 4 (ABB).

Low-loss material is more expensive than conventional core materials and special manufacturing techniques are required. Pole transformers tend to top out at 250 kVA (some can be up to 833 kVA) and larger transformers are pad-mounted. Pad transformers cost slightly less than pole types (in a new installation) but are more costly to install due to undergrounding of utility lines.[9,10].

First generation amorphous alloys were cast as a thin ribbon. Following furnace annealing, the alloy produced had the desired electrical and magnetic properties, but was extremely hard and brittle, making the winding of a transformer core labor-intensive, difficult, and costly. Consequently early transformer designs were larger and 15% to 30% heavier than conventional transformers. The first generation transformers also operated with a lower flux density and required a bigger core cross-sectional area, requiring larger coils and a larger footprint. When the length of the windings that surround the core increases, conductor or load related losses can also increase. Use of additional materials meant that early ACT transformer designs had a price premium or incremental cost of 20% to 30% relative to conventional transformers[4].

A continuous series of improvements in amorphous material alloys, in the amorphous ribbon casting process; and in annealing methods has resulted in the availability of a wider, flatter, flexible, curved, and ductile ribbon of increased thickness. These improvements resulted in higher core stacking or lamination factors, providing significant reductions in transformer weight and volume.

At the same time, conventional GO silicon steel transformers increased in weight and cost as they had to be re-designed to comply with the EPACT-2005 TP-1 and subsequent higher DOE 2016 mandatory minimum efficiency standards. As a result, current generation pole and pad-mount ACT transformers have greatly reduced weight and cost penalties when compared with conventional silicon-steel units.

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[8] M2 steel has a thickness of about 0.18 mm while amorphous core metal thickness is about 0.03 mm.

[9] Personal Communications with Jack Ward, Regional Marketing Manager, Howard Industries, 5/22 to 8/15/2019

[10] Personal Communication with Brian Wood, Design Engineer, Central Maloney, 5/30/2019

Total Cost of Ownership (TCO)

Distribution transformers are not "off-the-shelf" items. Customers must specify the primary voltage, secondary voltage (typically 480 V, 277 V, 208 V, 120/240 V), and impedance (which limits the current going through the transformer in the event of a ground fault). Other design variables include enclosure material (stainless steel when sea salt is present), encapsulated (if located in a vault and can be immersed in water), mounting bracket design, and coating[5]. Manufacturers offer ACT to a utility when they are the optimum and most cost-effective alternative. Several manufacturers can provide bids for both grain-oriented silicon steel transformers and ACTs.

Transformer manufacturers do not publish list prices for standard versus ACT as raw materials prices are constantly changing. In addition, distribution transformers are custom-designed in accordance with utility specifications and optimized in proprietary software programs in accordance with the utility-provided A and B loss valuation factors used in the Total Cost of Ownership equation (given below). Each utility determines its own loss valuation values based upon financing conditions, incremental cost of energy, and expected transformer loading.

In purchasing transformers, utilities often use a life cycle or "Total Cost of Ownership" (TCO) approach to capitalize the value of the transformer losses (Siemens) (ABB).

Equation 4. Total Cost of Ownership

$$TCO = CT + A \times PNL + B \times PLL \quad where:$$

TCO = Total Cost of Ownership ($)
CT = Transformer purchase price
PNL = No–load losses in W – this is a steady value when the transformer is energized
PLL = Load – losses in W (given at full load and at a reference temperature)
A = Capitalization factor or system capital investment to supply the no–load losses
B = Capitalization factor for load losses.

The multiplication factors A and B are dependent upon costs of new generation, transformer loading, operating hours, cost of capital, energy prices and market forecasts, and the expected transformer life (typically 32 years). Utility values for A and B are often in the range of $5/W to $10/W for P_{NL} and $1/W to $2/W for P_{LL} (Ramanan).

The IEEE Power and Energy Society (IEEE) notes that the A factor ($/W) used to determine the cost of no-load losses is:

Equation 5. "A" Factor

$$A = (SC + EC \times HPY) \times LM / FCR \times 1,000 \ where:$$

SC = Levelized avoided cost of new system capacity ($/kW per year)
EC = Levelized avoided cost of energy ($/kWh)
HPY = Hours of operation per year (generally 8,760)
LM = Loss on loss multiplier (per unit)
FCR = Fixed charge rate (%/100)

A utility's avoided costs for energy and capacity should be determined on a long-range incremental cost basis using an expansion planning computer program and should include planning for a reserve margin. The avoided cost of system capacity should also include components for the avoided cost of transmission capacity and for distribution capacity. The loss multiplier should account for transmission and distribution system loss avoidance. The IEEE methodology does not account for CO2 offset benefits.

Transformer manufacturers use the TCO design optimization software to optimize the design for a transformer that offers the lowest TCO for their utility customer. To enable the manufacturer to identify the most cost-effective designs, utilities must provide to the manufacturer both transformer specifications and appropriate A and B values. A representation of analysis results is given in Figure 5 (ABB).

Transformer Loss Capitalization Software Tools

Transformer manufacturer ABB has developed an on-line transformer TCO calculator. With the entry of only a few variables, the tool determines the A and B values that should be used to capitalize the values of the transformer no-load and load losses. The tool is useful in that the user can quickly observe the sensitivity of the A and B values with respect to changes in interest rate, electrical energy prices forecasted escalation rates, and the average transformer loading over its operating life. A screen image of the tool is shown in Figure 6.[11]

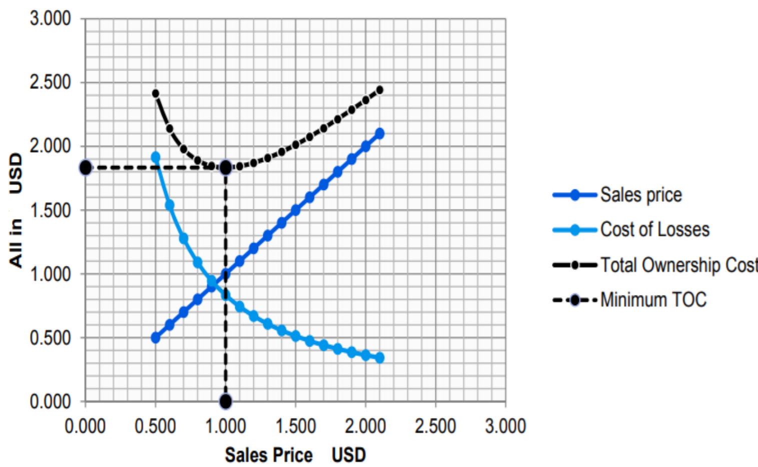


Figure 5. Use of TCO Methodology to Select the Most Cost-Effective Transformer

[11] The tool is available at: http://tcocalculator.abb.com/ .

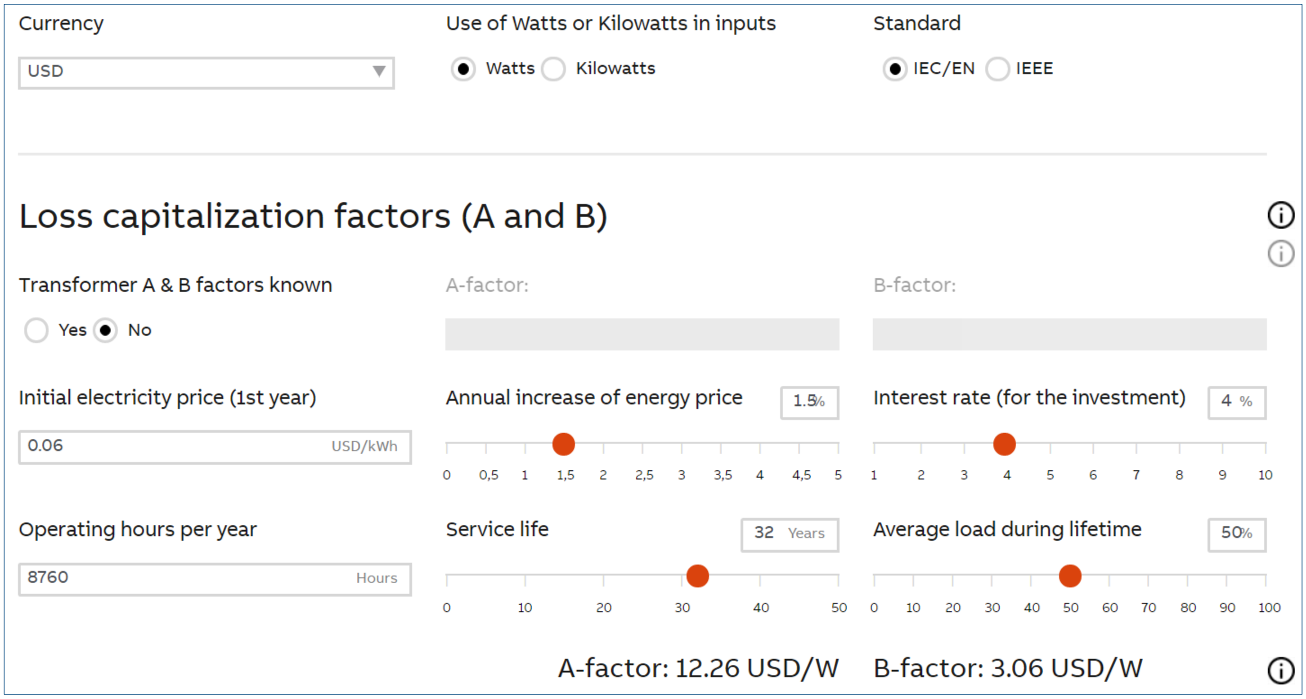


Figure 6. TCO Loss Multiplication Factor Calculator

DNV-GL, an international consulting company with an office in Seattle, has also developed a "Transformer Loss Calculation, Version 1.0.1" tool. The software tool allows the user to enter performance values for multiple transformers of the same rating, and a load profile. This tool, will also consider the costs of CO_2 emissions. A sample loss calculation for a 1,000 kVA transformer shows that the present value of the transformer losses greatly exceeds the capital costs of the transformer purchase over the transformer useful operating life. Given the input of an electrical rate of 6.82¢/kWh with an interest rate of 7.0%, and a 25 year transformer life, DNV-GL's tool determines a no-load loss valuation or A factor of $11.55/W with a corresponding B value of $3.50/W. This tool also takes into consideration a CO_2 emissions factor of 1.0 kg/kWh with an emissions cost of $41.32/short ton.[12]

[12] Additional information is at: https://www.dnvgl.com/energy/articles/TLCT_Example.html.

Loss Valuation A and B values used in the Northwest Region

BPA has completed a survey to establish a sample of A and B values used by its utility customers in the Northwest when purchasing distribution transformers (see Table 4). Sixteen utilities provided responses. The survey indicates that A and B values are generally low because many utilities purchase their energy from BPA at a low cost. Higher loss valuation is appropriate when the loss valuation is determined based upon the incremental cost of energy and capacity to BPA. When A and B values are low, the purchase decision tilts towards buying the cheapest and lowest efficiency transformer available. Reported transformer loss values are given below for Northwest utilities. One-third of the responders did not use the TCO approach and simply purchased the lowest cost transformer available. Only Clallam County PUD has a history of purchasing ACTs. An analysis of utility responses to the survey questions is contained in Appendix 2.

Table 4. PNW Utilities Loss Valuation Multipliers

Utility	A or no-load loss multiplier	B or load-loss multiplier
Utility #1	$5.47/W	$0.76/W
Utility #2	$4.93/W	$1.62/W
Utility #3	$7.50/W	$1.35/W
Utility #4	$3.96/W	$1.25/W
Utility #5	$3.75/W	$1.50/W
Utility #6	$4.11/W	$1.03/W
Average	**$4.95/W**	**$1.25/W**

ACT Incremental Cost and Weight Findings

A major national transformer manufacturer provided no-load and nameplate-load loss values for both liquid-immersed ACT and standard grain-oriented transformers that are designed to meet the 2016 DOE standards[9]. Data is supplied for all kVA ratings covered by the standards. The baseline transformers for each kVA rating is the standard grain-oriented steel core design that just meets the 2016 DOE mandatory minimum efficiency standard (A =$0/W B = $0/W). A second data set is provided for standard transformers and enhanced efficiency ACT that are designed to A and B loss valuations of $20/W and $5/W, respectively. This data set is used to define the technical potential for transformer savings. The transformer manufacturer also provided baseline and ACT purchase price information for all ratings in both single and three-phase pole and pad-mount configurations. This information is used to calculate the incremental cost and the energy savings due to purchase and installation of the higher efficiency ACT unit. Please, note that this is data from a single manufacture and is not to be interpreted as the market typical or average. It is a useful perspective as it covers pole and pad mount single phase units and three phase units.

Incremental Cost Analysis

Incremental cost calculations were conducted for single phase 12,470/7200 V liquid-immersed pole-mount and pad-mount transformers with a secondary voltage of 240/120 V. Results for transformers that meet the 2016 DOE standards are shown in Figure 7. The evaluation shows that the purchase price difference for all single-phase pole-mounted amorphous metal transformers is less than 13%, with the ACT actually being less expensive in ratings above 100 kVA. The incremental cost for the single-phase pad-mounted units never exceeds 5% and ACT are the least cost alternative in ratings above 500 kVA.

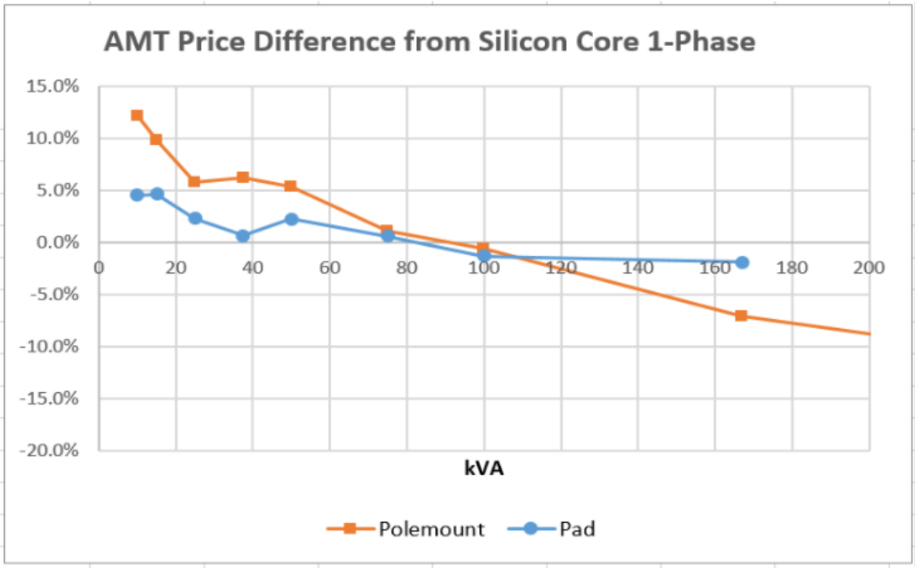


Figure 7. Incremental Costs for Single-Phase Pole and Pad-Mount ACT

The incremental cost or price difference due to purchase of three-phase ACT pad-mount transformers with primary voltages of 12,470/7200V and secondary voltages of 480/277V and 208/120V are shown in Figure 8. The evaluation indicates that the incremental cost for all three-phase pad-mounted amorphous metal transformers that meet the 2016 DOE standard is less than 3% with the ACT actually significantly less expensive in ratings above 500 kVA.

Incremental energy costs were also determined for technically achievable or enhanced efficiency single and three-phase ACTs. These transformers were optimized using the Total Cost of Ownership (TCO) equation with high loss valuations (A =$20/W and B=$5/W). While these loss valuations are far higher than currently used by any utility in the Northwest, the costs and energy savings from the enhanced efficiency transformers might represent an "upper bound" or technical potential for transformer energy efficiency savings. The baseline transformer is again a conventional grain-oriented silicon steel transformer that just meets the DOE 2016 standard.

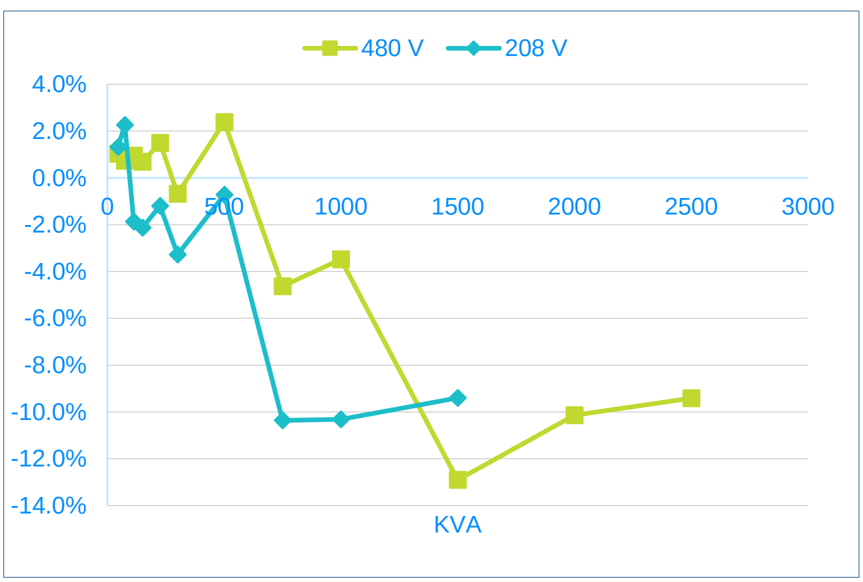


Figure 8. Three-Phase Pad-ACT Costs versus Baseline Transformers

The evaluation shows that the purchase price difference for all single-phase pole-mounted ACT rated up to 100 kVA increases to about 40% with the ACT costs being roughly equivalent in ratings above 300 kVA. The incremental cost for the single-phase pad-mounted units is in the range of 22% to 35%.

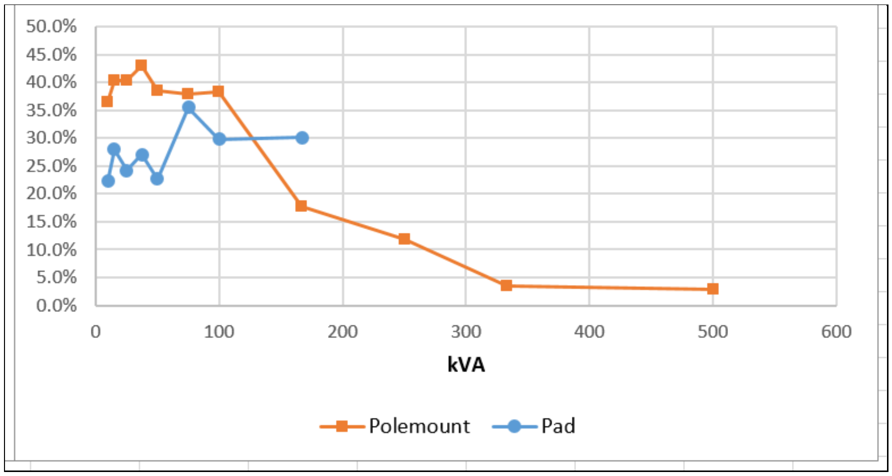


Figure 9. Single-Phase Pad and Pole-Mount Enhanced Efficiency ACT Incremental Costs versus Baseline GO Si-Steel Transformer

Incremental cost calculations for enhanced efficiency ACT single phase 12,470/7200 V liquid-immersed pole-mount and pad-mount transformers with a secondary voltage of 240/120 V are shown in Figure 9. The evaluation shows that the purchase price difference for all single-phase pole-mounted ACTs rated up to 100 kVA increases by about 40% with the ACT costs being roughly equivalent in ratings above 300 kVA. The incremental cost for the single-phase pad-mounted units is in the range of 22% to 35%.

The incremental cost for three-phase pad-mount ACT with primary voltages of 12,470/7200V and secondary voltages of 480/277V and 208/120V are summarized in Figure 10. The evaluation indicates that the incremental cost for all three-phase pad-mounted ACTs ranges from 15% to 30% in ratings up to 750 kVA.

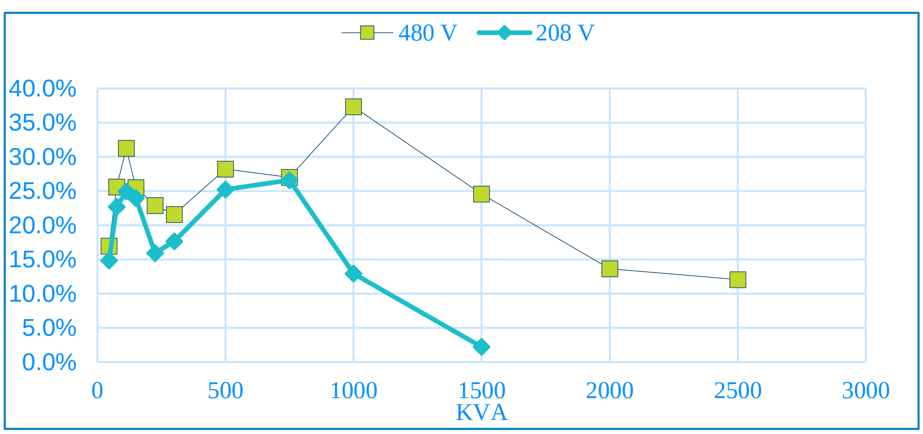


Figure 10. Incremental Costs Enhanced Efficiency ACT Three-Phase Pad-Mount versus Baseline Transformers

Incremental Weight Analysis

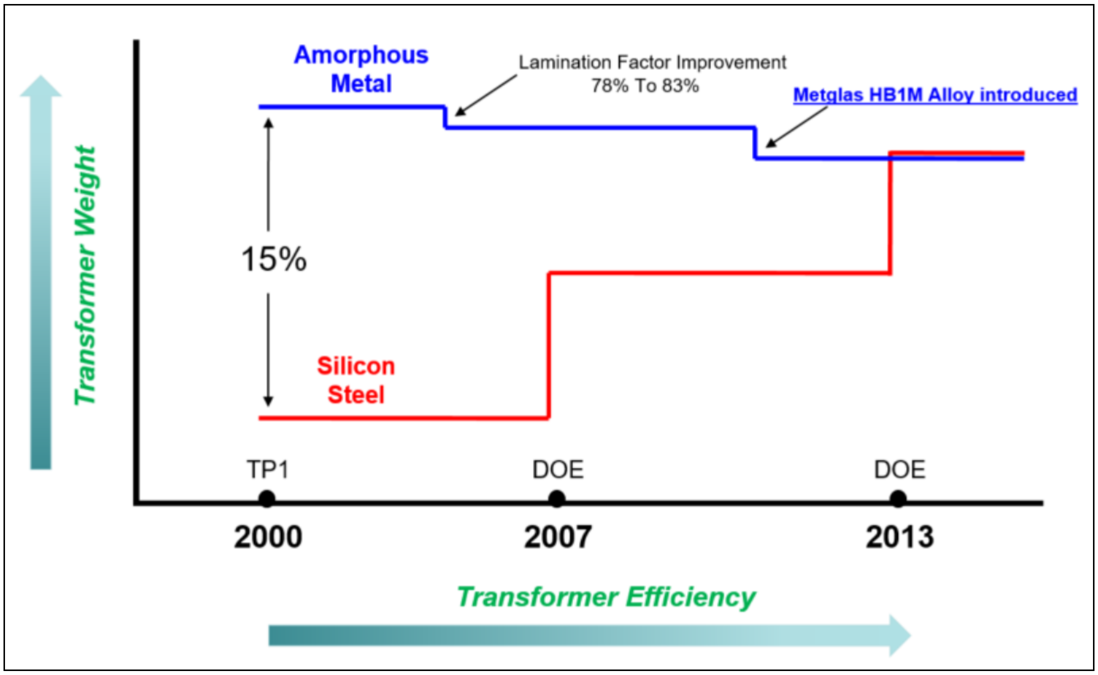
Early amorphous core transformer designs were 15% to 30% heavier than conventional transformers. A continuous series of improvements in amorphous material alloys, and in amorphous material casting and annealing methods has resulted higher core lamination factors, providing significant reductions in transformer weight and volume. Weight reductions for a 50 kVA transformer are depicted in Figure 11. As seen by going from right to left, the newest ACT transformer is noticeably smaller and has a weight reduction of 27.9% relative to the first generation unit.

Next Generation	2nd Generation	First Generation
88 min LF	84 min LF	80 min LF
88 SF Design	86 SF Design	82 SF Design
310 kg	335 kg	430 kg
0.119 m^3	0.134 m^3	0.212 m^3

From: “Metglas Continuous Quality Improvement”

Figure 11. ACT Weight and Size Reductions over Time

At the same time, conventional GO silicon steel transformers increased in weight when they were re-designed to comply with EPACT-2005 mandatory TP-1 mandatory efficiency standards and then DOE’s 2014 Final Rule for updated mandatory minimum efficiency standards (that became effective in 2016). As a result, pole and pad-mount ACT transformers have greatly reduced or negligible weight penalties when compared with conventional silicon-steel units designed to meet the 2016 efficiency standards. A comparison of the weights of amorphous core and silicon steel core transformers over time is indicated in Figure 12.



From “Metglas Continuous Quality Improvement”

Figure 12. Weight Comparison Between ACT and Silicon Steel Core Transformers

A major manufacturer that produces both amorphous core transformer and convention transformers utilizing silicon steel cores was able to provide weight information for both single-phase overhead and three-phase pad-mount units when all transformers are designed to just meet the Federal 2016 minimum efficiency requirements. A second set of weight data was provided for enhanced efficiency transformers (A = $20/W; B = $5/W). For single-phase pole mounted transformers designed to meet current DOE efficiency standards, the amorphous core units actually have a reduced weight for al ratings except for the 50 kVA and 75 kVA designs with the 50 kVA and 75 kVA ratings having a relative weight increase of 5% or less (see Figure 13). For the three-phase pad-mount transformers, as shown in Figure 14, amorphous core units actually weigh less than the traditional transformer designs in all but the 500 kVA rating.

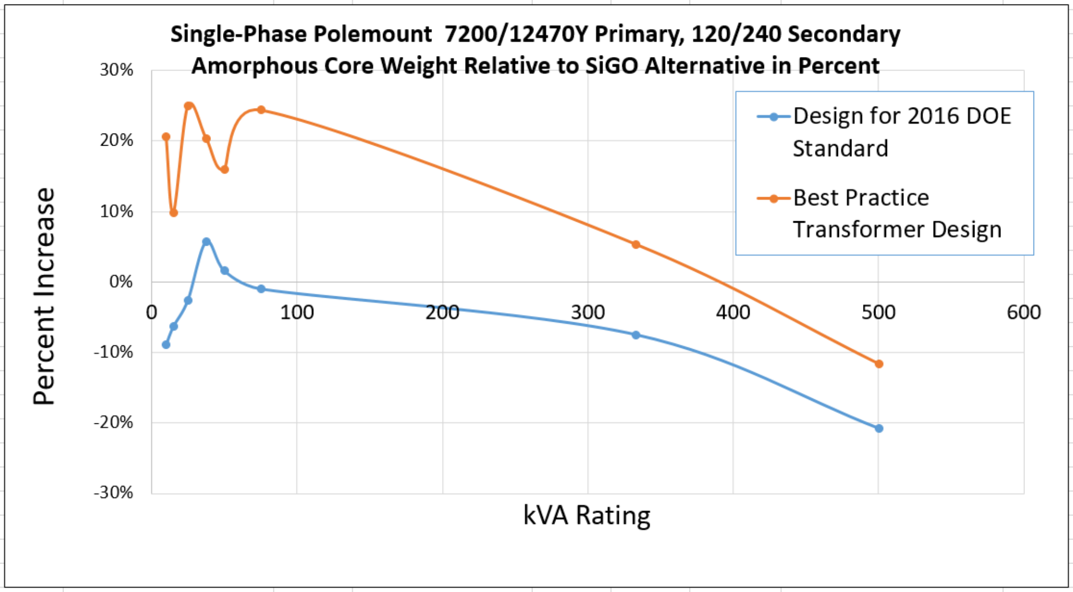


Figure 13. Weight of Single-Phase Pole-Mounted ACT Compared to Conventional Silicon Steel Core Transformers

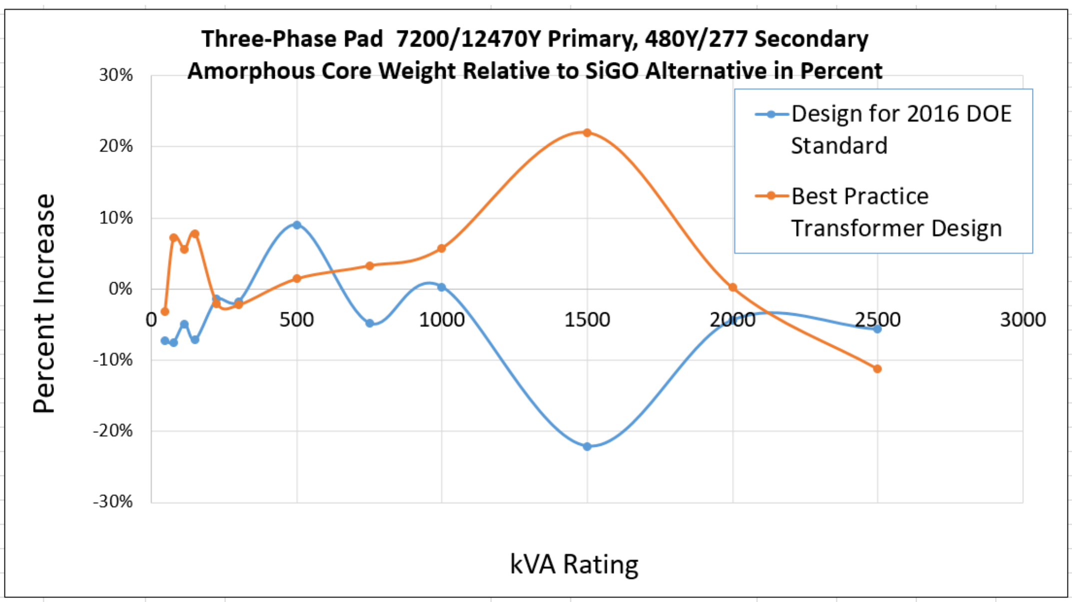


Figure 14. Weight of Three-Phase Pad-Mount ACT Compared to Conventional Silicon Steel Core Transformers

Annual Energy Savings

Annual Energy Savings were determined for each transformer kVA rating. Losses are determined using Equations 2 and 3. BPA's "Equivalent Hours" methodology takes into account the fixed no-load losses (NLL) plus load or conductor (winding) losses estimated as the product of an Annual Loss Factor times the Load Loss at the peak loading for the transformer. The annual load factor and annual peak power on each subject transformer must be known or assumed. The calculation of regional potential energy savings assumes a 50% load factor and a transformer peak at 50% of nameplate kVA. BPA assumes transformers are energized 8760 hours/year. Energy savings in Table 5 and Table 6 are the estimated annual energy savings given that both transformers are designed to meet the 2016 Federal Efficiency Standards.

Table 5 illustrates the savings from ACT compared to baseline single phase 12,470/7200 V pole-mount or pad-mount with a secondary at 240/120 V.

Table 5. Energy Savings of ACT vs. Baseline Single-Phase Pole and Pad-Mount Transformers

kVA	Core Savings	Conductor Savings	kWh	kVA	Core Savings	Conductor Savings	kWh
Pole or Overhead Mount				Pad Mount			
10	210	-66	144	10	184	-56	128
15	254	-80	174	15	237	-73	163
25	359	-106	253	25	377	-115	261
37.5	491	-147	344	37.5	491	-154	337
50	692	-220	472	50	578	-167	411
75	946	-292	654	75	920	-284	636
100	1086	-336	750	100	1261	-396	865
167	1594	-474	1120	167	1375	-409	966
250	1770	-515	1254	-	-	-	-
333	2129	-632	1497	-	-	-	-
500	2155	-640	1515	-	-	-	-

Table 6 illustrates the annual energy savings for three-phase pad-mount designs when both the AMC and baseline transformers are designed to just meet the Federal 2016 minimum efficiency requirements. Note that the no-load loss savings are always positive while the ACT transformers exhibit a negative energy savings or "savings takeback" due to an increase in conductor or load losses. Lightly loaded AMT transformers would exhibit a greater annual energy savings as the conductor losses are reduced at light loadings.

Table 6. Energy Savings ACT versus Baseline Three-Phase Pad-Mount Transformers

3 Phase Secondary Voltage 480			Total	3 Phase Secondary Voltage 208			Total
kVA	Core Savings	Conductor Savings	kWh	kVA	Core Savings	Conductor Savings	kWh
45	403	-130	273	45	403	-130	273
75	990	-213	776	75	990	-213	776
112.5	1086	-167	919	112.5	1086	-167	919
150	2006	-474	1532	150	2006	-474	1532
225	1927	-385	1542	225	1927	-385	1542
300	2961	-670	2291	300	2961	-670	2291
500	4564	-1453	3111	500	4564	-1453	3111
750	6263	-2002	4261	750	6263	-2002	4261
1000	7192	-2139	5053	1000	7192	-2139	5053
1500	8839	-2632	6207	1500	8839	-2632	6207
2000	8480	-2578	5901	-	-	-	-
2500	11808	-2066	9743				

Total energy savings are given in Table 7 due to selection and installation of **enhanced efficiency** ACT transformers versus baseline single phase 12,470/7200 V pole-mount or pad-mount transformer when both the AMC and baseline transformers are designed to take into consideration “A” and “B” values of $20/W and $5/W, respectively. The transformers under consideration provide power at a secondary voltage of 240/120 V.

Table 7. Energy Savings from ACT vs Baseline Single-Phase Pad and Pole Transformers

Single Phase Pole			Total	Single Phase Pad			Total
kVA	Core Savings	Conductor Savings	kWh	kVA	Core Savings	Conductor Savings	kWh
10	165	37	203	10	123	37	160
15	175	62	238	15	158	59	216
25	237	102	339	25	307	47	354
37.5	368	127	494	37.5	403	54	457
50	552	113	s665	50	508	5	513
75	718	181	899	75	736	150	886
100	823	233	1056	100	1060	118	1178
167	1235	263	1498	167	1121	315	1437
250	1410	355	1765	-	-	-	-
333	1577	390	1967	-	-	-	-
500	2181	-82	2099	-	-	-	-

Table 8 Illustrates the annual energy savings due to the purchase and installation of enhanced efficiency three-phase pad-mount designs with primary voltages of 12,470/7200 V with secondaries of 480 or 208 Volts. Both single and three-phase ACT transformers offer decreased conductor losses and increased overall transformer savings.

Table 8. Annual Energy Savings from Enhanced Efficiency ACT versus Baseline Three-Phase Pad-Mount Transformers

3 Phase Secondary Voltage 480			Total	3 Phase Pad Mount Secondary Voltage 208			Total
kVA	Core Savings	Conductor Savings	kWh	kVA	Core Savings	Conductor Savings	kWh
45	578	116	694	45	578	122	700
75	832	210	1042	75	894	166	1060
112.5	850	399	1249	112.5	841	353	1194
150	1542	314	1856	150	1367	311	1678
225	1332	656	1988	225	1215	626	1844
300	2409	636	3045	300	2610	383	2993
500	4091	727	4818	500	2497	918	3415
750	5414	881	6295	750	4380	788	5168
1000	6719	1377	8096	1000	4389	916	5305
1500	6990	2101	9092	1500	3863	536	4400
2000	6351	2227	8578	-	-	-	-
2500	11362	482	11843				

This comparison price and performance data was provided by a single major transformer manufacturer. To test the veracity of the silicon baseline transformer data provided by this manufacturer, it was compared to transformer bid values provided by BPA customer utilities. Comparisons showed an average difference in no-load losses of 2%, an average difference in load losses of 6%, with an average price difference of only (-)1%. This comparison suggests the BPA customer utilities are obtaining and responding to bids containing conventional transformer costs and performance that are similar to the silicon grain-oriented transformer baseline data provided by the national transformer manufacturer.

Canadian ACT Transformer Market Transformation

Transformer Manufacturers Perspective

Siemens Transformers invested in dedicated ACT transformer production in 2013 at its factory in Quebec, and since 2011, has delivered more than 50,000 ACT units to utility customers. All utilities in Canada, except Manitoba Hydro, have shifted to ACT transformer designs; over 90% of liquid-immersed distribution transformer sales to utilities in Canada are now said to be ACT units. ACT market transformation did not occur due to government standards or utility incentives. Rather it occurred naturally. Once utilities updated their TCO A and B loss valuation factors, higher efficiency ACT designs were best alternative. Siemens indicates that typical A and B values used in Canada are $11/W to $20/W for no-load losses and $1/W to $5/W for full-load losses (in CAD)[13]. Equivalent U.S. dollar values are $8.15/W to $14.80/W for no-load losses and $0.75/W to $3.70/W for conductor losses at full-load.

ABB has also ACT that can reduce total transformer no-load energy losses between 40 and 70%. Distribution transformers are available with either an amorphous or grain-oriented steel core, and are available with environmentally friendly biodegradable oil. About 60% to 70% of current liquid-immersed transformer production from its factory in Quebec City consists of ACT units[14].

Market transformation occurred naturally once utilities adjusted their TCO A and B loss valuation approach

ABB contends that Canadian utility customers appear to have different product quality, environmental, and efficiency values than American customers as many U.S. utilities neglect both quality and efficiency and want to purchase the lowest price unit. Canadian values are reflected in the valuation of the A and B constants that are applied to the no-load and load losses in the TCO equation. A “tipping point” from standard Silicon-steel transformer core material to ACT material is between $7/W to $8/W (CAD), equivalent to $5.20/W to $5.90/W in U.S. dollars. Quebec Hydro uses an A value of $15/W to $16/W ($11.84/W US) while Hydro1 of Ontario has an even higher A value. ABB reports responding to utility A values as high as $24/W (CAD) or $17.75/W (USD)[14]. Like BPA, both Hydro Quebec and Hydro1 have substantial hydroelectric generation with surplus renewable energy sold to utilities outside of their service territory.

Canadian Utility Transformer Evaluation and Selection

Hydro Quebec

Hydro Quebec manages the generation, transmission, and distribution of electricity in the Canadian province of Quebec. They serve over 4 million customers through operation of 63 hydroelectric projects with a combined generating capacity of 37,370 MW and 34,000 km of high-voltage distribution lines. In 2014 Hydro Quebec was the pioneering Canadian utility to widely adopt ACT transformers after they had conducted numerous tests and evaluations of the technology. After eight years of sales to the utility, Siemens has had no reports of problems

[13] Personal Communications with Francois Faisy, Engineer and CEO, Siemens Transformers Canada, Inc. 5/29/2019.

[14] Personal Communications with Martin Dore, Transformers Business Unit Market Manager, ABB, 5/23 to 6/26/2019.

or transformer defects. Hydro Quebec procurement staff indicates that the incremental cost of ACT transformers has declined and is now “more or less even” with conventional transformers. Cost adders for ACT technology are on the order of 1% to 2% after being in the range of 10% or more several years ago[15].

Hydro Quebec standards engineers indicate that the utility has long had high TCO equation loss valuation multipliers. Hydro Quebec changed its calculation methodology ten years ago to obtain a 2009 A loss valuation multiplier of $10/W. It is $15/W (CAD) at the present time. This high loss valuation led to the offer of ACT transformers by transformer manufacturers as the optimal selection from a cost-effectiveness standpoint. Hydro Quebec spent about three years evaluating and testing ACT transformers prior to switching to and standardizing on ACT designs in 2014. Hydro Quebec undertook a process of testing and “certification” of a sample of delivered transformers through conducting electrical tests as it would do for any new piece of electrical equipment—leading to refined designs if necessary. It even tested how transformer transportation might impact efficiency (through vibrations and handling) by transporting a transformer 500 km. This test led to improvements by the manufacturer in how the windings are affixed to the core. Hydro Quebec uses the approach outlined in IEEE Std. C57-120 – 2017 for determination of A and B values[15].

Hydro Quebec has a reputation for innovation and, after its rigorous evaluation of high efficiency ACT transformers, other utilities in Canada followed its lead. The market for high efficiency distribution transformers in Canada transformed very quickly, without any federal government intervention or financial incentives. The change in utility purchasing practices came about through education which resulted in the adoption of a superior methodology for determining A and B factors used for the valuation of transformer losses[13,14].

Hydro Quebec has over 700,000 total transformers in the field. They purchase ACT designs for pole and pad-mounted transformer applications in both new install and for end-of-life replacements. Single–phase 10 kVA to 167 kVA transformers are all pole-mounted. A two-pole support system is used with intermediate range single phase transformers with pad mounted used for ratings above 667 kVA, due to weight. The utility uses a blanket three-year purchase contract. When the current purchase contract expires, it will specify that only ACT transformers be selected for pad mount applications because of the overall cost advantages.

BC Hydro

BC Hydro is a Northwest utility in British Columbia with over 1.9 million residential, commercial, and industrial customers. Of their 342,000 distribution transformers, 280,000 and overhead with an additional single-phase pad-mounted units. BC Hydro is similar to BPA in that the bulk of their generation comes from hydropower. BC Hydro transformer procurement staff indicate that 90% to 95% of the overhead transformers it installs are liquid-immersed ACT units[16]. BC Hydro does not tend to obtain ACT units for pad-mount applications – its Procurement Analyst is not sure why, but it could be because of a higher differential price. All single-phase transformers are overhead mount. Pad mounts can be used for the entire range of kVA ratings, but tend to be used more for larger three-phase kVA ratings. Although transformer noise levels

[15] Personal Communication with Said Hachichi, Standards Engineer, Hydro Quebec, 6/17/2019.

[16] Personal Communications with Adrian Jacob, Procurement Analyst, and Madeline Schaefer, Distribution Standards Engineer, BC Hydro, 6/17/2019 and 1/28/2021.

are limited by IEEE specifications and the utility's own specifications, the Procurement Analyst indicates that the noise level "seems to be" higher for ACT transformers[16]. The increased noise level is likely due to core magnetostriction, or rapid expansion and contraction of ferromagnetic materials when exposed to a magnetic field. Displacements are greater in amorphous materials when compared to grain-oriented silicon steel. Incremental cost can be "up to" 30% over standard transformers[16].

BC Hydro adopted a phased approach to purchasing and observing ACT transformer performance. They began acquiring single-phase overhead 25 kVA ACT in 2009; expanded their procurement program to include 50 and 75 kVA ACT units in 2017 and included 10 and 100 kVA transformers in 2018. BC Hydro has over 20,000 in-service ACT transformers and is considering expanding their program to include 3-phase pad-mounted ACT units.

Calculation of the TCO A and B loss valuation factors is complex (the same A and B factors are used in the TCO analysis for all transformer kVA ratings). Utilities tend to use the same guidelines to calculate loss values, but inputs differ based upon generation mix and load forecasts. Load patterns can also differ by utility in part due to transformer sizing methods. BC Hydro staff believe that the biggest difference between Canadian and many U.S. utilities is that the Canadian utilities are provincial government-owned. BC Hydro takes a longer term perspective than investor-owned U.S. utilities that often simply purchase the least cost product. There is no consideration of CO_2 benefits in their value of losses determination[16].

ACT Transformer Education and Awareness Building

In 2014, a Powerstream representative (now Alectra Utilities) gave a presentation on a suggested methodology for determination of the A and B factors in the transformer TCO equation and introduced its Total Ownership Cost Calculator (TOC). A copy of the calculator (shown in Figure 15) was emailed to all workshop attendees[14]. The calculator provides A and B loss valuation multipliers for residential-rural, residential-urban, and non-residential load factors. The calculator inputs and results are shown below. As this tool became widely used, demand for ACT significantly increased.

***Total Cost of Ownership Calculation**

To customize the formula modify as many of the Green variables by entering different values

	Variable Description	Input	Source of Utility Value
1)	Determine cost of electricity $/kwh	0.1127	Cost of Electricity Workbook
2)	Determine the cost of Operating and Maintenance to be removed from cost of electricity	2.0	Utility Operations
3)	Determine transformer life; default is 40 years	40 years	Finance Depreciation Schedule
4)	Determine weighted cost of capital	0.068	Finance Cost of Capital
5)	Determine Single Phase, Residential -- Urban load factor	0.25	Planning Department
6)	Determine Single Phase, Residential -- Rural load factor	0.1	Planning Department
7)	Determine 3 Phase Non-Residential load factor	0.6	Planning Department
8)	Determine Peak Responsibility Factor	0.91	Smart Meeter data

Resulting Modified Total Ownership Cost Formula

TOC for Single Phase Residential – Urban Transformer					
TOC = initial cost of transformer +	22.4	x No Load Losses	+	1.7	x Load Losses
TOC for Single Phase Residential – Rural Transformer					
TOC = initial cost of transformer +	22.4	x No Load Losses	+	0.4	x Load Losses
TOC for Single Phase Residential – Rural Transformer					
TOC = initial cost of transformer +	22.4	x No Load Losses	+	7.4	x Load Losses

Figure 15. Total Cost of Ownership Calculator Distributed to Canadian Utilities

Kinectrics of Toronto, Canada offers a case study on “Transformer Loss Evaluation Formula Development”. They were approached by a large provincial utility that wished to determine the optimal designs for purchased transformers that would ensure the minimal lifetime costs when the transformers are installed in various applications. Kinectrics thus developed the appropriate transformer loss evaluation formulas. It ultimately took load profiles into account and developed three formulas for rural, urban, and commercial transformers (Kinectrics)[17]. The results, expressed in Canadian dollars, are summarized in Table 9.

Table 9. Loss Valuation Results for Rural, Urban and Commercial Applications*

Application	Transformer Total Ownership Cost Equation
Rural Applications	TOC = CAPCOST + $18/W * NLL + $3/W * LL
Urban Applications	TOC = CAPCOST + $18/W * NLL + $5/W * LL
Commercial Applications	TOC = CAPCOST + $16/W * NLL + $3/W * LL

U.S. Early Adopter Utility Experiences with ACT Transformers

Los Angeles Department of Water and Power (LADWP)

LADWP is the largest public power utility by customers served in the U.S. with a total of 1,419,468 in 2016 (from Public Power, 2018 Statistical Report). LADWP is also reported to be the largest user of ACT transformers in the U.S. The utility doesn’t specifically specify the procurement of ACT units, but uses the TCO equation to select the least cost transformer for the utility based upon both life cycle performance and equipment initial cost. LADWP A and B loss valuation values are $9.60/W and $2.00/W, respectively[18].

Weight issues are something that LADWP lives with – a 100 kVA ACT transformer is possibly 200 pounds heavier than the baseline transformer. Sometimes the utility gets complaints from the field when there is no truck access and a pole transformer must be hoisted into position. LADWP indicates that smaller kVA ratings have a greater percentage weight increase. Occasionally, a small minority of transformers in the larger size ranges (1500 kVA to 2500 kVA) emit unexpectedly high noise levels. Manufacturers have sent engineers to the field, and even exchanged a transformer and taken the old one to their plant to tear down – but have not discovered the cause nor suggested a solution[18].

LADWP uses a blanket bidding process with a broad solicitation. There is no bidder pre-approval process, but the utility may ask questions, conduct a factory audit, or ask for references from a new manufacturer. LADWP has separate blanket orders for pad and pole mounted transformers. It is currently purchasing ACT transformers from two Korean companies – SANIL for pad-mounted transformers and CHERYONG for pole-mounted units[18].

Reducing transformer losses offers additional net renewable energy opportunities

[17] Personal Communication with James Cross, Director, Transformer Services, Kinectrics, 7/20/2019.

[18] Personal Communication with Peter Wei, Power System Specifications and Administration, Los Angeles Department of Water and Power, 8/12 to 8/13/2019.

LADWP staff were never “directed” to purchase ACT units. Its higher than usual A value came about because upper management wanted to minimize losses from renewable projects – for instance a solar project might be productive for only 10 hours per day while the transformer core losses occur 24/7. Reducing transformer losses therefore achieves additional net renewable energy supplied to the utility[18].

Nashville Electric Service (NES)

NES is the 11th largest public power utility by customers served (384,986 in 2016). NES purchases energy from TVA and is known as a leader in the purchase and use of ACT transformers. Weight is not an issue for its pad mounted units and the utility’s Senior Engineer for Customer Engineering Networking Standards states that nameplate weights typically vary for pad and pole-mounted units due to cost of raw materials, liquid volume, and tank size. For pole applications, the utility is more interested in dimensions than weights and states that sometimes transformers can simply be too tall for a pole. NES purchases with spot orders and includes many manufacturers in its list of bidders – Carte, ABB, Central Maloney, Cooper-RTE, Eaton-Cooper, ARMCO, GE-Prolec (for network only units), and Power Partners[19].

NES calculates no-load and load loss valuation multipliers and uses the TCO approach for transformer purchases. Loss multipliers (A and B values) vary based upon the type of transformer being purchased, including a substation, pole (single or three-phase); pad (single or three-phase), or network applications. No-load loss values vary from $12.90/W to $13.94/W while load losses are in the range of $0.42/W to $1.08/W. See Table 10[20].

Table 10. Nashville Electric Service (NES) Transformer Loss Multipliers for 2019 Purchases

Transformer Loss Evaluation for Year 2018							
Variables	Sub161	Sub69	3pPole	1pPole	3pPad	1pPad	Network
Normalized Core Loss ($/watt)	$13.18	$13.34	$12.90	$12.90	$13.94	$13.94	$13.94
Normalized Load Loss ($/watt)	$1.32	$1.37	$1.33	$1.66	$1.08	$0.42	$2.15

Santee Cooper

Santee Cooper is a publically-owned utility in South Carolina that directly or indirectly serves about two million customers. Santee Cooper became interested in ACT transformers early on as Metglas, a supplier of amorphous metal, is in its service territory.

Santee Cooper uses a TCO methodology when purchasing transformers (for both standard construction and ACT units that meet the 2016 DOE mandatory minimum efficiency standard). The utility developed an engineering standard many years ago that is periodically updated, with bil (insulating rating), materials (stainless steel required when exposed to sea salt), color, and surge arrest capability specified. Santee uses “blanket” orders – buying all from one manufacturer at a guaranteed price with estimated numbers of transformers expected to be

[19] Personal Communication with Wesley Suddarth, Engineer, National Electric Service, 7/24/2019.
[20] Personal Communication with Jay Thompson, Buyer II, Nashville Electric Service, 8/8/2019.

purchased by kVA rating provided at the time of the bid; or "spot" purchasing – buying a number of 25 kVA or 50 kVA transformers every quarter[21]. Santee started spot buying during the 2008 housing crisis when transformer prices dropped as manufacturers became more competitive to maintain sales. Under those market conditions, the utility did not want to be locked into a fixed price contract.

Santee Cooper purchased several hundred ACT distribution transformers in the size range of 25 kVA to 2,500 kVA between 2010 and 2016 and experienced no problems. Most were three-phase pad mounts. ACTs are less likely to be offered when a utility generates or has access to low cost energy. Santee Cooper's Manager of Distribution Engineering points out that there used to be a weight difference between standard design and ACTs, but as U.S. DOE efficiency requirements have increased, the weight of the DOE baseline transformers has also increased, making the weight difference moot – to the point that there is no major effect on handling costs[21].

Santee Cooper reports that Howard Industries tends to provide two transformer bid sheets, one for ACTs and the other for silicon steel core transformers. ABB and GE do not even state whether the transformer quoted is ACT or not. The bid sheets might be mostly silicon steel units with a few amorphous core transformers mixed in when the TCO transformer optimization design software indicates that it offers the best value for a utility customer. Since efficiency values are not disclosed and there are not product labels, it is only possible to tell if a transformer is of an ACT design by examining the no-load losses.

Salt River Project

The Salt River Project (SRP) provides water and power to more than 2 million people living in central Arizona. SRP operates generating stations using a variety of fuel sources including coal, natural gas, geothermal, hydroelectric and solar generating projects. SRP was a participant in EPRI's liquid-filled amorphous core distribution transformer demonstration in the mid-1980's.[23] They have purchased and used amorphous core transformers for years---and have been purchasing and installing them in large numbers since 2010. They note no noticeable difference or issues involving amorphous core transformers except the mounting for a 167 kVA cluster of 3-pole mounted transformers may require a different band-type cluster mount to account for the weight difference. The utility has always specified Class 1 poles so no upgrade is necessary.

SRP did not adopt an 'Amorphous Core Transformer Purchase Program' or follow any directive. They consider amorphous core and conventional transformers to be "equals" i.e. equivalent and interchangeable and simply have long purchased amorphous core transformers due to their lower total cost of ownership. Their TOC analysis indicates that amorphous core units offer the best value given no-load and full-load (A and B) loss valuation numbers of A= $7.47/W and B = $1.73/W (for residential customers); to B = $2.42/W (commercial customers); and B = $3.23/W (industrial customers).

[21] Personal Communication with Greg Turbeville, Manager Distribution Engineering, Santee Cooper, 5/24/2019

[23] Personal Communication with Michael Dyer, Executive Engineer, Salt River Project, 6/22/2020

SRP issues a blanket bid solicitation, but does not select a single winning bidder or manufacturer based upon lowest cost for all kVA ratings expected to be purchased. Instead, they select the provider of the lowest cost transformer in each kVA rating---they thus simultaneously purchase amorphous core transformers from multiple manufacturers. SRP sees value in having a backup or "secondary" supplier for each transformer rating.

Transformer Sizing and Loading Considerations

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 16) (Burgess).

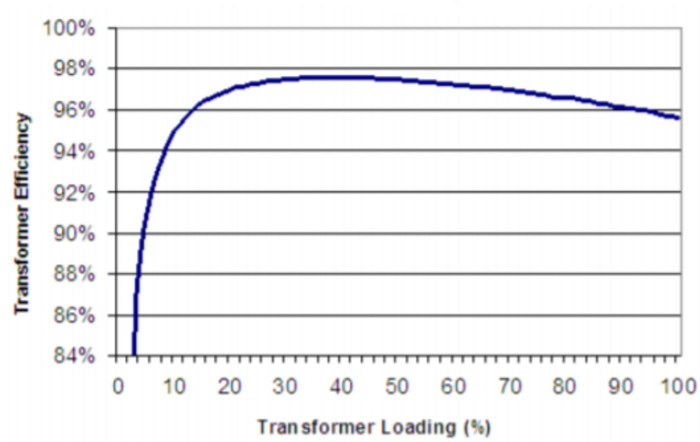


Figure 16. Transformer Efficiency Relative to Load

Lawrence Berkeley National Laboratory (LBNL) provided input to DOE when it was considering the 2016 standards and wanted load information for utility-owned liquid-immersed transformers. Figure 17 shows its data for average root-mean-square loading on a 50 kVA single-phase transformer. The average RMS loading was found to be 34% (LBNL). Note that the load factor is here defined as the ratio of the average RMS load to the transformer rating. Mean lifetime for a distribution transformer is estimated at 32 years.

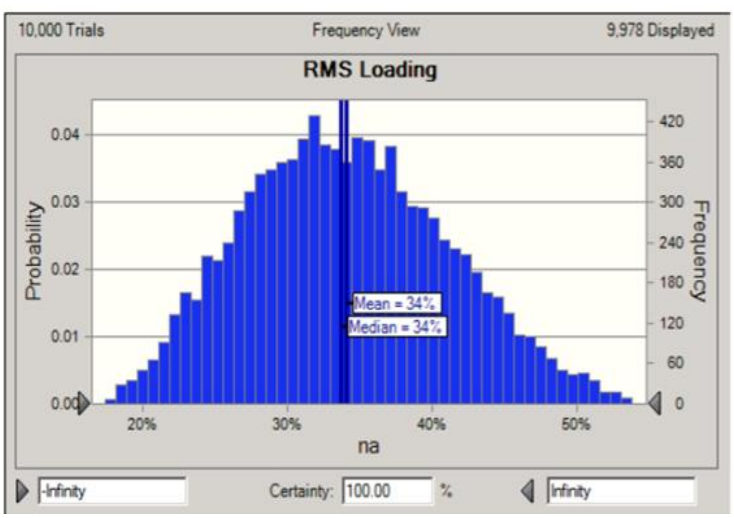


Figure 17. Average Loading on Utility-Owned Liquid-Immersed Distribution Transformers

Some utilities have developed transformer sizing trainings to eliminate the installation of oversized transformers that have increased no-load losses. ElectriCities, a municipally-owned utility with service territory in North Carolina, South Carolina and Virginia, has developed several methods for sizing of residential distribution transformers, including the Diversity Method, the Coincidence Factor Method, and the Square Footage Method. It has also developed several methods for determining the loading on commercial sector transformer applications including use of engineering data or

Watts per square foot tables. A residential transformer sizing example using the square footage method is given in Table 11 (ElectriCities). Note that transformer sizing for residential services is dependent upon multiple variables including climate zone, the number of customers to be served by a single distribution transformer, average house square footage, use of gas versus electrical energy for space and water heating, and the presence or penetration of air conditioning (ElectriCities).

Table 11. ElectriCities Residential Transformer Sizing Guide

Underground Residential Transformer Loading Guide
Homes Between 1,500 and 1,800 Square Feet

Number of Electric Customers	Number of Gas Customers														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	0	25	25	25	25	25	50	50	50	50	50	100	100	100	100
1	25	25	25	25	50	50	50	50	50	100	100	100	100	100	100
2	25	25	50	50	50	50	50	50	100	100	100	100	100	100	100
3	50	50	50	50	50	50	50	100	100	100	100	100	100	100	100
4	50	50	50	50	50	100	100	100	100	100	100	100	100	100	100
5	50	50	50	100	100	100	100	100	100	100	100	100	100	100	100

Discussion of Transformer Market Channels, Annual Shipments, and Estimate of Potential Annual Energy Savings for the Northwest Region

Estimate of Liquid-Immersed Distribution Transformer 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 12) indicates that 683,726 liquid-immersed single-phase low-voltage distribution transformers were shipped nationwide along with 49,739 three-phase liquid immersed units (US DOE).

Table 12. National Distribution Transformer Shipment Estimates for 2009

Distribution Transformer Equipment Class	Units Shipped	MVA Capacity Shipped	Shipment Value
Liquid-immersed, medium-voltage, single-phase	683,726	21,994	714.8
Liquid-immersed, medium-voltage, three-phase	49,739	32,266	786.0

A further breakout of liquid-immersed distribution transformer shipments by kVA rating is given in Table 13 (US DOE).

Transformer shipments to BPA's service territory are estimated based on responses to a survey sent out to 16 BPA utility customers that purchase a total of 6,857 transformers annually. These include single-phase pad and pole transformers, and three-phase pad transformers. To estimate the total transformers acquired in the region, the survey total of 6,857 purchased transformers is extrapolated by multiplying the number of transformers purchased by survey participants by 2.68. This multiplier is based on BPA preference customer load obligations (including block, slice block, and slice output from the Tier 1 system) of 6,969 aMW (BPA), divided by the customer load obligations of the survey responders of 2,597 aMW. This approach yields an estimate of approximately 18,401 distribution transformers purchased by BPA customer utilities annually.

Table 13. 2009 Transformer Shipments by Capacity kVA

Single-Phase		Three-Phase	
kVA	Units Shipped	kVA	Units Shipped
10	58,090	15	-
15	169,083	30	-
25	243,583	45	1,635
37.5	41,755	75	4,269
50	119,445	112.5	898
75	26,338	150	8,445
100	18,679	225	2,239
167	4,357	300	8,3478
250	1,905	500	7,563
333	238	750	3,982
500	238	1000	3,606
667	5	1500	3,345
833	-	2000	2,839
-	-	2500	2,571
TOTAL UNITS	**683,726**		**49,739**
TOTAL MVA	**21,994**		**32,266**

A "bottoms up" estimate of the annual energy savings due to incentivizing the purchase of ACT transformers by BPA customer utilities is given in Table 14. The savings potential in kWh/year is obtained through extrapolating the actual transformers purchased by utilities surveyed by BPA (by kVA rating) to the ratio of the total load of BPA preference customers divided by the load of the utilities that responded to the survey. The number of single and three-phase pole and pad-mount transformers expected to be purchased in each kVA rating is then multiplied by the calculated energy savings for that rating. Finally, the total energy savings potential is reflected as an "achievable" potential through multiplying by an expected

Table 14. Energy Savings from BPA Customer Purchase of ACT*

Potential Regional Energy Savings				**2,066,946**
Single-Phase Transformer			**Three-Phase Transformer**	
	Total kW			**Total kWh**
kVA	**Pole**	**Pad**	**kVA**	**Pad**
10	12,183	10,813	15	-
15	108,609	101,999	30	-
25	254,369	262,476	45	4,875
37.5	102,700	100,632	75	42,389
50	137,078	119,352	112.5	7,060
75	52,645	51,188	150	63,511
100	30,190	34,835	225	17,142
167	13,527	11,666	300	174,678
250	2,020	-	500	109,439
333	-	-	750	35,202
500	-	-	1000	53,990
667	-	-	1500	67,311
833	-	-	2000	38,007
			2500	47,060
TOTAL	**713,320**	**692,960**		**660,666**

Assumes 30 market penetration rate.

penetration rate of 30%. Energy savings are available over the 30+ year life of the transformer with a like amount of savings available due to additional transformer purchases in subsequent incentive program operating years.

18,401 distribution transformers are purchased by BPA customer utilities annually

Annual energy savings from purchasing ACT is about 2,066 MWh per year or 0.24 aMW (see Table 14). A like amount of energy savings is available for each subsequent year following incentive program adoption. Absent DOE adoption of a new mandatory minimum efficiency standard an annual energy savings of 2.4 aMW should be available over a 10-year period from ACT transformer procurement. Given the purchase of **enhanced efficiency** ACT transformers, annual energy savings increase to 2,852 MWh per year or 0.33 aMW (see Table 15).

Table 15. Annual Energy Savings due to Purchase of Enhanced Efficiency Liquid-Immersed ACT Distribution Transformers by BPA Customer Utilities
(Assuming a 30% Market Penetration)

Potential Regional Energy Savings				**2,852,401 kWh**
Single-Phase Transformer			**Three-Phase Transformer**	
	Total kWh			**Total kWh**
kVA	**Pole**	**Pad**	**kVA**	**Pad**
10	17,156	13,507	15	-
15	148,592	134,911	30	-
25	339,836	355,198	45	8,555
37.5	147,685	136,525	75	56,695
50	193,325	149,123	112.5	11,801
75	72,375	71,353	150	91,029
100	42,522	47,405	225	23,906
167	18,086	17,349	300	240,621
250	2,842	-	500	169,835
333	-	-	750	56,522
500	-	-	1000	86,306
667	-	-	1500	86,888
833	-	-	2000	55,245
			2500	57,207
TOTAL	**982,420**	**925,371**		**944,610**

Conclusions and Recommendations

The absence of common practice purchases of ACT in the PNW offers the possibility of new and incremental energy savings for BPA. It is estimated that if Northwest utilities procured 30% of their annual transformers as ACTs, regional savings could be 2,852 MWh per year, over a ten year period. There is clear availability of ACT product in the market. There is an increased cost for ACT in the small to medium sized transformers. In this segment a BPA energy saving incentive can be offered up to the cross over point where ACT cost less than non-ACT. BPA is excited to collaborate with its customer utilities to explore the most efficient and cost effective distribution transformer purchases.

In regard to new purchases of distribution transformers, BPA is in a unique position to be able to offer an energy savings incentive for a transformer with lower annual losses. A BPA incentive can be a strong tool to motivate savings that are not being captured by the DOE-2016 standard. The research performed for this report identified a new and remarkable finding. Because it is likely that most distribution transformers have average loadings of 20% (or less) of their nameplate capacity and DOE-2016 evaluates maximum transformer efficiency at 50% loading, there is a large misalignment between the DOE-2016 standard and factual operational loading reality. This means that there are significant energy savings that can be achieved by instructing the manufacturer to design a transformer whose maximum efficiency is coincident with "typical" loading, and still meet DOE-2016 requirements. **This "rightly loaded" design may yield a lower capital cost as well as a lower loss transformer**.

To achieve the "rightly loaded" design a utility should request an alternate bid with A and B values which have this relationship in their ration: B / A = (avg per unit loading (PUL))^2. And, in order to trigger ACT, the A value should be higher than $10/W. Calculations suggest that given BPA's current offering of $0.35/kWh/year energy savings, and using an average loading of 20%, appropriate A & B values might be: A = $25/W and B = $1/W. At first inspection the A value looks grossly high. However in this application the intent is to instruct the transformer manufacturer to design a very efficient core, thus maximizing transformer efficiency, which in this case is at 20% per unit loading, and still meet the requirements of DOE-2016. The resulting higher efficiency performance from the alternate bid can then be compared to the standard practice bids.

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Appendix A

Harmonics and Ferroresonance Considerations

Harmonics

Electrical distribution systems are increasingly serving nonlinear loads such as computers, ballasts serving fluorescent, high intensity discharge, and LED lights; electronically-commutated permanent magnet motors, variable frequency motor drives, power supplies and converters, and office equipment including personal computers, laser printers, display terminals, fax machines, battery chargers, universal power supplies, and some medical equipment. These loads draw non-sinusoidal currents from the utility and cause distortions in current and voltage waveforms. These distortions are typically characterized spectrally, revealing harmonic content driven by the periodic application of a nonlinear demand process such as sub-cycle switching (Pejovski, Hasegawa and Pruess).

The presence of high levels of harmonic distortion will result in lower system power factor plus increased dissipation and loss of efficiency in distribution equipment, cables, and distribution transformers. The fundamental power factor is degraded by $1/\sqrt{1+THD^2}$ in the presence of harmonic currents, where total harmonic distortion (THD) is estimated in the usual way as the ratio of the total RMS magnitude of the harmonic currents to the magnitude of the fundamental current. Also, transformer losses, both excitation and load dependent, are in practice larger in the presence of harmonics since the dissipation processes responsible for these losses are frequency dependent.

The load dependent losses, principally driven by winding conductor dissipation, depend only on the magnitude spectrum of the current harmonics, as the physical mechanism mainly responsible for the losses is the so-called skin effect in a non-ferromagnetic conductors.

The excitation dependent losses depend on both the magnitude and phase of the harmonic components of voltages, since the shape of the exciting waveform influences the induction process and the resultant hysteresis dissipation.

The increase in losses, however, is smaller in amorphous core transformers compared to the loss increases in SiFe CRGO core transformers. Consider the example depicted in Figure 18, illustrating the effect of harmonic content of the source voltage on excitation losses. The subject transformers are constructed with identical windings, one each on an amorphous metal core and on a cold-rolled grain oriented silicon steel core. When tested under sinusoidal excitation at the design RMS voltage and frequency, the ACT transformer has a no-load loss of 50 Watts versus the 230 Watts from the conventional grain-oriented silicon steel core transformer i.e. it is over 70% lower. When tested under conditions of a voltage distortion of 75%; the amorphous metal transformer shows a 60% increase in losses while the conventional transformer shows a 235% increase (see Figure 18). Percentages can be misleading as the ACT no-load loss is so low to begin with: the no-load loss for the ACT transformer increases by 30 Watts while the conventional transformer shows an increase of 540 Watts (Hasegawa,

Hasegawa and Pruess). Under conditions of 75% THD, the ACT transformer no-load losses are about 10% of those of the conventional unit.

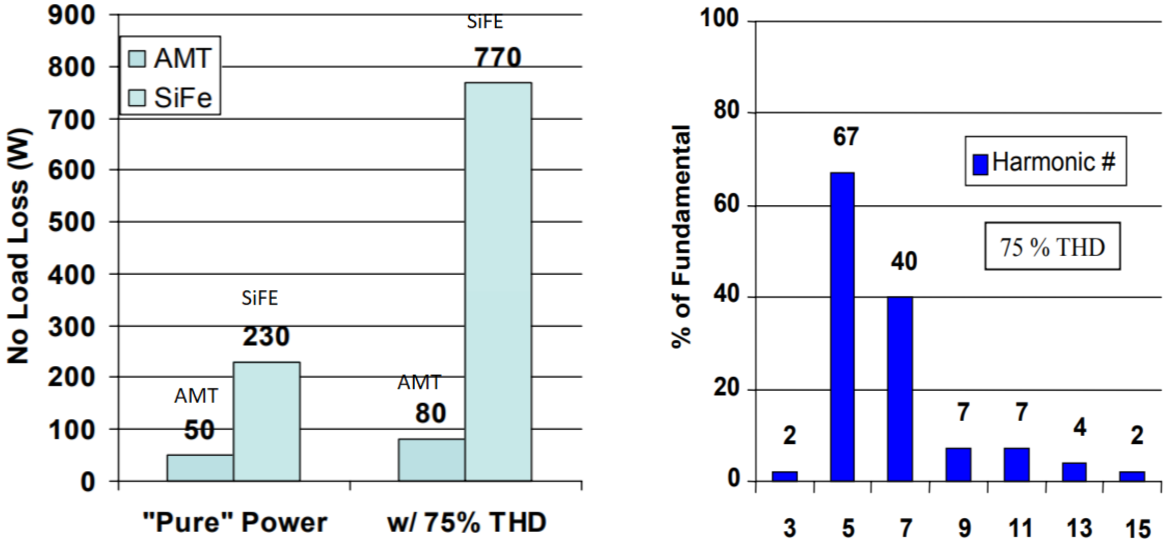

Figure 18. Laboratory Test Data Showing Impacts of Harmonic Distortion on No-Load Losses

ACT transformers have a "built-in" superior performance when operating under conditions with harmonic distortion. They are even more efficient than conventional units when harmonics are present in power distribution systems (Hasegawa, Gupta). Given their greatly reduced losses, ACT liquid immersed transformers will show a reduction in oil temperature rise which extends transformer life with no need for transformer de-rating, all while providing greater energy savings.

Some utilities are concerned that the reduced impedance of amorphous transformer cores will allow harmonics to pass through to the primary side where transformers serving nearby loads or substation transformers could be affected. Harmonic attenuation due to dissipation in transformers is dependent upon many variables including winding material and cross-section geometry (skin effect), core material resistivity and structure, and the spectral dependence of the core material induction (BH curve shape). The properties of the amorphous metals that result in reduced hysteresis dissipation (specifically very low coercivity) also result in reduced attenuation of the harmonic content of secondary harmonics referred to the primary. In practice, however, harmonic attenuation also depends on core configuration, winding arrangement, and connection configuration.

Transformer connection also affects response to harmonic currents introduced by switch-mode and other nonlinear loads. Considering two commonly used connections in the presence of so-called "triple-N" harmonic currents typically introduced by switch-mode electronic loads serves to illustrate this point.

First, consider a three phase wye-wye AC source with bonded neutrals on both primary and secondary. In this connection, while the harmonic currents cannot circulate in the load windings, the resulting induced voltages appear on both the primary windings and as high-order “ripple” voltage on the neutral point, such that the utility supply is now exposed to the effects of harmonics.

Second, consider a three phase delta-delta source. In this connection, the harmonic currents can be shown to circulate in the secondary windings, which substantially inhibits propagation to the utility source. However, these circulating currents flow in the secondary windings with reduced effective cross section due to skin effect and therefore increased effective resistance, causing increased dissipation in these windings with a corresponding increase in temperature rise in the transformer.

Transformer excitation results in the appearance of harmonic currents directly on the primary windings due to induction nonlinearity in practical core materials, including both ferromagnetic and ferrite-class materials. Amorphous core materials have a “sharp” transition to saturation that can give rise to a harmonic content in **no-load** excitation currents that is greater than that for silicon steel cores. Losses due to this effect, however, are less than those due to the incremental change in **load** losses due to harmonic distortion (Jayasinghe).

Ferroresonance

Ferroresonance pertaining to distribution transformers is an abnormal primary side operating condition which can result in transient sub-harmonic voltages in excess of 1.0 per unit (pu). Ferroresonance conditions typically occur following excitations with a broad spectrum and sufficient magnitude, and can occur in many different winding connection and core geometry configurations, consistent with simple requirements for charge storage and induction by coupled magnetic flux. Operational examples include faults or connecting (or disconnecting) a three-phase transformer on-line by single-phase switching (i.e. connecting one phase at a time) when using remote switches with all secondaries open-circuited (Howard Industries, Hi-technology).

Ferroresonance is physically just like an ordinary LC (inductor/capacitor) circuit resonance, except that the inductor is nonlinear and transitioning in and out of saturation. Susceptibility to this condition is dependent upon switching arrangements, transformer core configurations and winding connections, and loading conditions. The persistence of resonance depends upon the presence of dissipative elements including the end user loads on the transformers. Loads on the resonating circuit ultimately dissipate the resonant energy, a process to which connected transformers make insignificant contributions in most circumstances.

Transformer core configuration is influential in both initiating and sustaining ferroresonant conditions due to magnetic flux coupling between phase windings, regardless of the external connections made with winding terminations. Significantly, flux coupling in the core will induce voltages (perhaps in excess of 1.0 pu in resonant conditions) in windings that are intentionally open. Several common core configurations in three phase transformers as exemplars of the relevant flux coupling processes are briefly noted:

- Core Form (3-Leg) – characterized by three parallel core legs, fitted with one phase winding on each leg.

- 4-Leg stacked – characterized by four coplanar parallel core legs, with one phase winding on each of three of these core legs.
- 5-Leg stacked – characterized by five coplanar parallel core legs, with a phase winding on each of the three inner legs.
- 5-Leg wound – characterized by four magnetically separate rectangular cores, arrange with each of three individual phase windings coupling two adjacent cores; note that in this arrangement the core fluxes are not magnetically coupled by core paths.

Also of note is the Triplex core configuration, which is not susceptible to ferroresonance as supported by inter-phase flux coupling. This is not to say that transformers thus constructed are immune from resonance effects, since the other necessary conditions for the initiation of ferroresonance may be present.

Like any other circuital resonance phenomenon, ferroresonance requires energy exchange between the electric and magnetic fields in the circuit elements, clearly indicating the importance of flux coupling. The basic physics are twofold:

1) effective reluctances of the flux paths in the coupled flux core configurations differ since each manifests different degrees of saturation in a nonlinear magnetic medium;
2) voltages will be induced in any conductors surrounding a flux path, including any unterminated conductors.

While each of the cited shared core and winding configurations will manifest different excitation and fault current behaviors, inter-phase flux coupling in every case presents the possibility of excess induced voltages in one or more windings under resonance conditions. It should also be noted that the overall risk of induction of excess voltages in a resonance event is not equal amongst these core configurations, due in large part to differences in the magnitudes of flux coupling between phases.

It has been suggested that the reduced excitation loss characteristic of AMTs would allow resonant events to persist. This would be plausible if the excitation loads of transformers were a significant portion of total loading, but this is not the case. In view of the extent of possible flux path, winding, and connection combinations, as well as the vast extent of potential loading scenarios, a quantitative answer to this question is elusive. Rather, recognizing the stochastic nature of loading processes suggests a probabilistic approach. Consider the quantities that must be known in order to support a deterministic prediction of a ferroresonant event:

1) precise timing of the causative event (fault etc.);
2) location of the causative event;
3) real component of total load supported by the affected magnetic flux source(s) (transformers) at the time of the causative event;
4) re-connection behavior of all load elements in response to loss of nominal voltage;
5) configuration of the subject feeder or system, specifically including conductor lengths, capacitor ratings and connections, transformer types, ratings, and connections.

As a practical engineering matter, quantities (1), (3), and (4) will not be known, although (3) may be known approximately. However: - since (1) determines the available energy present in magnetic fields, a very important factor in ferroresonance, ignorance of this quantity alone undermines the fidelity of any deterministic prediction; - item (4) is expected to become increasingly important as load devices become “smarter”, in this case incorporating sensing and control elements that cause the load to remain at zero until nominal sine wave voltage is detected, thus reducing the available dissipation during a fault event and contributing to conditions that would allow a ferroresonant event to persist. The complexity of such a prediction thus renders it useless for operational purposes.

Alternatively, if the items (1) through (4) above are treated as random variables, and an estimate of the total dissipation required to prevent initiation of ferroresonance is available, we could proceed with estimation of the probability of occurrence of a resonant event given some assumed operating conditions. But there are problems here as well that degrade the utility of such an estimate; for example:

- a causative event could occur anywhere in the nominal voltage sinusoid period, with equal probability;
- the mix of loads with and without so-called smart connection behavior would have to be assumed in any practical circumstances.

It makes more sense to proceed by comparing the contribution of each class of transformer to the circuit (or system) dissipation under circumstances that would be expected to increase the likelihood of a ferroresonant event. In view of the sources of variation outlined above, we could confidently conclude that these conditions would simply be characterized by low real loading at high operating voltage. Then the relevant question reduces to the contribution of transformer losses to the total system dissipation as represented by the real loading.

This notion is easily illustrated by a simple numerical example using typical efficiencies at 0.10 pu loading on the secondary windings such that the winding losses are negligible; for a transformer that is 99% efficient at this load (typical for a modern CRGO core unit that meets DOE standards), the total load supported by primary current is thus 0.11 pu, and for a 99.5% efficient transformer (typical for a recent amorphous metal core unit) the primary load would of course be about 0.105 pu. Thus the suggestion that the amorphous core transformer would contribute significantly to the likelihood of ferroresonant events depends on reduced dissipation magnitude of about 0.005 pu at these loading levels; this assertion is unsupported by any current experimental results. Note that in either case the nonlinear induction behavior of the core material is sufficient to produce the saturation characteristics required for the incidence of ferroresonance.

Appendix A References

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Appendix B. DOE 2016 Transformer Efficiency Standards

Low Voltage Secondary, less than 600 V LIQUID – IMMERSED (liquid-cooled)

The efficiency of **a liquid-immersed distribution transformer** manufactured on or after **January 1, 2016**, shall be no less than that required for their kVA rating in Table 15 below. Liquid-immersed 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.

Table 16. Low Voltage Secondary, less than 600 V LIQUID – IMMERSED

Single-phase		Three-phase	
kVA	**Efficiency (%)**	**kVA**	**Efficiency (%)**
10	98.70	**15**	98.65
15	98.82	**30**	98.83
25	98.95	**45**	98.92
37.5	99.05	**75**	99.03
50	99.11	**112.5**	99.11
75	99.19	**150**	99.16
100	99.25	**225**	99.23
167	99.33	**300**	99.27
250	99.39	**500**	99.35
333	99.43	**750**	99.40
500	99.49	**1000**	99.43
667	99.52	**1500**	99.48
833	99.55	**2000**	99.51
		2500	99.53

Note: All efficiency values are at 50 percent of nameplate-rated load, determined according to the DOE Test Method for Measuring the Energy Consumption of Distribution Transformers under Appendix A to Subpart K of 10 CFR part 431.

Low Voltage Secondary, less than 600 V DRY-Type (Air Cooling)

The efficiency of a **low-voltage dry-type** distribution transformer manufactured on or after **January 1, 2016**, shall be no less than that required for their kVA rating in Table 14 below. 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.

Table 17. Low Voltage Secondary, less than 600 V DRY-Type

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 under Appendix A to Subpart K of 10 CFR part 431.

Appendix C. BPA Customer Utility Survey Template

Blank Questionnaire Template for Collecting Information on Current Distribution Transformer Purchasing Practices from a Cross-Section of BPA Customer Utilities

Background:
Bonneville Power Administration is performing, with the assistance of Washington State University, a national level review of current practices in the purchasing of **liquid-immersed**, utility grade, **distribution transformers**: both **single** and **three phase**. The intent is to learn if there are energy savings opportunities that may be designed into incentive programs and made available to BPA customers. Existing practice assumes that the transformer offered just meets the baseline DOE-2016 minimum efficiency standard. This data gathering is from the perspective of selecting units that exceed that minimum efficiency standard.

Utility name: Click or tap here to enter text.

Question	Response
1. Are you aware of the DOE-2016 minimum efficiency standard, and if so, do have an active process to verify the transformers your company purchases meet the standard? Comment: All distribution transformers covered by the standards that are sold in or imported into the U.S. must meet the 2016 minimum efficiency standards. Generally, checking should not be required as all sales should be compliant. Maybe ask if the manufacturer provides the efficiency at the 50% load point, the no-load losses and the load losses for the units offered.	
2. Do you use the Total Ownership Cost (TOC) methodology to purchase optimized transformers whether single or three phase, large or small?	
3. If you evaluate, do you use the same cost of losses (multipliers A and B in $/W) for all transformers (whether located in rural or urban locations or used in residential or commercial applications)? If not, please explain.	
4. Do you mind sharing your A and B values and indicate how they are derived?	
5. Have you had any experience with purchasing and using amorphous core transformers?	
6. If you have comments about amorphous core, please elaborate here.	
Single Phase units: 10 – 833 kVA	
7. Do you buy these units under a blanket order, or in smaller lots under a spot contract?	
8. Roughly per year: how many pole mounted and pad do you purchase for each size 10 – 833 kVA?	See table on following page for sizes and input.
9. Do you currently purchase any amorphous core single phase transformers? If so, for what kVA ratings and how many?	

10. Comment: Some transformer manufacturers will provide pricing for both grain oriented and amorphous core transformers. If pricing for both is available, and the utility is willing to share, we could learn much about incremental costs.	
Three Phase units: 15 - 2500 kVA	
11. What typical quantities do you purchase at a time?	
12. Roughly per year: how many pole mounted and pad do you purchase for each size 15 - 2500 kVA?	See table on following page for sizes and input.
13. Do you currently purchase any amorphous core three phase transformers? If so, what size and how many?	
Substation Power Transformers: 10 - 40 MVA	
14. Although out of the scope of this program, before making a final purchase, we recommend you contact BPA technical support to see if the purchase may qualify for an energy efficiency incentive. In some cases it may involve obtaining a higher efficiency transformer than your standard practice	

Table for Questions 8 and 12

Single-phase Transformer		Three-phase Transformer	
kVA	**Purchase roughly how many per year?**	**kVA**	**Purchase roughly how many per year?**
10		**15**	
15		**30**	
25		**45**	
37.5		**75**	
50		**112.5**	
75		**150**	
100		**225**	
167		**300**	
250		**500**	
333		**750**	
500		**1000**	
667		**1500**	
833		**2000**	
		2500	

Appendix D. BPA Customer Utility Survey Findings

Responses came from 16 utilities distributed across BPA's territory with the majority load served being residential. Responses to key survey questions are summarized in the figures below.

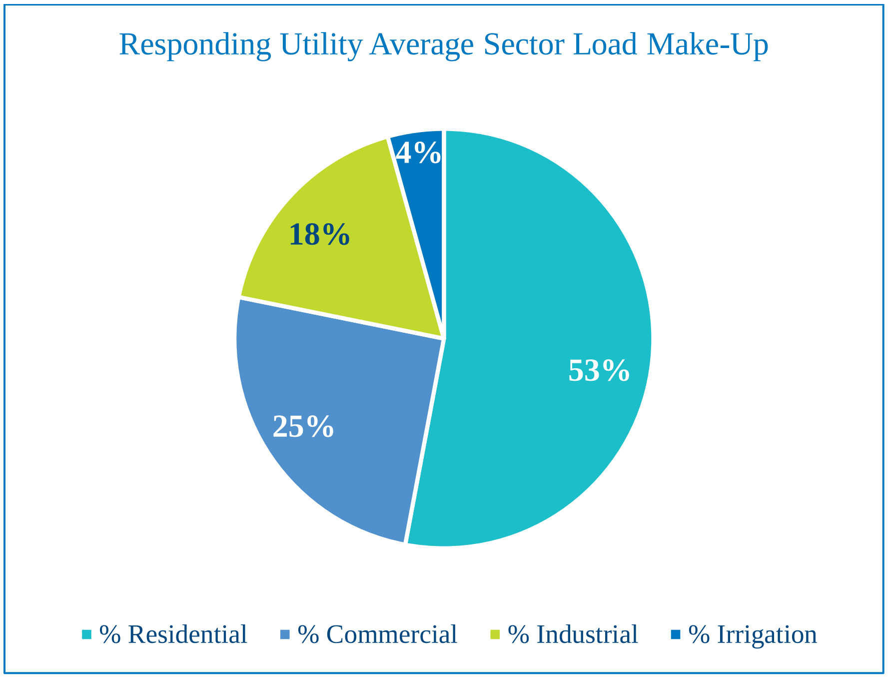

Figure 19. Responding Utility Average Sector Load Make-Up

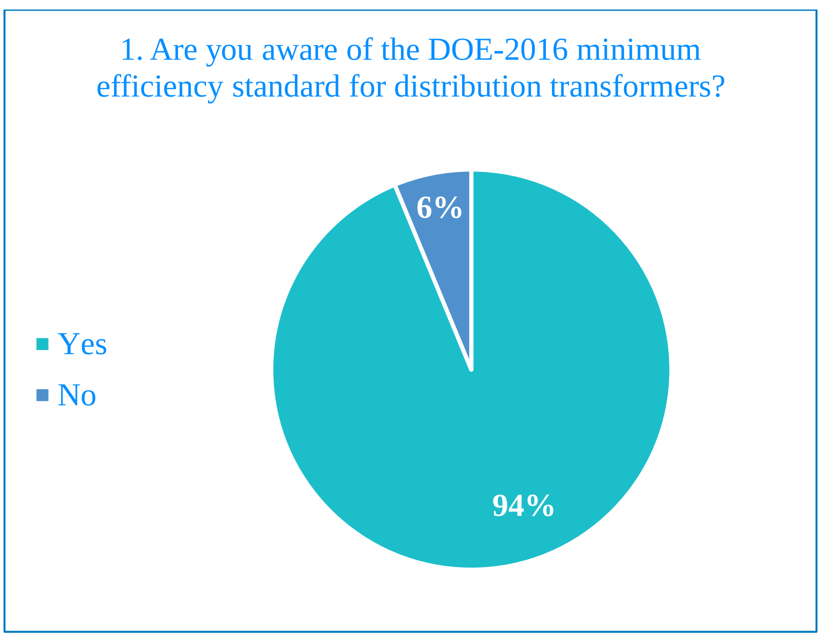

Figure 20. Are you aware of the DOE-2016 minimum efficiency standard for distribution transformers?

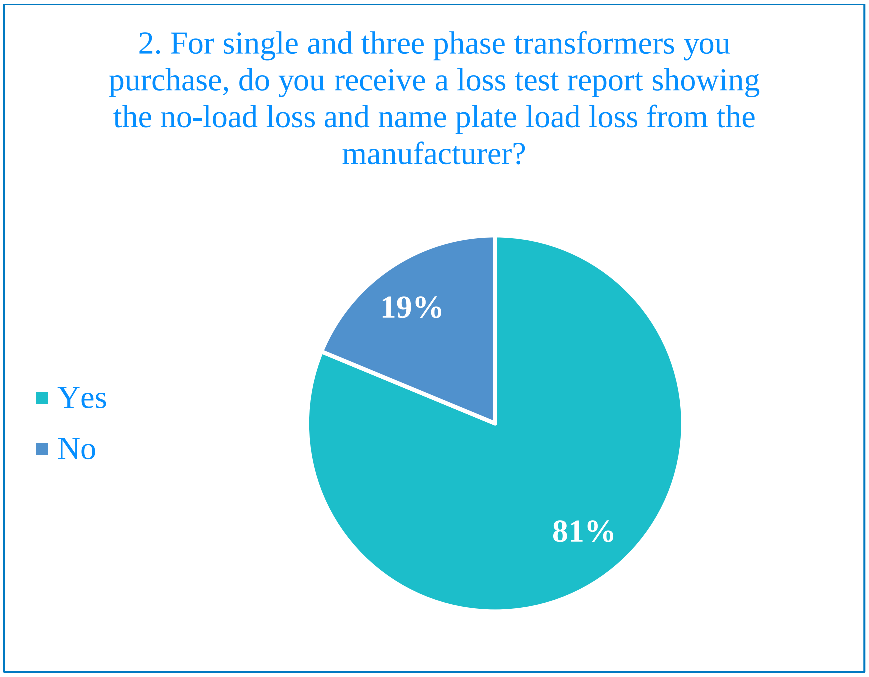

Figure 21. For single and three phase transformers you purchase, do you receive a loss test report showing the no-load loss and name plate load loss from the manufacturer?

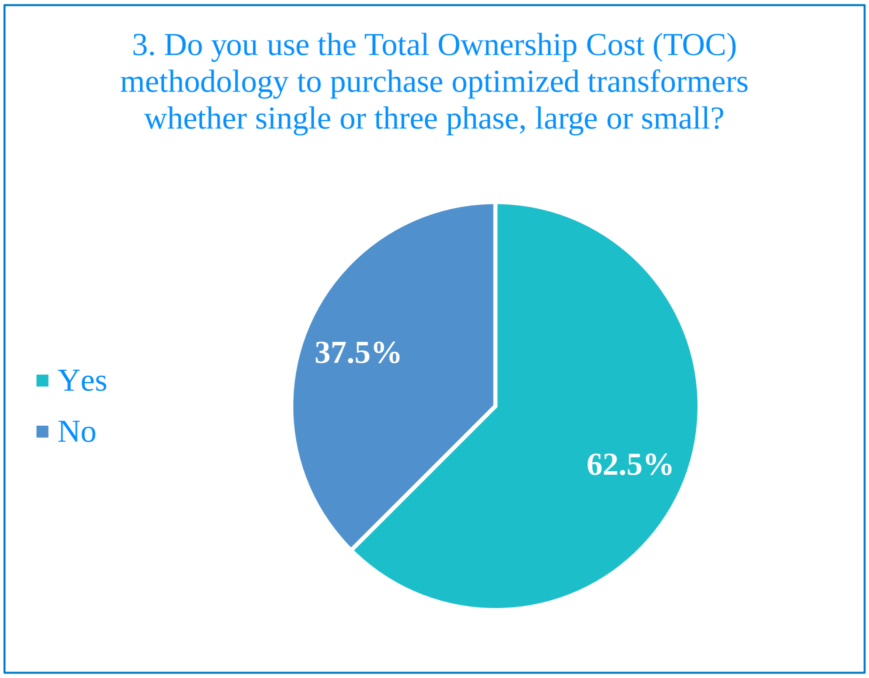

Figure 22. Do you use the Total Ownership Cost (TOC) methodology to purchase optimized transformers whether single or three phase, large or small?

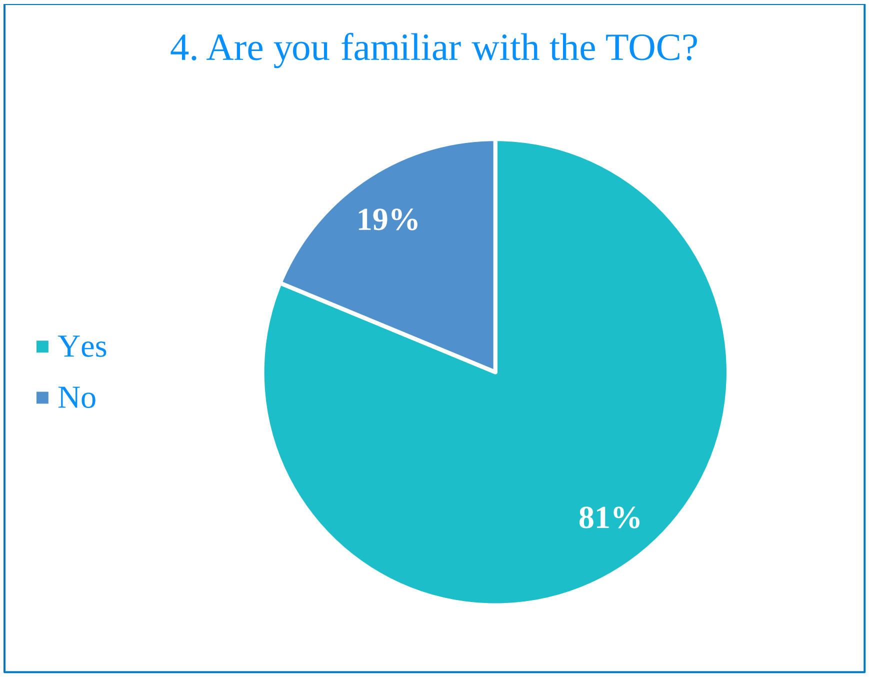

Figure 23. Are you familiar with the TOC test?

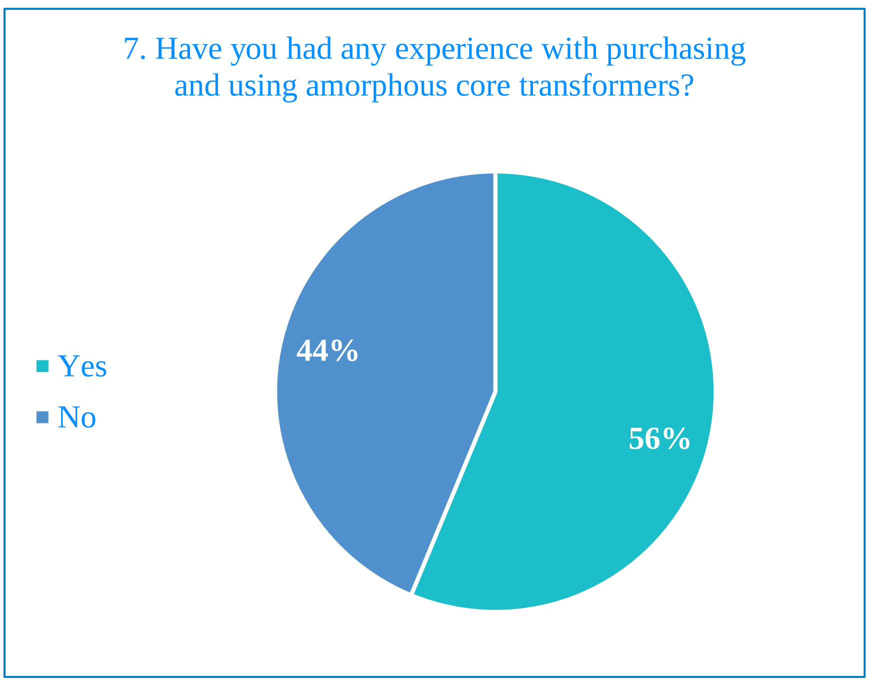

Figure 24. Have you had any experience with purchasing and using amorphous core transformers?

Table 18. Total Transformers Purchased by Size Gathered from Utility Questionnaire Responses

Single-phase Transformer			Three-phase Transformer	
	Total			Total
kVA	Pole	Pad	kVA	Pad
10	105	8	15	0
15	775	408	30	0
25	1247	1403	45	15.25
37.5	371	511	75	67
50	361	667	112.5	12
75	100	182	150	64
100	50	220	225	15.5
167	15	50	300	99
250	2	0	500	51.25
333	0	0	750	12.25
500	0	0	1000	16
667	0	0	1500	16
833	0	0	2000	8
			2500	6

Table 19. Price Comparison between Regional Utilities Average Distribution Transformer Bids and a National Transformer Manufacturer Provided Standard Grain Transformer Price and Performance Values

kVA	Type	Regional Utilities Average NL (W)	Howard NL (W)	NL % Diff	Regional Utilities Average LL (W)	Howard LL (W)	LL % Diff	Regional Utilities Avg. Price	Howard Price	Price %Diff
15	POLE1	39	43	10%	206	210	2%	$ 747.33	$ 788.00	5%
25	POLE1	66	61	-7%	281	316	13%	$ 1,029.59	$ 976.00	-5%
37.5	POLE1	78	82	5%	401	438	9%	$ 1,119.25	$ 1,157.00	3%
50	POLE1	107	111	4%	484	508	5%	$ 1,382.00	$ 1,364.00	-1%
75	POLE1	139	148	7%	734	716	-2%	$ 2,166.00	$ 1,937.00	-11%
15	PAD1	39	43	10%	196	210	7%	$ 1,201.00	$ 1,188.00	-1%
25	PAD1	68	65	-4%	237	304	28%	$ 1,664.05	$ 1,289.00	-23%
37.5	PAD1	79	84	6%	398	430	8%	$ 1,582.00	$ 1,552.00	-2%
50	PAD1	102	97	-5%	515	578	12%	$ 1,760.00	$ 1,754.00	0%
75	PAD1	137	149	8%	687	706	3%	$ 2,111.67	$ 2,108.00	0%
100	PAD1	167	197	18%	833	812	-2%	$ 2,742.00	$ 2,622.00	-4%
45	3-PHASE	121	122	1%	554	547	-1%	$ 6,685.00	$ 5,451.00	-18%
75	3-PHASE	204	187	-8%	774	804	4%	$ 5,892.50	$ 5,844.00	-1%
112.5	3-PHASE	240	225	-6%	1298	1242	-4%	$ 6,010.00	$ 6,933.00	15%
150	3-PHASE	310	324	5%	1515	1373	-9%	$ 6,729.50	$ 7,414.00	10%
300	3-PHASE	598	553	-8%	1850	2279	23%	$ 8,709.00	$10,436.00	20%
Averages				**2%**			**6%**			**-1%**