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Efficient Transformer Study: Analysis of Manufacture and Utility Data

Klaehn Burkes
Joe Cordaro
John McIntosh
Benjamin McConnell
Donald Hammerstrom

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1.0 Introduction

Distribution transformers convert power from the distribution system voltage to the end-customer voltage, which consists of residences, businesses, distributed generation, campus systems, and manufacturing facilities. The average transmission and distribution losses are approximately 5%[1] when combined, but distribution transformer losses consume 2-3% of energy generated in the U.S.[2] Losses within the distribution transformer consists of no-load and load losses. Load losses are due to the heat produced from current flowing through the metal windings of the transformer, and the amount of losses varies with the square of the load current. The no-load losses are due to the energy required to magnetize the transformer core, and therefore, are always present any time there is voltage present. Advances in core design have reduced these losses in silicon steel cores, and amorphous metal cores have been used to further reduce these no-load losses even more than the silicon steel transformers. The amorphous metal cores reduce the no-load losses by 60-70%, but because of lower operating magnetic fields (B=1.20-1.25 T vs 1.5-1.6 T for silicon steel) in the core require larger cores, which leads to higher load losses. Amorphous metal distribution transformers (AMDT) are also more expensive and heavier than conventional silicon steel distribution transformers. This and the difficulty to measure the benefit from energy efficiency and low awareness of the technology have hindered the adoption of AMDT.

This report presents the cost savings for installing AMDT and the amount of energy saved based on the improved efficiency. To determine these values, data on both AMDT and silicon steel distribution transformers were collected from different manufacturers for different distribution transformer ratings. Then information was polled from utility companies on both their installed AMDT and silicon steel distribution transformers. This information combined helps determine how much energy and money would be saved through installation of AMDT.

2.0 Data Collected from Manufacturers

Several transformer manufacturers were contacted for quotes on purchasing distribution transformers that spanned the power range of distribution transformers at a constant voltage level. At each power level two transformers were requested: one with a conventional silicon steel core, and one with an amorphous metal core. They were requested to meet DOE 2016 standard (Distribution Transformers, 10 C.F.R §431.193). The manufacturers were later asked to rebid the specification with the additional requirement that they meet total ownership costs with a no-load value of $5/watt and a load loss value of $2/watt. This information was gathered to compare the transformer efficiency curves for both AMDT and conventional transformers. Table 1 shows the specifications for the distribution transformers requested for purchase. These sizes were chosen based on data from utility partner Santee Cooper. These power levels are 25, 75, and 500 kVA, respectively. A 2,500 kVA distribution transformer was chosen because it is the largest rating for a distribution transformer.

Only two companies responded with bids, referred to as Company 1 & 2. They both manufacture three-phase pad-mount AMDTs. Only one company responded that manufactures pole-mount AMDTs, Company 2. The no-load losses and load losses for each transformer design were provided by the manufacturers and their efficiencies were plotted versus rated load. Equation 1 was used for calculating the efficiency of each distribution transformer at various loading levels. For simplicity, no temperature

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[1] Energy Information Administration (EIA). 2017. Transmission and Distribution Losses. Link accessed 5/10/2017 at https://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3

[2] Douglas Getson. 2013. "Green-R-Trafo™ Green Transformer Program." ABB Group, ZA Transformer Day, May 20, 2013.

correction is included in the evaluation and would be needed to bring the units into compliance with DOE 2016.

Table 1: Ratings for Four Transformer Types for which Bids were Requested

Rated Power	Primary	Secondary	Other	
25 kVA	12,470 V Y	240/120 V	1-Phase	Pole-Type
75 kVA	12,470 V Y	208/120 V	3-Phase	Pad-Mount
500 kVA	12,470 V Y	480/277 V	3-Phase	Pad-Mount
2,500 kVA	24,940 V Y	480/277 V	3-Phase	Pad-Mount

Equation 1: Efficiency Calculation for Distribution Transformers

$$\%Efficency = \frac{Power\ Rating \times \%\ Load}{Power\ Rating \times \%\ Load + No\ Load\ Losses + Load\ Losses \times \%Load^2} \times 100$$

2.1 Single-Phase Pole-Mount Distribution Transformer

The single-phase 25 kVA pole-mount distribution transformer is the primary workhorse in the U. S. distribution system, especially in residential areas, and it has the possibility of the greatest savings based on population density. Figure 1 plots the efficiency of both AMDT and silicon steel core transformers. The AMDT's efficiency is constantly better than the silicon steel, but as the loading on the transformers increases, the difference becomes minimal. This is because AMDT no-load efficiency is better than conventional transformers, but the AMDT load losses are higher. This allows for the efficiencies to converge as the loading increases on both transformers.

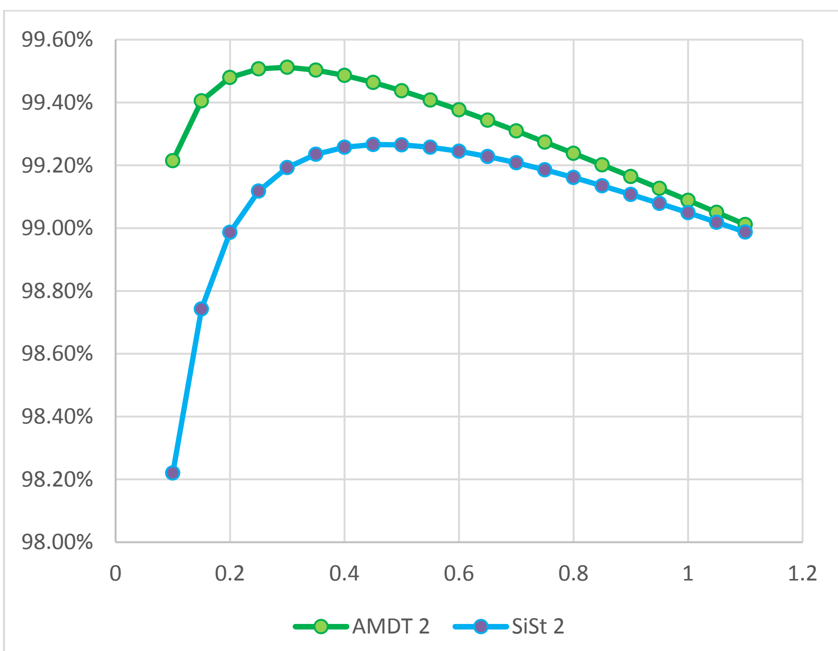

Figure 1: Efficiency Curve Comparison versus Load for 25 kVA Single-Phase Pole Top

Under normal design practice, the behavior shown in Figure 1 is almost never seen. Hence, the losses and associated efficiency plots present a very serious question. In proper design practice, the silicon steel transformer efficiency is always higher at loads above 50-60% and the associated total losses are lower in this range. It appears that the manufacturer has proposed to supply both units with a design to operate at the nominal B of 1.25 T. This was probably caused by the emphasis on the desire to test AMDT core performance. If the core losses were unchanged and the higher B value is used the core cross section is reduced allowing a larger conductor in the windings and lowering losses to about 350-400 watts, and the unit cost is probably not affected.

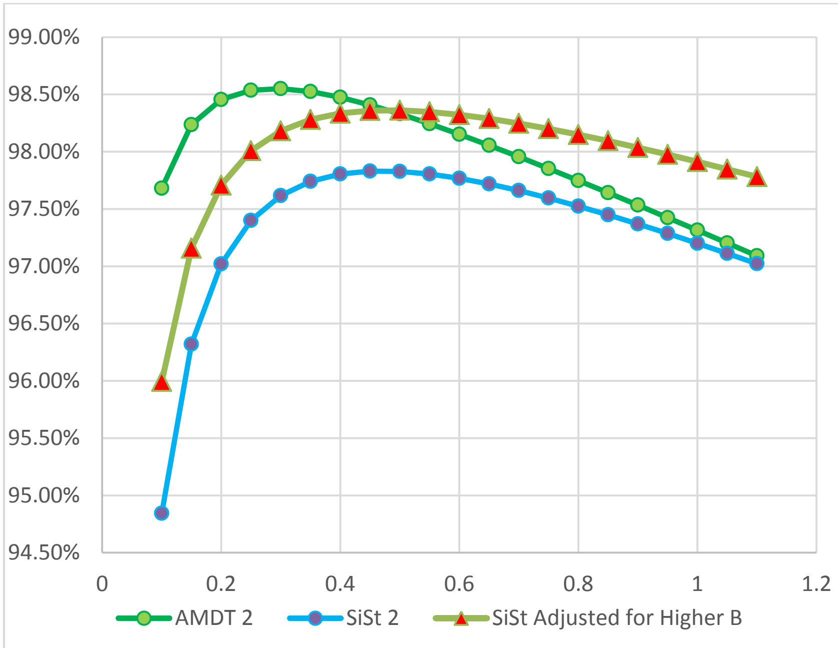

Figure 2: Efficiency Curve Comparison versus Load for 25 kVA Single-Phase Pole Top with SiSt Adjusted for Higher B

2.2 Three-Phase Pad-Mount Distribution Transformers

Competitive bids for the three-phase distribution transformers allow for a better analysis of how transformer design changes the efficiency curve. In all three pairs of distribution transformers, the AMDT are more efficient at 50% rated load and under. However, in Company 1's design, the efficiency of the AMDTs crosses the efficiency of the silicon steel transformers at 50% rated load. This efficiency curve is due to the design of the amorphous metal core being larger than the silicon steel core and thus requiring more copper to get the same amount of windings. This increases the loading losses on the AMDT and as the load increases the difference in load losses becomes greater than no-load losses for the two transformers.

Also, since the transformer quote stated that the manufactures must meet the DOE 2016 standard, it is concluded as the reason for the efficiencies of the AMDTs and silicon steel transformers being the same at 50% load. It may also look like Company 2 has a better design for AMDT because the AMDT is better than the silicon steel. However, based on the shape of the silicon steel efficiency, the silicon steel is being built to match the size of the amorphous metal core. This would result in greater winding losses for the silicon steel and thus cause the efficiency of the AMDT to be better across loading percentages.

Company 2's design of the three-phase silicon steel transformers is the same as the single-phase as previously discussed. However, the conventional transformers efficiency curves for Company 1 and 2 are very similar, and therefore, Company 2's three-phase distribution transformers can be used for cost analysis. Company 2 represents the results from a TOC bid for AMDT and conventional transformers, and Company 1 represents the results from an initial cost bid for AMDT and conventional transformers. From these comparisons TOC bids result in more efficient and cost effective method for distribution transformer design.

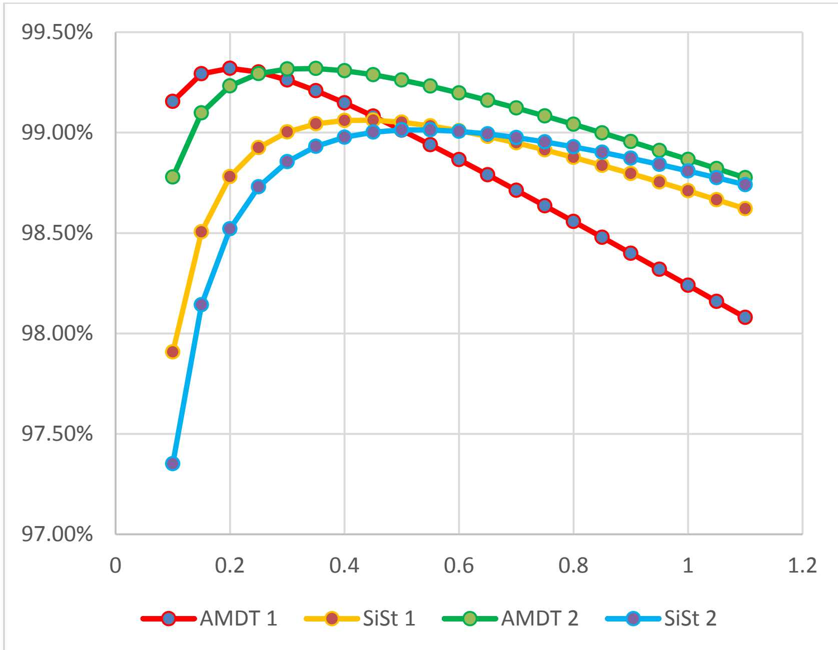

Figure 3: Efficiency Curve Comparison versus Load for Three-Phase 75 kVA Pad-Mount

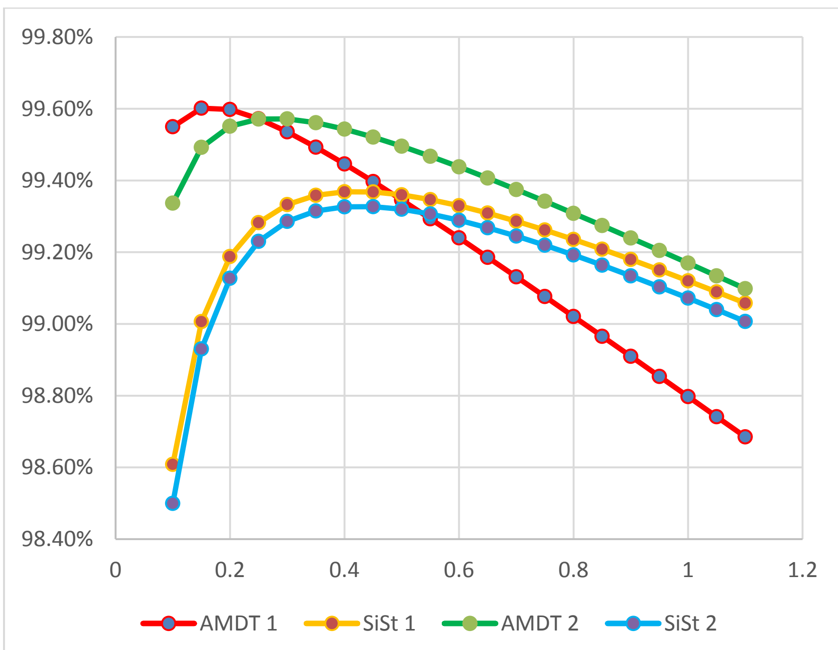

Figure 4: Efficiency Curve Comparison versus Load for Three-Phase 500 kVA Pad-Mount

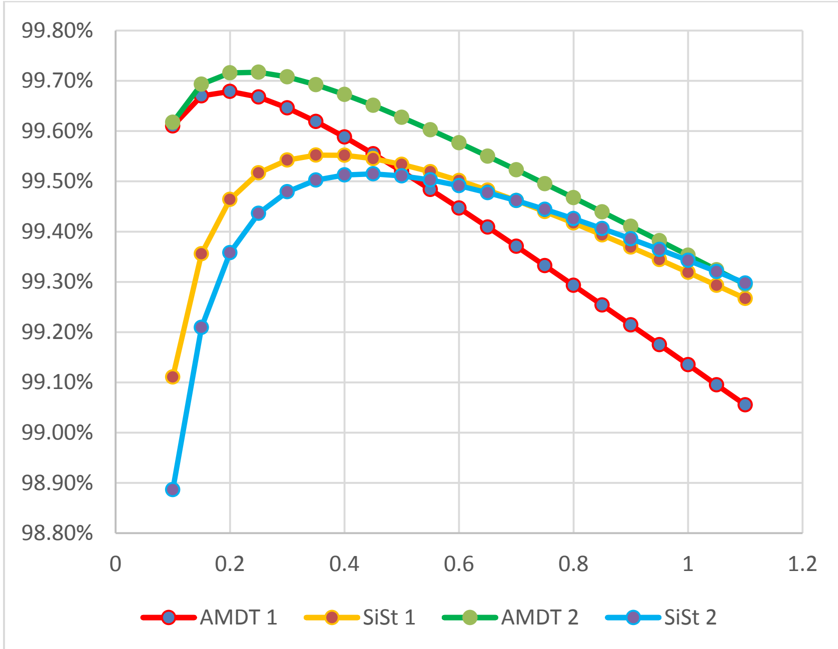

Figure 5: Efficiency Curve Comparison versus Load for Three-Phase 2,500 kVA Pad-Mount

2.3 Final Total Ownership Cost

Total ownership cost (TOC) is a common method for determining the true cost of distribution transformers. Many utility companies use TOC to select distribution transformers for purchase. The TOC takes into consideration the power losses of the transformer as a cost added to the final price. This adjusts the cost of the transformer due to the no-load and load losses as shown in Equation 2. The TOC for the distribution transformers previously discussed is shown below in Table 2. This table contains the purchase cost, up front price difference, no-load losses in watts, reduction in no-load losses between silicon steel and AMDT, load losses, TOC, and difference in TOC. The results from the table also agree with the previous statement about the design of the two transformers. Company 1 bid AMDT having low initial AMDT costs that were comparable to conventional distribution transformers while allowing for additional load losses for the AMDT designs; Company 2 bid AMDT that have load losses similar to the conventional counterparts but stated a premium initial cost for the AMDT designs.

Because the more competitive TOC design has better efficiency, these transformers will be used in the next study to show the cost savings per transformer population based on Santee Cooper data.

Equation 2

$$Total\ Owning\ Costs = Purchase\ Price + \ No\ Load\ Losses \times Afactor + Load\ Losses \times Bfactor$$

Table 2: Total Owning Cost Calculation for Distribution Transformers

Total Owning Cost Calculation for Distribution Transformers									
Manufacture	Core	Price (Each)	Price Difference	NL Watts	Reduction NL Losses	LL Watts	Increase in Load Losses	TOC	TOC Difference
25 kVA, 12,470/240 V Pole-Mount									
Company 2	AMDT	$3,041	$1,057	53	59%	637	8%	$4,580	$766
	IRON	$1,984		130		590		$3,814	
75 kVA, 12,470/208 V Pad-Mount									
Company 1	AMDT	$6,690	$435	51	66%	1,293	56%	$9,531	$860
	IRON	$6,255		152		828		$8,671	
Company 2	AMDT	$6,097	$1,107	85	57%	775	10%	$8,072	$683
	IRON	$4,990		197		707		$7,389	
500 kVA, 12,470/480 V Pad-Mount									
Company 1	AMDT	$12,560	$1,860	167	75%	5,919	57%	$25,233	$3,653
	IRON	$10,700		668		3,770		$21,580	
Company 2	AMDT	$13,365	$3,514	295	59%	3,892	2%	$22,624	$1,239
	IRON	$9,851		722		3,962		$21,385	
2,500 kVA, 24,940/480 V Pad-Mount									
Company 1	AMDT	$37,445	$150	768	63%	21,046	40%	$83,377	$5,511
	IRON	$37,295		2,093		15,053		$77,866	
Company 2	AMDT	$57,048	$28,113	805	70%	15,476	12%	$92,025	$21,975
	IRON	$28,935		2,677		13,865		$70,050	

3.0 Santee Cooper Transformer Data

Information about the population of AMDT is needed to understand how these transformers currently are utilized and what the value proposition is for purchasing these transformers. Several utility companies in the southeast and northwest were polled asking if they had purchased any AMDT. Unfortunately, some utility companies stated that they have purchased them but they have been on a limited basis and do not have any records for them. Most utility companies said they have not used AMDT.

However, Santee Cooper, a South Carolina state-owned electric utility company, has been purchasing AMDT since 1989 and has kept good records on the specific transformers. The reason for their initial purchase of AMDT was that AlliedSignal, a company that makes the amorphous metal ribbons for the cores, created a manufacturing facility on Santee Cooper’s grid. Santee Cooper serves 165,000 residential and commercial customers and generates power for distribution by South Carolina’s 20 electric cooperatives. They have a diverse fuel supply of coal, nuclear, oil, natural gas, hydro, and some renewable energy. The following sections are an analysis of Santee Cooper’s transformer fleet.

3.1 Single-Phase AMDT

When Santee Cooper started purchasing AMDT, between the years of 1989 and 1992, they only purchased single-phase distribution transformers not three-phase. These single-phase AMDT were purchased if the initial cost was less than 20% higher than conventional ones or if the TOC was less than

5% higher. This policy resulted in a few AMDT purchases, but the high cost of AMDT resulted in Santee Cooper suspending purchase of AMDT in 1995.

Single phase distribution transformers have a large value proposition in converting to AMDT because of the large population installed on the grid. In 2010 after the DOE transformer efficiency standard was enacted, AMDT became available again and Santee Cooper adjusted their specification to include AMDT. They purchased several hundred in the years between 2010 and 2012, but stopped purchasing after 2012 because TOC was no longer competitive for single-phase units. **Error! Reference source not found.** shows the amount of AMDT purchased within the two time frames. Santee Cooper purchased mainly 25 and 50 kVA pad-mount single-phase transformers from 2010-2012.

Table 3: Santee Cooper Single-Phase AMDT

Single-Phase 7.2kV AMDTs			
Year	Type	Total Purchased	Total Removed from Service
1989-1992	Pad	20	0
	Pole	49	5
2010-2012	Pad	308	3
	Pole	154	6

3.2 Three-Phase AMDT

Three-phase AMDT will have better opportunities to be competitive with the total cost versus conventional silicon steel core transformers because of the larger savings in power per each individual transformer. Therefore, there is a higher value proposition in replacing three-phase distribution transformers versus single-phase.

Santee Cooper did not purchase any three-phase AMDT before the DOE 2010 transformer standard was set in place. However, ever since then they have specified AMDT in the quotes for purchase and base each transformer purchase on the best TOC received. The amount of both conventional transformers and AMDT purchased by Santee Cooper from 2010-2016 are shown in Table 4. Santee Cooper has purchased about 30% of their three-phase transformers with amorphous metal cores based only on best TOC. However, the AMDT are not a 1:1 replacement at a competitive TOC value. The high power distribution transformers have a better return on investment over the lifetime of the transformer.

Table 4: Comparison of AMDT and SiSt 3-Phase Distribution Transformers

3-ϕ Santee Cooper Distribution Transformers Purchased 2010-2016							
Primary	Secondary	Type	SiSt	AMDT	Total	%SiSt	%AMDT
12.47 kV	208 V	Pad	273	120	393	69%	31%
		Pole	69	0	69	100%	0%
12.47 kV	480 V	Pad	113	43	156	72%	28%
		Pole	14	3	17	82%	18%

4.0 Results and Discussion

TOC is supposed to essentially provide the analysis of a cost tradeoff for initial upfront cost versus total life costs, but what TOC misses is the inclusion of externalities such as environmental impacts in the economic analysis. TOC is still a function of application, because A and B factors are simplifications, and it is difficult to make a prediction without the actual application power levels.

From the data received from the manufacturers and from Santee Cooper, the annual electricity saved and the 20-year potential cost savings were calculated. In the Data Collected from Manufacturers, it was presented that the distribution transformers do not have a constant efficiency over a power sweep, the annual electricity saved and 20-year potential cost savings were calculated over a power sweep. This allows for insight into distribution transformer system design for maximum efficiency and profit. The results of these sweeps are presented in Figure 6 and Figure 7. For all of these comparisons, the efficiency of Company 2 was used based on the fact that they had the best TOC for most of the transformers.

$$Annual\ Savings = (AMDT\ \eta\% - SiSt\ \eta\%) \times kVA\ Rating \times Power\ Sweep\ Rating \times Hour\ in\ Year \times \#\ of\ Santee\ Cooper\ XFRMs\ at\ Power\ Rating$$

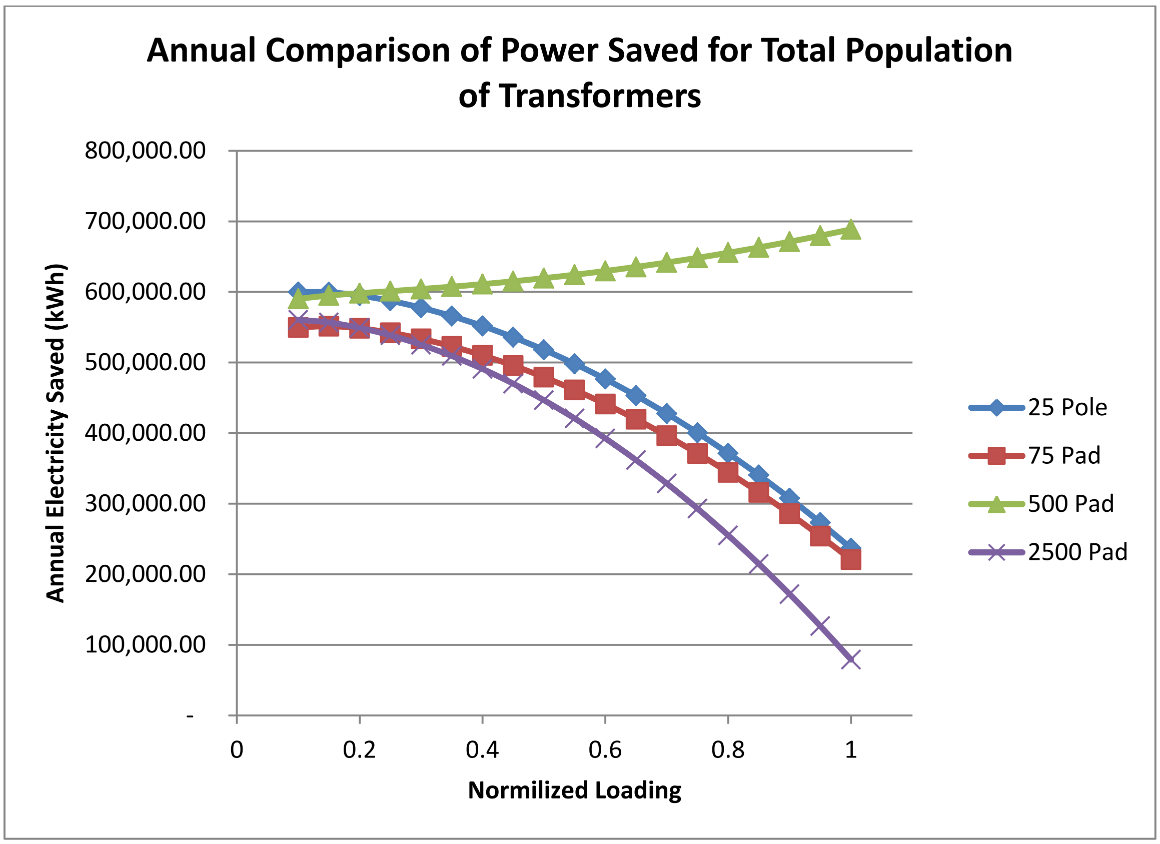

Figure 6: Annual Electricity Saved for the Total Population of Santee Cooper AMDT Transformers

The total population of distribution transformer at each power rating times the total amount of saved electricity for each distribution transformers studied allows for more equal annual electricity saved from a fleet of AMDT at each power rating, presented in Figure 6. This is because at the lower power rated the fleet of distribution transformers have a larger population installed whereas the higher power rated distribution transformers have very small populations in each fleet, but large amounts of savings individually.

The amount of electricity saved from each transformer reduced with increasing load except for the 500 kVA transformer. The 500 kVA AMDT electricity savings increased, because of the design presented by the Company 2. All of the other pairs of transformers' efficiencies were about equal at full rated load except the 500 kVA. This design is what causes the increase in electricity saved by the 500 kVA AMDT. Company 2's bid seems to have a perturbation toward the AMDT and causes a problem with the analysis.

The problem is best seen in the way the 500 kVA pad mount results are behaving. Therefore, the 500 kVA pad mount results will be removed from the economic analysis.

Discounted economic analysis favors the earlier saving more and as a result the payback period is much shorter than 20 years. Traditionally, units are loaded more lightly in the initial installation and the load increases with age but while conservation would seem to have an impact additional customers are added to most units over their lifetime; i.e., the number of customers per transformer increases with age in many areas.

The potential cost savings over a 20-year lifespan for each fleet of AMDT is compared to the increase in initial cost for purchasing AMDT versus conventional distribution transformers for all the transformers installed on Santee Cooper's system, Figure 7. This was calculated using the average U.S. retail price of electricity (10.58 c/kWh). For each one of the distribution transformers there is a cutoff rated power level at which the difference in purchasing AMDT becomes more than the lifetime savings, and therefore, use of AMDT is not cost effective. However, for 25 kVA single-phase AMDT cost effectiveness is at fewer than 60% rated load, for 75 kVA three-phase AMDT it is at fewer than 85% rated load, and for 2,500 kVA three-phase AMDT it is at fewer than 45% rated load. These points of transition are clear when observing the cost benefit for an individual transformer as well; because the factor for comparing population size is removed, the point of transition is still the same. This is a conservative estimate for the cost savings for AMDT. The lifespan for a distribution transformer is thirty years or more, and after thirty years the distribution transformers save more than the difference in cost at any rated.

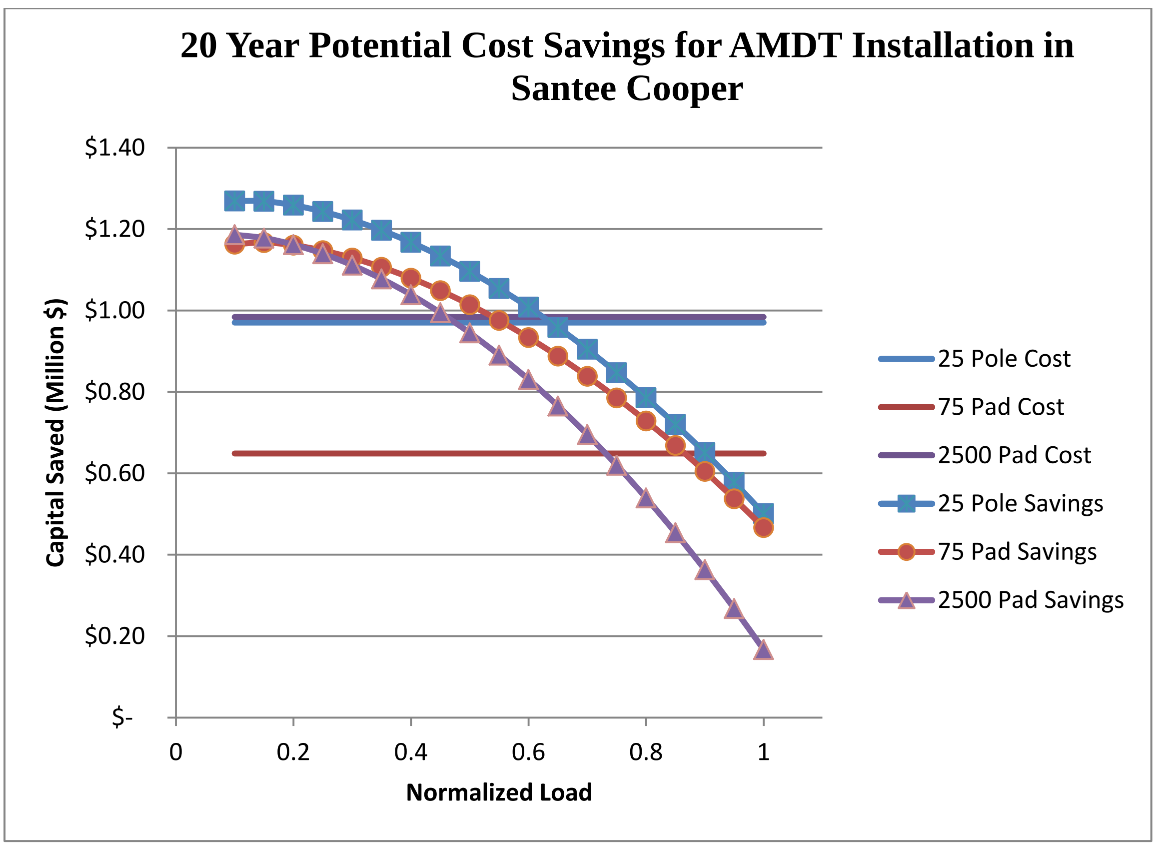

Figure 7: 20 Year Potential Cost Savings for AMDT Replacement in Santee Cooper

Santee Cooper is a smaller utility company serving about 0.9 billion kWh of direct serve with another 1.1 billion kWh for resale. Therefore, with the entire national net generation of 4,100 billion kWh of electricity in 2015[1], the conversion to AMDT would result in between 12 and 16 billion kWh annually of saved energy. This value would inherently be based on the percent load (Figure 8) because it fluctuates throughout the day and year.

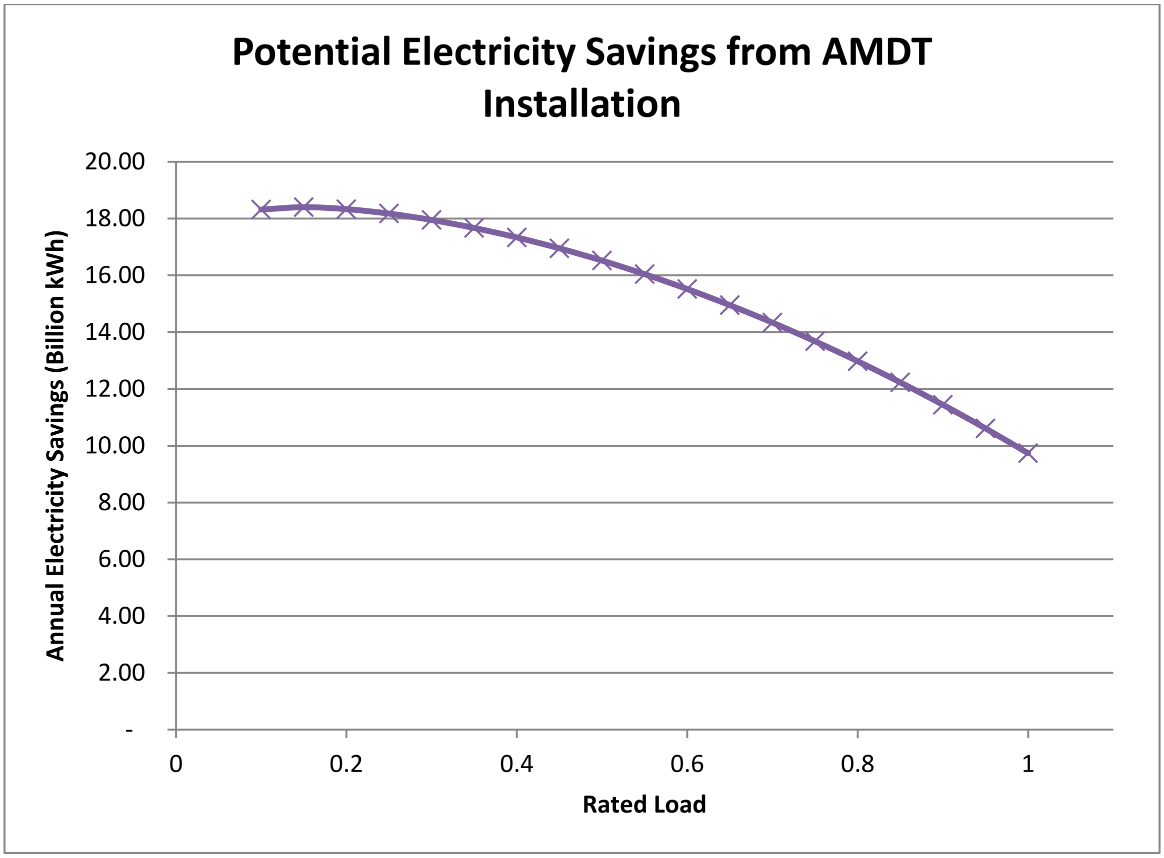

Figure 8: Potential Annual Electricity Savings from AMDT Installation

5.0 Recommendations, Path Forward, and Future Work

This report presents the cost savings for installing AMDT and the amount of energy saved based on the improved efficiency. To determine these values, data on both AMDT and silicon steel distribution transformers were collected from different manufacturers for different distribution transformer ratings. Then information was polled from utility companies on both their installed AMDT and silicon steel distribution transformers. This information combined helps determine how much energy and money would be saved through installation of AMDT.

From the data collected the potential annual electricity savings from AMDT installation based on rated load was between 12 and 16 billion kWh, which results in a national annual savings of $1.27 to $1.69 billion. These results are in agreement with previous reports from this project on the cost savings of AMDT at 14.4 billion kWh annually and $1.52 billion in savings[2]. This report highlights that the savings

[1] Energy Information Administration, Annual Energy Outlook 2017, Reference Case, Table 8, http://www.eia.gov/outlooks/aeo/

[2] "Improved Distribution Transformer Efficiency and Lifetime" Distribution Transformers Paper – DOE Review Draft

are variable based off of the loading of the transformer, but at operation at 50% rated load the annual savings are 16.52 billion kWh and $1.75 billion in savings.

The efficiencies for the distribution transformers presented in this report are taken straight from the manufacturer and represent the ideal loading conditions. They do not take into account the presence of harmonics, phase balancing, or effects due to aging. All of these effects have been extensively studied on conventional silicon steel transformers but not on AMDT. However, for wide adoption in the utility industry, AMDT must be better understood.

SRNL is currently working with Santee Cooper on testing a pair of single-phase pole and pad-mount AMDT and conventional distribution transformers. These single-phase distribution transformers are being supplied by Santee Cooper at scrap costs, and they are from Santee Cooper's original purchases between 1989 and 1992. These transformers have been in the field experiencing real-life conditions for over 25 years. Therefore, a functional acceptance test and efficiency baseline will be established for each pair of distribution transformers by conducting the IEEE C57.12.90-2015 standard and the DOE 2016 (10 C.F.R. §431.193).

Then a series of custom tests will be performed to understand how the AMDT differs from the conventional silicon steel distribution transformer. These, will include load sweep, harmonic injection, and a frequency and voltage fluctuation. Finally a degradation test will be performed on the pairs of transformers to determine differences in life spans. The custom tests will be set up as in Figure 9, this will allow for the ability to fully control both current and voltage on the transformers.

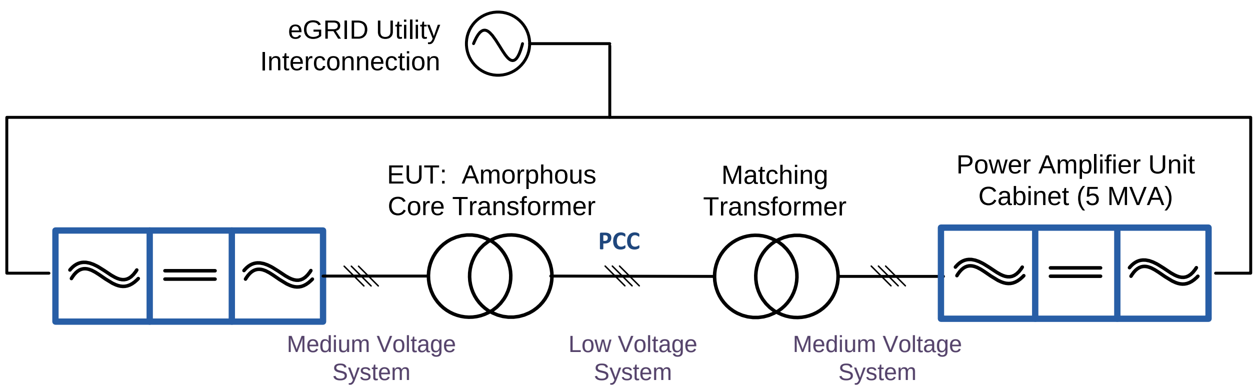

Figure 9: Test Setup for Distribution Transformers at eGRID

These tests will be very influential in determining how AMDTs can be utilized, but there needs to be more testing before they are widely adopted by the utility industry. The main reason for this is that the transformers that are currently being tested are only single-phase and are of older designs. The data collected presents that three-phase AMDT have a higher value proposition and more competitive TOC. Therefore, additional tests are needed on newly designed three-phase AMDT.

Some very important tests which cannot be performed the same with just single-phase units are those that examine how unbalanced systems, bi-directional power flow, and neutral currents affect the different core materials. These are extremely important because of the increasing amount of renewable generation in the distribution system, the movement toward improved resiliency through coordinated microgrids, and the threat of high altitude electromagnetic pulses. Because of coupled design of the three-phase core, the effect based on these three events cannot be extrapolated from the single-phase tests. After the testing of the single-phase distribution transformer pairs is complete, a path forward for testing three-phase AMDT will be developed.