Comprehensive Regression Modeling for Evaluating Chemical Properties of Transformer Oil under Thermal Aging Conditions

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***Abstract*—This study examines thermal aging effects on transformer oil's acidity and water content using an innovative exponential regression approach. Mineral oil samples were aged at 80°C, 100°C, 120°C, and 140°C for 5000 hours, with properties measured at 500-hour intervals. Results reveal temperature-dependent degradation, showing accelerated deterioration above 100°C. The exponential model achieved strong correlations ($R^2 > 90\%$) for both acidity and water content, demonstrating its effectiveness in predicting oil aging. These findings provide valuable insights for transformer condition assessment and maintenance planning, highlighting the model's potential for practical application in power system reliability management. The research establishes clear relationships between thermal stress, chemical degradation, and measurable oil properties, offering a robust framework for transformer health monitoring.**

***Index Terms*—Transformer oil, chemical properties, acidity, water content, thermal aging, correlation, regression.**

I. INTRODUCTION

Power transformers depend fundamentally on mineral oil insulation for reliable operation. As the oil degrades, continuous monitoring becomes vital to detect early deterioration and schedule maintenance, thereby protecting power system stability. This requirement reflects the oil's critical dual function as both electrical insulator and coolant [1], [2].

Transformer oils undergo progressive degradation from electrical, thermal, and chemical stresses, causing molecular alterations that reduce stability through oxidation and decomposition. These changes compromise oil performance, necessitating regular monitoring of key electrical, chemical, and physical properties. Such assessments enable early detection of insulation degradation, optimized maintenance, and enhanced network reliability [3].

Moisture ingress in transformers, driven by aging and environmental factors, degrades both liquid and solid insulation, impairing dielectric strength and partial discharge performance. Water and oxygen accelerate oil aging while compromising cellulose paper insulation, as moisture absorption and oxygen dissolution collectively weaken dielectric properties [4], [5].

Temperature fluctuations critically accelerate transformer insulation degradation through moisture redistribution between oil and paper components. These thermal cycles additionally modify the oil's physicochemical properties, further compromising performance. When combined with moisture, oxygen, and electrical stresses, temperature emerges as a dominant aging factor [6], [7].

Thermal aging progressively deteriorates transformer oil's insulating properties, reducing breakdown voltage and resistivity while increasing energy losses. This process also produces harmful dissolved gases and damages solid insulation by weakening paper's molecular structure and mechanical strength. These well-established degradation patterns highlight the critical link between oil and paper aging [8], [9].

Numerical models using regression analysis have extensively studied transformer oil aging. However, most fail to properly account for temperature's critical impact on degradation rates. Since temperature directly controls oil breakdown, its omission reduces model accuracy. Reliable aging predictions require explicit temperature integration to capture long-term deterioration [10], [11].

This study introduces a unified exponential model to simultaneously analyze thermal aging effects on transformer oil's acidity and water content, extending prior electrical property research [12]. Samples were aged at 80°C, 100°C, 120°C, and 140°C for 5,000 hours, with 500-hour measurements. The model quantitatively correlates these chemical properties with aging progression across all tested temperatures.

II. Experimental Work

Thermal aging experiments were conducted on new transformer oil samples (Borak 22, Nynas, Graz, Austria), which are utilized by the Algerian Electricity and Gas Company, Sonelgaz, in Algiers, Algeria. The properties of the new oil samples are detailed in Table I.

TABLE I: Properties of the Oil Samples

Property	Standard	Unit	Value
Breakdown voltage	IEC 60156	kV	79.8
tan δ (90 °C)	IEC 60247	—	$5\text{x}10^{-4}$
Resistivity (90 °C)	IEC 60247	Ω.cm	$7.66\text{x}10^{13}$
Permittivity	IEC 60247	—	2.13
Acidity	IEC 62021	mg KOH/g	$1.17\text{x}10^{-2}$
Water content	IEC 60814	ppm	8.2
Colour factor	ISO 2049	—	<0.5
Density (20 °C)	ISO 3675	g/ml	0.680
Flash point	ISO 2719	°C	140
Viscosity (40 °C)	ISO 3104	mm^2/s	6.998

In accordance with the established guidelines outlined in standard [13], the sampling procedure is meticulously executed to ensure sample integrity. The process begins with the cleaning, drying, and heating of glass bottles to eliminate contaminants and residual moisture. Fresh transformer oil is then introduced into these preconditioned containers and securely sealed using cork plugs wrapped in aluminum foil. The samples are subsequently subjected to controlled thermal aging in four independent ovens maintained at 80°C, 100°C, 120°C, and 140°C for 5000 hours.

Measurements of the acidity factor and water content are conducted at 500-hour intervals throughout the aging process under all specified temperature conditions, in accordance with the relevant standards [14], [15].

III. Correlation Based on Regression Approach

Regression analysis is a key technique for establishing the relationship between experimental values and statistical variables. By fitting data to a regression model, it helps identify patterns and dependencies, offering insights into system dynamics. Correlation analysis is used to assess both linear and nonlinear dependencies between variables, with stronger correlations occurring when the values closely align with experimental data. This enhances the applicability of regression analysis in exploring functional relationships. Numerical and graphical methods facilitate the visualization of these relationships. This study investigates potential nonlinear correlations between measured values and random variables, providing a comprehensive assessment of their interdependencies [16].

When random variables show nonlinear variation, their correlation is typically described by a nonlinear equation. Graphical analysis of the data helps to visualize the relationship, followed by nonlinear regression to model the dependencies. However, nonlinear data often show variability, and a low coefficient of determination suggests a weak correlation, indicating that the model may have limited accuracy. This could be due to other factors influencing the data or a more complex relationship. Even so, significant correlations can still be identified, highlighting the importance of analyzing the data distribution [17].

Our previous study [12]utilized an exponential regression model to assess the effects of thermal aging on the electrical properties, including breakdown voltage, dielectric dissipation factor, and resistivity of insulating oil. In this work, we extend our investigation to the chemical properties, specifically examining the acidity factor and water content.

The mathematical expression that characterizes the model is given in Equation 1

$$y_i = a * exp(bx_i) + c * exp(dx_i) \tag{1}$$

where,
x_i is the period of aging
y_i is the chemical property.
a, b, c and d are the parameters of the model.

Equation 2 defines the predicted values (Y) from the exponential regression model for acidity and water content.

$$Y = [y_1, y_2, y_3, ..., y_n] \tag{2}$$

The X vector, as defined in Equation 3, represents the aging period values of the oil at various aging temperatures.

$$X = [x_1, x_2, x_3, ..., x_n] \tag{3}$$

R-squared (R^2) is a measure used to see how well the regression model matches the data. It indicates how well the model explains data variation: a higher R2R2 implies a better fit, while a lower one indicates a weaker fit [18]. The value is calculated using the sum of squares, as shown in Equation 4.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(yi - \hat{yi})^2}{\sum_{i=1}^{n}(yi - \bar{yi})^2} \tag{4}$$

where,
y_i are the experimental values of each chemical property,
$\hat{y_i}$ are the values derived from the regression analysis correlated for each chemical property,
$\bar{y_i}$ are the average of the test values at each data point..

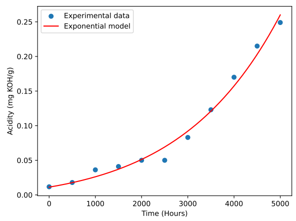
IV. Results and Discussions

A. Acdity Factor

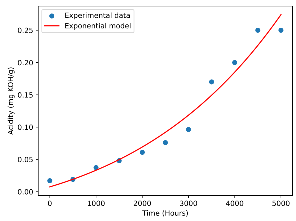
The acidity factor variations versus time for the four aging temperatures are presented in Figure 1.

The figure reveals a temperature-dependent rise in acidity during thermal aging. While 80°C and 100°C show gradual increases, 120°C exhibits faster growth, and 140°C demonstrates marked acceleration, confirming enhanced degradation at elevated temperatures.

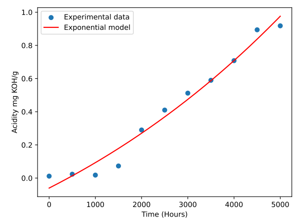
Figures 1a (80 °C) and 1b (100 °C) exhibit comparable acidity growth, increasing from 1.17×10^{-2} to $\sim 25 \times 10^{-2}$ mg KOH/g over 5000 h. Both trends remain within industry limits, confirming stable degradation under moderate thermal aging.



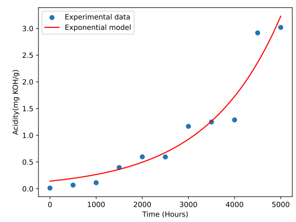
(a) 80°C



(b) 100°C



(c) 120°C



(d) 140°C

Fig. 1: Acidity factor variations with aging duration at different temperatures.

As shown in Figures 1c and 1d, the acidity increases significantly at elevated aging temperatures of 120 °C and 140 °C, reaching values of 91.8×10^{-2} and 301.9×10^{-2} mg KOH/g, respectively, after 5000 h of thermal aging. The industry-accepted limit is exceeded after 2000 h at 120 °C and within just 1500 h at 140 °C. These results demonstrate accelerated thermal degradation and highlight the necessity for careful monitoring to maintain acidity within permissible standards [14].

Thermal aging drives acidity growth in transformer oil through oxidative degradation. Higher temperatures exacerbate this process by promoting ionic mobility, fostering reactive species accumulation, and reducing viscosity. These interconnected mechanisms highlight temperature's pivotal role in accelerating chemical breakdown, ultimately determining the oil's long-term stability.

Regression analysis demonstrates a nonlinear correlation between acidity and thermal aging, as shown in Figures 1a–1d. The model achieves correlation coefficients of 98.53% at 80°C, 96.64% at 100°C, 97.35% at 120°C, and 93.96% at 140°C, confirming its accuracy in quantifying thermal degradation for long-term oil assessment.

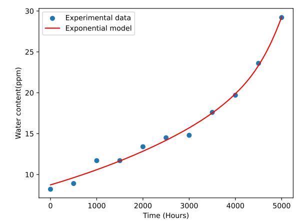
The regression parameters a, b, c, and d, which define the relationship between thermal aging and the acidity factor, are presented in Table II.

TABLE II: Acidity Factor Regression Parameters

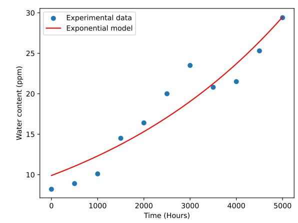
Parameter	**T = 80°C**	**T = 100°C**	**T = 120°C**	**T = 140°C**
a	-41.33	-93.74	-52.80	7.24×10^{-2}
b	3.35×10^{-4}	1.86×10^{-4}	7.30×10^{-5}	6.20×10^{-4}
c	41.34	93.75	52.74	6.95×10^{-2}
d	3.35×10^{-4}	1.87×10^{-4}	7.58×10^{-5}	6.20×10^{-4}

B. Water Content

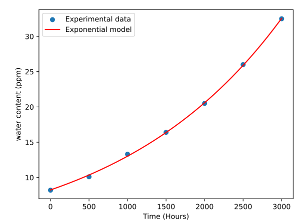
Figure 2 presents the experimental and numerical analysis of water content evolution in transformer oil under accelerated thermal aging at 80°C, 100°C, 120°C, and 140°C. The study compares measured data with simulated values to evaluate temperature-dependent behavior.



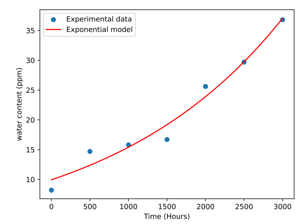
(a) 80°C



(b) 100°C



(c) 120°C



(d) 140°C

Fig. 2: Water content variations with aging duration at different temperatures.

Water content increases progressively with thermal aging across all tested temperatures. While this rise remains relatively steady at 80°C and 100°C, it becomes notably more rapid at 120°C and 140°C. The accelerated increase at higher temperatures highlights the intensified effects of thermal aging, emphasizing the greater impact of elevated temperatures on the degradation process.

Figures 2a (80°C) and 2b (100°C) show water content increasing similarly from 8.2 ppm to 29 ppm after 5000 hours. Both remain below the safety limits in industry standards [15], meaning the oil stays stable under normal operating temperatures.

Both Figures 2a and 2b, corresponding to aging temperatures of 80°C and 100°C, respectively, exhibit a similar upward trend in water content as thermal aging progresses. Specifically, Figure 2a (80°C) demonstrates an increase from an initial value of 8.2 ppm to 29.2 ppm after 5000 hours of aging, while Figure 2b (100°C) shows a comparable rise, reaching 29.4 ppm within the same period. These results remain within the acceptable industry standards, suggesting that under moderate thermal aging conditions, the oil maintains its stability and does not undergo significant moisture-induced degradation [15].

At elevated thermal aging temperatures of 120°C and 140°C, as illustrated in Figures 2c and 2d, the water content exhibits a pronounced increase, reaching 32.5 ppm and 36.8 ppm, respectively, after 3000 hours of aging. These values surpass the critical thresholds defined by industry standards, indicating a substantial accumulation of moisture and highlighting the intensified degradation effects associated with higher thermal stress [15].

The observed rise in water content is linked to the production of oxidation products due to prolonged overheating during thermal aging. Increased temperatures facilitate ionic mobility, which in turn exacerbates ionic conduction losses and leads to a subsequent rise in water content [19].

The regression analysis demonstrates a strong non-linear correlation between water content and thermal aging, effectively capturing the variations observed across different temperature conditions. The model exhibits a high degree of accuracy in representing the experimental data, as reflected in the computed correlation coefficients of 99.16%, 90.12%, 99.96%, and 97.02% for aging temperatures of 80°C, 100°C, 120°C, and 140°C, respectively.

Table III presents the regression parameters a, b, c, and d.

TABLE III: Water Content Regression Parameters

Parameter	T = 80°C	T = 100°C	T = 120°C	T = 140°C
a	7.73×10^{-4}	5.08	3.2	2.87
b	1.81×10^{-3}	2.18×10^{-4}	4.58×10^{-4}	4.38×10^{-4}
c	8.73	4.81	5.02	7.06
d	1.92×10^{-4}	2.18×10^{-4}	4.58×10^{-4}	4.38×10^{-4}

V. Conclusion

This study employs a regression-based methodology to examine the influence of thermal aging on the chemical properties of insulating oil, specifically the acidity factor and water content. Experimental analyses were conducted at temperatures of 80°C, 100°C, 120°C, and 140°C over a duration of 5000 hours. By implementing a regression analysis utilizing an exponential model, mathematical formulations were derived to characterize the temporal evolution of these chemical parameters under varying thermal conditions. In contrast to prior studies that predominantly assess these properties in isolation, this research integrates them within a unified analytical framework, thereby offering a more comprehensive and systematic understanding of the degradation mechanisms governing insulating oil under prolonged thermal stress.

As expected, thermal aging progressively increased both acidity and water content. This study advances the field by applying an exponential regression model to both parameters simultaneously at four aging temperatures (80°C, 100°C, 120°C, and 140°C). The unified modeling framework improves degradation assessment accuracy, with all correlation coefficients exceeding 90%, demonstrating robust capture of thermal aging effects. However, model applicability remains constrained to our experimental conditions.

This integrated approach significantly improves transformer oil assessment by simultaneously tracking acidity and water content evolution under thermal stress. The methodology enhances condition monitoring accuracy and enables predictive maintenance through early deterioration detection. These capabilities support proactive interventions, ultimately ensuring transformer reliability and operational efficiency.

References

[1] V. Wasserberg, H. Borsi, and E. Gockenbach, "A novel system for the prolongation of the lifetime of power transformers by reduced oxidation and aging," in *Conference Record of the 2004 IEEE International Symposium on Electrical Insulation*, Sep. 2004, pp. 233–236.

[2] T. O. Rouse, "Mineral insulating oil in transformers," *IEEE Electrical Insulation Magazine*, vol. 14, no. 3, pp. 6–16, May 1998.

[3] T. K. Saha, "Review of modern diagnostic techniques for assessing insulation condition in aged transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 10, no. 5, pp. 903–917, Oct 2003.

[4] V. Vasovic, J. Lukic, D. Mihajlovic, and Bran, "Aging of transformer insulation of experimental transformers and laboratory models with different moisture contents: Part ii — moisture distribution and aging kinetics," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 5, pp. 1563–1571, 2021.

[5] I. Fofana, H. Borsi, E. Gockenbach, and M. Farzaneh, "Aging of transformer insulating materials under selective conditions," *European Transactions on Electrical Power*, vol. 17, pp. 450–470, 2007.

[6] W. Zhang, J. Liu, and X. Wang, "Dielectric response of oil-paper insulation under varying temperature and humidity," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 2, pp. 153–162, 2023.

[7] J. Wang, L. Zhang, and Q. Liu, "Thermal aging of oil-paper insulation: Influence on dielectric properties," *Journal of Electrical Engineering and Technology*, vol. 18, no. 3, pp. 895–904, 2023.

[8] S. Abdi, A. Boubakeur, and A. Haddad, "Influence of thermal ageing on transformer oil properties," in *2008 IEEE International Conference on Dielectric Liquids*, June 2008, pp. 1–4.

[9] M. Singh, V. Jindal, and J. Singh, "Effects of thermal aging on blended oil characteristics in comparison to mineral oil and synthetic esters," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 4, pp. 1540–1547, Aug. 2023.

[10] S. Abdi, N. Harid, L. Safiddine, A. Boubakeur, and A. M. Haddad, "The correlation of transformer oil electrical properties with water content using a regression approach," *Energies*, vol. 14, no. 8, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/8/2089

[11] D. Peng, D. Yang, C. Wang, and M. Li, "Research of the dielectric loss factor tan delta of transformer oil by multi-parameter regression analysis," in *2009 Asia-Pacific Power and Energy Engineering Conference*, 2009, pp. 1–3.

[12] S. Abdi, B. A. Besseri, A. Haddad, N. Harid, and A. Boubakeur, "Advanced regression modeling for correlating transformer oil electrical properties with thermal aging trends," in *2024 59th International Universities Power Engineering Conference (UPEC)*. IEEE, Sep. 2024, pp. 1–6.

[13] *IEC 60475: Insulating Liquids – Oil-Impregnated Paper and Pressboard, Method of Sampling Insulating Liquids*, International Electrotechnical Commission (IEC), 2011.

[14] *IEC 62021-1: Insulating Liquids – Determination of Acidity – Part 1: Automatic Potentiometric Titration*, International Electrotechnical Commission (IEC), 2003.

[15] *IEC 60814: Insulating Liquids – Oil-Impregnated Paper and Pressboard – Determination of Water Content – Karl Fischer Method*, International Electrotechnical Commission (IEC), 1997.

[16] Z. Ádám Tamus, "Regression analysis to evaluate the reliability of insulation diagnostic methods," *Journal of Electrostatics*, vol. 71, no. 3, pp. 564–567, 2013, journal of ELECTROSTATICS, Electrostatics 2013 12th International Conference on Electrostatics. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0304388613000089

[17] U. Kovacević, M. Vujisić, B. Iričanin, P. Osmokrović, and S. Milosavljević, "The correlation and regression between the pre-breakdown current and breakdown voltage of the vacuum switchgear in dependence of switching operation," in *2014 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, June 2014, pp. 384–387.

[18] J. A. Esfahani, M. R. Safaei, M. Goharimanesh, L. R. De Oliveira, M. Goodarzi, S. Shamshirband, and E. P. Bandarra Filho, "Comparison of experimental data, modelling and non-linear regression on transport properties of mineral oil based nanofluids," *Powder technology*, vol. 317, pp. 458–470, 2017.

[19] B. P. Kang, "Thermal dependency of viscosity, power factor, and ion content of electrical insulating oils-iii predictions of power factor of oil blends through the concept of ion content," *IEEE Transactions on Electrical Insulation*, vol. EI-2, no. 2, pp. 121–128, Aug 1967.