PLN's Strategy to Mitigate the Risk of Power Transformer Failure Due to Hydrolysis in Insulation Paper

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***Abstract*— Power transformer failures caused by hydrolysis in insulation paper present significant challenges to the reliability of electrical systems. To mitigate these risks, PLN has implemented a comprehensive strategy that includes enhanced diagnostic processes, design improvements, and optimized treatment procedures. Diagnostic improvements have been achieved through ISO 17025 accreditation and participation in international proficiency testing, ensuring the accuracy and reliability of oil testing results. Design improvements focus on specifying the appropriate conservator type, transitioning from open to closed systems to prevent oxidation. In terms of treatment procedures, PLN has introduced a policy to assess the severity of hydrolysis through furan testing before proceeding with oil reclamation, ensuring the economic feasibility and effectiveness of the process. Several case studies are presented to provide a practical illustration of how these improvements are applied in PLN, demonstrating the company's commitment to extending transformer life and enhancing system reliability.**

Keywords—pln, power transformer, hydrolysis, oxidation, ageing

I. Hydrolysis in Insulation Paper

Insulation paper is a key part of the insulation system in power transformers, and like all materials, it ages over time. The aging of this paper can happen mainly in two ways: hydrolysis and pyrolysis.

Hydrolysis happens when the paper’s structure starts to break down due to water and acids, especially when there is moisture and high temperatures [1] as shown in Figure1. This process weakens the paper, making it less effective at insulating and protecting the transformer, which can eventually lead to failure if not properly controlled. Pyrolysis, on the other hand, occurs due to too much heat, often caused by poor cooling or overloading. This heat speeds up the breakdown of the insulation paper. Both of these processes, hydrolysis and pyrolysis are major factors in the deterioration of transformer insulation paper. To keep transformers working well, it’s important to understand and manage these risks.

Hydrolysis is a chemical reaction where water helps break down the insulation paper. This becomes a big problem in transformers because moisture can speed up the breakdown. But water alone isn’t enough to cause serious damage. Acids, particularly those that contain hydrogen, are needed to really start the process. These acids get into the weaker areas of the paper and cause it to fall apart.

One of the main sources of these acids is the aging of the transformer oil. As the oil gets older, it produces acids that make the hydrolysis process worse. At temperatures around 110-120°C, hydrolysis becomes the main way the paper breaks down. The process speeds up when there are small acids that dissolve in water, which work better than larger acids coming mostly from the oil due to oxidation [2].

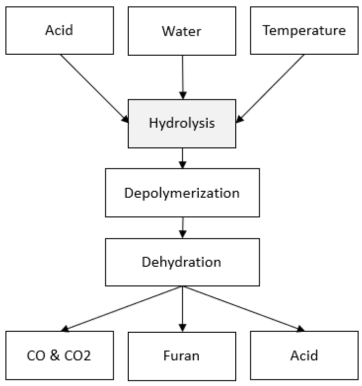

Fig. 1. Hydrolysis process

Hydrolysis is a self-feeding process. As the paper breaks down, it creates more acids, which then make the hydrolysis happen even faster. This makes hydrolysis especially dangerous for transformer insulation because it can cause fast and permanent damage once it starts. That’s why it's important to control moisture and oxidation in transformers to reduce the risks of hydrolysis and keep the insulation paper in good shape.

Pyrolysis is a process where materials break down without needing water, oxygen, or any other outside factor to start the reaction. At normal transformer operating temperatures or during minor overloads (below 140°C), pyrolysis doesn't usually happen and isn't something to worry about. However, at higher temperatures, which can be caused by issues like bad connections or local heating from electrical faults, pyrolysis can occur. When this happens, gases like carbon monoxide (CO) and carbon dioxide (CO_2) are produced [2], signaling that the insulation is breaking down. While it's not a concern during regular operations, pyrolysis can become a problem when there are defects or overheating.

II. PLN’s Challenges with Hydrolysis and Transformer Failures

In terms of design, some of the power transformers managed by PLN are still at risk of experiencing hydrolysis. This is because many of these transformers still use open breather conservators, where the insulating oil is exposed to oxygen from the outside air, increasing the risk of oxidation as shown in figure2.

The reason many power transformers still use open breather conservators is that the standardization for transformers with closed-type conservators was only introduced around 2010. As a result, older transformers were built with the older design, which allows more interaction with oxygen, leading to potential insulation degradation.

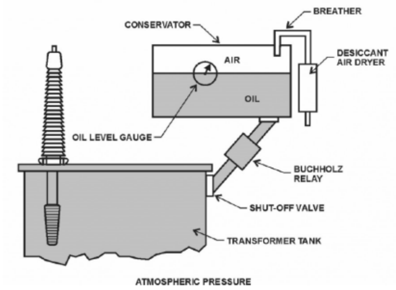

Fig. 2. Power transformer with open type conservator

The impact of hydrolysis can lead to insulation failure of the transformer’s paper, making the transformer unable to operate again. In some cases, it can even result in catastrophic events, such as fires, which can also damage surrounding equipment as shown in figure3

Fig. 3. Power transformer failure due to hydrolysis

III. PLN’S MITIGATION STRATEGIES: DIAGNOSTICS, TREATMENT AND DESIGN CHANGES

To reduce the risk of transformer failure caused by hydrolysis, PLN has taken several steps. These include improving diagnostic processes, treating oil that has oxidized, and redesigning transformer conservators to prevent oxygen from coming into contact with the oil.

A. *Improving Diagnostic Process*

PLN has been performing oil quality tests for a long time to check whether the insulating oil used in power transformers has undergone oxidation. This is assessed through various indicators such as the acid number, interfacial tension, and oil colour. These three test items demonstrate a strong correlation with one another, making them effective for cross-confirmation during the diagnostic process[3]. To enhance the accuracy and dependability of these test results, PLN has implemented several measures. These include obtaining ISO 17025 accreditation, taking part in proficiency testing programs, and benchmarking against other testing facilities.

Over the past five years, three of PLN's transmission units have received ISO 17025 accreditation specifically for testing the acid number. In 2024, two transmission units also participated in a proficiency test, achieving commendable results across several tested parameters.

Additionally, in 2024, PLN collaborated with the Institute Inter-lab Studies (ISS) to conduct a proficiency test covering various insulating oil test items. One of the key parameters assessed was the acid number, which was determined using the ASTM D 664 standard. The results of this acid number test were positive, as shown by a Z-score analysis. The Z-score is a statistical measure used to evaluate the consistency and reliability of results across different laboratories[4]. In this test, PLN identified as the 10th laboratory, achieving a Z-score of -1.17 for the acid number, as illustrated in Figure 4. This result demonstrates that PLN's measurements are consistent and reliable when compared to other participating labs and considered as satisfactory result.

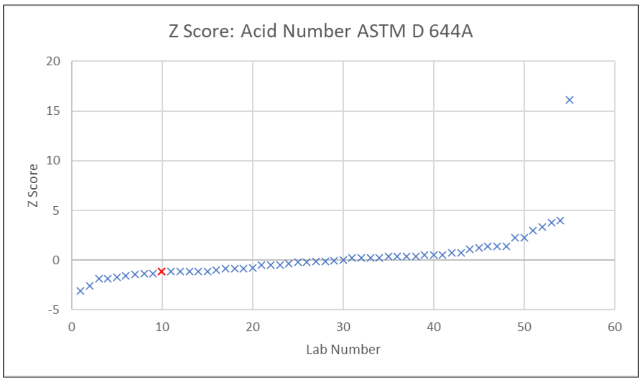

Fig. 4. Z Score for acid number test

Since the early 2000s, PLN has been part of a technical discussion group consisting of power transmission utilities from Southeast Asia. This involvement enables PLN to benchmark various technical aspects of asset maintenance, including transformer insulating oil testing. Figure5 illustrates an example of a benchmarking activity carried out by PLN at a transformer oil testing laboratory owned by an electricity utility abroad.

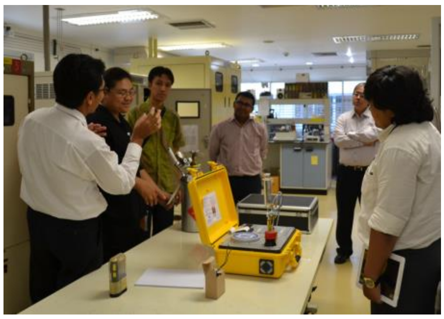

Fig. 5. Benchmarking with transformer oil laboratories of similar utilities abroad

B. *Treatment*

According to the IEC 60422 standard, when insulating oil experience oxidation which evidenced by a high acid number, decreased interfacial tension, and a darker oil colour, it is recommended to perform oil reclamation [6]. PLN has been implementing this practice since the early 2000s, initially relying on third-party services to handle the oil reclamation process.

Fig. 6. Reclamation process using PLN machine

Recently, PLN has made significant improvements by using its own equipment for reclamation, which is usually employed for filtering processes aimed at reducing moisture content in the insulating oil. This shift allows PLN to take more control over the reclamation process, enhancing flexibility and operational efficiency as shown in figure6.

Through a financial analysis based on a cost-benefit approach, PLN can determine which reclamation method is both economical and effective. The choice can be between using third-party services with the re-activated method or opting for the dumping method, which PLN can execute independently at a much lower cost.

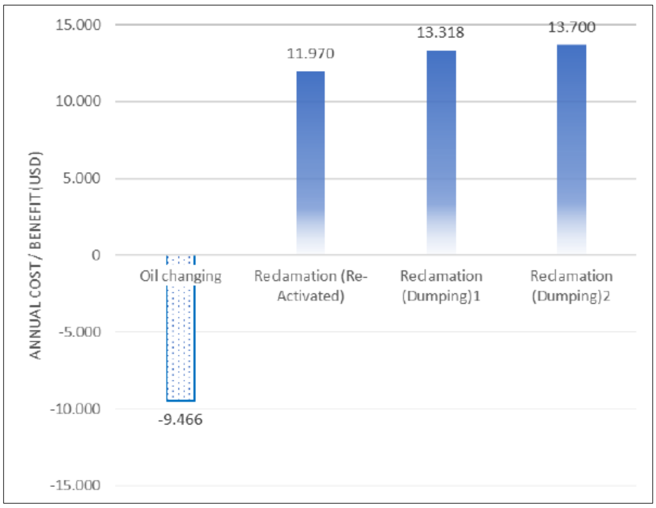

Fig. 7. Cost & Benefit Analysis on several treatment method

Based on the study conducted by PLN comparing the costs and benefits of various treatment methods for oxidized oil as shown in figure7, it was found that certain methods, such as oil changing, result in significant financial losses. In contrast, the Reclamation methods, particularly Reclamation (Dumping)1 and Dumping 2, offer considerable cost savings, with Dumping 2 proving to be the most cost-effective option[5].

To expand further, PLN has a policy that requires a thorough check of the paper insulation's health before proceeding with any oil reclamation efforts. This is done using a furan test, which helps determine the condition of the insulating paper. If the test reveals that the remaining lifespan of the paper is almost exhausted, meaning the paper strength is approaching 0%, then reclamation is not a practical or cost-effective solution. In such situations, it is best to shut down the transformer and replace it entirely. This is because, even if reclamation improves the oil quality, the weakened state of the paper insulation means that the transformer is still at high risk of failure. Ensuring the paper insulation is in good condition is a crucial step to prevent repeated breakdowns and maintain the reliability of the power transformer.

C. *Design changes*

One of the measures taken by PLN to eliminate the possibility of hydrolysis in transformer oil is to prevent oxidation. This is achieved by switching the conservator used in transformers to a closed-type design. By using a closed-type conservator, the insulating oil is no longer exposed to oxygen, which effectively stops the oxidation process from occurring.

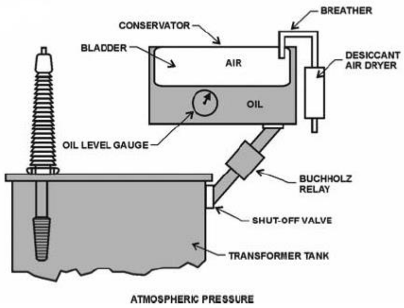

Fig. 8. Power transformer with closed type conservator

This policy was outlined in PLN's standards and began to be implemented around 2010. The shift to this design ensures better oil preservation and enhances the longevity and reliability of the transformers.

IV. CASE STUDY

This case study explains the right and wrong ways to handle oxidation that happens in insulating oil. If oxidation is not handled properly, it can make the oil break down through hydrolysis, which could eventually cause the power transformer to fail. The right handling can prevent damage and help the transformer work efficiently for a longer time, while improper handling can lead to serious issues, including transformer breakdowns.

A. *Improper handling on oil oxidation*

The IBT 500/150 kV power transformer at the Kembangan substation had a design with an open breather conservator. In 2007, it was discovered that the quality of the insulating oil had significantly deteriorated. The acid number, interfacial tension, and oil colour were all categorized as poor. In response, PLN carried out oil reclamation in 2008 to restore the quality of the insulating oil. This effort was successful, and the oil condition was brought back to a normal, acceptable state. However, because the conservator still used an open breather type, the oxidation process began again, leading to a recurrence of the problem.

By the time reclamation was performed, the process of hydrolysis had already progressed significantly. The paper insulation inside the transformer had lost nearly all of its strength, as shown by the furan test results, which estimated that the paper strength was almost zero. Despite the temporary improvement in oil quality, the damage to the paper insulation was too severe to fully recover the transformer's health.

Due to these issues, the transformer eventually failed in 2009 [7]. A short circuit occurred in the winding, leading to a complete failure of the transformer. This failure highlighted the risks associated with the use of an open breather conservator, which allows the oxidation process to persist and worsen over time.

To effectively handle transformers affected by oxidation, it is critical to first determine the severity of the hydrolysis process before deciding on any further action. Understanding how badly the paper insulation has been damaged is essential before deciding whether reclamation is viable or if a direct replacement is necessary. This step is crucial for ensuring that the right measures are taken, as trying to reclaim a transformer with severely degraded insulation might be ineffective and could lead to further failures. Proper evaluation helps in making informed decisions, potentially avoiding costly and dangerous transformer breakdowns in the future.

B. Proper handling on oil oxidation

Power Transformer unit 2 at the Mekarsari Substation showed signs of oxidation based on tests for acid number, interfacial tension, and colour of the oil. Before deciding to proceed with the oil reclamation process, a furan test was performed to determine how severe the hydrolysis had affected the transformer. Fortunately, the results of the furan test showed that about 75% of the paper insulation's lifespan remained, making it economically feasible to reclaim the transformer's oil.

TABLE I. BEFORE AND AFTER RECLAMATION TEST RESULT

Transformer unit 2 Mekarsari S/S	acid number (mg KOH/g)	Interfacial tension (mN/m)	Colour
Before reclamation	0.178	13.8	4.8
After reclamation	0.038	27.1	2.9

After a few weeks of the oil reclamation process, the results showed improvements in the insulating oil of the transformer, with better acid number, interfacial tension, and colour as shown in table1. This process was also carried out using equipment owned by PLN, making the entire procedure very economically efficient

V. CONCLUSION

Hydrolysis and oxidation in power transformer insulation paper and oil are critical factors that affect the performance and longevity of transformers. PLN has effectively addressed these challenges through a combination of diagnostic improvements, design enhancements, and refined treatment procedures. By obtaining ISO 17025 accreditation, conducting international proficiency tests, and specifying closed-type conservators, PLN has strengthened its approach to mitigating transformer failures. Furthermore, the policy of assessing hydrolysis severity through furan testing before reclamation ensures that the most cost-effective and technically sound decisions are made.

Case studies highlight the success of these strategies in extending the operational life of transformers, improving oil quality, and reducing the risk of catastrophic failures. Overall, PLN's initiatives have resulted in significant operational and economic benefits, reinforcing the company's commitment to maintaining high standards of system reliability and transformer health.

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