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To: DOE Stakeholders for
Distribution Transformer
Energy Efficiency Determination

Subject: DOE Distribution Transformer Loading Study

Dear Stakeholder:

This analysis of Distribution Transformer Loading was prompted by the interest of a number of Stakeholders who have requested that I provide insight. My objective is to provide unfiltered accurate analysis and recommendations based on my personal experience and other background documents. It is my suspect that a multiplicity of stakeholders may find this analysis and report to be useful. I will post a word version on my IEEE Transformers Committee DOE Energy Efficiency website for all interested parties to access. The following topics will be addressed:

1. Introduction
2. References
3. Analysis
4. Conclusions
5. Recommendations

A. Introduction

In 2007, I was elected to be Chairman of an IEEE Transformers Committee Task Force to address Stakeholders' concerns and issues with current and proposed changes to the Department Of Energy (DOE) regulations for Distribution Transformer Energy Efficiency. A very large task force now meets regularly at each of the IEEE Transformers Committee Meetings. This task force now has about 100 members and is composed of manufacturers, users and other interested parties. Data is regularly accumulated, analyzed and reported at each meeting with minutes and presentations posted on the IEEE Transformers Committee's site at www.transformerscommittee.org , Distribution Transformers Subcommittee, Task Force for Review of DOE Energy Efficiency Proposals.

I am not a stakeholder but will gladly participate where needed to be sure that the findings in this report are understood by those who will be selecting the next round of energy efficiencies for Medium Voltage and Low Voltage Distribution Transformers. Regardless of the efficiency levels that are selected and of any predisposed positions of any of the stakeholders, this attempt to display factual information should prove useful to the team.

I have examined distribution transformer loading from 1992 through present and recognize the difficulty of finding a one shoe fits all approach for all transformer applications. However, several types of information have been available to make a reasonable selection for use in setting Distribution Transformer Energy Efficiency Standards.

B. References:

1. FERC Form 1 Data
2. Electric Utility Total Owning Cost history
3. NEMA TP-1 from 2002 and from 1996
4. Distribution Transformer Size Optimization by Forecasting Customer Load by Jerrod Luze, Black Hills Power, Rapid City, South Dakota.
5. DOE Chapter 6 Energy Use and End Use Load Characterization.
6. ABB Total Ownership Cost (TOC) Calculator
7. Loading Study of a Manufacturing Plant by Philip J Hopkinson, PE (1995 and 2005)
8. Boston NEMA TP-1 Background (1995)
9. Optimizing Energy Efficiency Standards for Low Voltage Distribution Transformers a thesis by Ken Harden of Schneider Electric at Purdue University
10. NEETRAC Distribution Transformer Thermal Test Procedure from May 29, 2002
11. My experience as a distribution transformer design engineer from 1966-2011

C. Scope

1. Medium Voltage Liquid Filled Distribution Transformers
2. Medium Voltage Dry Type Distribution Transformers
3. Low Voltage Dry Type Transformers.

D. Assumptions

1. Transformers always remain energized and core loss (no load loss) is always occurring.
2. Transformer winding losses along with strays and eddies vary with the square of load current.
3. Historical no load and load loss relationships may be a significant indication for future decisions.
4. For all load considerations, peak transformer efficiency always occurs at the point where no load losses equal load losses.
5. Highest transformer losses occur at the highest permissible load. Hence differences in alternative transformer efficiencies at the highest load have greater impact on total watt losses.
6. Electric Utility Total Owning Cost (A and B factors) is representative of both the value of a watt saved and of their loading models.
7. Load cycles vary by regions of the country, by seasons of the year and by time of day.
8. RMS equivalent load is most representative of the watt losses that are being dissipated in the transformer in service.
9. Routine tests at a manufacturer's production facility should be converted to expected RMS equivalent load to verify the efficiency that will be most representative of the in-service condition.
10. The DOE measurement point for efficiency will normally occur at the most representative RMS equivalent load, which may or may not be equal to the point of peak efficiency where core loss equals load loss. However the transformer is usually most optimally designed for lowest cost when the measurement point occurs at the point of peak efficiency.

E. A look at the 25 kVA single phase pole type transformer

1. The 25 kVA pole type transformer has been the most representative kVA rating for pole type transformers for many decades of time.

2. Many of the relationships for the 25 kVA transformer apply broadly to other medium voltage transformers, such as Total Owning Cost relationships and loss ratios.
3. During the 1960's the 25 kVA transformer normally had 100 watts of core loss and 300 watts of load loss.
4. During the 1970's Total Owning Cost relationships were introduced with two factors, called A and B. The A factor was the present worth of a watt saved and was measured in $ / watt. The B factor was applied to adjust full load winding loss to the value of load loss that is most representative of the normal expected operating condition, or the RMS equivalent load in service. Mathematically, the following is a good way to visualize B:

   B= (PU Load)^2 * A (1)

   Where PU load is the per unit load of the transformer.

   Here, if PU Load is 0.5 then B becomes:

   B at 0.5 load = 0.5^2 * A = 0.25 * A (2)

5. In practice, the B factor is usually slightly greater than the square of per unit load times A to recognize the value associated with peak demand. By increasing B slightly, the transformer will have sufficiently low load losses as to maintain a relatively flat efficiency over wide changes in load. This is important because loading can vary significantly and even exceed transformer rated kVA. If the transformer efficiency deteriorates excessively at high load then the peak demand may result in higher net cost to serve the load.
6. Total Owning cost formulas initially focused on an A factor of $3/watt and a B factor of $1/watt and remained in that range from the 1970's to the mid 1980's.
7. During the 1980's and 1990's wide variations of loss evaluations occurred with A factors varying from a low of under a dollar to as high as $10/watt. Interestingly the B factors remained mostly in a range of 0.2-0.3 * A.
8. In 1996, NEMA introduced TP-1, but derived from the relationship of a B factor = 0.25 A. Many manufacturers were solicited to supply design data that became the basis for the published efficiencies.
9. In 2007, the DOE published new mandatory efficiency values that became effective in 2010 that assumed an RMS equivalent load of 50% of nameplate. Manufacturers report that the same efficiencies may be reached by using TOC methods with an A factor of $4/watt and a B factor of $1/watt.
10. In 2011, many Utilities purchase transformers that just meet the DOE published efficiencies however some Utilities purchase transformers to a TOC owning cost formula that reaches beyond the DOE requirements. The most common TOC formula for premium efficiencies is:
    a. A = $5.91/watt
    b. B = $1.81/watt
11. For any TOC relationship the RMS equivalent load is simply:

    RMS equivalent load = (B/A)^0.5 (3)

12. Recall that in the 1960's the 25 kVA no load watts were 100 and the load watts were 300. Hence the assumed per unit load was:

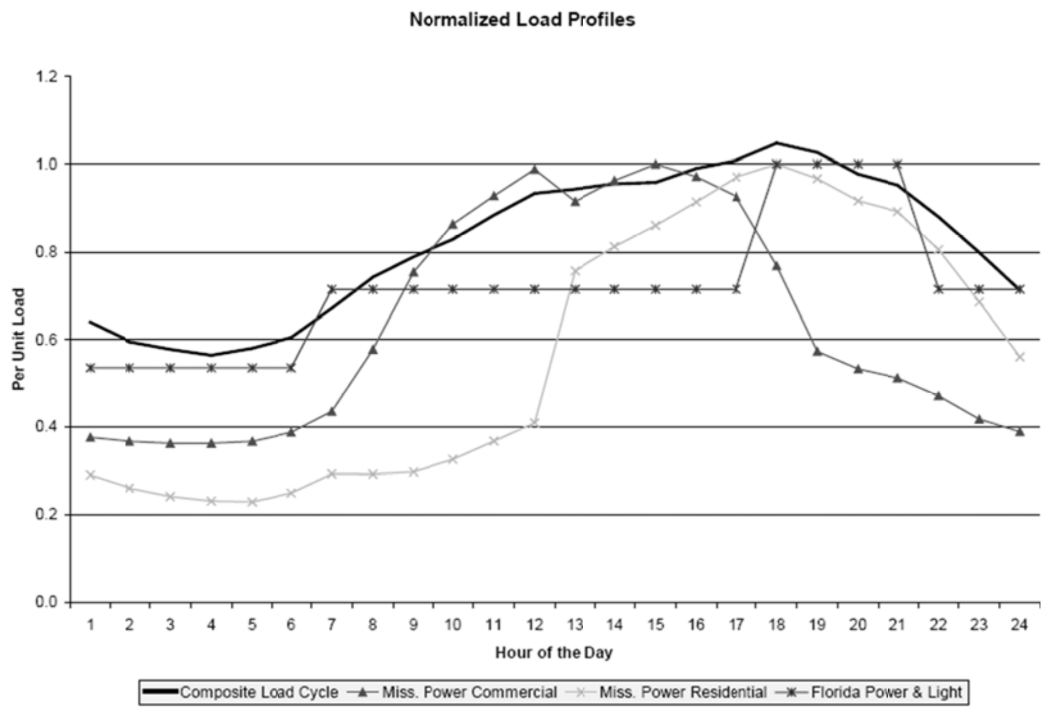
    PU load in the 1960's = (100/300)^0.5 = 0.58 (4)
13. From the 1970's to the mid 1980's the assumed per unit load remained unchanged
14. During the 1980's to 2000, some owning cost formulas had a B that was 0.25 A hence: PU load in the 2000-2011 period has ranged from 0.5-0.58 for all popular owning cost formulas.

F. **Other Loading relationships**

1. The FERC 1 report shows total installed capacity of distribution transformers and total kilowatt-hours of sales of electricity throughout the United States. From this relationship the simple average load would appear to be a little more than 20% of nameplate. However, this includes many times of light load such as at night as well as seasonal periods where loading may be either light or heavy. The simple average load does not measure the losses that are being dissipated by the transformer when it is in its normal service. RMS equivalent load is a true measure of the transformer losses that are present over long periods. The RMS equivalent load is closer to the 50% of nameplate.
2. Phil Hopkinson made a study of the loads on typical industrial transformers supplying power to a manufacturing plant. The RMS equivalent load to the liquid filled transformers were measured as 50% of nameplate. There he also learned that delta: grounded wye connected transformers do a wonderful job of absorbing third harmonics and making a path for zero sequence currents.
3. Typical load cycles are as shown below:

NEETRAC Distribution Transformer Thermal Test Procedure

Revision 02 29 May 2002



Note that loading can be quite variable as a function of time of day as in the Mississippi Power and Florida Power cases or flatter as in the composite curve. However, for 50% RMS equivalent load, each profile is replaced by a flat curve where the specific individual loads are normalized. In spite of the smoothing that occurs, any peaks in loading may result in additional peak demand expenditures by the Utility to account for generation requirements during the highest loading periods.

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4. **A Look at Low Voltage Transformers**

1. Measurements at the DOE Forrestal building in the early 1990's concluded that RMS equivalent loading for Low Voltage Dry Type transformers was close to 35% of nameplate.
2. Measurements during the summer months at a manufacturing plant of loads on 300 low voltage dry transformers suggested that loading could be less than 35% RMS equivalent. However repeated measurements in the winter months was more than 35% which in total was close to the 35% assumption for the year.
3. The Cadmus Group and Northeast Utilities conducted loading studies in the late 1990's that suggested loading of less than 35% of nameplate for low voltage dry type transformers in some Northeast locations and found loading to be as low as 18% of nameplate. It may be true in some locations but the consequences are not clear for the following reasons:
    a. When RMS equivalent load is less than 35% of nameplate and the efficiency peaks at 35% of load, the ratio of transformer load loss divided by no load losses is approximately 10.
    b. When RMS equivalent load is as low as 18% of nameplate and if efficiency peaks at 18% load then the ratio of load losses divided by no load losses is 42. However the consequence of such a ratio is that efficiency falls off very quickly for any conditions of high loading. The result of this is that such transformers may be less efficient during high load periods and lead to the need for greater total delivered load.
    c. Figure 1 below, courtesy of Ken Harden of Schneider Electric shows the efficiency plots for 3 conditions of peak efficiency, ranging from 30% to 35% to 40% of nameplate. Note that at high load the transformers optimized for 30% are considerably less efficient:

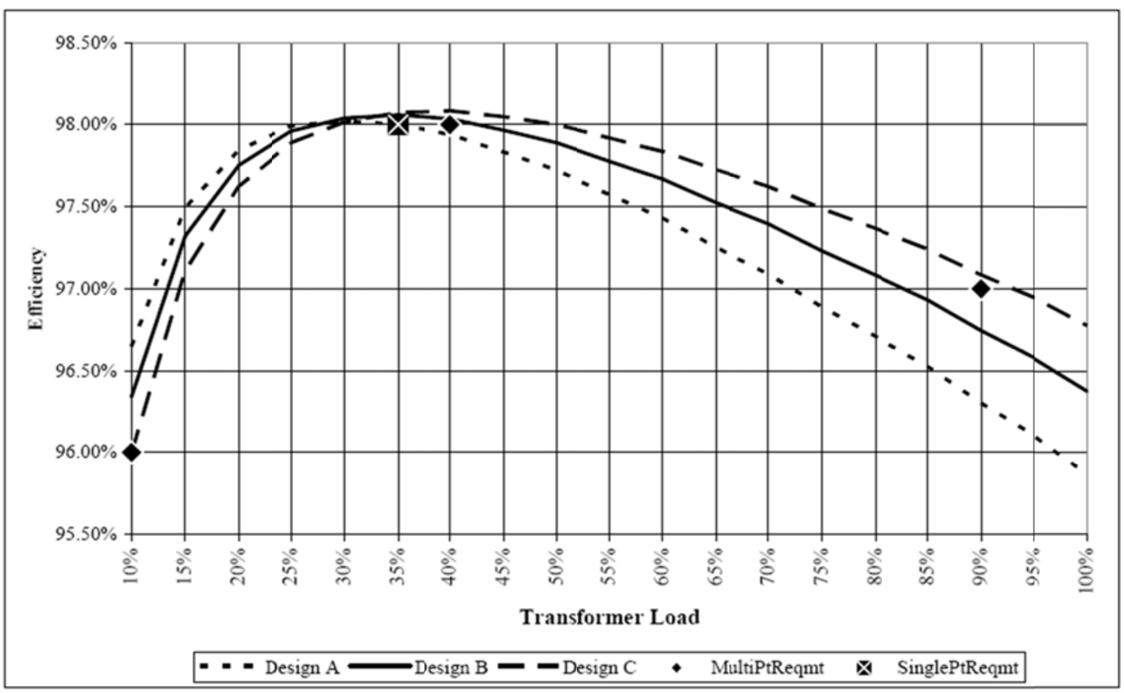

Figure 1 shows total efficiency versus percent load courtesy of Ken Harden of Schneider. Note that the efficiency of the three transformers is quite different at high loads. The impact on watts loss in the transformers is dramatically different at high loads. If a transformer achieved peak efficiency at only 18% of nameplate kVA the falloff at high load would be strikingly large.

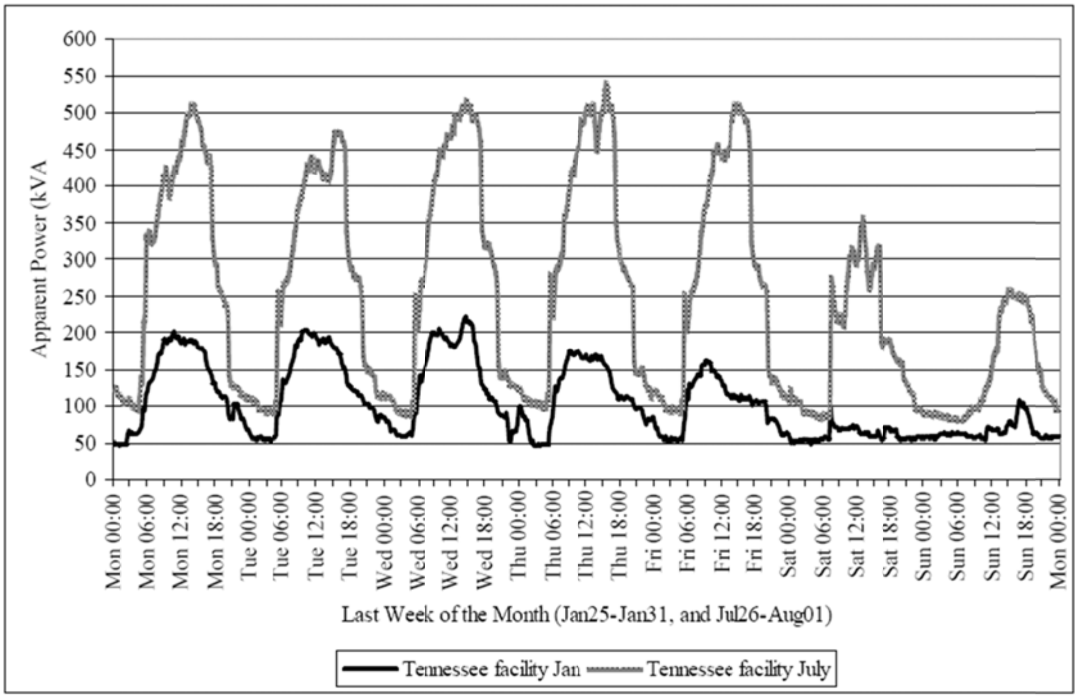

Figure 2 shows a clear view of load variation at a plant in Tennessee, again courtesy of Ken Harden. Note the clear differences in seasonal loads by more than 2:1 between seasons. This is the nature of much of the loading on low voltage dry type transformers.

G. Conclusions:

1. Historical purchases of medium Voltage transformers have been based on expected loads of 50-58% of nameplate RMS Equivalent load in service from the 1960's or earlier forward to today.
2. Historical purchases of low voltage dry transformers have been based on expected loads of more than 40% of nameplate prior to the mid 1990's and 35% of nameplate starting with the introduction of NEMA TP-1 in 1996.
3. Instantaneous loads are not a good indication of RMS equivalent loading which needs daily and seasonal effects to provide adequate information.
4. Peak Demand needs to be considered in the establishment of load loss allowance for a transformer such that the highest permissible loads do not produce excessive demands on the load supply.

H. Recommendations:

1. The DOE Negotiating team should work closely with EEI for the proper loss ratio between no load and load losses for Medium Voltage Utility transformers. Any departure from historical relationships should be carefully studied. The assumption of 50% RMS equivalent load has been in place since at least back to the 1960's.
2. Low Voltage loading information is not generally available but Ken Harden of Schneider Electric has done a commendable job of examining considerable information and any departure from the 35% load assumption should be examined closely for rational.

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