The Locomotive

An International Analysis of Transformer Failures, Part 2

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[Editor's Note: In the last issue, Part 1 of this article examined five-year loss trends of transformer break-downs as reported by international equipment break-down insurers. In Part 2, the author discusses the aging of the worldwide transformer fleet and shares a global perspective as seen by those in the transformer industry.]

Introduction

In our previous discussion of a five-year international study of loss trends for transformer failures, we concluded that Insulation Failure was the leading cause. Combined with Design/Material/Workmanship and Unknown causes, these three categories accounted for 65 percent of the total number of transformer breakdowns in our study of losses as reported by members of the International Association of Engineering Insurers (IMIA) (imia.com) and 85 percent of the total amount paid out for these claims.

Other causes of loss were spread among: Oil Contamination; Overloading; Fire/Explosion; Line/Surge; Improper Maintenance/Operation; Flood; Loose Connection; Lightning and Moisture (see An International Analysis of Transformer Failures, Part 1, *The Locomotive*, Winter 2004, Vol. 78, No. 1).

Transformer Aging

We did not categorize "age" as a cause of failure. 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 suffers 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.

Table 1 displays the distribution of transformer failures by age. The average age at failure among those transformers in our study was 18 years.

Table 1 – Distribution of Losses by Age of Transformer

Age of Failure	Number of Failures	Cost of Failure
0 to 5 years	9	$ 11,246,360
6 to 10…	6	$ 22,465,881
11 to 15…	9	$ 3,179,291
16 to 20…	9	$ 10,518,283
21 to 25…	10	$ 16,441,930
Over 25 Years	16	$ 15,042,761
Age Unknown *	35	$ 207,734,306

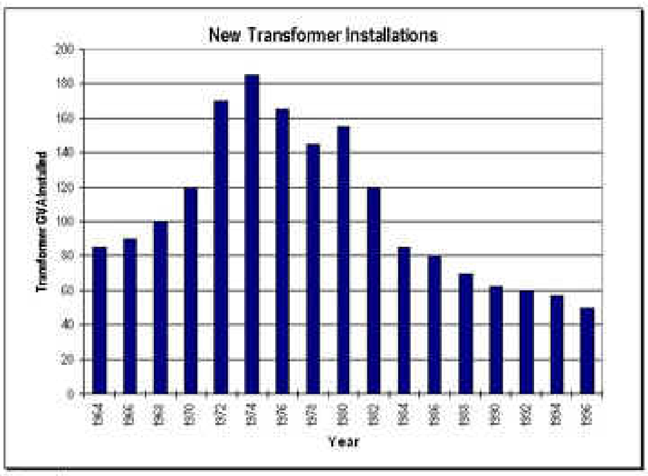

Figure 1

According to U.S. Commerce Department data, the electric utility industry reached a peak in new installations in the United States around 1973-74. In those two years, the country added about 185 GVA of power transformers. Figure 1 depicts the total transformer additions in the U.S. each year. Today, these transformers are about 30 years old. With today's capital spending on new or replacement transformers at its lowest level in decades (less than 50GVA /yr), the average age of the entire world transformer fleet continues to rise.

A risk model of future transformer failures, based on aging, was developed by Hartford Steam Boiler and first published in 2000[1] **(The formula appears in "An Analysis of Transformer Failures, Part 1, *The Locomotive*, Vol. 73, No. 2).** The model is based on mortality models that were first proposed in the 19th century.

The most influential parametric mortality model in published actuarial literature is that proposed in 1825 by Benjamin Gompertz, who recognized that an exponential pattern in age captured the behavior of human mortality. He proposed the failure function:

$$f_{(t)} = \alpha e^{\beta t}$$

where f(t) is the instantaneous failure rate, a is a constant; ß^{t} is a time constant; and t = time (in years).

In this article, the author will discuss an updated model for transformer failure predictions in the coming decade and shares the observations of industry executives about the condition of the transformer marketplace.

A New Failure Model

HSB's first publication on transformer failure predictions used the Gompertz model. In 1860, W.M. Makeham modified the Gompertz equation because it failed to capture the behavior of mortality due to accidental death, by adding a constant term in order to correct for this deficiency. The constant can be thought of as representing the risk of failure by causes that are independent of age (or random events such as lightning, or vandalism).

$$\text{Makeham's formula: } f_{(t)} = A + \alpha e^{\beta t}$$

Subsequent studies by HSB[2, 3] have adopted the Makeham formula. The Gompertz curve was further modified by W. Perks, R.E. Beard and others. In 1932, Perks proposed modifications to the Gompertz formula to allow the curve to more closely approximate the slower rate of increase in mortality at older ages.

$$\text{Perks' formula: } f_{(t)} = \frac{A + \alpha e^{\beta t}}{1 + \mu e^{\beta t}}$$

A more accurate model for transformer failures can be represented by the Perks formula and was included — for the first time — in connection with this study based on the IMIA survey of international transformer failures.

The instantaneous failure rate for transformers in a given year is the probability of failure per unit time for the population of transformers that has survived up until time "t." To include the frequency of random events (lightning, collisions, vandalism) **separate** from the aging component, the constant "A" is set at 0.005 (which represents one-half percent of 1 percent). Figure 2 is the corresponding exponential curve for a 50 percent failure rate at the age of 50.

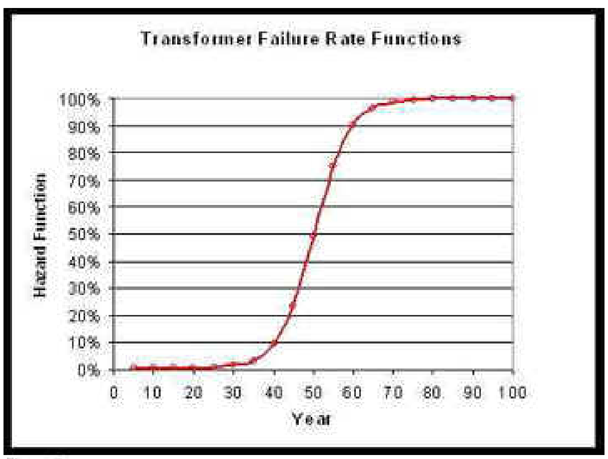

Figure 2

The correlation between calendar age and insulation deterioration is subject to some uncertainty — not all transformers were created equal. This prediction is a simple statistical model and does not take into consideration manufacturing differences or loading history. This failure rate model is based on the calendar age of the transformer, and does not address material and design defects such as "infant mortality."

With a failure rate model and population estimate for each vintage, future failures can be predicted for the entire fleet of transformers, by multiplying the failure rate times the population of the vintage:

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

Future Transformer Failures

Using the population profile from Figure 1, the predicted failures can be plotted for all U.S. utility transformers built between 1964 and 1992. The prediction is simply intended to illustrate the magnitude of the problem facing the utility industry and the insurance industry. Figure 3 is the failure distribution. The X-axis is the year of predicted failures. The Y-axis is the population of the failures (expressed in GVA). It should be noted that the graph is a failure rate of those that survived, until time ("t"). In this graph, a vertical line depicts each vintage. By 1975, each year has a cluster of six different vintages (1964, '66, '68, '70, '72 and '74); and after 1992, each cluster is 15 vintages.

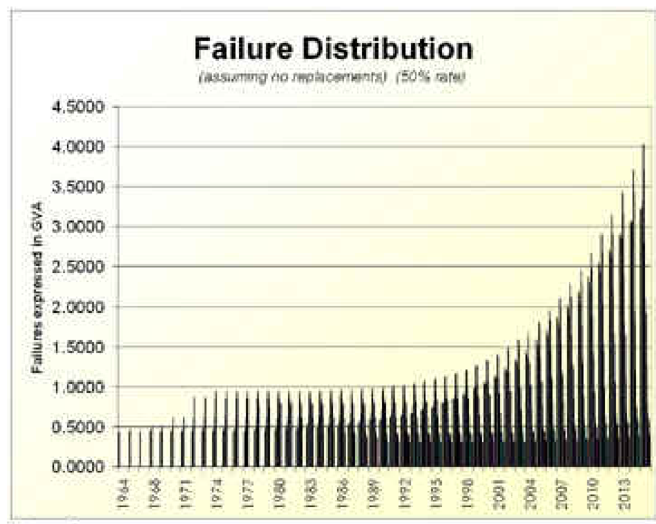

Figure 3

In our next chart (Figure 4), we take a closer look at predicted failures over six years (2003-2008). Due to the increased installations, the failures of 1972 vintage transformers will overtake the failures of the 1964 vintage in the year 2006. By 2008, the number of 1974 vintage transformers will easily exceed the failures of the 1964-vintage transformers. This prediction ignores rebuilds and rewinds of previous failures.

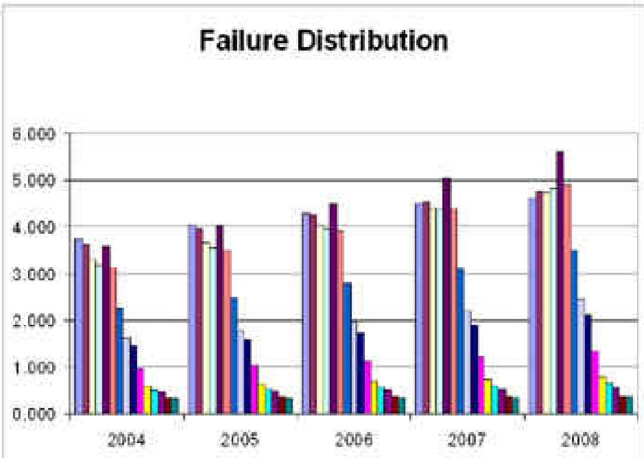

Figure 4

In order to examine the total predicted transformer failures in any given year, we can take the sum of the individual vintages, for each year. Figure 5 illustrates such a prediction.

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. Meeting the growing demand of the grid and at the same time maintaining system reliability with this aging fleet will require significant changes in the way the utility operates and cares for its transformers.

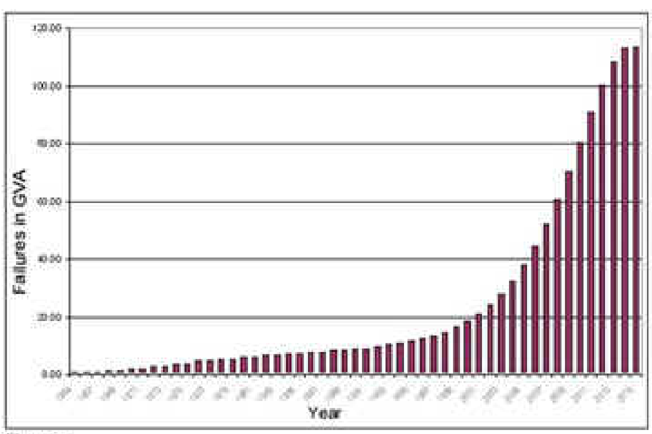

Figure 5

Action Plan

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 needlessly replace many transformers and cost the utility industry billions of U.S. dollars.

The ideal strategy is a life assessment, or life cycle 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; d.) transformers that should be retired. The insurance industry should be aware that both the Institute of Electrical and Electronics Engineers, Inc. (IEEE), and the International Council on Large Electrical Systems (CIGRE) are developing guidelines for aging transformers. [5, 6]

Electric Utilities and the Transformer Industry

The deregulation of wholesale electricity supply around the world has led to a number of changes and new challenges for the electric utility industry and its suppliers. In the last few years, many electric utilities have merged to form larger international utilities, and others have sold off their generating assets. All of this is being done in an attempt to enhance revenue streams, reduce the incremental cost per MW or react to spot market opportunities.

Years ago, utilities knew the needs of their native markets and built an infrastructure to keep pace with those needs, with associated construction costs being passed back to the ratepayers. Starting in the 1980s, utilities in the United States had to contend with regulatory mandates to utilize independent power producers to satisfy supply and meet demand. They were not able to plan projects for their native load projections. In this environment, it was possible that the utility's capital projects may not be afforded a favorable rate structure from the local utility com-mission in an openly competitive market. Therefore, many utilities understandably halted most of their capital spending, due to this regulatory uncertainty.

This significantly limited the activity taking place in terms of expanding the industry's infrastructure, including their transmission and distribution assets. In the 1990s, capital spending on new and replacement transformers was at its lowest level in decades. Many of the major manufacturers exited the power trans-former business. Many of the remaining manufacturers have undertaken cost-cutting measures to survive.

"The Boom is Over …"

Then in 1999-2000, the transformer market experienced a brief upswing in activity primarily due to a rush to build gas-turbine generating plants. The demand for generator step-up transformers in the United States almost doubled during these peak months. At that time, there were predictions that 750 Gigawatts of new generating capacity would be installed worldwide between 2000 and 2010.

But, the rush to build power plants in the United States has subsided; many of the energy companies are now drowning in debt. Many developers and investors had to sell their interests in existing plants in order to finance the completion of new plants. In 2001, projects worth 91 GW of generating capacity in the United States were cancelled (out of 500 GW). And in the first quarter of 2002, orders for 57 GW of capacity were cancelled.

Again, capital spending in the utility industry sharply declined. According to Dennis Boman, director of marketing, ABB Inc. Power Transformers, "the decline has far exceeded anyone's prediction to levels that post-dated the increase. Within a short six-month period, the power transformer market dropped by over 50 percent," he said. Added Joe Durante, vice president, VA Tech Elin Transformers, "...the boom of the late 1990s and early 2000 is over, and most likely won't be seen for another 30 years. Replacement opportunities will continue to remain flat and customer spending will continue only when necessary."

Based on Hartford Steam Boiler claim experience, new transformer prices are significantly lower than they were a few years ago. It is truly a buyer's market. New power transformers are being sold at a price less than the cost of a rewind, and the manufacturers are now providing three-year and five-year warranties.

Peter Fuchs, vice president sales and marketing, Geschaftsgebiet Transformers (Siemens), predicts "a stagnant market, on average, for the United States , Europe and the Far East ." However, "in other parts of the world, economic growth and business development are proceeding at high levels, including a resurgence in Asia ," he continued. "The need for power in this area already exists, and as international funding becomes available, we expect to see increased activity in this region."

Transmission Growth Opportunities?

Today, many of the transformer manufacturing plants and repair facilities have very little activity. Is this "slump" in the market due solely to government regulation —or deregulation? The three major manufacturers point to a number of different problems. According to Bowman of ABB, "We have seen a shift in focus to 'first cost' buying with little regard for any long term impact on buy decisions." Many buyers are choosing the lowest bidder, with little regard to quality, reliability or factory service. Fuchs of Siemens observes that "in addition to the price-driven decision, there is very little technical evaluation, and 'price-dumping' continues to go unpunished." Durante of VA Tech Elin confirms that the major obstacle is "ongoing deregulation uncertainty which is hindering capital investment."

Durante believes that the next growth opportunity in the North American utility market is the transmission segment. This includes inter-tie transformers, phase-shifter transformers and autotransformers. "However, this market is heavily influenced by government regulations and decisions," he added.

The U.S. Federal Energy Regulatory Commission (FERC) has mandated that all generators have equal access to transmission systems and required integrated utilities to turn over their transmission systems to independent entities. Some utilities have decided to sell their transmission assets and purchase transmission service. Other utilities are joining together and rolling their transmission assets into limited liability companies. But many utilities first want to understand exactly how transmission will be regulated. In other words, utility investors want to know whether the U.S. federal government or state governments will regulate the transmission assets. Until this is clear, overall capital spending will be deferred.

Summary

Electricity is much more than just another commodity. It is the life-blood of the economy and our quality of life. Failure to meet the expectations of society for universally available low-cost power is simply not an option. As the world moves into the digital age, our dependency on power quality will grow accordingly. The infrastructure of our power delivery system and the strategies and policies of our insureds must keep pace with escalating demand. Unfortunately, with regulators driving toward retail competition, the utility business priority is competitiveness and related cost-cutting — and not reliability.

References

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(5) IEEE C57.140, Draft 9 March, 2003 , IEEE Guide for the Evaluation and Reconditioning of Liquid Immersed Power Transformers, Rowland James & William Bartley Co- Chair.

(6) CIGRE 12-20 Guide on Economics of Transformer Management (draft 23.7.02).

About the Author

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