DISTRIBUTION TRANSFORMER THERMAL BEHAVIOR AND AGING IN LOCAL-DELIVERY DISTRIBUTION SYSTEMS

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ABSTRACT

This paper characterizes the thermal behavior and insulation aging of transformers applied in the local delivery concept of distribution based on measured load data and thermal models.

INTRODUCTION

In the "local delivery" concept of distribution, used throughout North America, medium voltage feeders reach within a few hundred meters of the individual customer loads. Distribution transformers are widely dispersed with each transformer serving relatively few customers; typically one to twelve residential customers, or often a single commercial customer, per transformer. Thus, the transformer loads are not very diversified and can vary widely in magnitude over a relatively short period of time.

Distribution transformer application practices in local delivery distribution systems are inherently an engineering art more than a rigorous science. Load demand characteristics are not well defined, nor are the acceptable loading levels on transformers precisely defined thresholds. Conventional distribution transformer application practices tend to base kVA rating selection solely on the expected peak load demand. Distribution transformers in North America are routinely applied so that the peak estimated load is above the rated transformer capacity. A fixed overload factor, typically 100% to 140% of rating, is commonly used. However, experience suggests that the typical overload factors are conservative as premature distribution transformer failures due to insulation thermal degradation are relatively infrequent.

Transformer rating selections based solely on peak load do not adequately account for the true relationships between transformer loading, ambient temperature, and expected insulation lifespan. Transformer insulation thermal degradation is a cumulative function of winding temperature, and winding temperature is a dynamic function of loading plus ambient temperature. Overloading leads to accelerated insulation aging, but operation of the transformer at less than rated load, or in reduced ambient temperatures, causes aging to progress at less than the nominal rate. Short periods of excess temperature due to overloading can be balanced with longer periods of under-loading such that the net transformer life is acceptable.

Distribution transformers comprise a very large segment of a power delivery utility's assets, and effective management of these assets is critical to the utility's financial success. The Distribution Systems Testing, Application, and Research consortium (DSTAR) commissioned a research project to investigate transformer thermal behavior and insulation aging in actual applications, thus yielding information crucial to improving transformer asset management by its member utilities. In this investigation, actual transformer hourly loadings and ambient temperature conditions have been applied to transformer thermal and aging models. This paper summarizes key results of the investigation.

TRANSFORMER THERMAL BEHAVIOR

The relationship between acceleration of aging and temperature, as specified in [1], is plotted in Figure 1. When the hottest spot on the transformer winding is at 110°C, the aging acceleration factor (FAA) is 1.0, meaning that the transformer ages at a rate yielding a useful insulation life of 180,000 hours of continuous exposure to this temperature. Every 7°C increase in temperature yields a doubling of the rate at which the insulation deteriorates. Conversely, a decrease in temperature decreases the aging rate.

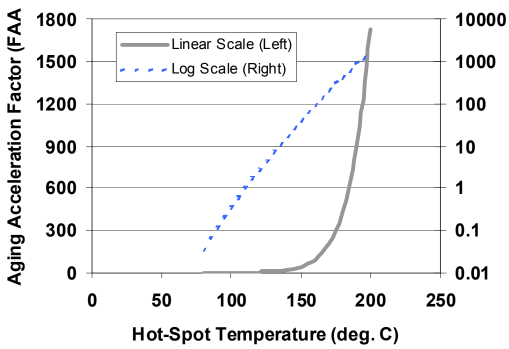

Figure 1 – Relationship between transformer insulation aging acceleration factor and winding hot-spot temperature.

A change in loading does not result in an instantaneous change in winding temperature because it takes an accumulation of thermal energy to heat the transformer's windings, core, and oil. Reference [1] provides a simplified thermal dynamic response model having two effective time constants: the hot-spot time constant and the top-oil time constant. The hot-spot time constant relates to the rise of the winding hot-spot above the temperature of the transformer's oil, and is typically a few minutes. The top-oil time constant relates to the rise of the transformer's oil above the ambient temperature. This time constant is several hours long for a typical distribution transformer, and has a large role in "smoothing" the effects of loading spikes on the transformer temperature.

The total temperature rise of the winding hot-spot, above ambient, is due to the load placed on the transformer. The absolute temperature upon which insulation aging is dependent is the sum of the load-caused temperature rise plus the ambient temperature. This means that when the ambient temperature is less than the prescribed value (30°C) on which nameplate rating is based, a greater amount of transformer loading can be tolerated.

Most loads have some correlation between kVA load and the ambient temperature, primarily due to the heating and cooling loads served. A positive correlation, such as where electric cooling load is dominant, provides more severe transformer duty than a load dominated by space heating demand that is negatively correlated with ambient temperature. A transformer serving a load peaking in winter, with a lesser secondary summer peak, may actually have its most severe thermal duty at the smaller summer peak.

Using the thermal model and the relationships between winding hottest-spot temperature and insulation aging acceleration, the cumulative aging per year can be calculated given the loading and concurrent ambient temperature histories. Transformer kVA rating can then be iteratively adjusted until the calculated insulation life exceeds a desired value. There is a firm limit, however, to the peak transformer overload. In addition to accelerating aging, very high winding temperatures can lead to gas evolution, which can result in immediate failure. For this reason, [1] recommends that, independent of accumulated aging considerations, loading of distribution transformers with 65°C rated winding rise insulation should observe the following maximum limits:

- 300% of rated nameplate load
- 120°C top oil temperature
- 200°C winding hot-spot temperature.

In addition to these thermal considerations, voltage drop considerations can be an important practical limit to distribution transformer kVA rating selection.

LOAD CHARACTERIZATION

Commercial and residential loads have substantially different characteristics. Within the commercial category, load patterns differ widely depending on the nature of the enterprise served. Distribution transformer application practices also differ. Commercial loads typically have a dedicated transformer, but multiple residences are served by a single transformer except in rural areas. For these reasons, the characterizations of commercial and residential loads were considered separately. Figure 2 compares peak-day load cycles for two commercial loads, a school and a health-care facility, with a four-customer residential load.

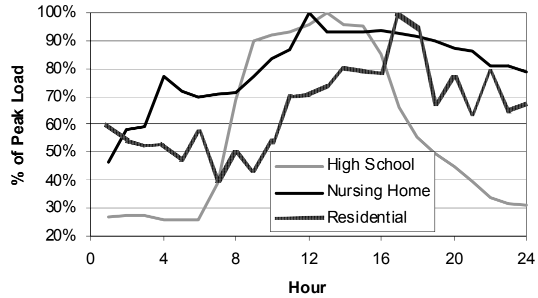

Figure 2 – Peak day load profiles.

Commercial and Institutional Loads

Hourly integrated demand measurements were made on a total of twelve loads in six categories and four locations with reasonably diverse climates in the southeastern U.S. (Atlanta, Rome, and Savannah, Georgia, and Panama City, Florida). Table 1 lists the loads along with their respective peak demands and annual load factors. Each of these load histories, along with concurrent hourly ambient temperatures for each location, were applied to a thermal model. The model yielded hour-by-hour transformer internal temperatures and the cumulative transformer insulation aging. Figure 3 shows the dynamic response of transformer temperatures to loading and ambient temperature for the Savannah high school load for the peak load day, as well as the resulting aging acceleration factor.

Type	Atlanta	Rome	Savannah	Panama City
Nursing Home	484 kW_{pk} 0.59 LF			
Large Office	973 kW_{pk} 0.69 LF	1583 kW_{pk} 0.57 LF	387 kW_{pk} 0.49 LF	
Small Office	17 kW_{pk} 0.32 LF			
High School	513 kW_{pk} 0.26 LF	1343 kW_{pk} 0.27 LF	1509 kW_{pk} 0.33 LF	
Retail	509 kW_{pk} 0.48 LF			
Grocery	485 kW_{pk} 0.69 LF	474 kW_{pk} 0.63 LF		642 kW_{pk} 0.68 LF

Table 1 – Peak demands and load factors of commercial loads in study.

The kVA rating of the transformer was varied until the cumulative aging in the one year modeled was equal to the aging the transformer would sustain if continuously loaded to nameplate rating at a standard (30°C) ambient temperature for the one year (i.e., mean FAA = 1.0). For the purpose of this analysis, transformer kVA ratings were not limited to standard values.

This thermal analysis yielded interesting results. One of the most significant findings is that, for most loads, almost all of the insulation aging occurs during a relatively few days of the year. Figure 4 plots the aging hours per day over one year, along with the ambient temperature and loading, for the Atlanta nursing home load. (Normal aging is equal to 24 aging hours per day.) For this same load, Figure 5 shows histograms of cumulative transformer aging plotted versus days, ranked by decreasing average ambient temperature, for two different loads. For the summer-peaking nursing home load, over half of the aging sustained by the transformer occurs in the thirty hottest days of the year. In the cooler half of the year, almost no thermal aging takes place. The other aging histogram plotted in Figure 5 is for the large office building load. This load is less ambient-temperature-dependent, and transformer aging is somewhat more evenly distributed through the year.

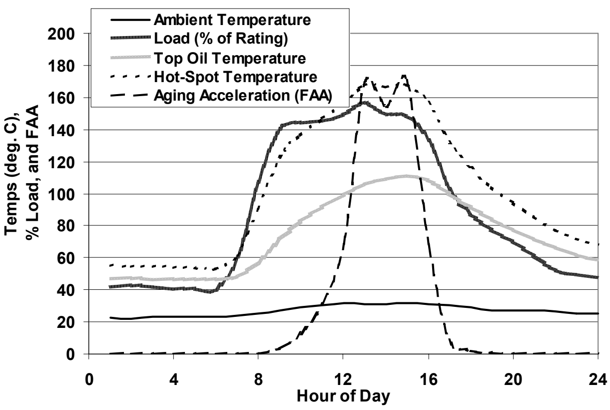

Figure 3 – Loading, thermal behavior, and resulting aging for peak day, Savannah high school load..

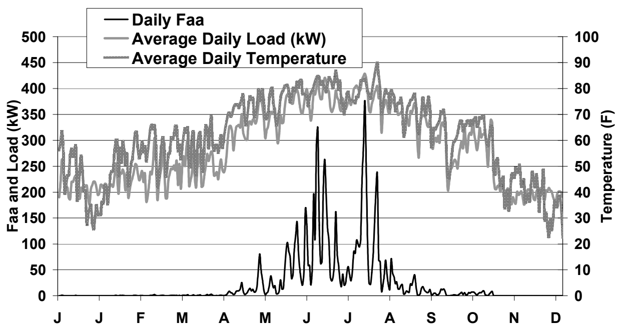

Figure 4 – Daily aging hours for Atlanta nursing home load

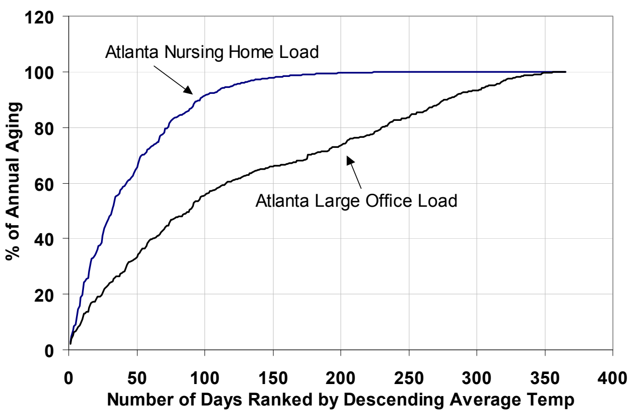

Figure 5 – Comparison of transformer aging histograms

The ratio of peak load to transformer nameplate kVA yielding normal insulation aging (8760 aging hours per year), was found to vary with the load profile. If summer and winter peaking loads are separated, it was found that the allowable peak transformer overload is well correlated with the load factor. This is clearly shown in Figure 6. A key conclusion reached in this research is that a fixed maximum transformer overload factor does not yield best management of transformer assets; sizing must also consider the characteristics of the load profile including the shape of the load profile and correlation between peak load and ambient temperature.

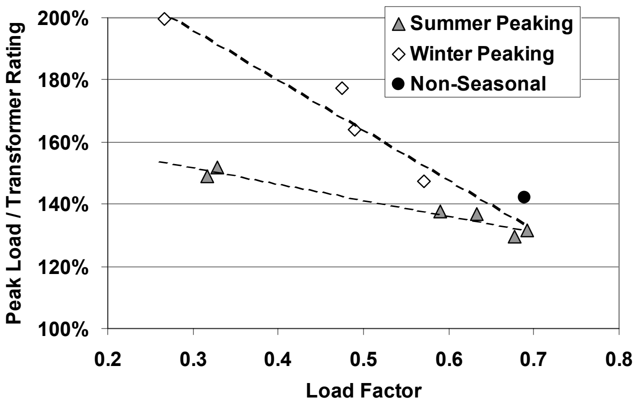

Figure 6 – Relationship of peak transformer overload factor, yielding nominal insulation life, to load factor for commercial loads.

Residential Loads

Hourly load and ambient temperature recordings for twenty individual residences, ten with electric heat and ten without. The load factors of the individual all-electric loads ranged from 0.09 to 0.26, with an average of 0.185. For the non-all-electric loads, the load factors ranged from 0.13 to 0.31, with an average of 0.20. These load factors are substantially less than those of the commercial loads studied in this project.

Although these residential loads are not physically adjacent, they were combined in this research to investigate the impacts of load coincidence on transformer insulation aging. A number of different groupings of two, four, six, and eight services were studied as if each grouping was served by one distribution transformer. Each grouping was applied to a transformer thermal model having typical residential distribution transformer parameters. Figure 7 shows insulation aging histograms for typical non-all-electric and all-electric groupings of four load services. It can be seen that a transformer serving the composite load without electric heat sustains over half of its annual aging in only about the fifteen hottest days of the year. A transformer serving the composite load with electric heat sustains aging in both the summer and winter. For the example shown, about 20% of the annual aging occurs spread over about two months, but about 60% of the aging occurs in the coldest few days of the winter. It should be noted that heat pumps with electric resistance heat backup for very cold periods are common in the area where these load data were acquired.

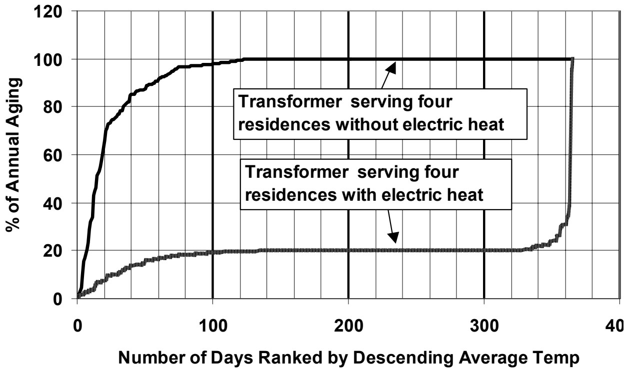

Figure 7 –Aging histograms transformers serving typical four-residence loads, with and without electric space heating

A very significant difference between commercial and residential loads was observed in the transformer thermal analysis. When the residential transformer kVA rating was selected so that the overall insulation aging was normal (8760 aging hours per year), the peak winding hot-spot temperature exceeded 200°C for many of the load groupings. Because residential load factors are so low, transformer rating on an accumulated aging basis tends to lead to very high short-term overloads. This risk of failure from gas evolution during these short-time high-temperature events becomes the dominant factor in transformer size selection. In contrast, the critical 200°C threshold was not approached when transformer ratings for commercial loads were based on accumulated aging.

The residential transformer ratings in the study were based on the larger of the sizes in order to meet the criteria of nominal average aging, and peak transformer temperatures were limited to the values recommended by [1]. For the loads without electric heat, peak overload factors of 200% for transformers serving one customer were deemed acceptable, decreasing to 160% overload for transformers serving eight customers. For the loads with electric heat, acceptable peak overloads were on the order of 230% for transformers serving one customer, and 200% of rating for transformers serving eight customer loads.

Residential transformer rating selection, however, is not as simple as applying a fixed overload limit because maximum hot-spot temperature is a function of the shape of the load curve, as well as the ambient temperature, on the peak day. The peak coincidence factor of a multi-customer load grouping is the ratio of the peak coincident load divided by the sum of the peak loads of the individual customers. Similarly, a transformer thermal coincidence factor can also be defined as the rating of the transformer needed to serve the composite load, divided by the sum of the transformer ratings needed to serve the customers individually. Figure 8 plots the peak and transformer thermal coincidence factors for different numbers of loads served by a common distribution transformer. For both the all-electric and non-all-electric loads, the thermal coincidence factor is substantially greater than the peak coincidence factor. Utilities typically use coincidence factors based on peak loads for various design calculations, including distribution transformer application. The results of this research imply that the benefits of load diversity, from the standpoint of distribution transformer application, are not as great as is commonly assumed.

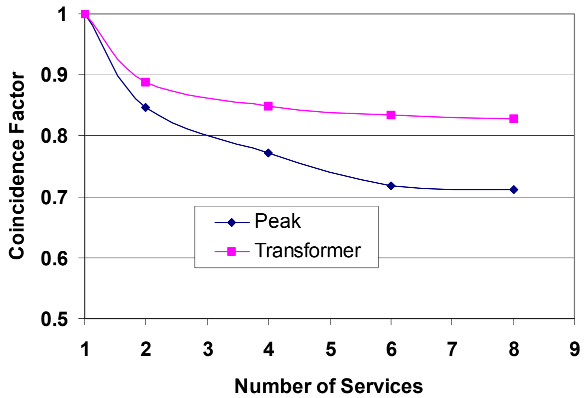

Figure 8 – Comparison of peak and transformer thermal coincidence factors for residential loads without electric space heat.

CONCLUSIONS

The research described in this paper has shown that distribution transformers can be applied to loads substantially exceeding the transformers' nameplate rating. While the optimized rating of distribution transformers serving commercial loads tends to be constrained by accumulated insulation aging, residential transformers are more likely to be constrained by peak temperature considerations during very-high short-term loads. Best management of commercial and residential transformer assets, however, cannot be achieved using fixed maximum transformer overload factors. Optimal sizing must also consider the characteristics of the application including the shape of the load profile, recurrence of peak periods, and correlation between peak load and ambient temperature.

ACKNOWLEDGMENTS

The support of the DSTAR (Distribution Systems Testing, Application, and Research) consortium of utilities, and the direct participation of Gulf Power Company and Missippi Power Company, operating companies of the Southern Company, are gratefully acknowledged.

REFERENCE

[1] IEEE® Standard C57.91-1995, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*, Institution of Electrical and Electronic Engineers, Piscataway, NJ, USA.