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Full Length Research Article

ANALYSIS OF THERMAL AGEING EFFECTS ON TRANSFORMER OIL DIELECTRIC PROPERTIES

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ABSTRACT
This study investigates the thermal ageing effects on transformer oil dielectric properties by analyzing three key parameters: breakdown voltage (BDV), operating temperature, and load in oil-immersed distribution transformers. Transformer oil samples were randomly collected from operational units rated at 200, 300, and 500 kVA and subsequently tested in the laboratory. The dielectric strength was measured using an FS 2080 dielectric oil tester, while transformer load was monitored with a 1000-ampere digital clamp meter. Analysis of the data revealed that approximately 60% of the transformers exhibit a degraded BDV, with values reduced below the America standard for testing and measurement (ASTM) minimum standard of 30 kV from the 60–70 kV typical of new oil. Elevated operating temperatures were also observed, exceeding manufacturer nameplate ratings by an average of 10°C for 200 kVA, 6°C for 300 kVA, and 12°C for 500 kVA units, which significantly accelerates the oxidation process in the oil. This thermal stress, often resulting from excess load, localized internal heating, and issues such as loose contacts, low oil level, and water ingress, enhances oxidation reactions that lead to the release of hydrocarbon gases and formation of acidic compounds. These chemical changes degrade the oil's dielectric strength, thereby increasing the risk of sudden transformer failure. The findings underscore the critical need for real-time temperature monitoring and control to mitigate the rapid degradation of insulation oil and extend transformer life.

Keywords: Thermal Ageing, Transformer Oil, Dielectric Properties

INTRODUCTION
Transformers are critical and costly components in electrical power systems, playing a vital role in voltage transformation and efficient energy delivery (IEEE, 1995). [2]. Oil-immersed distribution transformers are used to step down high transmission voltages to lower, usable levels for end users, ensuring that electrical energy reaches consumers safely and reliably (Ab Ghani, 2019) [1]. These transformers operate on the principle of electromagnetic induction; however, during operation they generate heat, which must be effectively absorbed and dissipated by the transformer oil.

Transformer oil commonly a hydro-treated light naphthenic distillate is primarily composed of a complex mixture of hydrocarbons, including both saturated (alkanes) and unsaturated (cycloalkanes or naphthenes) compounds (Kassi, 2015) [3]. Its dual functions of electrical insulation and cooling are essential for maintaining transformer performance. The dielectric strength of the oil, typically quantified by its breakdown voltage (BDV), is a key indicator of its insulating capability. New transformer oil usually exhibits BDV values between 60 - 70 kV; however, field evidence and empirical studies have shown that insulation degradation is a leading cause of transformer failure, with a significant number of units operating with BDV values reduced to or below the ASTM minimum standard of 30 kV (Ab Ghani, 2019) (Petruzella, 1996) [1], [4].

Sustained high temperatures—resulting from excessive load, low oil level, or internal faults such as loose connections—accelerate oxidation reactions within the oil. These reactions lead to the formation of hydrocarbon gases and acidic compounds, as well as a gradual accumulation of moisture (Petruzella, 1996) [4]. Moisture, which can also enter through external sources via weak seals or damaged bushings, is inherently present in transformer tanks due to trapped atmospheric air. When the moisture content exceeds the ASTM D1533 threshold of 35 ppm, the oxidation process is further accelerated, resulting in rapid degradation of both the liquid insulation (oil) and the solid insulation. (Petruzella, 1996) (Mustafa, 2024)[4], [5].

The operational reliability of transformers is heavily dependent on the quality of the transformer oil. Empirical evidence collected over decades indicates that a significant number of transformer failures are attributable to insulation degradation, with studies showing that as many as 90% of in-circuit failures are linked to reduced dielectric strength or low breakdown voltage (BDV) of the oil (Ab Ghani, 2019) (Petruzella, 1996) [1], [4]. New transformer oil typically exhibits BDV values in the range of 60–70 kV, but thermal ageing caused by prolonged exposure to high operating temperatures, excessive load, moisture ingress, and oxidation gradually reduces this value. When the BDV falls to or below the ASTM D877 minimum threshold of 30 kV, the insulation is no longer adequate to protect against electrical discharges, dramatically increasing the risk of sudden transformer failure (Petruzella, 1996) (Mustafa, 2024) [4], [5]. Thus, ensuring that transformer oil maintains high dielectric performance is not only a technical necessity but also a critical economic and safety imperative.

Despite their critical role, many oil-immersed distribution transformers in the field are observed to operate with degraded insulation oil, where the BDV has fallen below the acceptable minimum. This degradation is primarily caused by thermal aging processes, wherein sustained high temperatures accelerate oxidation reactions within the oil. Oxidation not only reduces the oil's BDV by breaking down its hydrocarbon chains but also leads to the accumulation of moisture, either from internal oxidation or from external ingress through compromised seals, which further exacerbates the degradation (Ab Ghani, 2019) [1]. Internal factors such as overload, localized heating due to loose contacts, and low oil levels contribute to this process, ultimately leading to an increased incidence of transformer failures. These operational deficiencies underscore the need for a detailed analysis of the thermal aging effects on the dielectric properties of transformer oil. Given the importance of maintaining high dielectric properties for safe transformer operation, it is crucial to understand how thermal aging is driven by elevated operating temperatures and associated factors of impacts transformer oil's BDV and overall dielectric

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performance. This study analyzes the effects of thermal aging by evaluating breakdown voltage, operating temperature, and load in oil-immersed distribution transformers. The findings underscore the need for real-time temperature monitoring and effective maintenance practices to prevent insulation degradation, thereby reducing the risk of sudden transformer failures.

MATERIALS AND METHODS

This section details the comprehensive methodology and materials used to evaluate the thermal aging effects on transformer oil dielectric properties by measuring transformer load, temperature, and dielectric breakdown voltage (BDV).

Materials

Thermometer, 250 mL Beaker: 1000-Amp Clamp Ammeter, FS 2080 Dielectric Oil Tester:

Method

The experimental procedure was divided into two main parts:

(i) Field data collection and sample acquisition and
(ii) Laboratory testing and system for monitoring transformer oil health.

To ensure accurate assessment of transformer performance, the process begins with transformer load calculation and temperature measurement before conducting further evaluations. The load measurement was performed using a 1000A digital clamp meter while the transformers remained in operation. This measurement was taken from the secondary output cables of each transformer across the Red (R), Yellow (Y), and Blue (B) phases. The clamp meter was applied simultaneously to each phase to obtain the respective load values in amperes.

Following the load measurement, the average load values were determined, and the percentage loading was calculated based on the maximum rated capacity of each transformer. The percentage loading capacity was derived using eqn. (1).

Transformer average loading:

$$A = \frac{R\theta + Y\theta + B\theta}{n} \quad (1)$$

Where n represents the total number of phases.

The percentage (%) loading capacity is computed using eqn. (2).

$$\left(\frac{100 \times A}{L}\right) \quad (2)$$

Where L is the total load capacity of the transformer.

Temperature readings were obtained either from the transformer's built-in temperature gauge, measured in degrees Celsius, or with an external thermometer in cases where the gauge was faulty. The recorded temperatures provide insight into the thermal conditions of the transformer, which is critical in assessing its insulation health and overall operational efficiency.

By establishing the load distribution and temperature conditions, the collected data served as the foundation for further evaluations, including insulation oil testing and condition monitoring of the transformers.

Collection of Insulation Oil Sample:

The insulation oil samples were collected from several actively operating distribution transformers to assess the impact of thermal ageing on dielectric properties. Only transformers in service for less than five years, with unmaintained insulating oil, were selected to capture early degradation indicators. For safety, each transformer was disconnected from its potential before sample collection. Oil samples were obtained through the bottom drain valve of each transformer tank, allowing moisture and particulates to settle naturally within a 15-minute window. Clean, dry 250 mL beakers were used to collect the oil, ensuring that no external contaminants were introduced during the process. Once collected, each sample was clearly labeled with the transformer's identification details and capacity information, then taken to the laboratory for dielectric strength testing. In the lab, the breakdown voltage of each oil sample was measured using standardized procedures, providing essential data to evaluate the health status of the transformer oil and its impact on the overall performance of the distribution transformers.

Measurement and Insulation Oil Test Procedure:

At the Kaduna Electricity Distribution Company transformer workshop, a standardized ASTM method was implemented to assess the dielectric strength of transformer oil samples. Once collected from transformers using the bottom drain valve with care taken to avoid contamination and ensure the samples were representative of oil from units that had been in operation for less than five years the oil was tested to obtain its breakdown voltage (BDV). For this purpose, the FS 2080 oil dielectric tester was employed. This device, powered by a 230 V, 50 Hz, 13 - amp AC mains outlet, is housed in a rectangular aluminum box featuring Liquid Crystal Display (LCD) that shows the BDV readings. The tester utilizes a porcelain glass test cup that accommodates up to 20 mL of oil, and is equipped with two protruding magnetizing brass rods positioned opposite each other with a fixed 2.5 mm gap. During testing, these rods are fully submerged in the oil sample to ensure accurate measurements by preventing localized heating, which could otherwise distort the BDV values. The test cycle automatically records the breakdown voltage for every 60 s, repeating the measurement for a total of six cycles to yield an average BDV for each sample. This comprehensive testing protocol, combined with the prior measurements of transformer load and temperature as well as proper sample collection procedures, provides a detailed understanding of the oil's dielectric condition and overall transformer health. (Degeratu, 2015).

RESULTS AND DISCUSSION

Insulation Oil Dielectric Test Result and Temperature Record

The study examined three categories of public distribution transformers rated at 200 kVA, 300 kVA, and 500 kVA selected based on their history of high failure rates attributed primarily to insulation breakdown. Prior to collecting oil samples, temperature measurements were recorded for each transformer to ensure that the data reflected their operational thermal conditions. The transformer oil samples were then collected, collated, and sent to the laboratory for detailed dielectric strength testing and evaluation. In this investigation, the selected transformer categories represent the most commonly used units within Nigeria's public power distribution network that exhibit a notable incidence of insulation failures. Each oil sample underwent a standardized testing process, and the resulting breakdown voltage (BDV) values were systematically tabulated in table 4 and analyzed for every individual transformer within each category. The comprehensive results provide valuable insight into the relationship between transformer operating conditions specifically load-induced temperature variations and the degradation of insulation oil dielectric properties.

Table 1: Insulation Oil Dielectric Strength Test Results from 10 Sampled 200kVA Transformers

				LOAD IN AMPERE(AMPS)						DIELECTRIC STRENGHT SAMPLED OF TRANSFORMER OIL MEASURED KILOVOLT(**KV**)						
Name of Distribution subs-station	Capacity (KVA)	Secondary Voltage (KV)	Transformer maximum load (amps)	Red Phase	Yellow Phase	Blue Phase	Average Peak Load (Amps)	Percentage (%) load	Temp °C	1ST TEST	2ND TEST	3RD TEST	4TH TEST	5TH TEST	6TH TEST	Average BREAK DOWN VOLTAGE **(BDV)**
AMBAM KAF	200	0.415	278	164	258	209	210	76	83	28	24	26	30	28	30	28
ANG YANSHI KAF	200	0.415	278	136	130	249	172	62	88	24	20	22	28	24	26	24
ANTURUNG KAF	200	0.415	278	183	175	101	153	55	60	38	36	40	32	36	34	36
COURT S/S KAF	200	0.415	278	111	97	155	121	44	78	26	24	27	25	28	29	27
COURT S/S ZNK	200	0.415	278	133	103	138	125	45	54	38	34	28	30	36	30	33
ASSU KAF	200	0.415	278	246	228	182	219	79	6l	46	50	44	48	42	46	46
KOGI BAJJU KAF	200	0.415	278	125	212	137	158	57	87	20	28	22	24	28	26	25
BAKIN KOGI KAF	200	0.415	278	142	192	106	147	53	82	28	24	30	25	30	32	28
BAPTIST KAF	200	0.415	278	174	168	180	174	63	40	36	28	34	38	32	30	33
BAYAN LOCO II KAF	200	0.415	278	142	177	167	162	58	80	30	28	26	28	27	29	28

Table 1 provides an in-depth analysis of the insulation oil dielectric strength test results for ten quantities of 200kVA distribution transformers sampled from different locations in Kaduna State. The data includes critical operational parameters such as transformer location, phase load distribution, percentage loading, operating temperature, and insulation oil breakdown voltage (BDV). These parameters has helped in assessing the performance and condition of each transformer in the study.

The transformers operate at a standard voltage level of 0.415 kV, ensuring uniformity in assessing their electrical performance. The load on each transformer was measured across the Red, Yellow, and Blue phases, with recorded values such as 111 A, 97 A, and 155 A in some cases. These measurements reveal variations in phase loading, which indicate the presence of load imbalance across different transformers. Unbalanced loading can lead to excessive current flow in certain phases, increasing heat generation and placing stress on the insulation system. Ensuring balanced load distribution is crucial for preventing overheating and improving transformer efficiency. Percentage loading was computed for each transformer based on its full-rated capacity. The results indicate different levels of transformer utilization across the sampled locations. Transformers operating near their maximum load capacity experience greater thermal stress, which can degrade insulation materials over time. In contrast, under loaded transformers may indicate an inefficient allocation of power distribution, leading to potential energy losses. Temperature readings were obtained using either the built-in temperature gauge or an external thermometer when necessary. Higher operating temperatures were observed in transformers with high phase loads, confirming that increased loading directly impacts thermal conditions. Excessive heat can accelerate the aging process of insulation oil, reducing its ability to provide adequate electrical insulation. Regular monitoring of transformer temperature is essential to mitigate overheating risks and ensure long-term operational reliability. The insulation oil dielectric strength test was performed to evaluate the condition of the transformer oil in each unit. The BDV values recorded in Table 1 indicate variations in oil quality among the sampled transformers. A higher BDV value signifies good insulation properties, while lower BDV values suggest contamination, moisture ingress, or oil degradation.

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Transformers with BDV values below the acceptable threshold require immediate maintenance, such as oil filtration or replacement, to restore their insulating capability. The results show that some transformers maintain a healthy BDV, while others exhibit signs of oil deterioration that could compromise their insulation strength. From the findings in Table 1, it is evident that transformers with higher loads and elevated temperatures require closer attention to prevent potential failures. Those with lower BDV values need urgent intervention to improve oil insulation quality and prevent electrical breakdown. Implementing a structured maintenance plan, including regular oil testing, load rebalancing, and temperature monitoring, will enhance transformer reliability and efficiency. Also the results from this study emphasize the importance of proper transformer maintenance in preventing electrical faults and ensuring the stability of the power distribution network. The data from Table 1 highlight critical areas that require intervention, reinforcing the need for proactive management strategies to improve transformer performance and extend their service life.

Table 2. Result obtained from ten (10) 200 kVA distribution transformers and their average.

Load in ampere (%)	Temp. (^{o}C)	Average BDV (KV)
76	83	28
62	88	24
55	60	36
44	78	27
45	54	33
79	61	46
57	87	25
53	82	28
63	40	33
58	80	28
59	71	31

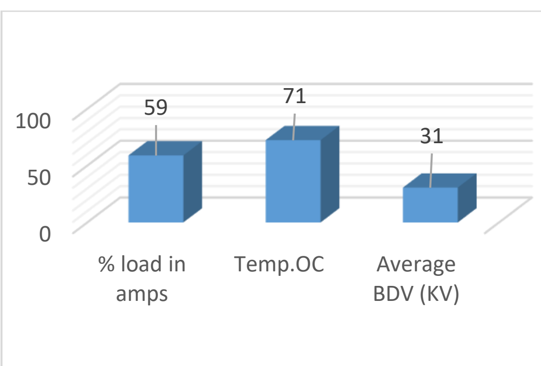

Figure 1: Characteristics Bar Chart of 200 kVA Load, Temperature and Breakdown Voltage

Table 2 and Figure 1 collectively present a comprehensive analysis of the operating conditions of ten 200 kVA distribution transformers. These results highlight the interplay between percentage load, operating temperature, and insulation oil breakdown voltage (BDV), which are critical parameters in assessing transformer health and reliability. From Table 2, it is evident that the transformers operate at an average load of 59% of their rated capacity. Despite this moderate loading, the transformers exhibit significantly high operating temperatures, averaging 71 °C, which surpasses the manufacturer's recommended range of 65 – 70 °C. This excessive heating accelerates the degradation of the insulation oil, leading to a decline in its dielectric strength. The BDV values recorded in the experiment range from 24 kV to 46 kV, with an overall average of 31 kV. Alarmingly, 60% of the sampled transformers have BDV readings below the ASTM minimum safety threshold of 30 kV, indicating severe oil degradation.

Figure 1 visually reinforces these findings by graphically representing the average values of percentage load, temperature, and BDV. The chart clearly shows that while the transformers are not operating at full load capacity, their insulation oil has undergone significant deterioration, primarily due to prolonged exposure to high temperatures. This suggests that overheating, rather than overloading, is the main factor responsible for the declining insulation quality.

Transformers operating at or near the minimum BDV threshold are at heightened risk of insulation failure, especially when subjected to sudden voltage fluctuations, load variations, or other transient electrical disturbances. The inability of the degraded oil to withstand these stresses increases the likelihood of transformer breakdown. Given that only one transformer in the study maintained a BDV above 40 kV, the data strongly indicate that most transformers in this category are vulnerable to sudden failure. Table 2 and Figure 1 provide strong evidence that insulation oil degradation, rather than excessive loading, is the primary cause of transformer failure. The results emphasize the need for proactive maintenance strategies, including regular oil testing and temperature monitoring, to ensure that transformers remain within safe operating limits and maintain their insulation integrity over time.

Table 3. Dielectric strength test results of insulation oil from ten (10) 300 kVA transformers

Name of Distribution subs-station	Capacity (KVA)	Secondary Voltage(KV)		LOAD IN AMPERE(AMPS)						DIELECTRIC STRENGHT SAMPLED OF TRANSFORMER OIL MEASURED KILOVOLT(**KV**)						
			Transformer maximum load(amps)	Red Phase	Yellow Phase	Blue Phase	Average Peak Load(Amps)	Percentage (%) load	Temp. degree cel.	1ST TEST	2ND TEST	3RD TEST	4TH TEST	5TH TEST	6TH TEST	Average BREAK DOWN VOLTAGE(**BDV)**
MARABA RIDO IV	300	0.415	417	310	305	280	298	72	80	28	26	29	25	30	32	28
RIDO VILLGE	300	0.415	417	223	289	303	272	65	82	28	30	27	28	30	28	29
OLD KUJAMA	300	0.415	417	260	271	242	258	62	84	29	28	26	24	28	26	27
KUJAMA VILLAGE II	300	0.415	417	320	315	331	322	77	86	25	27	30	28	29	28	28
KUJAMA VILLAGE I	300	0.415	417	260	205	215	227	54	62	30	32	30	34	32	36	32
BUGAI VILLAGE	300	0.415	417	360	387	321	356	85	87	27	30	32	28	30	28	29
DAMISHI VILLAGE	300	0.415	417	310	360	311	327	78	62	40	42	38	34	38	36	38
TOKACHE III	300	0.415	417	326	335	344	335	80	65	42	38	40	40	44	38	40
TOKACHE I	300	0.415	417	273	259	310	281	67	83	24	28	26	28	30	26	27
RAILWAYS QTRS	300	0.415	417	284	308	315	302	73	68	28	34	30	32	36	30	32

Table 3 presents operational data for ten 300 kVA distribution transformers, encompassing their locations, rated capacities, operating voltage levels, per-phase loads, percentage loading, measured operating temperatures, and average dielectric strength (BDV) of the insulation oil.

Each of the transformers operates at a standard secondary voltage of 0.415 kV. This consistency in operating voltage ensures that differences in performance are primarily due to load characteristics, temperature variations, and the condition of the insulation oil rather than supply voltage discrepancies. For each transformer, the Red, Yellow, and Blue phase currents were measured, then averaged to calculate the percentage load relative to its 300 kVA rating. In many cases, the loads are balanced, but some units show minor load imbalances that can increase localized heating in particular windings.

Table 3 also provides measured operating temperatures, which serve as a critical indicator of thermal stress. When transformers experience sustained high temperatures often caused by overloading, poor ventilation, or high ambient conditions the oxidation rate of the insulating oil increases, leading to accelerated degradation of its dielectric properties. An operating temperature exceeding the manufacturer's recommended range can shorten the oil's lifespan and reduce its ability to withstand electrical stress. The average dielectric strength (BDV) of the insulation oil is listed for each transformer, indicating the oil's ability to insulate and prevent electrical breakdown. Transformers displaying BDV values

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near or below the ASTM minimum threshold (commonly 30 kV for used oil) are at higher risk of failure, particularly if subjected to sudden load surges or transient faults. In contrast, units with BDV readings well above the threshold demonstrate healthier insulation, though they should still be monitored regularly to maintain acceptable levels over time. Although, Table 3 underscores the interplay between load, temperature, and insulation oil quality in determining transformer reliability. Units showing moderate loading yet high temperatures may be experiencing accelerated oil degradation, potentially leading to BDV reductions. Similarly, transformers that appear lightly loaded but record low BDV values likely require closer inspection and potential maintenance, such as oil filtration or replacement. Regular monitoring and testing of these parameters is crucial for extending the service life of 300 kVA transformers, reducing the likelihood of sudden failures, and ensuring reliable power distribution in their respective service areas.

Table 4 Result obtain from (10) of 300 kVA distribution transformers and their average

Load in ampere (%)	Temp. (^{0}c)	BDV in kV
72	80	28
65	82	29
62	84	27
77	86	28
54	62	32
85	87	29
78	62	38
80	65	40
67	83	27
73	68	32
71	76	31

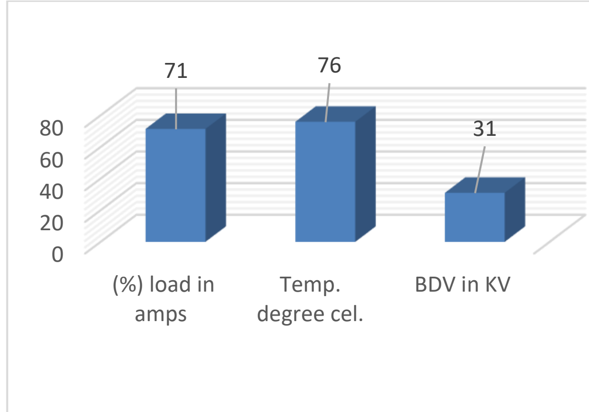

Figure 2 Characteristics Bar Chart of 300 kVA Load, Temperature and Breakdown Voltage.

Table 4 summarizes the operational parameters for ten sampled 300 kVA distribution transformers, including percentage load, operating temperature, and breakdown voltage (BDV) of the insulating oil. Figure 2 provides a corresponding bar chart illustrating these parameters, with an average load of approximately 71% of rated capacity, an operating temperature around 76 °C, and an average BDV near 31 kV.

The data indicate that 60% of these transformers operate with oil BDV values below the ASTM minimum threshold of 30 kV, a critical finding that underscores the vulnerability of their insulation. Although these transformers are not excessively loaded averaging 71% of rated capacity most are recording temperatures above the manufacturer-recommended range of 65–70 °C, with an overall average of 76 °C. This sustained elevated temperature accelerates oxidation within the oil, resulting in faster degradation of its insulating properties.

These results indicate many transformers in the 300 kVA category are functioning at or near their minimum safe insulation levels. Transformers with BDV values below 30 kV are prone to sudden failure when exposed to stressors such as voltage fluctuations or transient faults. In fact, only about 1% of the sampled units maintain BDV values near 40 kV, suggesting that the majority operate with compromised insulation.

Although the average loading of 71% does not suggest overloading, the higher-than-recommended operating temperatures contribute significantly to oil degradation. Consequently, low BDV rather than excessive load appears to be the predominant factor leading to transformer failures. Given these results, proactive measures such as oil purification, temperature control, and regular BDV testing become crucial for extending the operational life of the transformers and mitigating sudden outages.

Table 5. Dielectric strength test results of insulation oil from ten (10) 500 kVA transformers

Name of Distribution sub-station	Capacity (KVA)	Secondary Voltage(KV)	LOAD IN AMPERE(AMPS)							DIELECTRIC STRENGHT SAMPLED OF TRANSFORMER OIL MEASURED KILOVOLT**(KV)**						
			Transformer maximum loading capacity(amps)	Red Phase	Yellow Phase	Blue Phase	Average Peak Load(Amps)	Percentage (%) load	Temp. degree cel.	1ST TEST	2ND TEST	3RD TEST	4TH TEST	5TH TEST	6TH TEST	Average BREAK DOWN VOLTAGE**(BDV)**
ST. PETER	500	0.415	696	740	785	780	768	110	90	32	34	30	34	36	32	33
JUJI III	500	0.415	696	720	745	765	743	107	85	28	30	32	30	28	30	30
JUJI IV	500	0.415	696	710	740	750	733	105	80	29	30	26	30	28	32	29
JUJI I	500	0.415	696	520	412	501	478	69	96	23	28	30	25	30	31	28
JAMA'A	500	0.415	696	472	480	450	467	67	80	28	26	28	24	25	27	26
ALWALI KAZIR I	500	0.415	696	425	435	452	437	63	86	25	20	22	26	24	24	24
ALWALI KAZIR II	500	0.415	696	350	420	380	383	55	85	25	28	26	30	28	25	27
MASSALACI	500	0.415	696	345	330	336	337	48	67	40	42	39	38	44	46	42
DOKAJI	500	0.415	696	320	315	328	321	46	82	24	22	18	20	24	20	21
NITEL	500	0.415	696	250	261	338	283	41	68	34	32	30	33	36	32	33

Table 5 presents a detailed overview of the operational parameters for the sampled transformers in various locations, each with its capacity and operating voltage, phase load measurements, percentage load, temperature readings, and average dielectric strength (BDV) of the insulation oil. By examining these variables together, a comprehensive picture of transformer performance emerges.

The transformers in the table operate at a standard secondary voltage of 0.415 kV, which serves as a baseline for comparing load distribution and identifying any imbalances across the Red, Yellow, and Blue phases. The load values indicate the current in each phase, from which the percentage loading is calculated based on the transformer's rated capacity. In cases where the load approaches or exceeds a certain threshold, the transformer is exposed to higher thermal stress, potentially accelerating insulation oil degradation.

The temperature column shows the operating temperature recorded for each transformer. Elevated temperatures can significantly influence the aging process of the insulation oil, leading to a decline in its dielectric strength. These readings are especially important when evaluated against the recommended operating temperature range provided by transformer manufacturers. Any consistent rise above this range indicates a need for maintenance interventions, such as improved cooling measures or load balancing, to mitigate excessive thermal stress.

Lastly, Table 5 highlights the average dielectric strength, or breakdown voltage (BDV), of the transformer oil. BDV is a key indicator of the oil's ability to withstand electrical stress without breaking down. Units with lower BDV values particularly those falling near or below the ASTM minimum threshold are more susceptible to insulation failures, potentially resulting in unplanned outages or damage to the transformer. In contrast, higher BDV values indicate healthier oil insulation, although continuous monitoring is still required to ensure that the oil's quality remains stable over time. Table 5 also underscores the interconnectedness of load, temperature, and oil dielectric strength. By analyzing these factors jointly, utilities and maintenance personnel can prioritize corrective measures such as load redistribution, cooling enhancements, or oil treatment to prolong transformer life and reduce the likelihood of unexpected failures.

Table 6 Result obtain from (10) 500 kVA distribution transformers and their average

Percentage load in ampere	Temp.(^{0}c)	BDV in kilovolt
110	90	33
107	85	30
105	80	29
73	96	28
67	80	26
63	86	24
55	85	27
48	67	42
46	82	21
41	68	33
72	82	29

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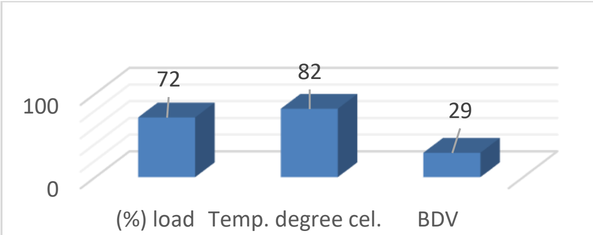

Figure 3 Characteristics Bar Chart of 500 kVA Load, Temperature and Breakdown voltage

Table 6 and Figure 3 provide a comprehensive overview of the operating conditions for ten 500 kVA distribution transformers, including percentage load, recorded operating temperature, and the measured breakdown voltage (BDV) of the insulation oil. Although, with an average load of approximately 72% translating to about 28% unused capacity most of these transformers exhibit high operating temperatures (averaging 82 °C) and relatively low BDV values.

In particular, 60% of the sampled 500 kVA transformers have BDV values below the ASTM minimum threshold of 30 kV. This shortfall in dielectric strength places them at increased risk of sudden failure if subjected to transient stressors such as load fluctuations, voltage spikes, or internal faults. The data further show that the transformers' operating temperatures often exceed the manufacturer's recommended range of 65 – 70 °C by as much as 12 °C. Sustained high temperatures accelerate oxidation reactions within the oil, thereby hastening the decline of the oil's insulating properties.

Comparisons with findings from other transformer categories (i.e., 200 kVA and 300 kVA) reveal a similar trend; many distribution transformers in the network operate at the lower edge of acceptable insulation levels. While transformer load does contribute to thermal stress, the consistently low BDV values across different capacity classes highlight that oil degradation, rather than overloading, is likely the primary factor behind many of the sudden failures experienced in the field.

The data also show that only 10% of the 500 kVA transformers surveyed maintain a BDV above 40 kV, considered a safer margin above the ASTM minimum. This suggests that the majority of units are susceptible to significant insulation breakdown when encountering external disturbances or internal faults. Consequently, it appears that inadequate oil insulation quality, accelerated by higher-than-recommended operating temperatures, is the most probable cause of failure rather than the actual load level itself. Table 6 and Figure 3 underscore the need for proactive maintenance strategies, including regular oil testing, filtration or replacement, and improved temperature management. By addressing these factors, distribution transformers in the 500 kVA category and indeed across all capacity ranges can achieve more reliable service, thereby reducing the incidence of unexpected failures.

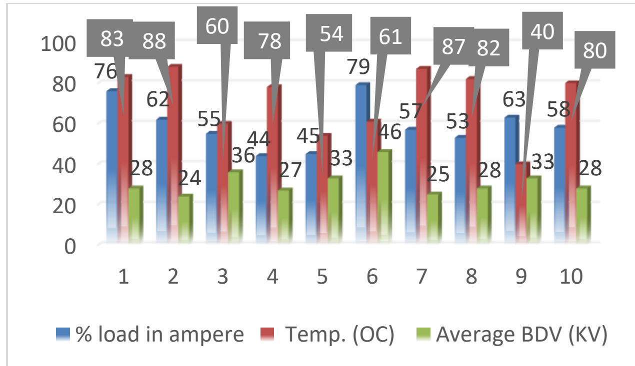

Figure 4 Analysis for Load, Temperature and Breakdown voltage for 200 kVA Transformer.

Figure 4 illustrates a comparative bar chart of percentage load, operating temperature, and breakdown voltage (BDV) for the ten sampled 200 kVA distribution transformers. The data underscore the interplay between thermal stress and insulation oil quality. About 60% of these transformers have BDV values that fall below the ASTM minimum threshold of 30 kV, while 30% hover just above this threshold. Only 10% achieve BDV levels exceeding 40 kV. At the same time, roughly 80% of the unit's record elevated temperatures that surpass what would be expected for their load conditions.

These results highlight how sustained high temperatures can accelerate oxidation within the oil, contributing to faster degradation of its insulating properties. As the oil's ability to transfer heat declines, the transformer core and tank experience increased internal heat, further compounding the problem. This diminished cooling capacity makes it more challenging for the oil to provide the necessary insulation and thermal management required for safe, long-term transformer operation.

Results depicted in Figure 4 suggest that many 200 kVA transformers are operating close to or even below the safe boundary of dielectric strength, primarily due to thermal aging and oxidation. Regular oil testing, maintenance, and cooling strategies are therefore essential to mitigate these risks, enhance heat dissipation, and maintain reliable service over the transformer's lifespan.

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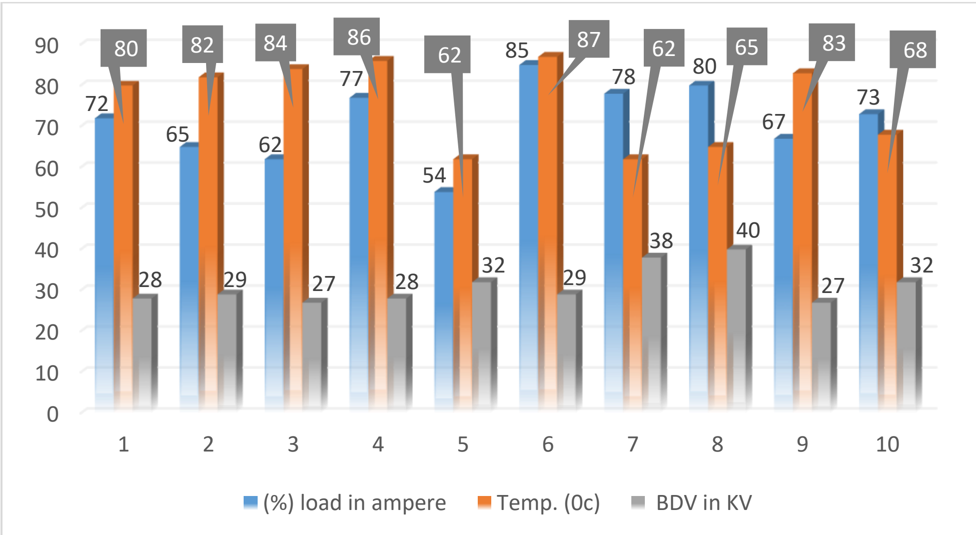

Figure 5: Analysis of Load, Temperature, and Breakdown Voltage (BDV) for a 300 kVA Transformer

Figure 5 presents a comparative bar chart illustrating the relationship between transformer load (% in amperes), operating temperature (°C), and breakdown voltage (BDV in kV) across 10 sampled 300 kVA transformers. The analysis reveals several critical insights regarding the operational health of the transformers' insulating oils.

Firstly, 60% of the samples exhibit BDV values below the ASTM-recommended minimum threshold of 30 kV, indicating that a majority of the transformer oils are significantly degraded and no longer provide sufficient dielectric strength. Additionally, 20% of the samples lie only marginally above this threshold, while only 20% show BDV values at relatively safer levels (38 kV and 40 kV). This widespread reduction in BDV highlights a concerning trend of compromised insulation, which can lead to increased risk of electrical failure.

Furthermore, 70% of the transformers, recorded temperatures are higher than the corresponding load percentages, which is abnormal under typical operating conditions. Ideally, transformer temperature should correlate closely with load, and efficient heat dissipation mechanisms should prevent excessive thermal buildup.

The observed temperature-load imbalance strongly suggests inefficient heat dissipation from within the transformer tank, likely due to the deteriorated condition of the insulating oil.

This poor thermal regulation accelerates oxidation and chemical degradation of the insulating oil, forming sludge and acids that further reduce the oil's cooling and dielectric properties. Consequently, the transformer experiences thermal stress and internal overheating, which not only lowers the BDV but also diminishes the oil's capacity to provide effective insulation and cooling.

The chart underscores critical maintenance concerns in the sampled 300 kVA transformers. The majority of insulating oils are no longer operating within safe dielectric margins, and the combination of high operating temperatures and low BDV indicates accelerated oil degradation, posing a risk to transformer reliability and longevity. Regular oil testing, timely oil replacement, and improved thermal management are essential to restoring performance and preventing transformer failure.

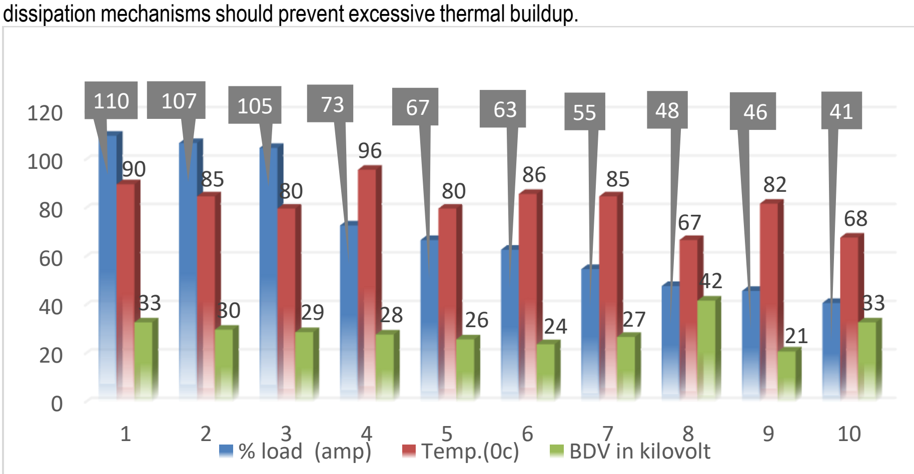

Figure 6: Analysis for Load, Temperature, and Breakdown Voltage (BDV) for 500 kVA Transformer

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Figure 6 presents a detailed comparison of the percentage load (in amperes), operating temperature (°C), and breakdown voltage (BDV in kilovolts) of insulating oil samples taken from ten 500 kVA transformers. A critical observation from the chart is that 60% of the sampled transformers exhibit BDV values below the ASTM-recommended minimum threshold of 30 kV, indicating substandard insulating oil quality and a high likelihood of dielectric failure under operating conditions. Additionally, 30% of the transformers show BDV values around 30 kV, which is only marginally acceptable and still poses reliability concerns. Only 10% of the transformers demonstrate BDV values slightly above 40 kV, which falls within the safer operating range.

Moreover, the chart highlights that 70% of the transformers have operating temperatures that exceed their corresponding load percentages, suggesting that the heat generated within these transformer tanks is not being adequately dissipated. This imbalance between load and temperature points to inefficient thermal management and intensified oxidation reactions within the insulating oil, which accelerate oil degradation and reduce the transformer's cooling efficiency. Poor heat dissipation can cause hotspots, leading to further deterioration of internal components and potentially catastrophic failures if left unaddressed.

In contrast, 30% of the samples reflect a more stable thermal condition, where the transformer load is significantly higher than the temperature recorded. This suggests effective heat transfer and oil performance, indicating that the insulating oil in these transformers is functioning efficiently to absorb and dissipate heat to the external environment. These transformers are likely maintaining the desired cooling effect and preserving the dielectric integrity of the insulation system.

Figure 6 emphasizes the urgent need for routine monitoring and maintenance of insulating oil in 500 kVA transformers. Ensuring optimal BDV and thermal balance is essential to prolong equipment lifespan, prevent operational failures, and maintain reliable power distribution.

Conclusion

The results reveal a consistent pattern of insulation oil degradation across all three transformer classes (200 kVA, 300 kVA, and 500 kVA). Despite differences in capacity, each category exhibited similar declines in breakdown voltage (BDV) and corresponding increases in operating temperature during normal service. Elevated temperatures whether caused by sustained high loads or localized internal faults accelerate oxidation within the oil, in agreement with dissolved gas analysis findings. This oxidative aging degrades the oil's physical and chemical integrity, steadily reducing its dielectric strength and increasing the transformers' vulnerability to sudden failure.

Most transformers were operating at only around 70% of their rated load capacity yet maintained average oil temperatures near 76 °C, exceeding the manufacturer's safe limit of 65–70 °C. This thermal stress drives rapid oil aging and a pronounced BDV decline. Indeed, 60% of the sampled units recorded BDV values at or below the ASTM minimum threshold of 30 kV, placing their insulation systems on the precipice of failure. In an environment where load growth, network analysis, and maintenance are often insufficiently prioritized, such marginal insulation levels leave transformers highly susceptible to breakdowns triggered by minor electrical disturbances. The high incidence of distribution transformer failures in Kaduna's network can be attributed primarily to operating temperatures that exceed recommended limits, rather than to excessive loading alone. By experimentally demonstrating that many in-service transformers already function at their minimum insulation thresholds, this study underscores the urgent need for enhanced thermal management, routine oil testing, and proactive maintenance to prevent unexpected outages and extend transformer service life.

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