Q. Re: Upgrade Power Transformers Volume II (Tab 17)

Please provide copy of the Hardford's Team Boiler Institute Report which outlines the average life of utility transformer, referred to on page 15.

A. Please see the attached report.

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Keeping the Lights On: An Action Plan for America's Aging Utility Transformers

By William H. Bartley, P.E., The Hartford Steam Boiler Inspection and Insurance Company

Introduction

The United States is demanding more electrical power. At the same time, the age of transformers in the electric utility industry continues to rise. From a peak of new installations in the United States in the mid-1970s, today's capital spending on new and replacement transformers is at its lowest level in decades. To make matters worse, the load on each transformer (or its utilization) continues to grow. Power consumption is increasing at a rate of about 2 percent per year.

The failure rate of transformers in the United States is expected to rise sharply in the coming years as units installed in the 1950s and 1960s reach the end of their useful lives. Utilities may have to make significant changes in the way they operate and care for their transformers. Otherwise, power producers could be hard-pressed to meet future demand for electricity and maintain system reliability.

Transformer Breakdowns

Hartford Steam Boiler has been insuring power equipment since it was founded in 1866. Over several decades, we have conducted a series of studies of transformer claims. The latest results were published in **The Locomotive** ("An Analysis of Transformer Failures, Part 1 and 2," Spring and Summer 1999). The analysis examined types of breakdowns, frequency, severity, causes, and recommended ways to achieve maximum service life. One trend stood out and warrants special attention — the issue of transformer age.

The study concluded that America's aging transformer fleet poses a serious challenge to power producers, insurers, industry, public institutions and the entire U.S. economy. Year after year, "transformers" as an object class have consistently ranked in the top five objects for claims paid by HSB. We have investigated thousands of transformer failures, some covered claims and some not, and many occurring in power generation facilities. In 1993, for instance, HSB had 25 failures with claims of over $100,000 each — most occurring in the electric utility industry.

When They Fail

Most transformer engineers believe that a transformer can be expected to last 30 to 40 years under "ideal conditions." But in HSB's study, the data showed the average age at failure was 14.9 years for all

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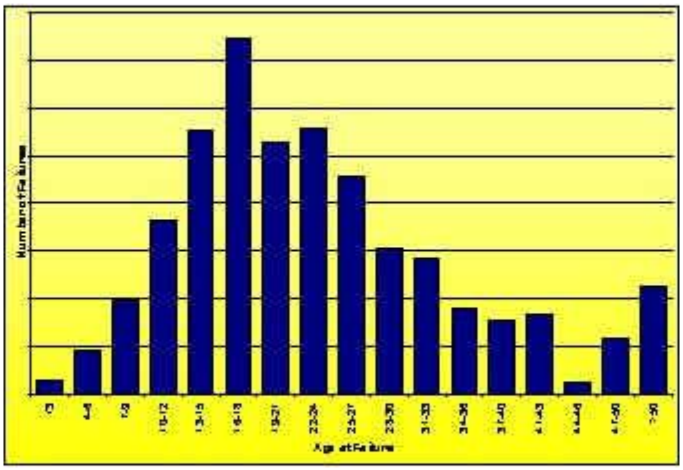
occupancies (commercial buildings, primary metals, health care, manufacturing, etc.). The mean age at failure for utility transformers was 17.7 years.

Figure #1 below is a histogram of the utility failures. The graph is not a "bathtub curve" because it only illustrates the transformers that failed. It does not reflect the age distribution of the population.



Future Failure Predictions

Most utility engineers know that aging of the insulation system reduces both the mechanical and dielectric withstand strength of the transformer. As the transformer ages, it is subjected to faults that result in high radial and compressive forces. As the load increases, with system growth, the operating stresses increase. In an aging transformer failure, typically the conductor insulation is weakened to the point where it can no longer sustain mechanical stresses of a fault. Turn-to-turn insulation then causes a dielectric failure, or a fault causes a loosening of winding clamping pressure, which reduces the transformer's ability to withstand future short circuit forces.

Although we have not yet seen an alarming increase in end of life failures, such a rise must be expected eventually. The most difficult task for the utility engineer is to predict the future reliability of the transformer fleet, and to replace each one the day before it fails. There have been a number of excellent papers presented in recent years [1] on the assessment of transformer life and the techniques employed by utility engineers to establish transformer condition and decide on remedial action.

The forecast presented in this article is simply a statistical model and does not take into consideration individual design differences or loading history. Admittedly, the correlation between calendar age and insulation deterioration is subject to some uncertainty. Our statistical model, based only on the calendar age and the population explosion, illustrates the magnitude of the problem facing the utility engineer.

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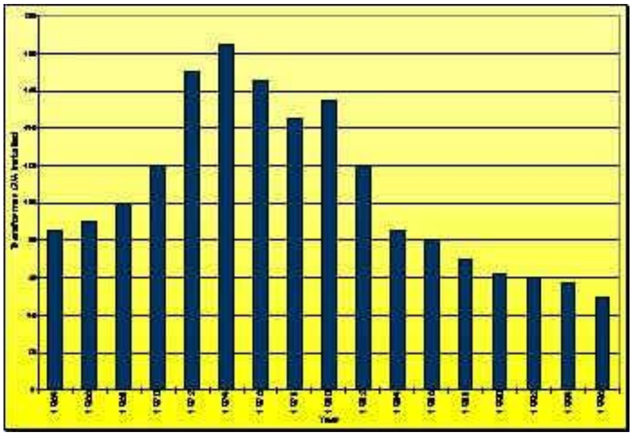
Figure #2 below, from a paper by M.A. Franchek and D.J. Woodcock,[2] depicts the total transformer capacity additions in the United States each year.



Exponential Model

For time-aging reliability models, the instantaneous failure rate can be represented by the exponential equation[3] that follows:

f(t) = a eb t

The instantaneous failure rate is defined as the probability of failure per unit time for the population that has survived up until time t. In a previous paper,[4] we modeled the risk of future transformer failures, using the expression, f(t) = 0.005 e 0.1002 t . We now believe that a more accurate model for future transformer failures must treat the frequency of random events separate from aging. From our claims database, we know that the frequency of random external events (lightning, collisions, vandalism) is approximately 0.005 (or 0.5 percent). Therefore, the risk of future transformer failures (due to aging and external events) can be expressed as:

f(t) = 0.005 + a eb t

To solve the variables, we know that when the transformer is new, "t" is near zero, e bt is nearly 1.0 and most failures are due to external events (f(t) = 0.005). Therefore, the constant "a" is very small; and we have set it at 0.0001. To complete our model, we have to make an assumption for "end of life". This assumption is fairly subjective, but we used the projection that by the age of 50 years, 75 percent of all power transformers will fail. We can thus solve for "b" for this scenario, which is 0.1780.

Thus, our model for future transformer failures can be expressed as:

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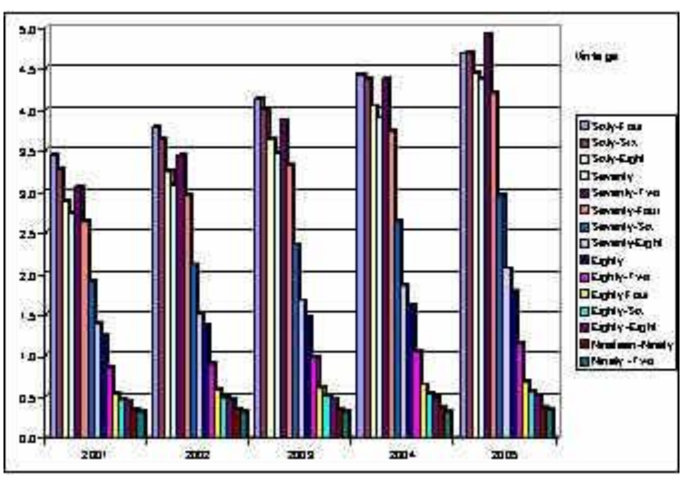
f(t) = 0.005 +.0001e 0.1780 t [75 percent rate]

With a probability model and population estimate for each vintage, we can then model the future failure rate for several different vintages of transformers, by multiplying the failure rate times the population of the vintage:

Number of failures, at year "t" (in GVA) **= [Failure rate]** x [**population** that is still surviving]

Using the population profile from Figure #2, we have plotted the predicted failure rate for all U.S. utility transformers built between 1964 and 1992 (Figure #3, above). The X-axis is the year of predicted failures. The Y-axis is the population of the failures (expressed in GVA). In Figure #3, a vertical line depicts each vintage. By 1975, each year has a cluster of six different vintages and after 1992 each cluster is 15 vintages. In our next chart (Figure #4 below), we take a closer look at predicted failures in the next five years (2001 to 2005).



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According to our model, the number of failures for 1964 vintage transformers continues to rise, reaching a peak in 2006. Due to the population increase, the failure rate of the 1972 vintage transformers will overtake the failures of the 1964 vintage in 2005; and the failure rate of the 1974 vintage will equal the failures of the 1964 vintage in 2006.

Our last chart (Figure #5 below) is the cumulative predicted failures for each year. If the model proves to be true, the utility transformer failure rate will increase five-fold in the next 15 years.

Action Plan

Meeting the growing demand of the grid and at the same time preserving system reliability may require significant changes in the way the utility operates and maintains its transformers. One conservative strategy suggests that the industry start a massive capital replacement program that duplicates the construction profile of the 1960s and 1970s. But this would cause many transformers to be replaced needlessly and cost the utility industry billions of dollars.

Another strategy suggests that we leave all the transformers in service until they fail, and let the insurance companies pay for it. But your insurance program may have high deductibles, and probably does not cover all the costs. And the cost of an unexpected failure can be several times the cost of the original transformer installation, when you consider system outages, lost power sales and possible environmental clean up costs. The time required to rewind or rebuild a large power transformer can take 6 to 12 months, or more!

Life Management Program

The ideal strategy is a life assessment or life management program, that sets loading priorities, and provides direction to identify: a) transformer defects that can be corrected; b) transformers that can be modified or refurbished; c) transformers that should be relocated; and d) transformers that should be retired.

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Such a program usually begins with an engineering review, and then a condition assessment. Some of the assessment tools include Dissolved Gas Analysis (see "Transformer Oil Testing: An Early Warning System That Works, **The Locomotive**, Summer 1998), Insulation Power Factor, Degree of Polymerization, Furanic Analysis, and Frequency Response Analysis.

A number of utilities have already adopted a loading (overloading) program, based on the Institute of Electrical and Electronics Engineers (IEEE) Guide C57.91 and includes limits based on top oil temperature, hottest spot temperature, calculated daily loss of life and the limitations of ancillary equipment.

Relocating transformers should not be overlooked in a life cycle program. Transformers may be relocated for several reasons: a) better voltage regulation; b) loading/overloading limitations; and c) customers that require a more reliable power source.

Modification or refurbishment of a transformer may involve re-tightening and blocking of loose windings, the addition of fans or radiators, or a complete rewind. However, in the decision to rewind versus replace old transformers, it is important to include the costs of transformer losses. The cost of core and copper losses for a 1950s transformer may be twice that of a new transformer. In several recent cases, our insureds have decided to replace the transformer because the reduction in core losses could economically justify it.

Summary

Transformers installed in the 1950s and 1960s are approaching their end of life. Managing these assets will require considerable effort by the utility engineer in the coming years. An optimum strategy includes:

- A condition assessment of the entire transformer fleet
- The development of a dynamic loading/overloading policy
- A life cycle management program that sets priorities to repair, relocate, refurbish or replace the transformer.

Footnotes

[1] M. Perkins, L. Pettersson, N.L. Fantana, T.V. Oommen, S.Jordan, "Transformer Life Assessment Tools with Special Application to Nuclear Power Station Generator Transformers," IEEE Transformer Committee Meeting, November 1999, Monterrey, Mexico

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[2] M.A. Franchek and D.J. Woodcock, "Life Cycle Considerations of Loading Transformers Above Nameplate Rating," Proceedings of the Sixty-Fifth Annual International Conference of Doble Clients, 1998, Sec 8-10.1

[3] P.A.Tobias & D. Tindale, "Applied Reliability," Van Norstrand Reinhold Co., New York, NY, 1986

[4] W.H. Bartley, "Analysis of Transformer Failures," Proceedings of the Sixty-Ninth Annual International Conference of Doble Clients, April 2000

About the Author

William Bartley, P.E., received a Bachelor of Science degree in electrical engineering from the University of Missouri at Rolla. Bill joined Hartford Steam Boiler as an electrical inspector in 1971 and is now a Principal Engineer in HSB's Engineering Department, specializing in the assessment and analysis of large electrical apparatus, primarily generators and transformers. He is responsible for developing standards, OEM relations, fleet problems, large failure investigations, repair procedure development, and new testing technologies.

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