High load, electromagnetic stress, and water penetration after manufacturing and during the transformer operation lead to initial degradation of insulation

# Transformer insulation regeneration and drying in online mode

## Revitalization of power transformer insulation


### ABSTRACT

Transformer insulation consists of liquid (mineral oil) and solid (cellulose) parts. The influence of temperature, oxidation and moisture degrades the insulation, creating acids and sediments that negatively affect its characteristics. While there are different methods of insulation renovation, this article will present regeneration and drying in online mode, which is one of the best methods that siginificantly extends the life of the transformer.



### KEYWORDS

transformer, insulation, regeneration, drying, revitalization


### 1. Introduction

Mineral oils in combination with cellulose are the most common form of insulation in transformers, distinguished by very good characteristics such as resistance to oxidation and other chemical degradation, stability at high temperatures, viscosity and high dielectric strength. However, a high load, electromagnetic field and water penetration after manufacturing and during the transformer operation lead to the initial degradation of insulation. Also, the products of aging accelerate this process and over time become a dominant factor degrading the insulation system. If the degradation process is not stopped or mitigated, the insulation will lose properties and jeopardize the reliability and safety of the transformer operation. The damage caused as a result of breakdown of insulation can be extensive leaving long-term consequences and posing significant financial losses.

### 2. Degradation of transformer insulation

Over time, under the influence of temperature, electromagnetic fields, catalytic impact and oxidation the transformer oil starts to lose its characteristics [1]. Oil oxidation leads to the formation of acids which attack cellulose fibers and metals, forming metallic soaps, lacquers, aldehydes, alcohol and ketones which are deposited as acid precipitate. The precipitate increases the oil viscosity and therefore reduces its heat dissipation. In the electric field it can also cause partial discharges, and in severe

cases lead to breakdown of transformer insulation.

A problem that often occurs during the lifetime of a transformer is the appearance of water in the insulation system. Water as a polar molecule negatively affects the insulating capability of the material, deteriorating its electrical and mechanical characteristics. Water can penetrate from the atmosphere through the places where the oil is leaking, during inspections of transformers, but also as a product of cellulose degradation. Paper insulation has a higher affinity to water than oil, which means that the water is not evenly distributed in the transformer insulation. It is considered that approximately 99 % of water in the transformer is contained in the solid insulation [2]. Water and oxygen together accelerate aging of the oil, and with the aging of the transformer oil, interfacial tension decreases while the level of acids increases, as shown in Figure 1.

**An oil sample should be taken each year for the transformer units larger than 5 MVA to perform dissolved gas analysis and basic tests**

Thermal and electrical failures are partly caused by the destruction of transformer insulation. Dissolved gas analysis (DGA) is a method that can determine the condition of the transformer and also predict its future behavior – a gas chromatography method. The causes and consequences of the aging of the transformer insulation are shown in Figure 2.

## 3. Testing of insulating oil

Transformers are robust power units, but their regular maintenance is very important. The maintenance, in addition to the review of the mechanical parts and measuring insulation resistance, also includes oil sampling. An oil sample should be taken each year for the transformer units

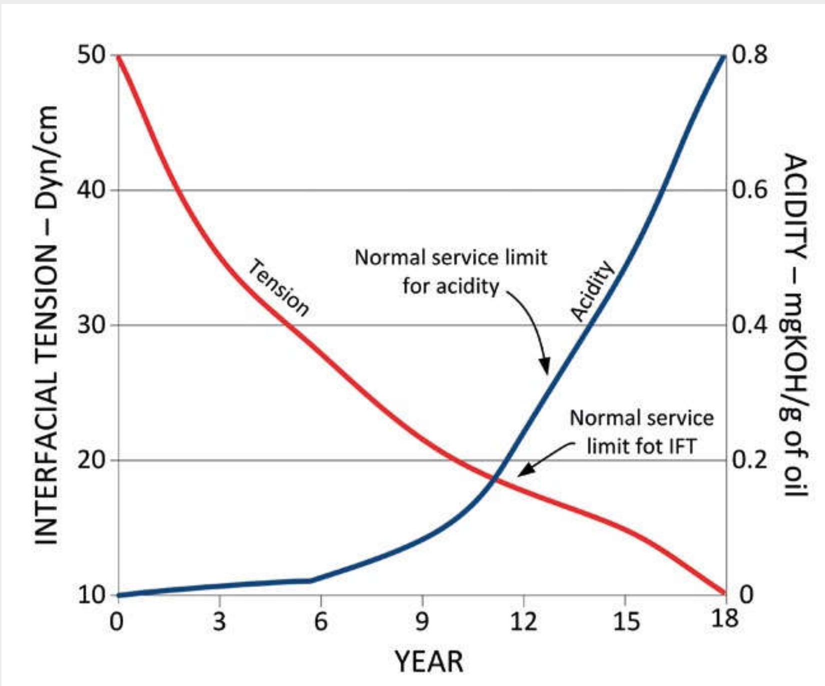


Figure 1. Interfacial tension and acidity in relation to the oil lifespan

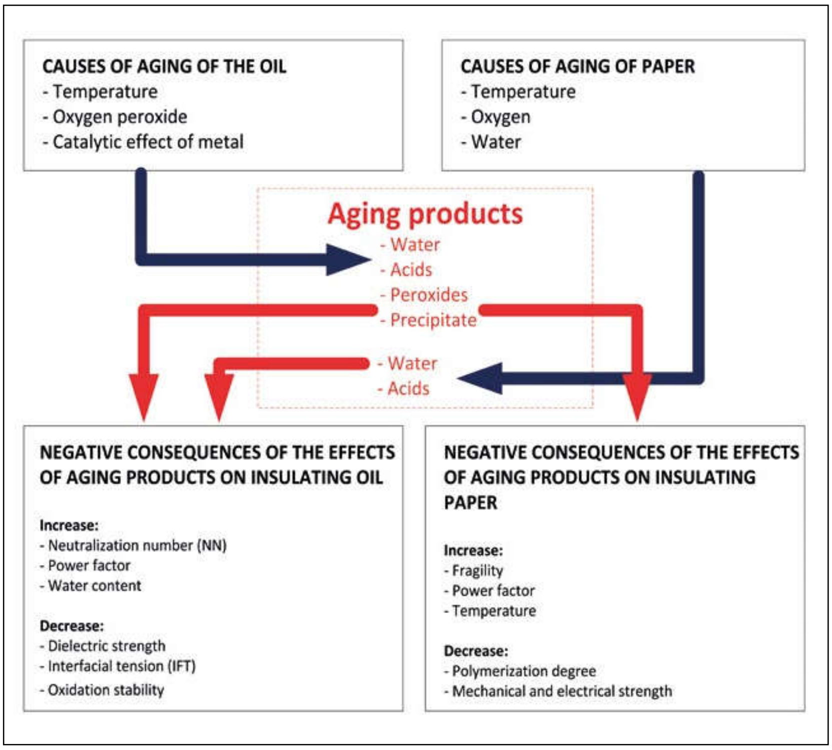


Figure 2. Aging of the oil-cellulose insulation system

**Reasonably accurate diagnosis can be obtained using tests of water content, dielectric strength, neutralization number, interfacial tension, and power factor**

larger than 5 MVA in order to monitor changes in the oil condition and possibly take some steps in order to put the transformer in an optimum condition. There are five basic tests of insulating oil which provide a reasonably accurate diagnosis with respect to the serviceability of the insulating oil [3]. These tests are presented below.

### 3.1. Water content test

Transformers are dried during the manufacturing process. Prior to commissioning, the maximum content of moisture in the cellulose insulation should be 0.5 %. After the initial drying, the percentage of moisture in the transformer will depend on the exploitation conditions and the preventive maintenance measures. Water is very harmful to the transformer even in small quantities, as it accelerates the degradation of the oil and solid insulation. Once the paper insulation has been degraded, it can never be restored to its original condition. While the oil can be regenerated, for the insulation to be functional it is necessary that both segments are in proper condition. Water may arise from two sources: atmospheric (through the silica gel breather, leaks in power equipment, cracked insulation, etc.) and internal sources (as a product of paper and oil degradation).

### 3.2. Dielectric strength test

Dielectric strength of the transformer oil is the ability of the oil to withstand electrical stress without failure [4]. The test is performed by immersing the testing device that uses AC voltage between two electrodes in the insulating liquid. When the electric arc appears between the electrodes, the voltage recorded at that instant is the dielectric strength of the insulating liquid. Water, sediment and other conducting particles in the oil and in the cellulose insulation reduce the dielectric strength of the oil. Figure 3 illustrates how the penetration of water in insulation affects the dielectric strength of transformer.

### 3.3. Acidity or neutralization number (NN) test

The acids appear in the oil as a result of the oil decomposition and oxidation, but they can also enter from external sources such as atmospheric contamination. An increase in the acidity is an indication of the rate of the oil deterioration with the sludge [5]. The acidity of the transformer oil should never be allowed to exceed 0.15 mg KOH/g. Up to 0.1 mg KOH/g acid sludge is dissolved in oil. The values exceeding 0.1 mg KOH/g cause the formation of solid sludge (acids and particles) at all internal surfaces, which leads to insufficient cooling and cellulose degradation. This is the critical acid number and deterioration increases rapidly once this level is exceeded [6].

### 3.4. Interfacial tension (IFT) test

The interfacial tension (IFT) represents the tension at the interface between two liquids (oil and water) which do not mix, which is expressed in dyne/cm (mN/m). This test is sensitive to the presence of oil decay products and soluble polar contaminants from solid insulating materials. The oil with good characteristics will have an interfacial tension of 30 mN/m or higher. Oil oxidation and degradation products lower the interfacial tension and have an affinity for both water (hydrophilic) and oil. Badly deteriorated transformer oil will have an IFT of 22 mN/m or less [7].

### 3.5. Power factor test

The power factor of an insulating oil equals the cosine of the phase angle between the AC voltage applied to the oil and the resulting current. Power factor indicates the dielectric loss of the oil and its insulating value. This test is recommended for large transformers (greater than 500 kVA) to ensure insulation integrity. The power factor of the new transformer oil should not exceed 0.05 % at 25 °C. A high power factor in oil indicates deterioration or contamination with carbon, moisture, sodium soaps, or similar products. Used oils with a power factor greater than 0.5 % should be analyzed in the laboratory to determine the cause of their high power factor. Oil with a power factor of 2.0 % or greater may pose an operational hazard and they need to be thoroughly tested, treated or replaced.

## 4. Treatment of transformer insulation

After certain deviations are detected during the transformer oil tests, it is necessary to take some steps to bring the oil or the entire insulation system to a satisfactory state. There are various methods of reconditioning transformer insulation, such as:

- Natural precipitation
- Filter presses
- Cartridge filters
- Centrifuges
- Vacuum dehydrators
- Revitalization of insulation with adsorbents in offline and online mode

Restoration of the transformer insulation can be divided into purification, regeneration and renewal (revitalization). The difference between purification and regeneration is that in the former only oil is treated, while in the latter, a complete transformer insulation is treated with certain chemical processes and materials. Using these methods, the products of aging are removed from the insulation system, and these include water, oxygen, acids, gases, precipitates, etc. The method of replacing the transformer oil is rarely used today for the simple reason that unwanted particles remain in the paper insulation or remain in a precipitate and cannot be completely removed [8]. This method is also the most costly. For example, replacing 25 tons of transformer oil costs about 70,000 euros (according to prices in Bosnia and Herzegovina). Filtering and degassing of oil often require additional oil heating, which further raises the cost of such treatments. Apart from that, the transformer must be switched off, and in some situations the interruption of work itself causes significant financial losses. In contrast to this, the insulation regeneration method in the online mode for 25 tons of oil costs around 12,000 euros.

**Transformer insulation regeneration in online mode using synthetic adsorbents includes oil regeneration, purification and drying of liquid and solid insulation**

## 5. Transformer insulation regeneration in online mode using adsorbents

This method includes oil regeneration, purification and drying of liquid and solid transformer insulation. It is based on the process of oil circulation between the transformer and the revitalization device. The oil from the bottom valve of the transformer boiler goes through the containers in which the adsorbents are placed in the form of granules [9]. The oil passes through the filters and returns to the transformer.
In this method, it is possible to use both natural and synthetic adsorbents. However, the experience and the behavior of adsorbents during the oil regeneration has shown that synthetic adsorbents are a better choice. Natural adsorbents cannot be reactivated like synthetic, and also after a while they become hazardous carcinogenic waste. The main feature of the synthetic adsorbents is the high adsorption capacity of all polar molecules, which are a product of degradation of cellulose and oil within the transformer. Granulated adsorbents attract water, acids, peroxides, furans, etc. and permanently hold them on the active surface in their pores. By treating the oil, the imbalance between water and oxidation products within the oil-paper system is created and maintained. In this way, the water and oxidation products are "forced" to pass from the paper to the oil. In a heated/loaded transformer, this migration is faster and more intensive. The length

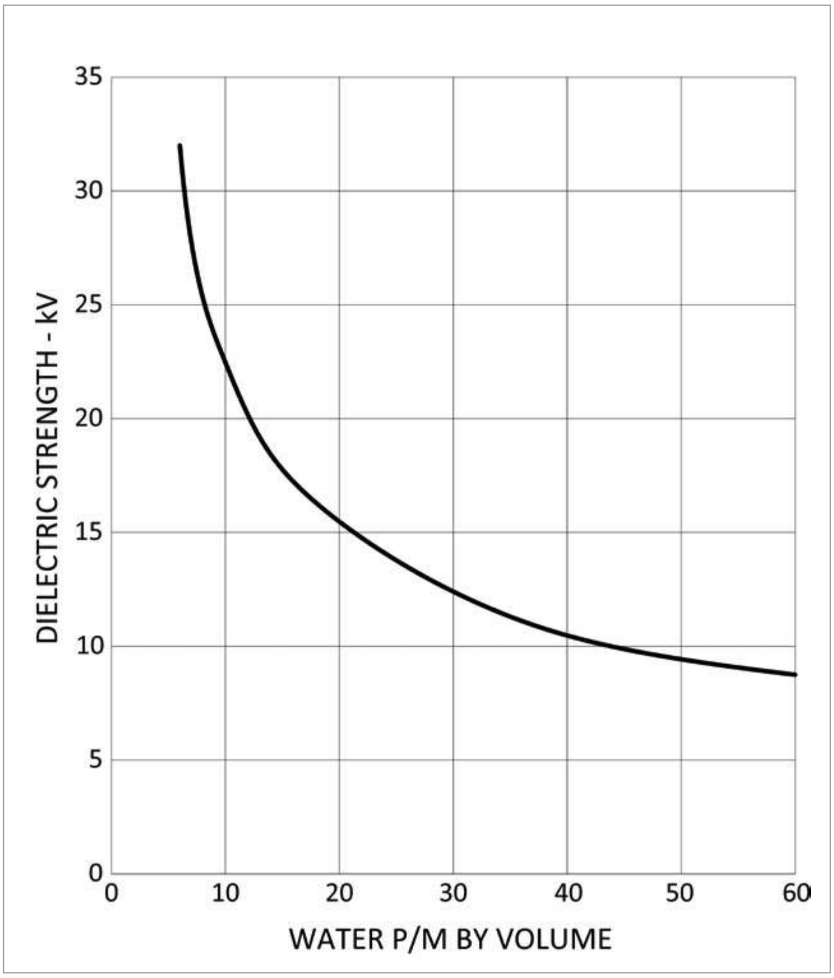


Figure 3. The relation between the dielectric strength and the amount of emulsified water in mineral oil

**The online method eliminates the need for replacement of the old oil with new, extends the lifetime of the transformer, and does not interrupt the normal operation in case of oil regeneration system failure**

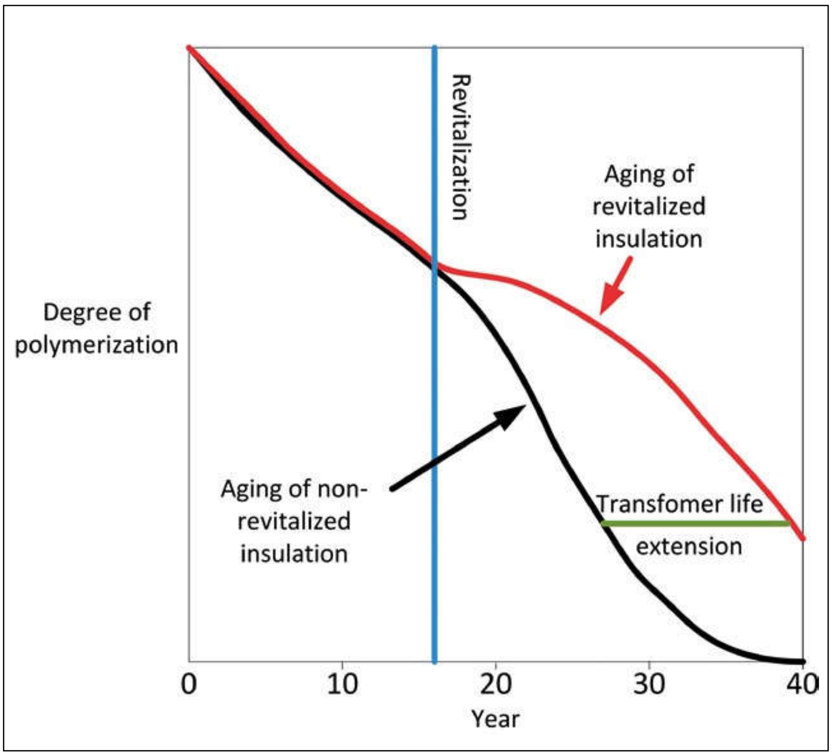


Figure 4. Diagram of transformer aging with and without revitalization

of treatment depends on the condition of the insulation as well as on the load, i.e. the temperature. This results in deep drying and revitalization of transformer insulation. With this method, no additional heating and vacuuming of the oil is required, which can be harmful to the insulation system. The working temperature of the transformer is also working temperature of the treatment.

From the financial standpoint, the benefits of this method are significant. It eliminates the need for the unjustified replacement of the old oil with new, which is an extremely expensive option. Also, the paper that remains contaminated will very quickly contaminate the new oil, which will then lose its properties. A timely application of the regeneration of the complete insulation system can significantly extend the life of transformers. Figure 4 illustrates transformer aging with and without revitalization of insulation.

It should be noted that the transformer is almost 100 % safe from interruption caused by a failure of such transformer oil regeneration systems. They are equipped with a Buchholz relay and other protective equipment which immediately turns off the circulation and leaves the transformer in the operation mode.

### 5.1. Criteria for the application of the transformer insulation revitalization and drying

Drying and revitalization of transformer insulation should be undertaken when the conditions listed in Table 1 are met. ΔTgδ represents the difference in the power factor after the measurement in relation to its initial value. The formation of degradable aging products begins as soon as the transformer is put into operation. Catalysts of this process are: high temperature, acids, vibrations, impact voltage and high electrical shock (overvoltages). Degradable products become non-degradable as the oxidation continues. Finally, they begin to settle first in the cooler area and then on the warm construction parts – the windings and the transformer core.

Table 1. Criteria for undertaking revitalization and drying of transformer insulation (transformer temperature 70 °C)

| | Voltage (HV side) | | |
|---|---|---|---|
| | ≥400 kV | 220 kV | ≤110 kV |
| Water content in paper (%) | ≥1.5 | ≥2.0 | ≥3.0 |
| Water content in oil (ppm) | ≥15 | ≥20 | ≥40 |
| Interfacial intension (mN/m) | ≤30 | ≤30 | ≤30 |
| Power factor ΔTgδ (%) | ≥100 | ≥200 | ≥300 |
| Neutralization number (mgKOH/g of oil) | ≥0.1 | ≥0.1 | ≥0.1 |

**Drying and revitalization of transformer insulation should be undertaken when boundary values of relevant criteria are exceeded**

Table 2. Additional criteria for the application of the insulation revitalization method

| Limit values | Criteria |
|---|---|
| IFT / NN | ≤300 |
| Peroxide content | max. 8 ppm |
| Particle content | max. 10,000<br>(>5 μm in 100 ml of oil) |

An important data for the evaluation of the transformer oil condition is the relationship between interfacial tension (IFT) and neutralization number (NN). In addition, the values of peroxides and particles in oil are observed. Peroxides belong to radicals, and thus belong to compounds that are catalysts of transformer oil polymerization. The removal of peroxide compounds from the oil prevents the progressive chain formation of free radicals, which results in significant improvement in the oxidation stability of the oil. Table 2 presents the limit values of this ratio, and the maximum content of peroxides and particles in oil. Each of the listed limit values indicates that the transformer oil is in poor condition and that certain measures must be taken to stop or significantly slow down the accelerated aging. These values relate to very important transformers such as block transformers, excitation transformers, transformers at important energy nodes, etc.

## 6. Example 1: Steel factory in Zenica, Bosnia and Herzegovina

### 6.1. Background

Zenica steel plant is over 125 years old. Its equipment is quite old and has been successively modernized. It is powered at 110 kV voltage by over six power transformers between 31.5 and 120 MVA (110/35/6 kV and 110/35 kV). Most of the transformers are old, some over 45 years old.

Table 3. Results after transformer insulation regeneration and drying in the online mode

| Transformer no. 1: 31.5 MVA, 110/35/6 kV - 48 years old | | | |
|---|---|---|---|
| Characteristics | Unit of measure | Before treatment | After treatment |
| Dielectric strength, Ep | kv/cm | 219 | 279 |
| Power factor, tg δ [90 °C] | - | 0.272 | 0.0865 |
| Water content at the operating temperature of the transformer [40 °C] | mg/kg | 35 | 14.5 |
| Density of oil at 20 °C | g/cm³ | 0.889 | 0.882 |
| Interfacial tension, σ at 20 °C | mN/m | 18 | 23.9 |
| Neutralization number | mgKOH/g | 0.256 | 0.0538 |
| **Transformer no. 2: 31.5 MVA, 110/35/6 kV - 41 years old** | | | |
| Characteristics | Unit of measure | Before treatment | After treatment |
| Dielectric strength, Ep | kv/cm | 156 | 241 |
| Power factor, tg δ [90 °C] | - | 0.00316 | 0.00229 |
| Water content at the operating temperature of the transformer [40 °C] | mg/kg | 24.6 | 16.2 |
| Density of oil at 20 °C | g/cm³ | 0.872 | 0.866 |
| Interfacial tension, σ at 20 °C | mN/m | 33.4 | 42.2 |
| Neutralization number | mgKOH/g | 0.0437 | 0.0075 |

**The lifetime of the transformer is closely related to the lifespan of its insulation and can be prolonged for over ten years using the online method of insulation regeneration**

### 6.2. Requirements

The results of the physical, chemical and electrical characteristics test revealed that two transformers had characteristics that were not within the allowed values. The oil had poor dielectric strength, high water content, low interfacial tension, and high neutralization number. Since the production at the plant is continuous, it is almost impossible to turn off the transformers over a longer period of time in order to revitalize the entire insulation system. The production cycle is circular and a shutdown of a single plant would lead to large losses.

### 6.3. Solution

The solution included revitalizing and drying transformer insulation in the online mode. Transformers remained in operation, while the boiler was connected to a device with synthetic adsorbents and was constantly circulating for 15 days per transformer. The amount of oil in the transformers was about 24 tons, so with an average flow of 400 kg/h, the entire amount of oil in the transformer passed through this treatment six times.

### 6.4. Results

After the treatment, the results of the transformer oil test showed significant changes. According to IEC 60422:2013, the treated transformers fall into category A – power transformers with a nominal system voltage above 170 kV and below 400 kV, or transformers of any rated voltage where continuity of supply is vital for production process. The dielectric strength of the oil increased to reach a value over 240 kV/cm (according to the standard the value should be over 120 kV/cm for this type of transformer), the water content in the oil decreased, while the neutralization number was brought down to the recommended limits. The complete results are shown in Table 3.

## Conclusion

The lifetime of the transformer is closely related to the lifespan of its insulation (both liquid and solid parts). In order to ensure a timely reaction, it is important to monitor the insulation parameters regularly (for units larger than 5 MVA this includes annual performance of dissolved gas analysis and basic tests). In industrial systems, transformers are exposed to higher loads, overvoltages, dirty environment, all of which can lead to acceleration of insulation degradation process. If the insulation parameters go beyond the permitted limits, it is necessary to employ a method that will revitalize the insulation and possibly extend the transformer lifetime. Larger and more important substations should fulfil the N-1 criteria with the backup transformer, so that one transformer can be taken out of operation and treated. However, especially in industrial applications, there is a high probability of an interruption in the transformer operation, which can lead to large losses due to the suspension of operation. The method of revitalizing transformer insulation (both liquid and solid parts) in the online mode using synthetic adsorbents is an acceptable, cheap, safe and efficient solution for demanding industrial systems. Since most of the water inside a transformer resides in the solid insulation part, it is important to monitor the migration of water to oil after revitalization and repeat the treatments if necessary. A timely reaction and the application of this kind of revitalization can prolong the operation of the transformer for over ten years.

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