Present study suggests the review of the classical bathtub for failure hazards and the foremost probability of failures which is in the middle life period

Proposition for different life hazard curve for transformer and substation equipment

ABSTRACT

Today the classical bathtub curve model is the main model for life expectancy calculation of all the electrical equipment and, especially, all kind of oil-filled transformers. Most of the stakeholders and maintenance engineers make their decisions on tests, treatments and most importantly, replacement, on the bathtub curve concept. The costs that are associated with the classical bathtub curve are substantial, mainly driven by the unnecessary treatment or unnecessary replacements.

KEYWORDS

bathtub curve, failure probability, life extension

1. Introduction

The classical bathtub curve for electrical equipment evolved from the old mortality bathtub curve for humans presented 200 years ago by Gompertz–Makeham law [1] as shown in Figure 1, and even before, in the 15th century [2]. For humans, as well as for modern manufactured transformers, the infant mortality decreased substantially. Electrical equipment of modern substation is designed, manufactured and maintained much better than the equipment in the past and their operational life will be longer.

The classical bathtub curve model for the electrical and electronic equipment was confronted with the real failure rate distributions curves almost 30 years ago by Wong [5] as shown in Figure 2a, and more recently, by different scholars from different disciplines [6,7] as shown in Figure 2b. The classical bathtub is widely presented in [8].

Even a minuscule change of view on the replacement and tests policy could result in a huge cost reduction, replacement postponement, and cost-effective maintenance.

> **During the last few decades, the manufactures have invested many efforts to increase the electrical equipment reliability**

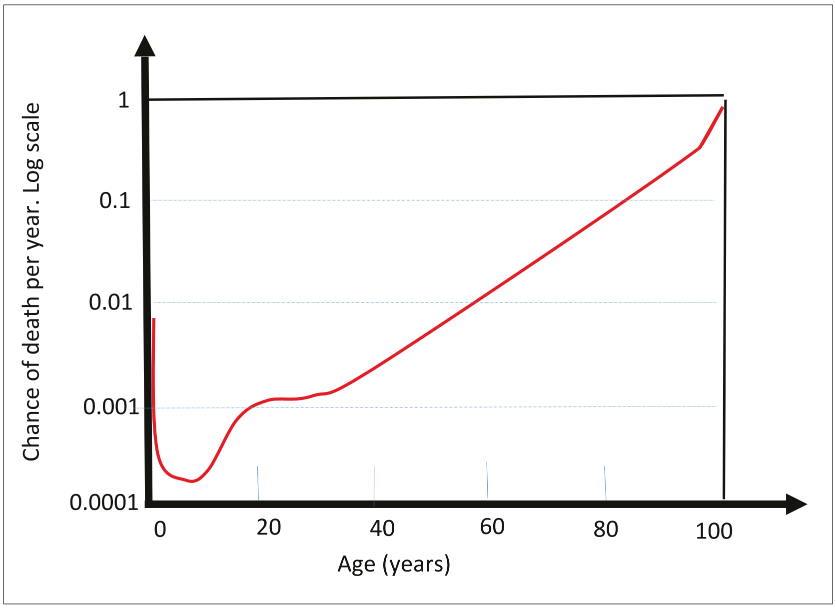

Figure 1. Estimated probability of a person dying at each age in the U.S. in 2003 [3,4]

Power transformers allow the distribution of electrical energy almost everywhere on the planet, increasing the opportunity for equality by making energy available to everybody. In most of the life assessments modules, the technical staff has to comply with a very limited budget allocated for the maintenance of a healthy fleet. As the privatisation process is developed and the finances are increasingly constrained, the time spent on tests, treatments, and replacement must be reduced significantly. Twenty years ago most of the electric equipment in power stations and substations, especially transformers, were built with very

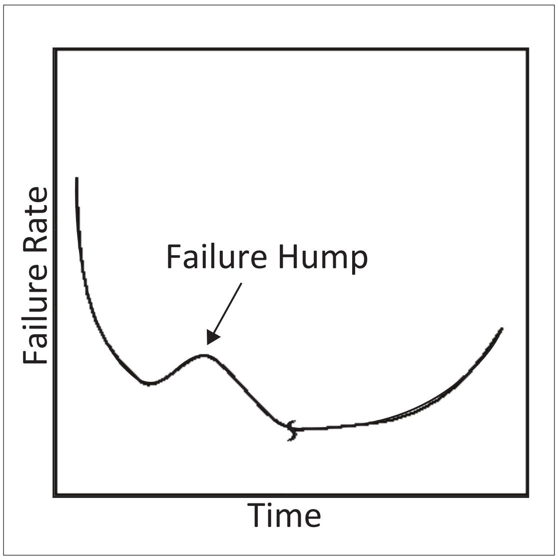

Figure 2. a) The roller-coaster hazard curve proposed by Wong [5]

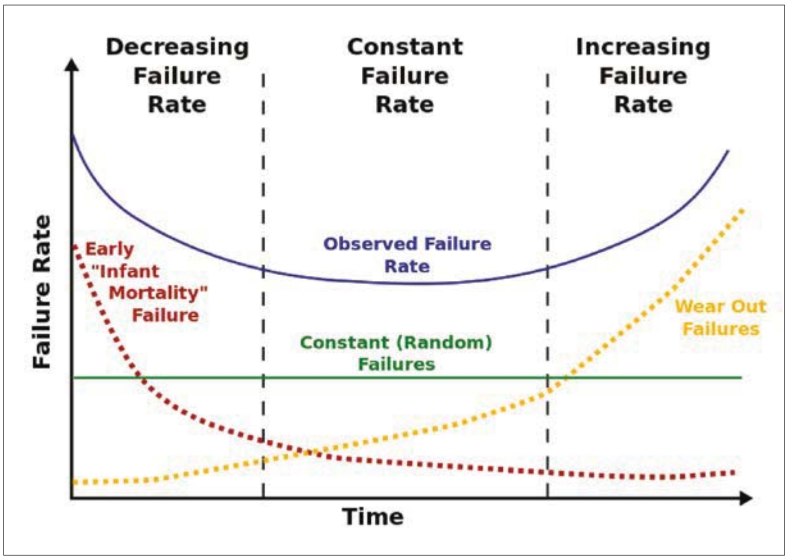

Figure 2. b) The classic bathtub hazard curve [8]

> **The services companies have much more know-how data regarding the transport, installation and energizing**

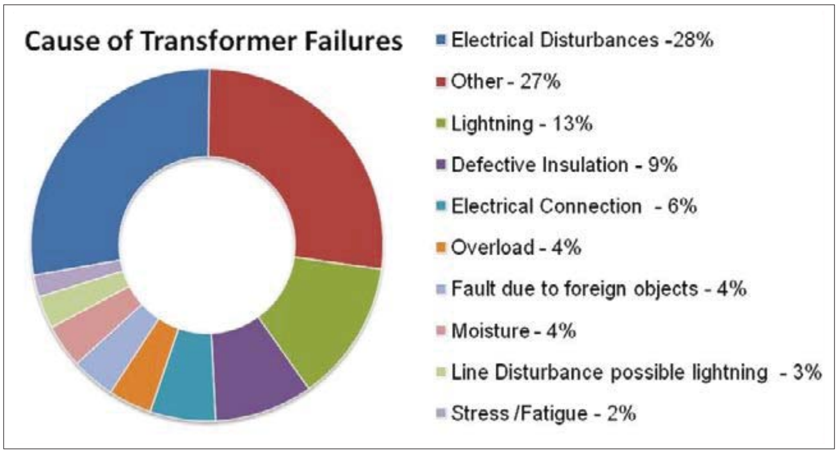

Figure 3. a) Causes of transformer failure [9]

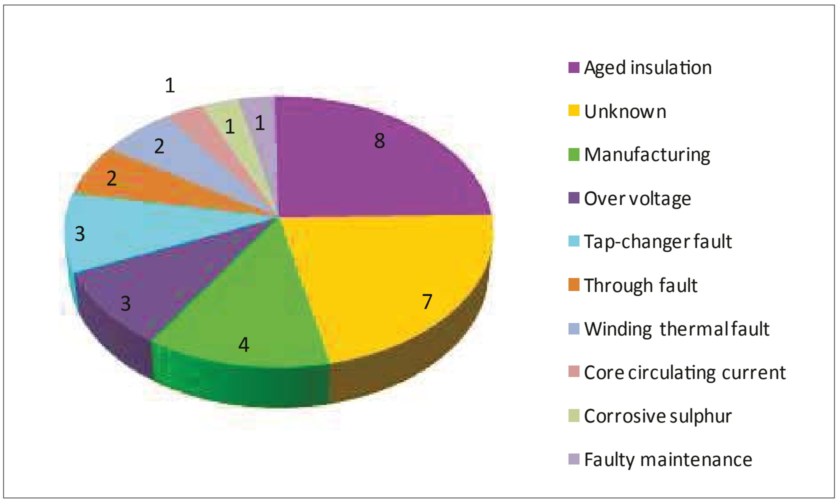

Figure 3. b) Distribution of transformer faults percentage [8]

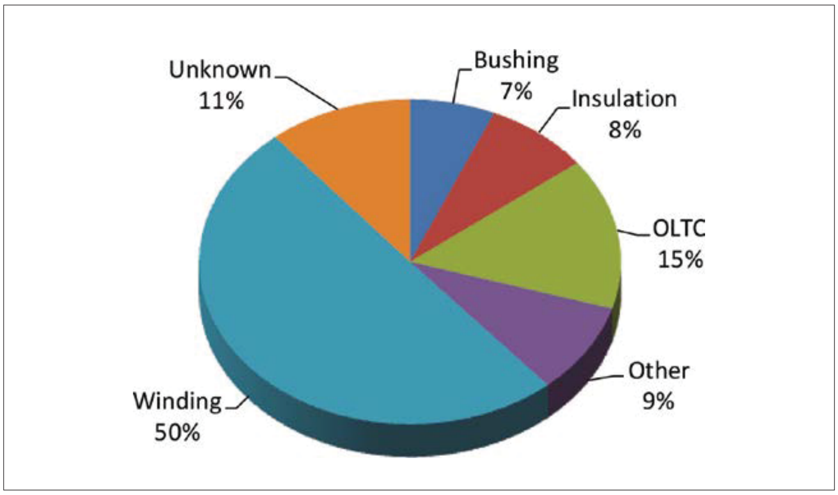

Figure 3. c) Distribution of failures (non-catastrophic + catastrophic) for all transformers [10]

generous insulation margin. In post-privatisation epoch, everything becomes tidier, from the dielectric margin via equipment prices through tides bids up to maintenance costs. The inclination to reduce the budget from procurement to later conservation imposes a different concept on tests, diagnosis, and treatments.

Based on those drastic improvements, present study suggests the review of the classical bathtub for failure hazards and the foremost probability of the transformer failures which is in the middle life period. In present time, the internal failures are substantially reduced in the infant and the elderly stage. The intense manufacturing quality control and the selection of better insulation and conductor materials during the manufacturing stage combined with the improvements in the preventive maintenance procedures and condition monitoring schemes at the utility, influence the shape of hazard failure curve. The end of planned operational life become the primary reason behind the transformer replacements, as opposed to ageing related defects or internal failures. By adopting new failure hazard models and conducting intensive research in equipment failure mechanisms, it is possible to reduce the overall replacement cost for all substation equipment and especially for transformers.

2. Transformer failure statistics

Causes of transformer failures [8-10] are shown in Figure 3a to 3c. They can bring confusion regarding the adaptation of adequate strategic concepts to diminish the failures. In addition, the percentages of failures differ substantially among surveys.

3. Fault mechanisms in substation equipment and transformers

- **The pre-energizing condition:** Includes all the stages from the design, materials involved construction, quality control and transport to the site, oil filling and operation. Majority of features are not revealed in the beginning and remain hidden throughout. One of the suitable ways to avoid failure in the first life period is the efficient quality control, from the design up to the exploitation. By carefully and strictly following all the pre-operational procedures and processes, it is possible to be recompensed for it by longer and healthier operational life. The same is applied for humans when extensive treatments and blood test are used to observe women before and during pregnancy resulting in reduction of infant diseases and mortality.

- **External reasons:** Even though good design, manufactured and maintained transformer or any other equipment piece can resist more adverse conditions such as loading, stresses, etc., there is always a limit over which even the most robust one will fail. This category includes accidents, animal related issues, or unusual events such as earthquakes, hostile geomagnetic disturbances, or any other hostile activities such as gunshots.

- **Maintenance issues during transformer life:** Maintenance tests policy and treatment have a significant impact on the equipment health. A strong one will be capable of enduring even exaggerate loading and stresses. Investment in adequate and reliable monitoring and preservation makes it possible to reduce the exploitation and leads to higher safety insulation margin.

The shareholders' decision to invest during the exploitation is based on two main key factors:

- The importance of investing for the power system or cost impacts due to its failure. For the transformers, as well for other critical and unique substation equipment, both the cost and impact are obviously high.

- Cost of the electrical equipment itself, including the cost of replacement time because each substation is special due to its specification, loading, geography, age, the complexity of manufactures mixing and many other reasons, and because of that the replacement is not a simple issue. As is the case with transformers, the availability of most of the equipment types is limited. Therefore, one of the main concerns of the owner is how to preserve spare units and how to secure spare storage. This is important due to the fact that some costly and important equipment is much more vulnerable to ageing when it is not energized.

Figure 4. a) and b) Defects in pre-energizing stage appear 3 years after energizing in a furnace transformer of 80 MVA rating

4. Proposed life hazard curve model for modern transformers and substation equipment

The most popular model for transformer failure probability is the classic bathtub used for the calculation of failure rate probability. Different extensive studies [8], [11] and [12] suggest that the classical shape of bath curve, shown in Figure 2b, is not adequate for real electrical equipment, especially the transformer life model. The proposed model is shown in Figure 5. The reasons behind these shapes are described below and electrical equipment manufacturing and operations circumstances specify that the design, fabrication and test processes used in the last decade are different from those used 40 years ago.

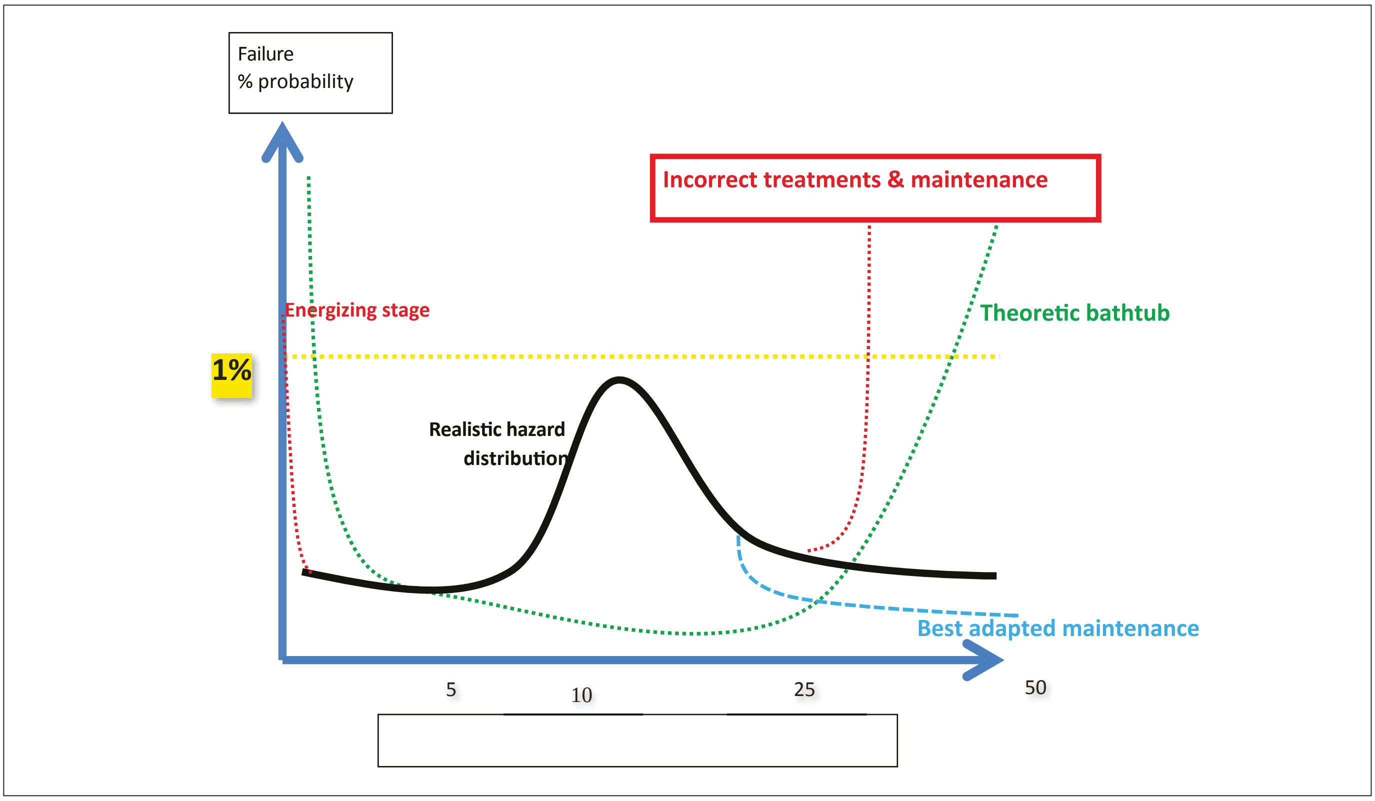

Figure 5. Proposal of new life hazard curve for contemporary transformers and substation equipment - the black line

> **Most of the users perform electrical and chemical offline tests on a regular basis or even install online devices for the most important equipment**

4.1 Transformer malfunctions at the infant operation stage

Transformer failure in pre-energizing stage and during one week after energizing can be caused by incorrect handling during manufacturing and assembly process such as foreign objects, metal parts, painting or the transportation issues during transportation from the factory to the commissioning site, etc. These types of failures are practically non-existent these days due to the intense tests and maintenance programs performed before energizing. In the last few decades, utilities and operators follow certain procedures to solve all of those premature failures. Most of the manufacturers of electrical equipment release their product after rigorous and sophisticated quality control that is capable of eliminating most of the manufacturing defects that may affect the first energizing stage. Other type of malfunctions are juvenile failures. This failure type includes sulfur corrosion issues, material compatibility, the improper sealing, moisture absorbed in deep cellulose layers, and so on. They may occur between 5 and 15 years of operation and they are caused by undiscovered defects from before the energizing stage. They are slightly dependent on operating conditions, but they probably appear if the transformer is energized and the loading will catalyze the failure appearance.

4.1.1 Sulfur corrosion issue

Copper connections affected by sulfur corrosion and improper section of the material may produce faulty condition as shown in Figure 6. In addition, stray gases with the recent mineral and non-mineral insulating oil originate from chemical reactions between internal components of the transformer and the oil or within the oil itself.

The black line pattern on the cellulose is the characteristic zebra pattern of decomposed copper caused by sulfur reactions. The copper-sulfur compounds deposit on cellulose and affect the insulating properties of the cellulose matrix. Improper earthing connections will also appear a few years after the first energizing as shown in Figure 7.

4.1.2 Moisture deposition in solid and liquid insulation

Before and during the energizing phase, moisture can be absorbed in many parts of the electrical equipment. The 99 % of the water content inside the transformer is found in solid insulation in any of the cellulose materials; however, more than 50 % of water content is stored in the parts of cellulose that are not directly involved in the electric or magnetic circuit [14]. During the equipment exploitation, the water can migrate from inactive cellulose parts to the active parts due to fluctution of temparature gradients. These processes can last for a few years and at the end they will increase the failure hazard. The electrical tests prior and immediately after energizing, as well as most of chemical or physical tests, cannot reveal the presence of water content. Those failure types can be avoided by using modern sophisticated techniques [15] or careful dew point tests. The hidden internal moisture can cause serious problems for any type of equipment. Equipment is prone to absorb moisture during fabrication, transportation or in the worst case, during the storage.

4.1.3 Improper sealing

One of the worst consequences of improper sealing for a transformer is free water that can unexpectedly reach the upper part of the windings. This type of faulty situation may occur in the first few years of operation and cannot be discovered by any preliminary tests. A fissure in the sealing, caused by tempearure fluctuation and other ambient conditions is shown in Figure 8b. Free water reaches the insulations through a gap and may initiate a fatal short circuit of the upper part of the winding as shown in Figure 8a.

4.1.4 Improper connections

High amount of gases produced in 5 years old 60 MVA industrial transformer due to improper connection that activated Buchholz relay to trip is shown in Figure 9. Produced gas profiles were predominantly ethylene by nature. The common reason behind this is hot metals caused by inadequate sizes or materials.

Any transformer without malfunctions in first operation phases will survive as long as it is not exposed to extreme ex-

> **The current generation of most of the electrical equipment used in modern substations became much more reliable than the equipment in the past**

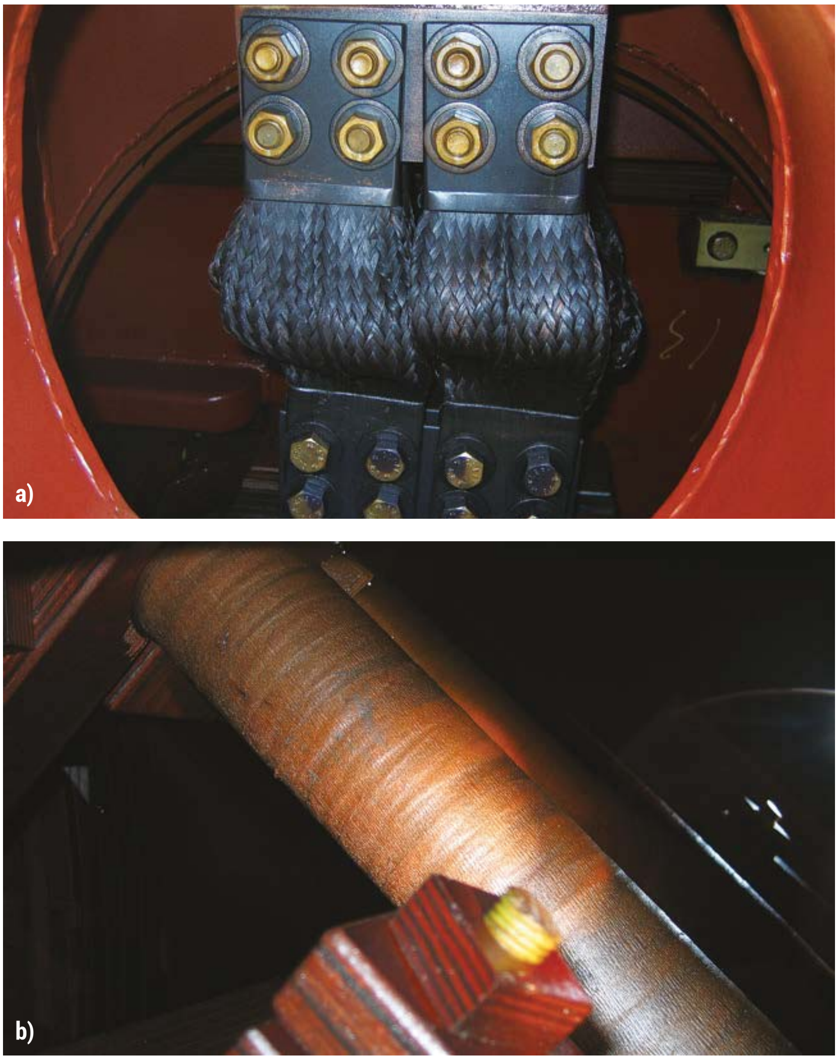
a)
b)

Figure 6. a) and b) Copper connections affected by sulfur corrosion in a corrosive oil without dibenzyl disulphide (DBDS) [13]

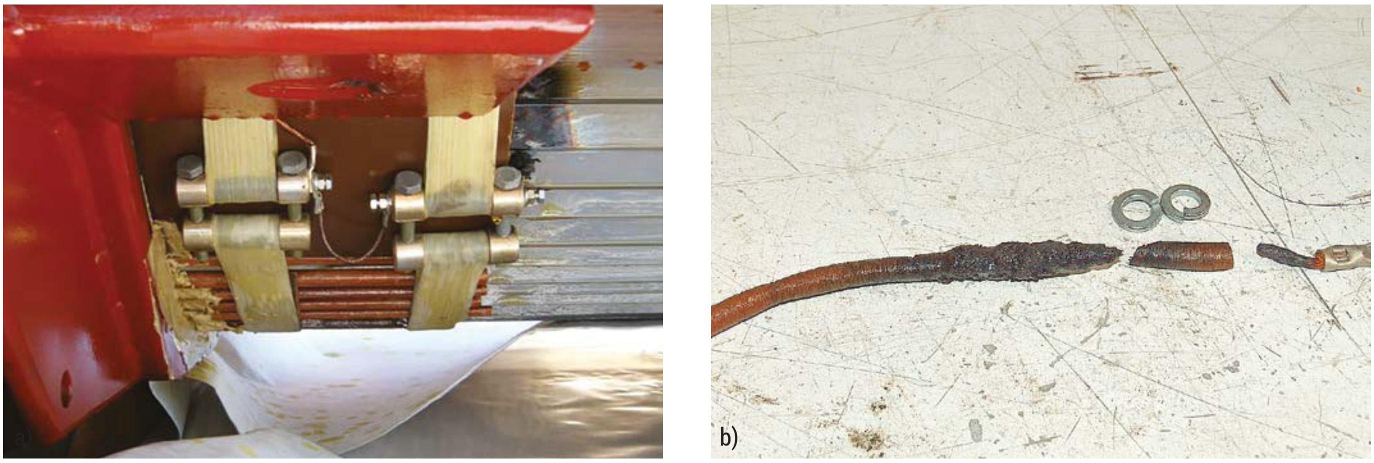
b)

Figure 7. a) and b) Improper earthing induces an abrupt gas increase three years after energizing

Figure 8. a) Winding damage due to insulation failure

Figure 8. b) Improper gasket sealing in the bushing

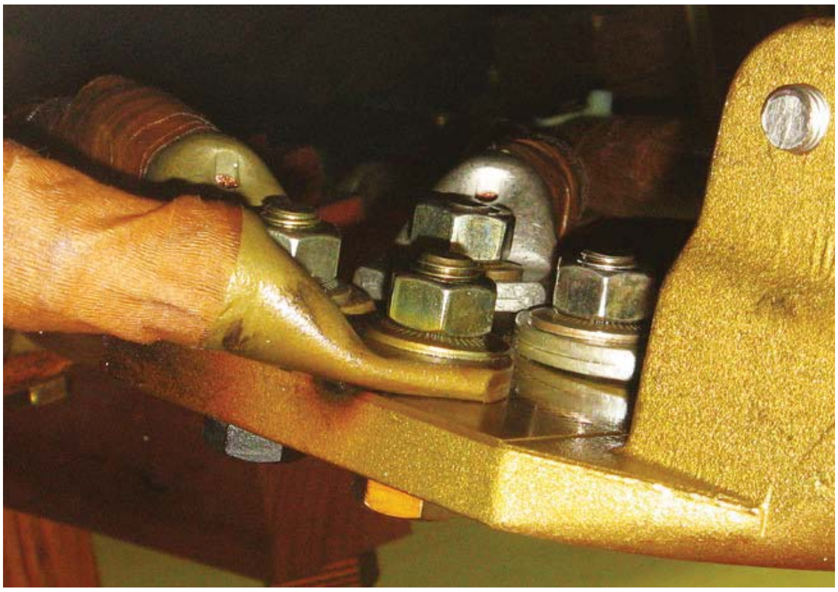

Figure 9. Improper connection in 60 MVA industrial transformer

> **There is a decrease in the infant mortality and increase in the failure rate for an approximately 10 years old transformer**

ternal environment and is prudently preserved. Preserving electrical equipment in a healthy state is mainly focused on preserving its insulation matrix.

Following factors may cause breakdown or degradation of the insulation matrix:

- **Ageing**: The most economical and advantageous technique to avoid the ageing process is to preserve the antioxidant concentration well above the 40 % of the initial concentration of antioxidant or above 0.15 % of the oil volume, i.e. 1500 ppm as described in IEC 60422 [16]. Ageing destroys the insulation and mechanical properties of the oil and cellulose insulation, mainly through oxidation mechanism of organic compounds. In Figure 10a and 10b, it is clear that inhibited oil with inhibitor content above 0.15 % does not become acid as shown in Figure 10a and the dissipation factor (tan δ) of the oil will not increase due to the ageing process [17] as shown in Figure 10b. Non-acid mineral oil will not be aggressive to other internal parts of the equipment as well. By inhibitor monitoring and refilling when necessary, it is possible to keep entire insulation system in a good condition, no matter the actual age of the equipment.

- **Moisture ingress:** Moisture is always present but is very difficult to monitor and track it. In fact, it is impossible to measure the moisture content inside the cellulose, and the users have to realize that water content in the oil is mostly the tinny tip of the iceberg and is irrelevant to the real amount of the internal moisture.

The failure hazard due to excessive water content in oil may be lower in mineral liquids for aged oil because aged oil is more polar and more soluble for water and decreases the chances of breakdown through the oil and the cellulose

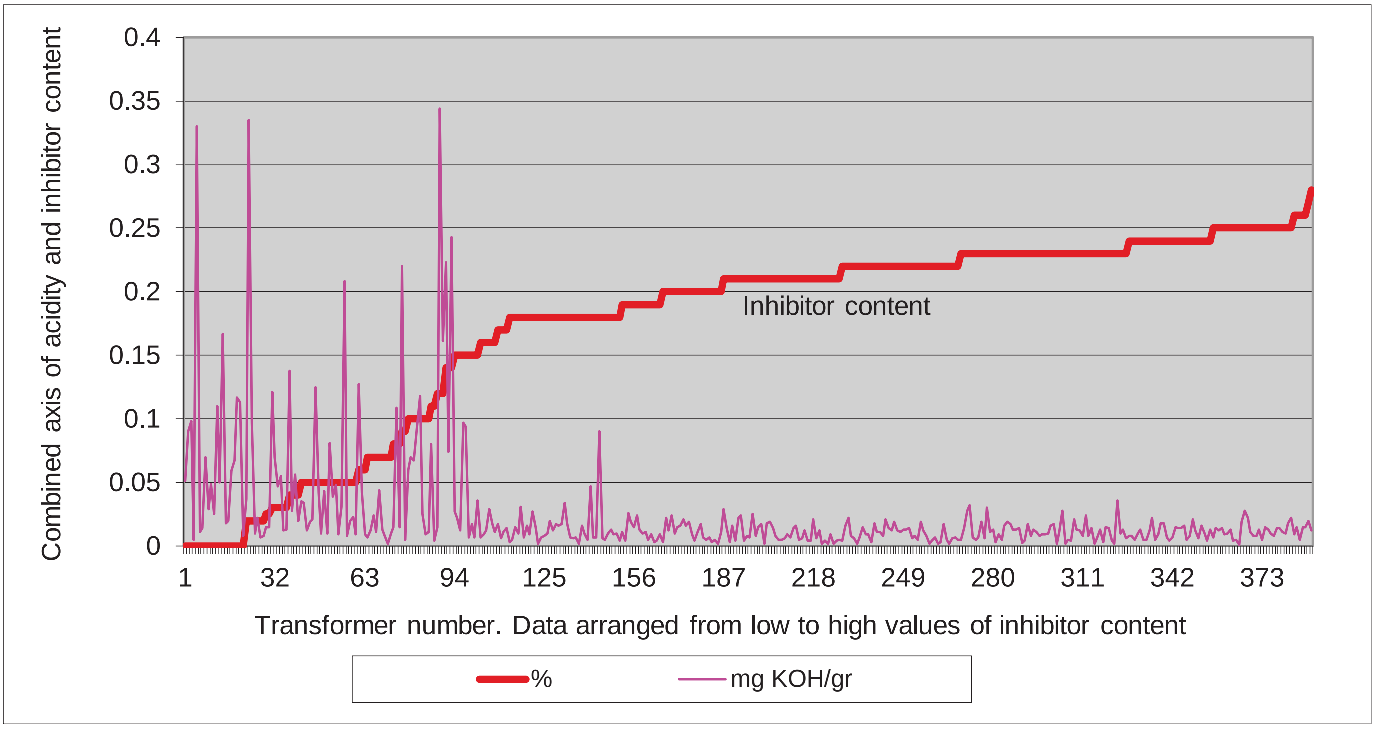

Figure 10. a) Values of acidity versus the inhibitor content % values in a transformer fleet of 378 units [17]

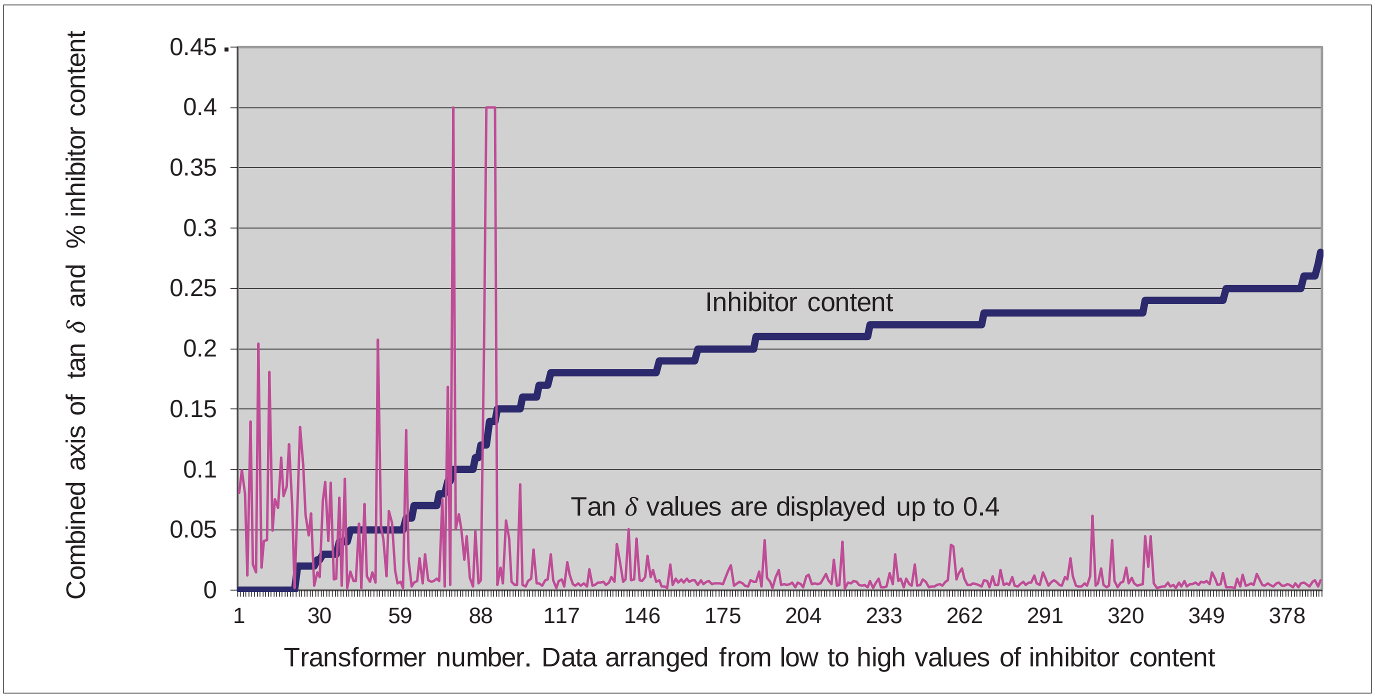

Figure 10. b) Values of tan delta versus the inhibitor content % values in a transformer fleet of 378 units [17]

Table 3. Correlation between water content, acidity and breakdown voltage for mineral oil at 25°C

Water content (ppm)	Acidity of the oil (mgr/kg) measured as per IEC 60814 [18]	Breakdown voltage (kV) at power frequency measured as per IEC 60156 [19]
50	0.01	20
	0.1	42
	0.5	50

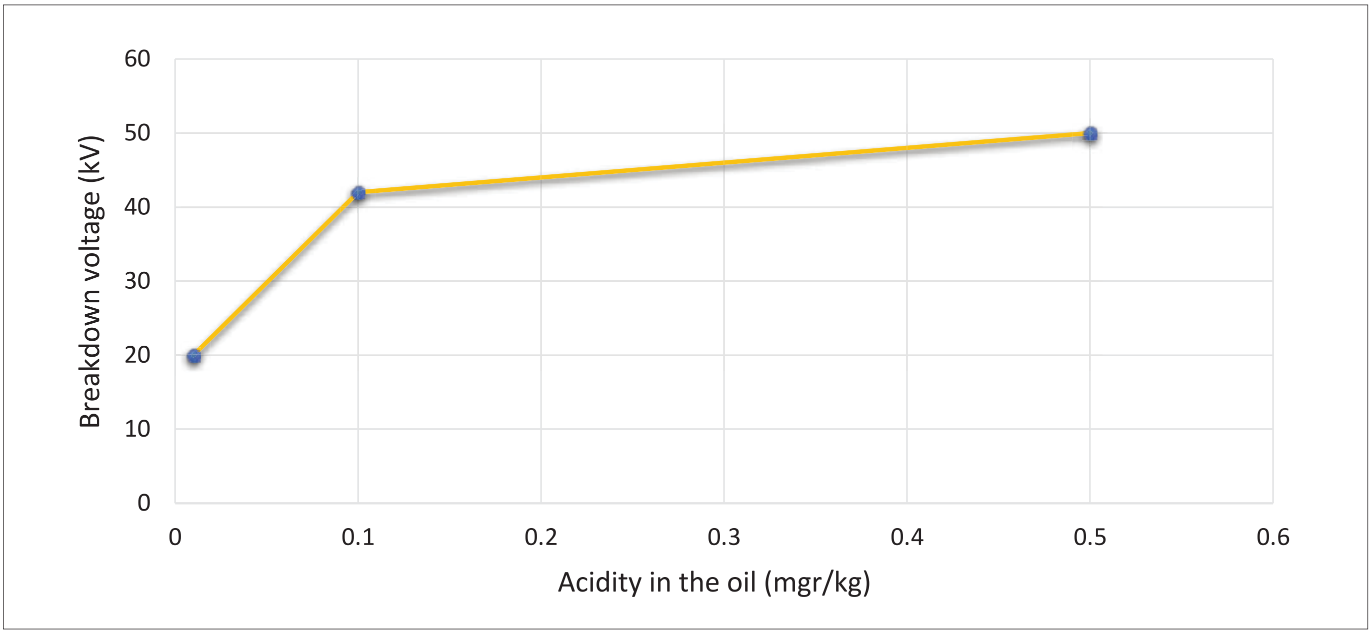

Figure 11. Acidity level in the oil versus breakdown voltage at 50 ppm water in oil

insulation. Increase in the solubility of water results in a decrease of a_w (water activity) and it increases breakdown voltage values. The experimental results of this theory are provided in Table 3.

> **Non-classical behavior of age at failure moment vs number of failures was found to fit the UK fleets and other modern fleets**

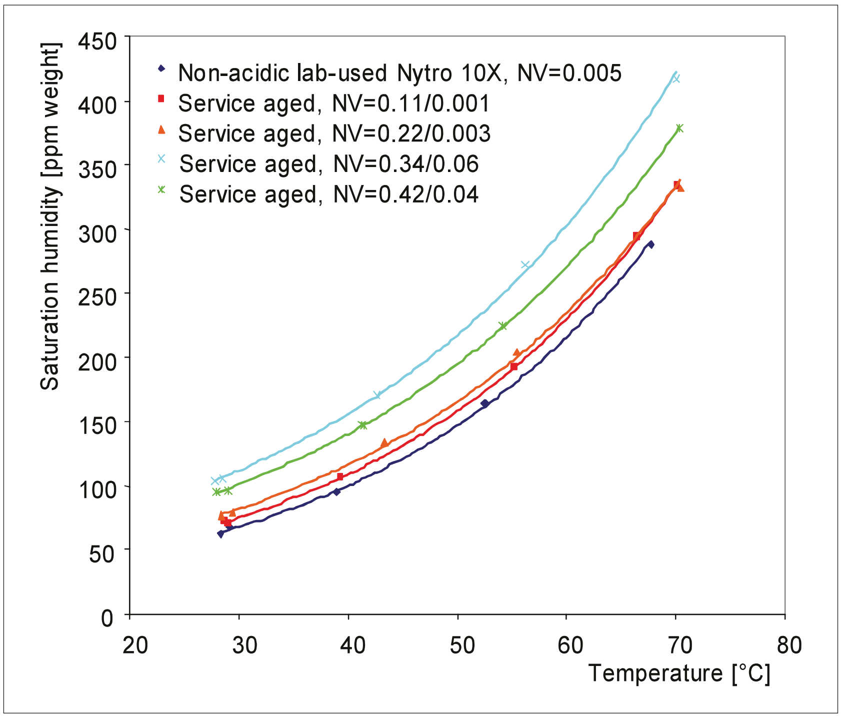

Figure 12. Moisture solubility in four service aged oils compared to a non-aged laboratory used oil [20]

For ester liquids, as well as for mineral oil with high water solubility, the amount of moisture in paper is reduced and therefore, the arcing and bubbling risk will be lower. The water solubility increases with ageing as shown in Figure 12. At 40°C the saturation is at around 80°C for new oil and about 150°C for most of the aged oils. That means the aged oil may contain twice as much water for the same relative saturation (RS) value. At a RS of 70-80 %, the dielectric strength of the acid oil will be low [20]. The acid oil is a larger reservoir for water than the new oil, and consequently, it will have a lower RS and a higher dielectric strength at the same absolute water content.

Of course, intentionally acidizing the oil is a not a great practice for prolonging the life span but it means that in some case, oil ageing may even lower the failure hazard due to extensive moisture. The procedure for oil replacement or depolarization reduces the water confined in the cellulose of insulation, but it can increase the failure hazard. In this case, the careful study of insulation matrix can be a better alternative for prolonging the life span.

Increasing the liquid solubility of the insulting liquids is also a promoter for the ester-based insulating liquids. Presently, the treatments for life extension are much simpler and easier. This may reduce the ageing risk failures and introduce the way to modify the shape of classical bathtub curve to an almost flat hazard curve as shown

> **Substantial life extension option is already a fact in the 21st century and the hazard bathtub curve should be amended accordingly**

in Figure 5. The main consideration regarding the negative effects of acidity are less important for new generation of oil and cellulose that are becoming more synthetically processed and less vulnerable to oxidation. Furans or any other byproduct of cellulose decomposition are in most cases not a reliable sign of ageing and need for replacement, even if the paper and cellulose is damaged [21].

When it comes to the new electrical equipment in a modern substation, and especially when we talk about transformers, the age of the equipment does not always signify an increase in failure probability [8]. The hazard failure is more connected to other parameters such as the initial quality control or the maintenance policy. Another important factor is the time from manufacturing to energizing. This period is crucial for all substation equipment, in most cases the ageing in stored equipment is higher than in energized equipment.

In many parts of the world, the majority of substation equipment, including costly transformers, end their operational life not because of the ageing or failures or malfunctions, but due to grid parameters such as voltages or power supply needs, industrial developments and population increase.

After 15 years of operation, if no faults or failures or any other issues are discovered in transformers and other electrical equipment, it can be kept in operation if the long periodic tests and well-planned maintenance are performed. Even without active maintenance, a well-designed and robust unit can be operated safely for a much longer period than that predicted by tests such as furans compounds, dissolved methanol in oil or interfacial tension (IFT).

In our times, the need for replacing of substation equipment is mainly due to grid developments. The last few decades also saw a significant improvement in the manufacturing and reliability of the equipment. Those two processes result in a potential decreasing of failures connected to age.

Conclusion

As was already pointed out by different researchers and experts: "It's remarkable that we have not observed symptoms of increasing failure rates for GSU (Generator step-up transformers) transformers with time" [22].

Non-classical behavior of age at failure moment vs number of failures was found to fit the UK fleets and other modern fleets [23]. There is a decrease of the infant mortality and increase in the failure rate for an approximately 10 years old transformer.

The classical bathtub curve model for failure hazards for contemporary components of modern substation should be revised and reevaluated. During the last few decades, the manufactures have invested many efforts to increase the electrical equipment reliability and the services companies have much more know-how data regarding the transport, installation and energizing. Most of the users perform electrical and chemical offline tests on a regular basis or even install online devices for the most important equipment. The current generation of transformers and most of the electrical equipment used in modern substations became much more reliable than the equipment in the past. The substation owner has the responsibility to select the reliable and quality manufacturers of substation equipment, free of juvenile malfunctions with the best available core material, conductors and insulation materials. If the transformers and all other substation equipment is exploited properly, then the classical bathtub hazard curve is less applicable. As is the case with human life, which saw the substantial decrease in infant mortality once the expected life span became longer and healthier in our times as opposed to the past, the properly designed and manufactured electrical equipment and their lifespan in normal usage conditions will be much longer than that of the past generations, if we compare the classical failure hazard bathtub curve with the old mortality curves for humans.

Ageing of the oil and paper insulation is not a frequent reason for failures and must not induce the replacement initiative. In some cases, utilities may save huge budget by continuing to operate the old design transformers even if their oils pass the current standard limits values of acidity, dissipation factor (tan δ), moisture content in oil, the furans value is high or some abnormal dissolved gases in oil are found. The relative risk of failures for relatively new units is not always lower than failure risk for aged and probably more robust ones. The decision regarding the oil replacement or treatment has to always be considered very carefully including all possible aspects. Sometimes such activities themselves can promote faulty conditions [24].

Knowledge, together with the fruitful experience concerning the relevant model and maintenance policy, is the key for economic exploitation of the electrical equipment for an infinite practical time. As is the true for the humans [25], the same can be applied to the transformers and other electrical equipment of the modern substation. Substantial life extension option is already a fact in the 21st century and the hazard bathtub curve should be amended accordingly.

> **If the substation equipment is exploited properly, then the classical bathtub hazard curve is less applicable**

> **The relative risk of failures for relatively new units is not always lower than the failure risk for aged and more robust ones**

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He trains and educates electrical staff on insulating matrix issues from a chemical point of view. He is an active member of relevant Working Groups of IEC, CIGRE and former member of ASTM.

He is also the author and co-author of many papers, CIGRE brochures and presentations at prestigious international conferences on insulation oil tests, focused on DGA, analytical chemistry of insulating oil and advantageous maintenance policy for oil and new transformers.