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Analysis of Transformer Failures

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SUMMARY

This paper will address the transformer failure statistics over the last 5 years, the aging of our worldwide transformer fleet, and a global perspective of the transformer industry.

INTRODUCTION

Major losses involving large oil-cooled transformers continue to occur on a frequent basis. An IMIA Working Group was established in 1995 to examine this topic and presented a report at the 1996 Conference. The magnitude of the losses has increased significantly since the last study. Increased equipment utilization, deferred capital expenditures and reduced maintenance expenses are all part of today's strategies for transformer owners. To make matters worse, world power consumption is increasing, and the load on each aging transformer continues to grow.

SCOPE OF STUDY

A request was sent to all national delegations seeking information on losses of transformers rated at 25MVA and above, for the period 1997 through 2001. Information was requested concerning Year of loss, Size in MVA, Age at failure, Application (utilities, industrials etc.) Cause of failure, Property Damage portion, and Business Interruption portion. Data was obtained on 94 cases. An estimate of the total population of power transformers would have been useful, but it is impractical to obtain this information. Some of the contributors were not able to identify the age of the transformers, and in some cases, the size of the transformer. Thus, the analysis is annotated wherever data is missing. All amounts of losses were converted to U.S. dollars, using the following exchange rates: 0.9278 Euros; 8.542 Swedish kronas; and 6.0858 French francs.

FIVE YEAR TREND

During this period, the number of transformer claims reached a peak (25) in 1998. But, the dollars-paid out, reached a maximum in 2000 due to several claims in the multi-million dollar range, plus one large Business Interruption loss. The largest transformer loss also occurred in 2000, at a power plant, with a Business Interruption portion of over $80 million Euros, or $86million US dollars. Three of the top four Property Damage claims were in industrial plants. Table#1 displays the annual transformer claims (We have included Property Damage, Business Interruption and Total Paid). Unfortunately, all of the data contributed did not have size information. Thus, we could only analyze 78 claims for cost per size. The average cost (for Property Damage only) was approximately US$9000 per MVA (or $9 per kVA). Table #1-A displays the annual transformer claims and Cost per MVA.

Table 1 – Number and Amounts of Losses by Year

Table 1	Total # of Losses	Total Loss	Total Property Damage	Total Business Interruption
1997	19	$ 40,779,507	$ 25,036,673	$ 15,742,834
1998	25	$ 24,932,235	$ 24,897,114	$ 35,121
1999	15	$ 37,391,591	$ 36,994,202	$ 397,389
2000	20	$ 150,181,779	$ 56,858,084	$ 93,323,695
2001	15	$ 33,343,700	$ 19,453,016	$ 13,890,684
Grand Total	94	$ 286,628,811	$ 163,239,089	$ 123,389,722

** Total losses in 2000 includes one claim with a business interruption portion of over $86 million US*

Table 1A – Number and Amounts of Losses by MVA and Year

Table 1 A	Total # of Losses	Losses w/data	Total MVA reported	Total PD (with size data)	Cost /MVA
1997	19	9	2567	$20,456,741	$7969
1998	25	25	5685	$24,897,114	$4379
1999	15	13	2433	$36,415,806	$14967
2000	20	19	4386	$56,354,689	$12849
2001	15	12	2128	$16,487,058	$7748
Total	94	78	17,199	$15,4611,408	

During this five year period, the average cost is $8,990 per MVA, or about $9 per kVA.

TYPE OF APPLICATION

During this period, the largest number of transformer claims (38) occurred in the Utility Substation sector, but the highest paid category was Generator Step Up transformers, with a total of over US$200million. If the extraordinary Business Interruption loss is ignored, the generator step up transformer is still significantly higher than any other category. (This is to be expected due to the very large size of these transformers.) Table 2 displays the annual claims, by application.

Table 2 – Losses by Application

Year	Generator Step Up		Industrial		Utility Substations		unknown		Annual Totals	
1997	$ 29,201,329	3	$ 2,239,393	4	$ 5,243,075	11	$ 4,095,710	1	$ 40,779,507	19
1998	$ 15,800,148	8	$ 3,995,229	6	$ 5,136,858	11			$ 24,932,235	25
1999	$ 3,031,433	4	$ 24,922,958	4	$ 6,116,535	6	$ 3,320,665	1	$ 37,391,591	15
2000	$ 123,417,788	10	$ 24,724,182	4	$ 2,039,810	6			$ 150,181,779	20
2001	$ 32,082,501	11			$ 1,261,199	4			$ 33,343,700	15
Totals	$ 203,533,199	36	$ 55,881,762	18	$ 19,797,476	38	$ 7,416,375	2	$ 286,628,811	94

CAUSE OF FAILURE

For the failures reported, the leading cause of transformer failures is "insulation failure". This category includes inadequate or defective installation, insulation deterioration, and short circuits, ... but *not* exterior surges such as lightning and line faults. Table 3 lists the costs and number of failures for each cause of failure. A description of each cause category is found below.

Table –3 Cause of Failures

Cause of Failure	Number	Total Paid
Insulation Failure	24	$ 149,967,277
Design /Material/Workmanship	22	$ 64,696,051
Unknown	15	$ 29,776,245
Oil Contamination	4	$ 11,836,367
Overloading	5	$ 8,568,768
Fire /Explosion	3	$ 8,045,771
Line Surge	4	$ 4,959,691
Improper Maint /Operation	5	$ 3,518,783
Flood	2	$ 2,240,198
Loose Connection	6	$ 2,186,725
Lightning	3	$ 657,935
Moisture	1	$ 175,000
	94	$ 286,628,811

The risk of a transformer failure is actually two-dimensional: the frequency of failure, and the severity of failure. Figure 1 is a scatter plot, or sometimes referred to as an "F-N curve" (frequency –number curve). The number of failures for each cause is on the X-axis, and the dollars paid for each cause is on the Y-axis. The higher risks are in the upper right-hand corner. According to this analysis, the Insulation Failure is the highest risk for all types of transformer failures.

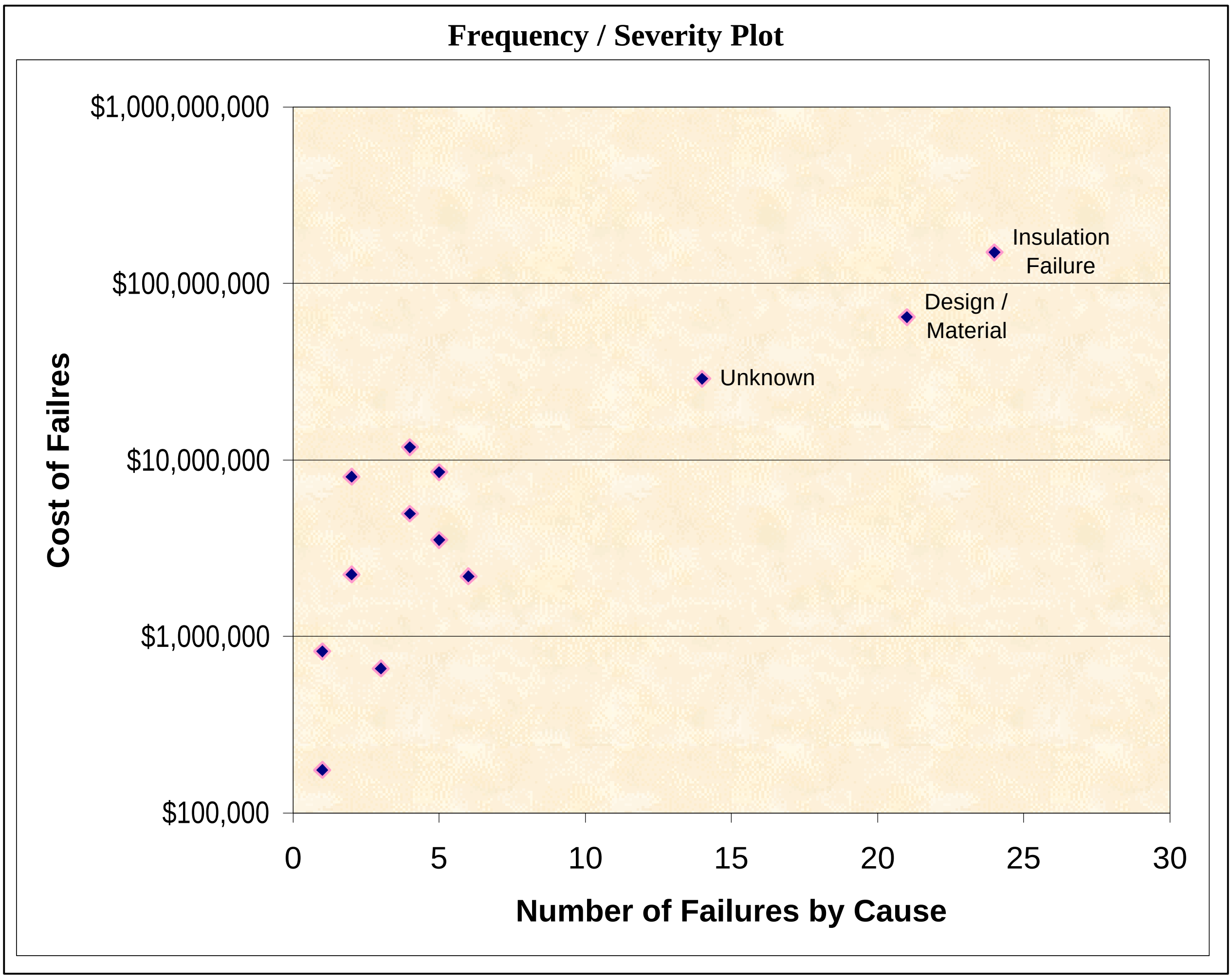


Figure 1 – Frequency - Severity of Transformer Failures

Cause of Failure

Insulation Failures – Insulation failures were the leading cause of failure in this study. This category excludes those failures where there was evidence of a lightning or a line surge. There are actually four factors that are responsible for insulation deterioration: pyrolosis (heat), oxidation, acidity, and moisture. But moisture is reported separately. The average age of the transformers that failed due to insulation was 18 years

Design /Manufacturing Errors - This category includes conditions such as: loose or unsupported leads, loose blocking, poor brazing, inadequate core insulation, inferior short circuit strength, and foreign objects left in the tank. In this study, this is the second leading cause of transformer failures.

Oil Contamination – This category pertains to those cases where oil contamination can be established as the cause of the failure. This includes sludging and carbon tracking.

Overloading - This category pertains to those cases where actual overloading could be established as the cause of the failure. It includes only those transformers that experienced a sustained load that exceeded the nameplate capacity.

Fire /Explosion - This category pertains to those cases where a fire or explosion outside the transformer can be established as the cause of the failure. This does not include internal failures that resulted in a fire or explosion.

Line Surge - This category includes switching surges, voltage spikes, line faults/flashovers, and other T&D abnormalities. This significant portion of transformer failures suggests that more attention should be given to surge protection, or the adequacy of coil clamping and short circuit strength.

Maintenance /Operation - Inadequate or improper maintenance and operation was a major cause of transformer failures, when you include overloading, loose connections and moisture. This category includes disconnected or improperly set controls, loss of coolant, accumulation of dirt & oil, and corrosion. Inadequate maintenance has to bear the blame for not discovering incipient troubles when there was ample time to correct it.

Flood – The flood category includes failures caused by inundation of the transformer due to man-made or natural caused floods. It also includes mudslides.

Loose Connections - This category includes workmanship and maintenance in making electrical connections. One problem is the improper mating of dissimilar metals, although this has decreased somewhat in recent years. Another problem is improper torquing of bolted connections. Loose connections could be included in the maintenance category, but we customarily report it separately.

Lightning - Lightning surges are considerably fewer in number than previous studies we have published. Unless there is confirmation of a lightning strike, a surge type failure is categorized as "Line Surge".

Moisture - The moisture category includes failures caused by leaky pipes, leaking roofs, water entering the tanks through leaking bushings or fittings, and confirmed presence of moisture in the insulating oil. Moisture could be included in the inadequate maintenance or the insulation failure category above, but we customarily report it separately.

TRANSFORMER AGING

Notice that 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 4 displays the distribution of transformer failures by age. The average age at failure was 18 years.

Table 4 – Distribution of Losses by Age of Transformer

Age at 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

** This line includes the one claim with a business interruption element of $80 million Euros or $86 million US*

The age of transformers deserves special attention, because the world went through significant industrial growth in the post World War II era, causing a large growth in base infrastructure industries, especially the electric utilities. World energy consumption grew from 1 trillion to 11 trillion kwhr in the decades following the war. Most of this equipment is now in the aging part of its life cycle.

According to U.S. Commerce Department data, the electric utility industry reached a peak in new installations in the U.S. around 1973-74. In those two years, the U.S.A. added about 185 GVA of power transformers. Figure #2 depicts the total transformer additions in the U.S.A. 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.

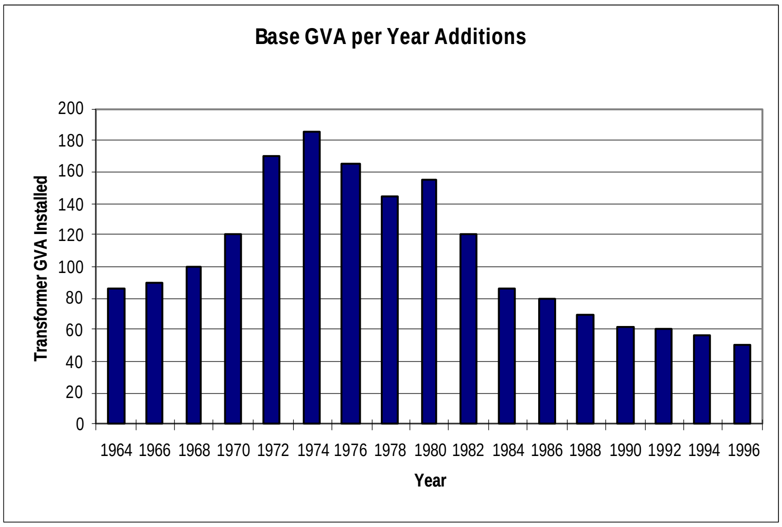


Figure 2

A risk model of future transformer failures, based on aging, was developed by HSB and published in 2000. [1]. 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 by Benjamin Gompertz in1825, 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; b is a time constant; and t = time (in years).

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, vandalism etc.).

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

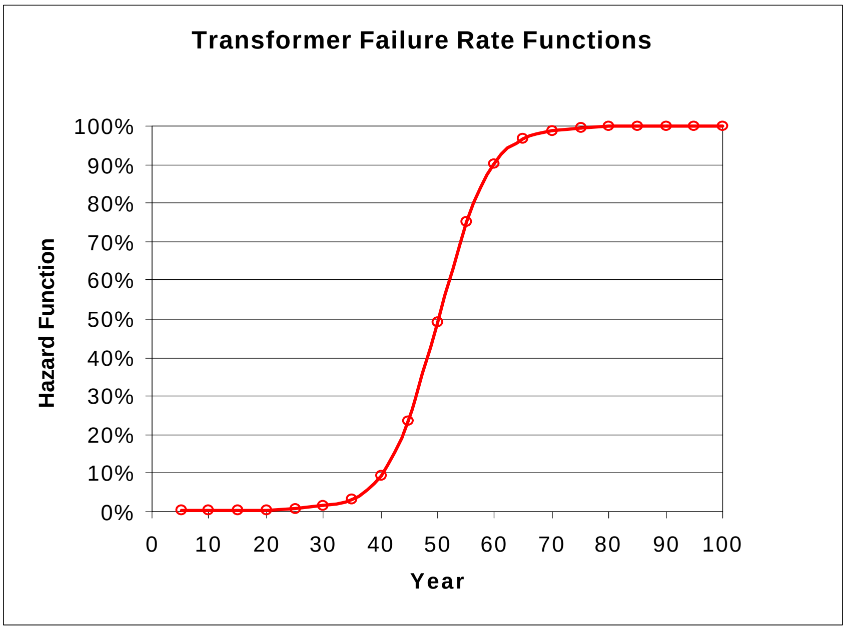
Subsequent publications by HSB [2, 3] have adopted the Makeham formula.

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.

$$\text{Perks' formula:} \quad f_{(t)} = \frac{A + a\, e^{b t}}{1 + m\, e^{b t}}$$

Thus, a more accurate model for transformer failures can be represented by Perk's formula and is included – for the first time -in this paper. 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 (e.g. lightning, collisions, vandalism) *separate* from the aging component, the constant "A" is set at 0.005 (which represents ½ of 1%). Figure 3 is the corresponding exponential curve for a 50% failure rate at the age of 50.

Figure 3 Transformer Failure Rate



Admittedly, 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 only on the calendar age of the transformer, and does not address material and design defects, (i.e. "infant mortality").

With a failure rate model and population estimate for each vintage, future failures can be predicted for the entire 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**]**

Using the population profile from Figure #2, 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 #4 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, ('64, '66, '68, '70, '72, and '74); and after 1992, each cluster is 15 vintages.

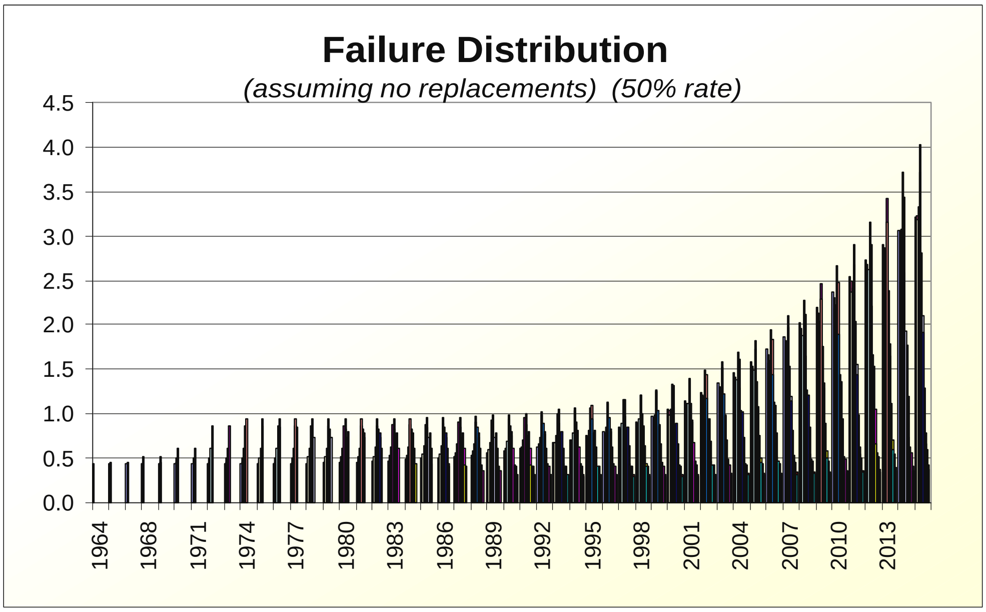


Figure 4 – Failure Distribution of all vintages 1964- 1992

In our next chart, we take a closer look at predicted failures over the next six years (2003 to 2008). Due to the increased installations, the failures of 1972- vintage transformers will overtake the failures of the 1964-vintage in the year 2006; and 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.

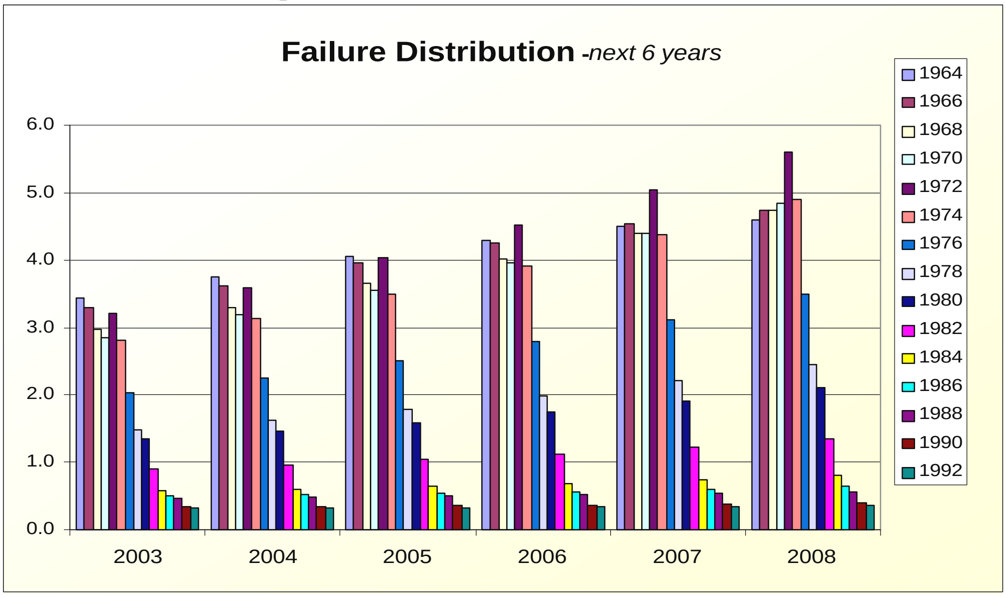


Figure 5 - Failure Distribution –Next 6 Years

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 6 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.

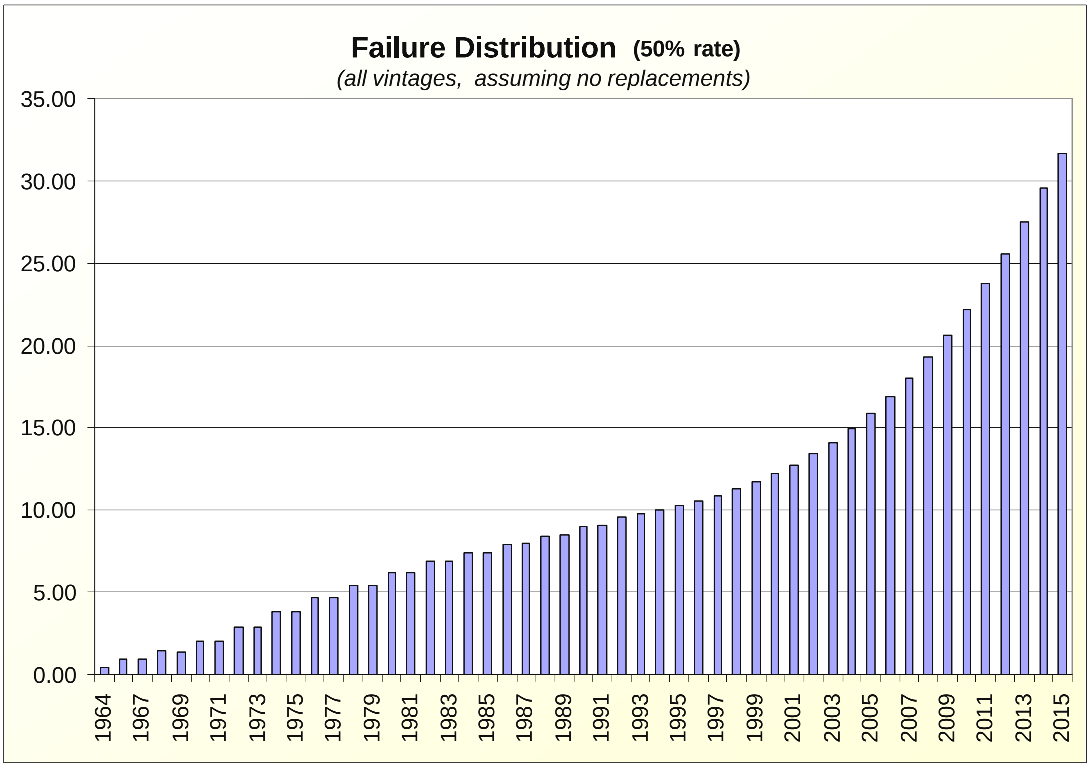


Figure 6 Failure Distribution - all vintages

ACTION PLAN

One conservative strategy suggests that the industry start a massive capital replacement program that duplicates the construction profile of the 60's and 70's. But this would cause many transformers to be replaced needlessly and cost the utility industry billions of US 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 re-located and d) transformers that should be retired. The insurance industry should be aware that both IEEE and 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 1980's, utilities in the US 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 Commission 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 1990's capital spending on new and replacement transformers was at its lowest level in decades. Many of the major manufacturers (General Electric, Westinghouse, Allis Chalmers, McGraw Edison and others) exited the power transformer business. Many of the remaining manufacturers have undertaken cost-cutting measures to survive.

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 US 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 U.S. 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 US, were cancelled (out of 500 GW). And in the first quarter of 2002, orders for 57 GW of capacity were cancelled.

Capital spending in the utility industry sharply declined, again. According to Dennis Boman, Director of Marketing for Power Transformers, ABB North America, "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%." According to Mr. Joe Durante, Vice President, Commercial Operations, North America, Elin /VATech, "…the boom of the late nineties and early two thousand 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 HSB claims 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 3-year and 5-year warranties.

The prognosis, according to Mr. Peter Fuchs, Vice President Sales & Marketing, Siemens Transformers, is " …a stagnant market, on average, for the US, 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. The need for power in this area already exists, and as international funding becomes available, we expect to see increased activity in this region."

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 major three manufacturers point to a number of different problems. According to Bowman (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 (our insureds) are choosing the lowest bidder, with little regard to quality, reliability or factory service. According to Fuchs (Siemens) "..in addition to the price-driven decision, there is very little technical evaluation, and 'price-dumping' continues to go unpunished." Durante (Elin /VA Tech) confirms that the major obstacle is "ongoing deregulation uncertainty which is hindering capital investment".

According to Durante, 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", says Durante. In the U.S., the 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 federal government or the state government 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 the regulators driving toward retail competition, the utility business priority is competitiveness (and related cost-cutting) and not reliability.

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