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Benefits of Dielectric Oil Regeneration Systems in Power Transmission Networks: A Case Study

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Abstract

The criticality of transformers and reactors in the power transmission network and the paramount importance of ensuring their reliability through maintenance of the insulating oil is known. This paper presents a comprehensive examination of the efficacy and economic viability of a dielectric oil regeneration system, as implemented by the Transmission System Maintenance Department (TSMD) of the Independent Power Transmission Operator (IPTO), Greece's sole transmission operator. Through a detailed chemical analysis and performance evaluation, we assess the impact of the regeneration system on treated insulating oil quality over multiple cycles. The study reveals that the electrical properties of the insulating oil are fully restored after regeneration, negating the need to fully replace it, while the investment becomes cost-neutral within weeks from the commissioning of the regeneration system. This economic analysis, coupled with the system's environmental benefits of reducing waste oil generation, positions the dielectric oil regeneration system as a compelling solution for the maintenance of power transmission assets.

Keywords

Insulating Oil Regeneration, Transformer Maintenance, Economic Analysis, Preventive Maintenance, Case Study

1. Introduction

Transformers not only are the core component of a power transmission network but also are the most expensive and difficult to replace. Ensuring the reliability of transformers is known to be vital for both the availability of the power network and its profitable operation, which is why all Transmission System Operators (TSOs) monitor closely such assets.

Insulation degradation is the core cause of transformer failures. This is closely connected to the quality of the insulating mineral oil contained within the transformer, which must always meet some minimum quality parameters, as those are defined by [1]. Insulating oil in service gradually degrades due to external parameters, such as partial discharges and heat, which will affect the solid insulation of the transformer if left unchecked, greatly reducing its service life. Unlike solid insulation, transformer oil can be treated during a maintenance cycle, thus extending the service life of a transformer.

The application of reclamation techniques for the maintenance of liquid insulation and the extension of the electrical equipment's lifetime has been proposed several decades ago [2]. Earlier purification techniques were focused on the removal of moisture and basic gases, such as oxygen [3]. However, researchers quickly identified that the removal of moisture alone did not offer the expected positive results on the condition of electrical equipment [4]. As the aged insulation oil contains much more than just moisture, such as acids, mud, and numerous gases, the removal of the moisture alone will have little effect on the final quality of the treated insulation oil. Even the complete replacement of the insulating oil only has a partial effect, as it does not clean the oil-soaked insulation of the equipment [5]. That is to be expected because the state of the solid insulation that determines the lifetime of transformers [6]. As the complete replacement of insulating oil on a large transformer requires several dozens of tons of fresh oil and creates an equal amount of waste oil, resulting to high equipment downtime and totaling to a costly procedure, all with questionable results on the lifetime of the equipment, TSOs rarely result to this solution unless it is deemed absolutely necessary.

More recently, researches identified that the use of molecular sieves in combination with classic dehydration and degasification techniques directly on electrical equipment gives significantly better results than simply changing the insulating oil, as the regeneration process also cleans the solid insulation of the equipment [5] [7] [8]. With the oil regeneration process significantly increasing the expected lifetime of critical equipment that is very costly and disruptive to replace, studies suggest that oil regeneration may be, at the very least, a powerful tool, if not the panacea for electric power utility companies [9] [10].

Several researchers investigated the performance and viability of various materials as molecular sieves, such as activated carbon [11] [12], kaolin clay [13], bentonite [14], fuller's earth [15], and even combined strategies [16]. Studies and product availability suggest fuller's earth may be the best all-around solution due to its high availability, low cost, and capacity for easy on-site reactivation of the absorbent [17] [18].

A high-capacity oil regeneration system has been deployed three years ago by the Transmission System Maintenance Department (TSMD) of the Independent

Power Transmission Operator (IPTO), Greece's sole transmission operator. This paper presents a technical and economic analysis of this regeneration system, evaluating its efficacy and cost-effectiveness.

2. Experimental Setup

2.1. Regeneration System Description

The high-capacity oil regeneration system used by IPTO for the treatment of insulation oil and servicing of 40 MVA to 380 MVA transformers.

The regeneration system is divided into five sections: the degassing section, the regeneration section, the control section, and the transformer security system. The basic layout can be seen in Figure 1.

The degassing section removes moisture and basic gases from the oil via heating and high vacuum. For the treatments included in this study, the oil temperature was set to 70˚C and the vacuum is continuously kept below 0.1 bar. The oil input features three filters (100, 25, and 5 μm) for basic particle filtering.

The regeneration section filters the oil via sorbent (fuller's earth). It features twelve sorbent pillars with a total capacity of 1800 kg of sorbent. It is capable of reactivating the sorbent via burning. The gases produced by the reactivation process are processed via an activated charcoal filter.

The control section features the devices and controllers for the pneumatic valves, pumps, heaters, and secondary devices. It is controlled via a PC and secondary PLC controllers, with a SCADA-type software. The operator can control the system's operational parameters and monitor its state via the PC or remotely (4G modem access). Numerous sensors (pressure, foaming, temperature, etc.) and software subroutines comprise the safety structure of the regeneration system.

The system has a maximum throughput of 4 m^3/h but, depending on the moisture content and contaminants, it usually is not feasible to operate the system with a throughput greater than 2.5 m^3/h due to oil foaming. A high

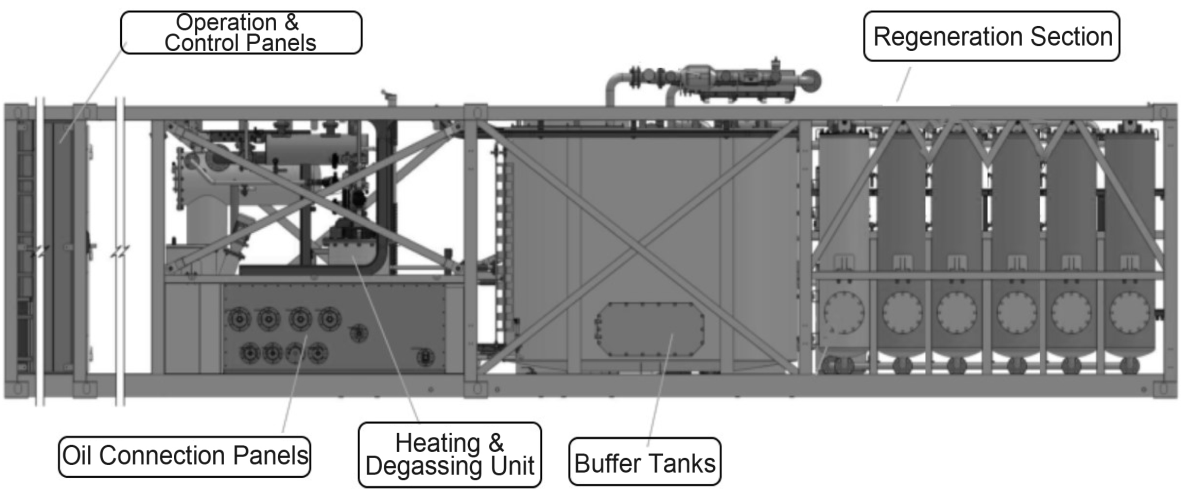

Figure 1. Regeneration system basic layout.

throughput also affects the efficacy of the treatment. For consistency and comparability, the throughput was set to 1.6 m^3/h for all treatments that were included in this study.

2.2. Chemical Analysis

All chemical analyses were performed by IPTO's chemical laboratory. The laboratory is equipped with state-of-the-art testing equipment in order to provide robust accuracy on quality data of transformer oils in relation to their function. Test services are operated in accordance with ISO/IEC 17025:2018, accredited by Hellenic Accreditation System S.A. (ESYD), and performed by highly qualified chemists and chemical engineers.

The dielectric breakdown voltage of transformer oil was measured according to IEC 60156:2018 [19] using an Automatic Oil Breakdown Tester. In each test, 400 mL of oil was added in the test vessel. A standard gap between the mushroom-shaped electrodes was set to be 2.50 ± 0.05 mm and the voltage build-up rate was 2.0 ± 0.2 kV/s.

Water content of oil was measured using an Automatic Karl Fischer Coulometric Titration according to ASTM D6304-20 (Procedure B) [20]. Elevated water content in transformer oil could reduce its dielectric strength, and consequently reduce the life of transformer due to chemical decomposition.

The presence of soluble contaminants and oxidation by-products dissolved in insulation liquids was determined by measuring the interfacial tension between water and oil, according to ASTM D971-20 [21], using an Automated Force Tensiometer.

Oil oxidation and contamination products could also increase the acid content, indicating oil degradation. Total acid number (TAN) was expressed by the quantity of potassium hydroxide (in mg) needed to neutralize the acid in 1 g of oil, according to ASTM D8045-17E1 [22], using a Thermometric Titrator and an Automatic sample preparation system.

Higher rate of degradation or oxidation could cause higher viscosity in insulating oils, decreasing the cooling performance of a transformer. Oil density and oil viscosity determine how oil circulates within the winding structure. Dynamic and kinematic viscosity measurements were performed at 40˚C, whereas density at 20˚C, according to ASTM D7042-21A [23] using a Kinematic Viscometer SVM.

Oil quality is further determined by Dielectric Dissipation Factor (DDF) testing, which measures the leakage current through a transformer oil and reveals the level of contamination. DDF is expressed by the value of Tan δ and it should be as low as possible, with a maximum factor of 0.1. DDF of transformer oil was measured according to IEC 60247:2004 [24] using an Oil Tan Delta Tester.

Phenolic antioxidant 2,6-ditertiary-butyl paracresol (DBPC) is an oxidation inhibitor added to transformer oil in order to prevent its oxidative degradation and extend transformer life. Concentration of DBPC was determined by a FT-IR

Spectrometer according to IEC 60666:2010 [25].

Spectrophotometric determination of the color of lubricating oils was conducted by a Colorimeter according to ASTM D1500-12 (2017) [26].

3. Results and Discussion

3.1. System Efficacy

In order to assess the efficacy of the dielectric oil regeneration system, we performed a chemical analysis of the treated oil before and after a single pass. Each cycle corresponds to roughly 5.600 kg of oil, stored into a single metallic tank. The metallic tanks feature a breather with a moisture absorber installed.

Sorbent reactivation took place after the 9th, 22nd and 30th cycle.

From **Figure 2** and **Figure 3**, we can make several observations on the performance and repetitiveness of the oil regeneration system. The quality of the output deteriorates after each cycle but only the breakdown voltage declines at first, while the tanδ remains steady for several cycles. After the sorbent is fully saturated, the tanδ of the output oil greatly degrades, hinting that the sorbent

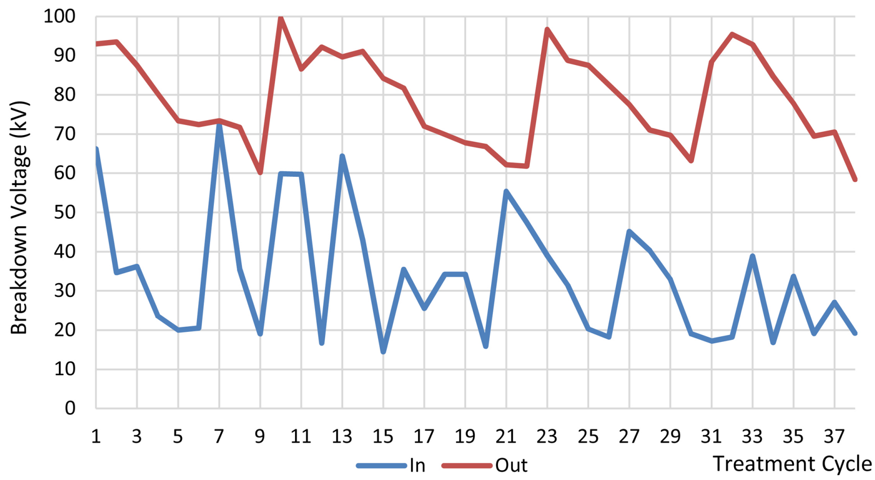

Figure 2. Dielectric strength improvement per treated batch.

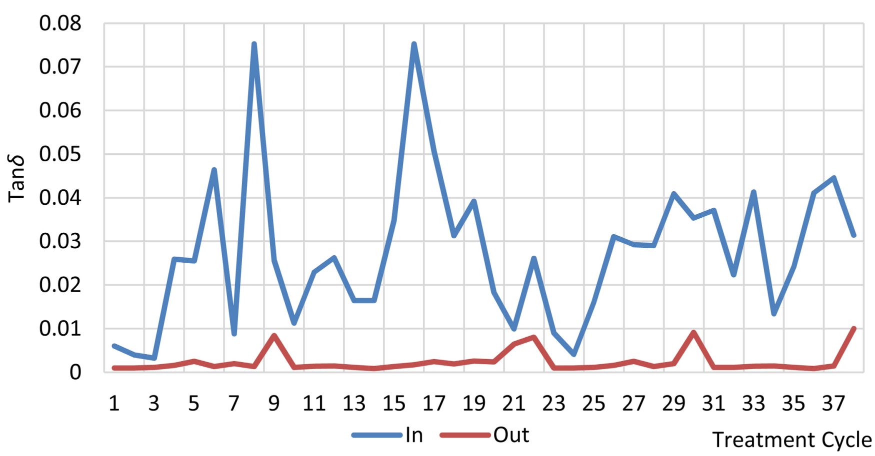

Figure 3. Tanδ improvement per treated batch.

needs to be reactivated for the system to be efficient again. Depending on the quality of the input oil, the system requires a sorbent reactivation roughly per 60.000 lt of treated oil in order to produce acceptable results. It can also be seen that even if the breakdown voltage is improved very slightly, the tanδ of the treated oil can still be significantly improved (cycle #7).

The water content of the oil after the regeneration process was always below 8 ppm, even when the breakdown voltage and tanδ of the oil significantly degraded due to sorbent saturation. This secernates the function of the degassing section from the regeneration section and proves that even if the former performs continually, the regeneration section requires constant monitoring and frequent reactivation of the sorbent in order to produce viable results.

There were no notable variations of the treated oil's dynamic viscosity, kinematic viscosity, or density before and after the regeneration process.

Color is a measurement of the pollution level, with researchers suggesting that a change in color indicates that the oil is polluted with impurities, such as metals, antioxidants, or oxidation products [27] [28]. Nonetheless, color proved to be an ineffective measurement of quality, as it shifts randomly after the regeneration process (**Figure 4**), yet the electrical properties of the oil are greatly improved. The regeneration system filtrates the treated oil with particle filters at both the input and the output of the system. A 1-micron filter is present at the input of the regeneration system that withholds any large particles from entering the sorbent columns. Smaller particles are then captured by the sorbent. The 0.3-micron output filter ensures that no sorbent particles are carried out. This process removes all impurities and additives from the insulating oil, including any oxidation inhibitors such as butylated hydroxytoluene (BHT). Insulating oils exiting the regeneration system are uninhibited and an inhibitor must be added where applicable.

3.2. Cost Analysis

The oil treatment system has a peak power of 70 kW and our energy meters

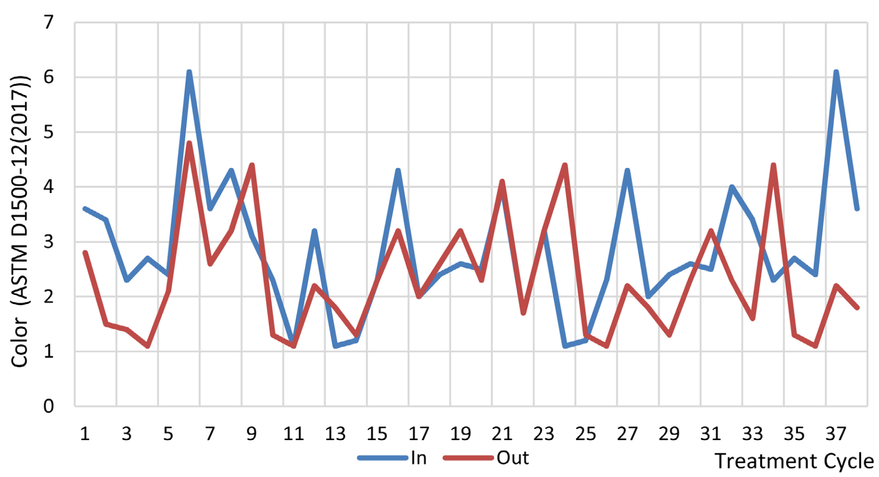

Figure 4. Color shift per treated batch.

reported an average of 42 kW/h during constant operation at 1.600 lt/h. This corresponds to 26.25 kWh per 1.000 lt of output for a single pass. At current energy prices, which are less than 0.2 €/kWh in Europe, the energy cost of the system is negligible (lower than 0.0055 €/lt).

The maintenance requirements of the system are as follows. First, the system produces waste oil that must be appropriately recycled and it corresponds to 2% of its output. The recycling cost varies greatly per location—in Greece, where this study takes place, at the time of this publication the handling and recycling cost is 1.100 € per 1.000 lt of waste oil. This corresponds to a cost of 0.0011 €/lt.

The second requirement lies with the replacement of the system's consumables, which are the sorbent after it can no longer be effectively reactivated and the regular replacement of the filters. The manufacturer of the system suggests that the sorbent can be reactivated up to 100 times but, in our experience, the sorbent had to be replaced after roughly 35 reactivations, with the system having treated about 1.250.000 lt of oil. The replacement of the sorbent, the output filter and the charcoal filter cost 4.100 €, resulting to a cost of 0.00328 €/lt. However, it should be noted that the frequency at which the sorbent needs to be reactivated increases per cycle, which may require optimization if the regeneration system is being used to treat the insulating oil of deenergized equipment, as the frequent reactivation cycles would severely increase the time required to complete the treatment. Furthermore, the personnel and transportation costs are not included in the means of this study.

Summarizing the above, the direct operating cost per treated lt of oil is 0.00988 €, radically lower than the price of new insulating oil (currently at 2.25 €/lt at the time of this article). The capital cost of the regeneration system itself is fully repaid after treating roughly 90.000 lt, or after just 56 operating hours. Therefore, even if the direct costs shift significantly and indirect costs are added to the analysis, the break-even time of the investment is very short.

4. Conclusion

In conclusion, the analysis presented herein unequivocally demonstrates that the dielectric oil regeneration system fully restores the electrical properties of insulating oil, such as the dielectric strength, tanδ, and water content, but also establishes itself as an economically viable and environmentally sustainable solution. The cost analysis further substantiates the economic viability of the system, revealing that the direct operating costs are significantly lower than the expenses associated with procuring new insulating oil, with the system becoming cost-neutral after treating approximately 90,000 liters of oil. This not only underscores the system's financial benefits but also highlights its contribution to environmental sustainability by facilitating the reuse of insulating oil rather than resorting to its replacement and subsequent recycling, reducing new insulating oil requirements by hundreds of tons per annum. Consequently, this study advocates for the adoption of dielectric oil regeneration systems as a financially and environmentally responsible approach to managing insulating oils, thereby supporting the broader objectives of resource conservation and environmental stewardship.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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