An Evaluation and Correlation Study of Oil and Solid Insulation in Power Transformers using Composite Index Considering Operating Age

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Abstract: Power transformers, integral to electrical systems, necessitate substantial investment. Their operational longevity hinges critically on the quality of their insulation system. This study focuses on evaluating the condition of both oil and solid insulation within transformers, which is vital for preventing operational failures. The condition of oil insulation is influenced by a blend of chemical, electrical, and physical properties, while the aging of solid insulation is an irreversible process that ultimately dictates the end of a transformer's service life. Recent advancements, notably the guidelines from CIGRE TB 761, have provided a comprehensive framework for assessing transformer insulation. These guidelines employ a multi-parameter approach to derive a consolidated insulation index. This study applies the CIGRE TB 761 methodology to a population of 357 power transformers, facilitating a detailed comparative assessment of the oil and solid insulation. This paper discusses the methodology used and presents the results, highlighting the evaluation of both oil and solid insulation aspects. Furthermore, it investigates the relationships between various testing parameters and the overall insulation index in relation to the transformer's age. For oil insulation, key parameters include interfacial tension, color, breakdown voltage, acidity, and moisture content. Solid insulation assessment predominantly revolves around parameters such as methane, ethylene, ethane, carbon monoxide, carbon dioxide, CO2/CO ratio, and DP value. This study also correlates the insulation condition in power transformers to the operational age, and thereby contributing to more effective monitoring and maintenance strategies.

Keywords: Power Transformer; Condition Assessment; Oil Insulation; Solid insulation; Health Index; Transformer Assessment Index; Scoring Matrix; Transformer Operating Age.

1. Introduction

Power transformers are essential electrical components that need hefty system investments. Based on the manufacturer's intended lifespan, they should last for a number of years, providing consumers with a dependable supply of electrical energy [1]. Power transformers are supposed to last 25 to 40 years, according to manufacturers. However, in reality, some transformers in the field experience failures before reaching the manufacturer's expected operational lifespan [2]. These failures are often attributed to the aging of transformer insulation, and repairing or replacing such transformers can be a time-consuming and costly process [1].

It is possible to determine how old transformer oil is by looking at the insulation materials—oil and solid. Aspects such as chemical, electrical, and physical variables can have an impact on transformer oil insulation quality [3]. On the other hand, solid insulation ages and is difficult to replace; in reality, oil insulation in transformers may be changed on a regular basis [4]. As a result, the longevity of a transformer is contingent upon the state of its solid insulation. Four factors contribute to the aging of cellulose solid insulation in oil-filled power transformers: high temperatures, oxygen, acidity, and humidity. Depolymerization or chain breakage as a result of this deterioration lowers the tensile strength of the solid and produces glucose. Furans are therefore only created when the insulating solid degrades [5].

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Transformer solid insulation has varying assessments for each characteristic based on prior research, which results in disparate conclusions and understandings of the transformer's state. [6] [7]. References [2] and [6] discuss transformer oil insulation studies. The relationship between transformer age and a number of oil and solid factors has been investigated in earlier research. The majority of studies show a significant relationship between transformer age and acidity [1] [8] [9] [10] [11].According to some research, the color and moisture content of the oil can act as markers of age for the solid as well as the [12] [13] [9] [11]. Nevertheless, no study has examined the relationship between the age of the transformer and oil and solid indices. As a result, this study provides a weighting technique of 1 for each parameter and evaluates the solid index using the CIGRE TB 721 (2019) standard [14].

This study employs an evaluation matrix to generate assessment indices for transformer oil and solid insulation at PT. PLN UIT JBM. Utilizing the scoring matrix technique, a singular value representing the transformer's condition can be computed based on multiple test parameters for both transformer oil and solid insulation. These insulation parameters adhere to the standards outlined in CIGRE TB 761 (2019) [14]. Additionally, the primary objective of this research is to establish the connection between the transformer's age and oil and solid indices, along with various parameters such as CO, CO2, CO2/CO, CH4, C2H4, C2H6, dp value, moisture in oil, acidity, Interfacial Tension (IFT), color, and acidity. Employing linear regression analysis, the study uncovers a robust correlation between the oil and solid indices, as well as diverse oil parameters, and the transformer's age [15].

2. Transformer Insulation Assessment Index

A. Definition and Purpose of the Transformer Insulation Assessment Index

The Transformer Insulation Assessment Index is an evaluation of the condition of transformer oil and solid insulation as a composite measure of transformer health. The assessment of the insulation index is done by combining the evaluation of transformer insulation from several oil and solid parameters into a single assessment, which becomes the composite transformer index [14]. By assessing using the composite index, it becomes easier to comprehensively evaluate the health of the transformer since it provides only one value for the transformer's condition [16]. Additionally, the composite index also facilitates the implementation of assessments on a large number of power transformers. Using this approach, it becomes easier to identify poor conditions in transformers and ensure that their maintenance becomes a priority.

B. Parameters considered in the index calculation

The computation of the composite index necessitates the examination of both mineral oil and insulation solid characteristics in the transformer, as these factors enable the assessment of transformer oil degradation and the detection of various failure modes such as arc flash, partial discharges, excessive heat, overload, and aging of the insulation solid [17]. Testing the oil and insulation solid is vital for identifying damage to construction materials that can compromise electrical equipment's functionality and decrease the transformer's lifespan [13]. The assessment of transformer oil insulation encompasses tests to evaluate physical, chemical, and degradation contamination modes. Physical contamination is gauged through breakdown voltage and moisture in oil tests, while chemical contamination is assessed by examining moisture in oil, BDV, acidity, and Interfacial Tension (IFT) [14]. Moreover, measuring BDV, acidity, IFT, and color changes determines degradation. Heat generated by the insulation system can lead to increased water presence in insulation oil, resulting in accelerated oxidation and hydrolysis processes. The decrease in insulation quality is indicated by combining two failure modes, hot metal covered by solid and accelerated cellulose aging, with parameters such as Ethylene (C2H4), CO, CO2, 2FAL, CO2/CO ratio, moisture in oil, IFT, acidity, and color scale playing essential roles in this assessment [18][13][19][20][21]. Factors like the degree of polymerization, water content, and the presence of furan in the transformer oil are also influential in ga uging solid insulation degradation [4].. The concentration of furan is impacted by operating temperature, age, and the quality of solid insulation material [22].

C. Aggregation method used to calculate the composite index

To perform the aggregation of the composite index for transformer insulation based on CIGRE TB 761 (2019), several scoring and weighting steps are required for each parameter [14]. Scoring involves categorizing each transformer oil and solid insulation parameter into different levels, namely A, B, C, D, E, and F, as shown in Table 1. Then, the score for each parameter is determined based on its category. Category A has a score of 0, category B has a score of 1, category C has a score of 2, category D has a score of 4, and category E has a score of 10 [14]. Meanwhile, category F is proposed to have a value of 20. Table 1 provides the scoring table for each parameter of the composite mineral oil- solid insulation in transformers based on CIGRE TB 761 (2019).

Table 1. Scoring of Each Mineral Oil- Solid Composite Insulation Parameter [14]

Composite Index	Condition Indicator	Category	unit	Scoring Matrix					
				F	E	D	C	B	A
				20	10	4	2	1	0
solid Insulation	Methane/CH_4	All	ppm	> 2000	> 1500	< 1200	401– 1000	121- 400	< 120
solid Insulation	Ethylene/C_2H_4	All	ppm	> 700	> 400	< 250	101– 200	51– 100	< 50
solid Insulation	Ethane/C_2H_6	All	ppm	> 800	> 500	< 200	101-150	66-100	< 65
solid Insulation	Carbon Monoxide/CO	All	ppm		< 5000	< 2500	571 -1400	351 - 570	< 350
solid Insulation	Carbon Dioxide/ CO_2	All	ppm		< 35000	< 17500	4001 - 10000	2500 - 4000	< 2500
solid Insulation	CO_2/CO Ratio	All				< 3			> 3
solid Insulation	DP Value Est	All			< 200	200 - 300	301 - 400	401 - 500	≥ 500
solid Insulation / Oil Insulation	Moisture in Oil	<72,5	ppm		>40		30-40	<30	<20
		72,5-170			>30		20-30	<20	<10
		>170			>20		15-20	<15	<10
solid Insulation / Oil Insulation	Acidity	<72,5	mg KOH/g		>o.30		0.15-0.30	<0.15	≤0.03
		72,5-170			>0.20		0.10-0.20	<0.10	
		>170			>0.15		0.10-0.15		
solid Insulation / Oil Insulation	Inter-facial Tension	Inhibited	mN/m		<22		22-28	>28	>35
		Uninhibited			<20		20-25	>25	
Oil Insulation	Color (by Lab testing)	All		Dark Brown (5.5 - 8.5)	Amber (4.0 - 5.5)	Bright Yellow (2.5 - 4.0)	Yellow (1.0 - 2.5)	Pale Yellow (0.5 - 1.0)	Clear (0.0 - 0.5)
Oil Insulation	BDV IEC 60156 2.5mm	<72,5	kV		<30		30-40	>40	>55
		72,5-170			<40		40-50	>50	>60
		>170			<50		50-60	>60	

After the scoring process, weighting is employed to determine the relative importance of each parameter in influencing the composite index of transformer insulation. Prior research has used different weighting factors, including 1 for acidity, 2 for Interfacial Tension (IFT), and 3 for breakdown voltage, moisture content, and various gases. Some studies have utilized the Analytic Hierarchy Process (AHP) to derive weighting factors [2][7] [23][24]. In this study, a weight of 1 is assigned to each parameter, assuming equal importance in determining the composite index of transformer insulation.

3. Methodology

A. Selection of power transformer population

The data used in this research consists of test results of the insulation oil and solid of power transformers. This is because power transformers have a high investment value and are vital equipment. The study utilizes the test results of oil and solid insulation from 357 transformers located within the population of the Transmission Network Unit - East Java and Bali, Indonesia. All the measurement data were collected from three-phase power transformers with primary voltages of 70 kV, 150 kV, and 500 kV. The observed operation time of the transformers ranged from 1 year to 47 years, and the power ratings ranged from 10 MVA to 500 MVA. With diverse samples of transformers analyzed, it allows for comparison of each transformer based on its age conditions.

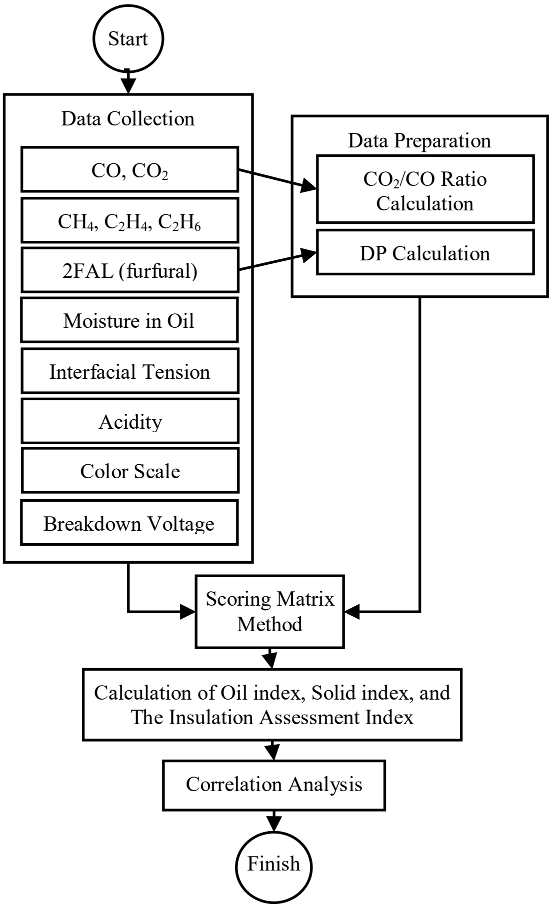


Figure 1. Flowchart of Insulation Assessment Index

B. Calculation of the Transformer Insulation Assessment Index

For computing the transformer insulation evaluation index through the scoring matrix method, which involves scoring, weighting, and aggregation, the subsequent weighted average equation is applied [14]:

$$\text{Mineral Oil- solid Composite Insulation Index} = \frac{\sum_{i=1}^{N} Si \ x \ Wi}{\sum_{i=1}^{N} Wi} \quad (1)$$

The variable "n" represents the number of parameters used, while the symbol "S" is used to denote the assessment score for each parameter. Furthermore, the symbol "W" is used to indicate the appropriate weight assigned to each parameter. This process enables the calculation of the solid insulation assessment index and the evaluation of this index for each specific transformer. The study then suggests a range for the solid insulation index and organizes it into categories labeled as A, B, C, D, E, and F, as detailed in Table 2, according to the calculated results.

Table 2. The Proposed of Mineral Oil- solid Composite Index

Insulation Index	Category
0-0.65	A
0.65-1.4	B
1.4-3	C
3-6.4	D
6.4-13.67	E
>13.67	F

4. Results and Discussion

A. Correlation analysis of age and the Transformer Insulation Assessment Index

In this section, we elaborate on the correlation analysis between age and the evaluation of the composite index for both transformer oil and solid insulation, along with the individual oil index and solid index. To investigate the connection between each transformer insulation index and the transformer's age, we employ the linear regression method [18]. The correlation coefficients resulting from the linear regression analysis of each parameter in relation to the solid index and the transformer's age are presented in Table 3.

Table 3. The Correlation of Insulation Index to Age

Parameter	r	p-value
Insulation Index	0.701	0
Oil Index	0.480	0
Solid Index	0.651	0

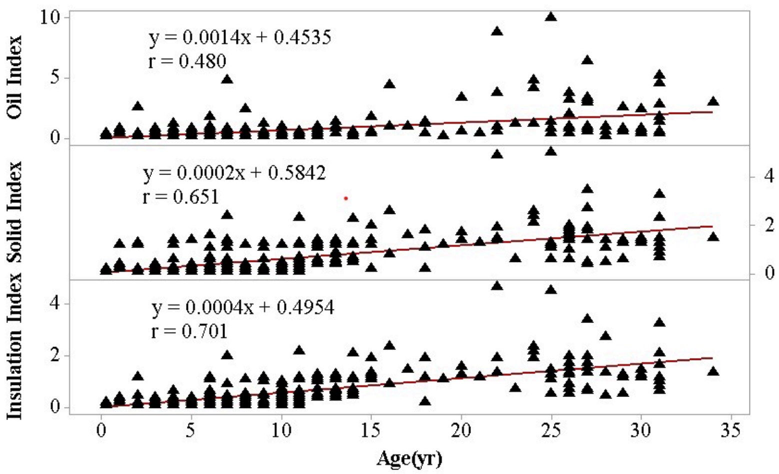


Figure 2. The Correlation Coefficient Between the Insulation Index, Oil Index, and Solid Index with The Operating Transformer Life

Table 3 underscores that when assessing transformer insulation using a composite index, it displays the strongest correlation with the operational age of the transformer. Figure 2 additionally affirms a positive relationship between the age of the transformer and the insulation index of the transformer. As the transformer's operational age increases, the insulation index value tends to rise. This strong and significant correlation is evidenced by the correlation coefficient of 0.701 with a P-value of 0.00, signifying a strong correlation

[15][18][12]. Moreover, the correlation is considered significant as the P-value is less than 0.05 [18]. Consequently, employing the transformer insulation composite index offers an accurate representation of the transformer's aging condition.

Table 3 reveals that evaluating transformer oil using the oil index and solid index shows a reasonably strong correlation with the transformer's operational age, although it's not as strong as the correlation with the insulation index. Figure 2 confirms a positive correlation between transformer age and both the oil and solid indexes, where higher transformer age corresponds to higher index values. The correlation coefficients of 0.480 and 0.651, with a P-value of 0.00, indicate a strong and significant correlation[18][15][12]. Utilizing the composite index for transformer solid assessment allows for an accurate representation of solid aging.

B. Correlation analysis of each parameter with age

Table 4. The Correlation of Each Parameter with Age

Parameter	r	p-value
CO	0.135	0.022
CO_2	0.457	0
CO_2/CO	0.217	0
CH_4	0.434	0
C_2H_4	0.197	0
C_2H_6	0.446	0
Acid	0.194	0
IFT	-0.414	0
Moisture in Oil	0.461	0
BDV	-0.269	0
Color	0.613	0

Table 4 shows the correlation of each parameter of solid and oil insulation with the age of the transformer. Parameters that have a strong and significant correlation with the age of the transformer are CO_2, CH_4, C_2H_6, IFT, moisture in oil, and color. These parameters have an "r" value greater than 0.4 and a p-value less than 0.005. On the other hand, in this study, parameters CO and C_2H_6 have the weakest correlation with the age of the transformer because they have the lowest "r" value.

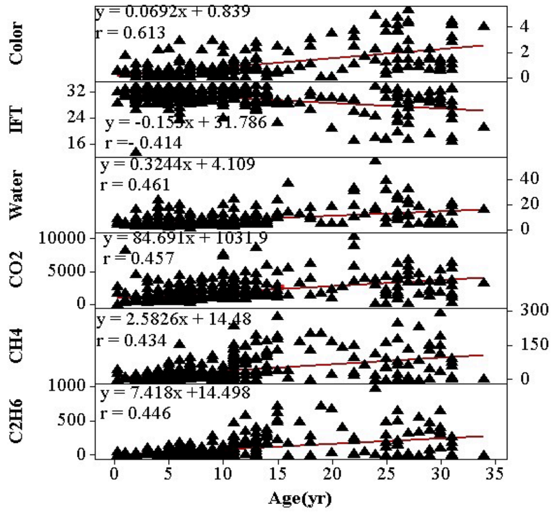


Figure 3. The Correlation Coefficient Between Color, IFT, Water content, CO_2, CH_4, C_2H_6 and Operating Transformer Life

Table 4 and Figure 3 show that the color index strongly correlates with transformer age, with a significant correlation coefficient of 0.613 [18]. This correlation is considered significant because the p-value for this parameter is < 0.05. Darkening of insulating oil, resulting from the accumulation of oxidation by-products over the transformer's operating life, serves as a reliable indicator of aging and the presence of contaminants [18][21][25][26]. As the transformer ages, the color of the oil insulation progressively darkens, reinforcing this correlation [18].

IFT (Interfacial Tension) strongly correlates with transformer age, with a correlation coefficient of -0.414, signifying that as the transformer ages, IFT decreases [18]. IFT reflects the oil-water interface strength, and contamination with substances like soap, varnish, and oxidation products makes the oil more susceptible to degradation [27][28]. When IFT falls below an acceptable threshold, cooling issues may arise, indicating the presence of contaminants like water, primarily due to oxidation product contamination [27].

Moisture in oil strongly correlates with transformer age, with a correlation coefficient of 0.461. As the transformer ages, moisture content in the oil increases, serving as an indicator of aging and potential contaminants[25]. Aging and oxidation processes contribute to this increase, primarily through oxidation and hydrolysis[14][29]. With continued transformer operation, especially under high loads or faults[30], moisture content rises[26], posing risks like degradation in solid insulation, bubble formation, and electrical disturbances such as partial discharges[14]. Interestingly, in the early life of the transformer, moisture in oil is relatively high and decreases as the transformer ages.

Parameters such as IFT, color, and moisture in oil can indicate aging in the transformer due to their high correlation with the age of the transformer [18][9][10][31]. The presence of water in the oil can be generated through the processes of hydrolysis and oxidation, which produce water as a by-product [13]. These parameters can then be used to interpret the aging of transformer insulation.

CO_2 exhibits a significant correlation with transformer age, with a correlation coefficient of 0.457. As the transformer ages, the CO_2 content increases increase [10], as depicted in Figure 3. Initially, at a young age, the transformer has low CO_2 content, which rises over time.

Figure 3 shows a strong correlation between transformer age and the levels of CH_4 and C_2H_6. As the transformer ages, the concentrations of CH_4 and C2H6 in the oil insulation gradually rise, leading to an accelerated aging rate. This relationship is expressed through a linear regression equation. High values of Dissolved Gas Analysis (DGA) in the oil insulation are primarily linked to transformer aging, with oxygen influencing oil insulation degradation and water affecting cellulose aging [32]. Additionally, excessive heat and discharges play a role in aging by producing hydrocarbons like CH_4 and C_2H_4.

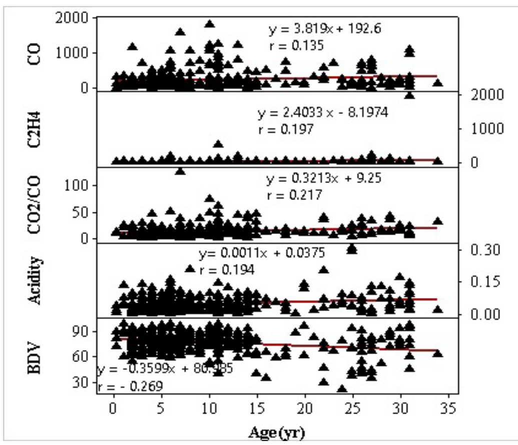


Figure 4. The Correlation Coefficient Between CO, C_2H_4, CO_2/CO, acidity, BDV and The Operating Transformer Life

On the other hand, Table 4 displays the correlation between the age of the transformer and CO, CO_2/CO, C_2H_4, acid, and BDV (Breakdown Voltage) parameters. The correlation is considered weak because “r” values are less than 0.4, and the corresponding P-values indicate a lack of significance. Figure 6 presents the scatter plot for all these parameters.

Figure 4 reveals a positive link between CO, C_2H_4, CO_2/CO, and acidity levels in transformer insulation and its age, while the breakdown voltage has a negative correlation. As the transformer ages, CO, C_2H_4, CO_2/CO, and acidity increase, and breakdown voltage decreases, as evident from the trend lines in the scatter plots.

Cellulose aging leads to the production of water, CO, and CO_2 as primary byproducts, resulting from oxidation and hydrolysis processes [32]. The quantities of these products increase as cellulose aging progresses. However, it's essential to note that, while CO_2 is often utilized as a marker for cellulose aging, its increase is not a linear accumulation over time. The quantity of CO_2 can decrease due to factors like evaporation, interactions with other gases, or potential losses during reclamation processes. In the end, the CO_2 level will revert to its original value, reflecting the extent of aging [5]. Despite serving as an indicator of cellulose aging, the rise in CO_2 is not solely linked to continuous accumulation. The CO_2 amount may also diminish due to factors such as evaporation, interactions with other gases, or potential losses during reclamation procedures [15].

C. Comparison of index correlation vs. single parameter correlation with age

From Table 4, it is evident that assessing the transformer's condition using an index has a higher correlation with its age compared to assessing the transformer's insulation using individual parameters. This correlation indicates that the index has a stronger and more significant relationship with the age of the transformer. Therefore, evaluating the transformer's insulation using an index can better represent the aging of the transformer compared to evaluating the insulation based on individual parameters. Assessing the transformer's insulation with an index also allows for a comprehensive evaluation, which is particularly helpful when dealing with a large number of transformers. Using an index combines several values into a single score, making it easier to determine the next treatment for the transformer.

On the other hand, the correlation of single-parameter insulation assessments with age has lower values, indicating weaker correlations with the age of the transformer compared to the index-based evaluation. The best correlation among the single parameters with the age of the transformer is the color scale parameter, with an r-value of 0.613.

However, there are limitations to calculating composite indices as the determination of weighting for each parameter may vary. If weighting values are not appropriate, it could lead to a failure mode of the transformer's insulation not being detected due to a seemingly good index value. This could result in a decrease in the accuracy of assessing the actual condition of the transformer.

D. Interpretation and discussion of the findings

Utilizing a scoring matrix for the computation of the oil index, solid index, and insulation index will simplify the assessment of the transformer's state, facilitating the prioritization of required maintenance procedures.

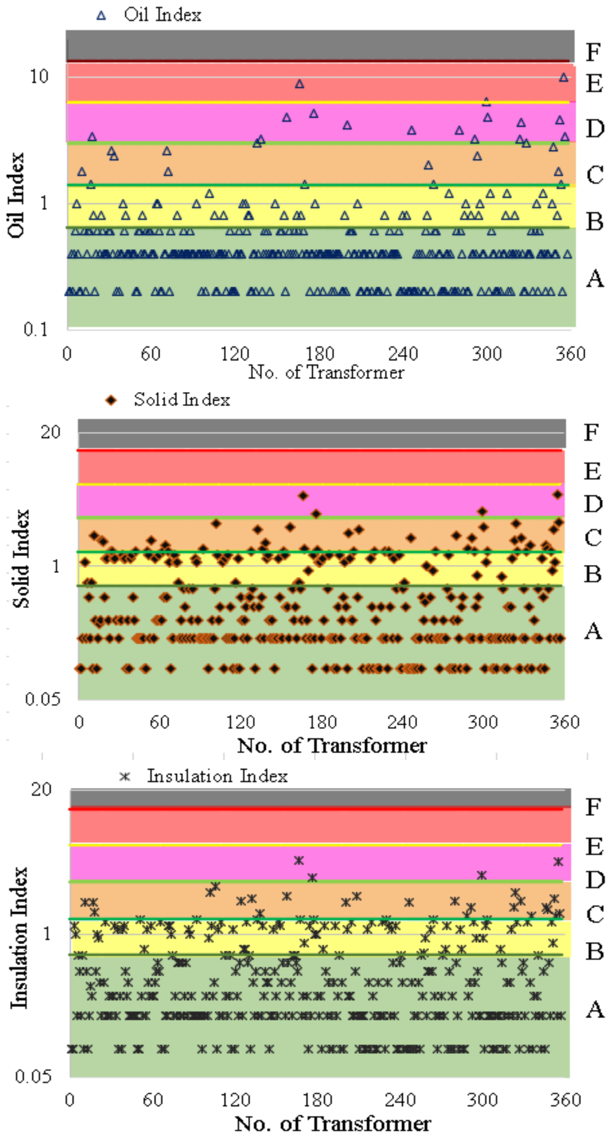
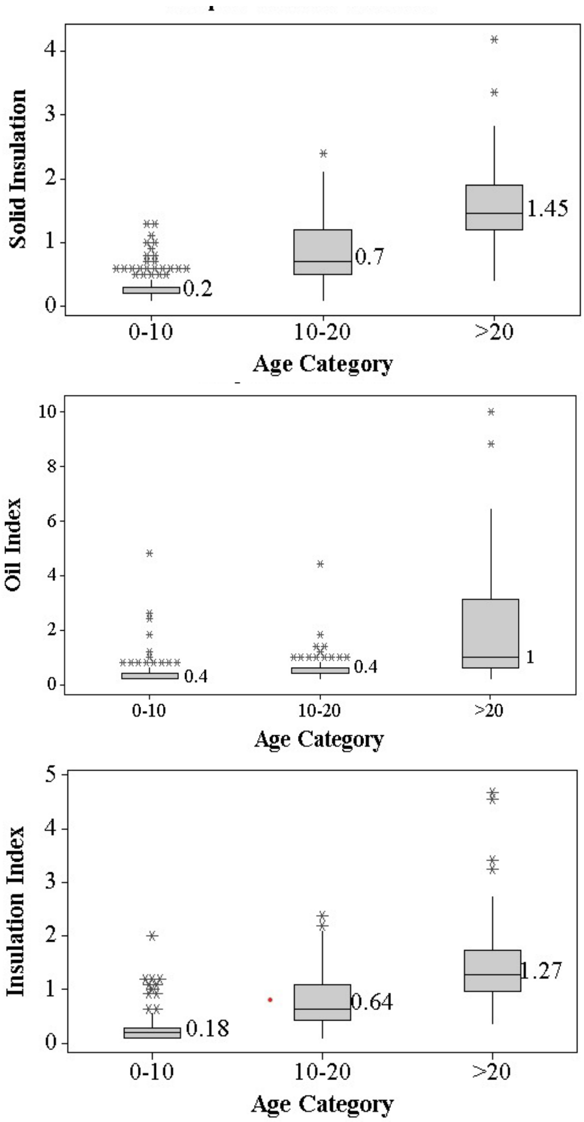


Figure 5. Condition Assessement Index of 357 Power Transformers

In Figure 5, which shows the scatter plot of oil index of transformers at UIT JBM, there are 3 transformers that have an index categorized as E. Hence, it is advisable to promptly undertake reconditioning, reclamation, or replacement of the dielectric liquid for these transformers [14]. The transformers with index category E are transformers 166, 299, and 355. Taking immediate action for these transformers is essential to address the potential degradation in the dielectric liquid and ensure the reliability and longevity of the transformers. On the other hand, this shows the scatter plot of the insulation index and the solid index of transformers at UIT JBM, there are 4 transformers that need to be prioritized for treatment because they have a D index: transformers 166, 176, 299, and 355. It is advisable to address the underlying factors contributing to the degradation of the dielectric liquid and explore options for reconditioning or reclamation.



		0-10 year	11-20 year	>20 year
Solid Index	Q1	0.2	0.5	1.2
	Q2	0.2	0.7	1.45
	Q3	0.3	1.2	1.9
	n	225	78	55
Insulation Index	Q1	0.09	0.41	0.95
	Q2	0.181	0.63	1.27
	Q3	0.27	1.09	1.72
	n	207	93	57
Oil Index	Q1	0.2	0.4	0.6
	Q2	0.4	0.4	1
	Q3	0.4	0.6	3.1
	n	207	93	57

Figure 6. Box Plot of Assessment Index and Age Category

An analysis of the box plot reveals a clear pattern: transformers in the 0-10 years age category show an average Solid Insulation Index of 0.2, indicating relatively minimal solid insulation damage. As transformers move into the 10-20 years age group, the median index value increases to 0.7, signifying more significant degradation. Transformers aged over 20 years exhibit the highest median index value at 1.45, indicating severe solid insulation damage.

Similarly, in the case of transformer oil insulation, those within 0-10 years age range have an average index of 0.181, suggesting lower levels of damage to both oil and solid insulation. In 10-20 years age range, the median index value rises to 0.63, reflecting increased degradation. Transformers older than 20 years have the highest median index value of 1.27, pointing to more severe insulation damage. These trends also apply to the oil index.

These findings emphasize the progressive and irreversible deterioration of power transformer solid insulation systems as they age. The rising median Transformer Insulation Index values across different age categories, combined with the strong correlation between the insulation index and transformer age, provide compelling evidence of the cumulative impact of aging on transformer insulation. This underscores the irreversibility of the process, particularly in the context of solid insulation.

5. Conclusions

This research evaluated the aging of transformer insulation in 357 transformers, focusing on the oil index, solid index, and an overall insulation index. We found that the insulation index assessment shows the strongest correlation with the transformer's age, more so than the solid index, oil index, or individual parameters. This indicates that the insulation index more accurately reflects the real condition of both transformer oil and solid insulation by integrating multiple parameters. The study also revealed that color and moisture content in transformer oil are significant age indicators, although their correlation values are lower than those of the insulation index and solid index. The insulation index, oil index, solid index, acidity, moisture content, oil color, CO_2, CO, CH_4, C_2H_4, and C_2H_6 positively correlate with the transformer's age, while IFT and BDV show negative correlations. This means that as a transformer operates longer, values of the insulation index, oil index, solid index, and related parameters tend to increase, whereas IFT and BDV decrease. In summary, using a scoring matrix technique for assessing transformer insulation provides valuable insights into their state and aging patterns, highlighting the need for proactive maintenance and ongoing monitoring for consistent and reliable operation. It's also crucial to note that comprehensive evaluations of actual transformer failures should include DGA (Dissolved Gas Analysis) assessments.

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