Experimental Validation of Dynamic Hot-Spot Temperature Profile-Based Accelerated Thermal Ageing for Lifetime Assessment of Distribution Transformers under Solar PV Penetration

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Abstract – *The rise of solar photovoltaic (PV) integration significantly alters distribution transformer loading patterns and hot-spot temperatures, which directly impacts the insulation aging and overall operational lifespan. This paper experimentally validates a dynamic accelerated thermal aging methodology to accurately assess this impact. Using a thermal aging chamber (oven), 0.05 mm kraft paper and Shell Diala B mineral oil were aged under two simulated daily load curves: a base line of 0% PV penetration and an optimal operational threshold of 30% PV penetration. Results demonstrate that the 0% PV scenario caused faster degradation, decreasing kraft paper tensile strength by 52.4% and dropping oil breakdown voltage to 24.38 kV within 31 days. Conversely, 30% PV penetration mitigated thermal stress, extending the equivalent insulation lifespan to 36 days while maintaining breakdown voltage above IEC 60422 standards. Eventually, this dynamic profiling approach offers a more realistic and practical framework for assessing transformer degradation under PV integration compared to traditional constant temperature models.*

Keywords: *Accelerated ageing; breakdown voltage; hot-spot temperature; solar photovoltaic; transformer insulation*

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I. Introduction

The worldwide movement towards green energy is steadily picking up steam with the world changing climate and consequently the adoption of solar energy systems in the industrial, commercial and residential industries is quickly becoming the norm [1]. Coupled with the world transition to the modern power grids where fossil fuel-based power generation has been substituted with renewable or clean energy sources, the photovoltaic (PV) technology has emerged as one of the most important technologies to support the sustainability of the energy infrastructure, as the cost of the technology has dropped and the availability of the technology has declined.

This tremendous growth has led to a necessity to comprehend how the renewable resources will be incorporated into the existing distribution infrastructure. High levels of penetration of renewable energy can change power flows, thus necessitating an examination of grid asset stability and operational accommodation of the extremely dynamic load profiles of these new sources of energy generation.

PV systems (particularly the rooftop photovoltaic systems) are used in both residential and commercial sectors at a high pace and have now been regulated all over the world to ensure that the power grid is used safely [2]. The control measures are geared towards avoiding technical malfunctions and also making sure that the power grid can accommodate the growth of the solar power generation.

This change of structure is accompanied by continuous technical advances in the residential technology sector that actively facilitate the entry of renewable energy sources in the domestic setting using inverter controls and smart energy management systems [3]. These integration initiatives have increased the pace of modernization of the power distribution network in the entire world and in essence, have turned the conventional energy consumers to active prosumers and influence the power grid.

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In a macro level, PV system integration into the distribution grid has a great economic and operational advantage to utility companies and grid operators. The greatest advantage is that the creation of solar energy has a positive impact of decreasing the loading of the transformers and grids that are normally coupled with high electricity demand [4]. Such a reduction in peak load can significantly lower thermal loads on substations and distribution lines during daytime. The overall impact of this result is that the reduced peak load demand allows utility companies can postpone their costly infrastructure upgrades, make the most of their assets and minimise losses incurred in transmission line losses across the distribution system resulting in increased overall efficiency.

The use of solar power systems however, technically is not easy as well since it demands environmental conditions [5]. These fluctuate cause unpredictable voltage profiles, rapid fluctuation of voltage and reversal of current. In order to address the issues of power quality, the knowledge of how to vary the loads affect electrical equipment in a short period of time is needed.

The effects that determine the life of a transformer are the ambient temperature, transformer oil temperature and shape of load consumed [6]. The resultant grid instability usually causes distribution equipment, including distribution transformers, to operate with unpredictable load profiles which are not within their normal design parameters. Transformers can therefore be operated at temperatures that are not within the normal operating temperature range of the transformer and the extreme change in temperature can make the development of thermal stress occur quickly and shorten the service life of the asset [7]. Physical degradation can also be related to mechanical expansions in the transformer tank as a result of heating and cooling due to of unstable PV penetration. These dynamic thermal stresses are significant to control so that the grid can be considered to work reliably as prolonged outages occur due to premature failures of transformers and the utility companies must pay money losses.

The reliability of operations of transformers largely depends on the long-term performance of the internal insulation system of transformers: the inner insulation system typically uses a mixture of cellulose paper and mineral oil as a dielectric insulation medium and a cooling medium [8]. To prevent overheating (heat aging the insulation system too fast), it is necessary to have an effective heat dissipation system especially when using high load equipment [9]. Transformer insulating oils are mainly used to insulate the parts of the transformer and to take away the heat produced in the operation of the transformer [10]. The degradation will happen faster as the insulation materials will be subjected to a lot of heat and thermal pressure which will lead to the reduction of the service life of the insulation material [11]. Destruction of the cellulose structure reduces the mechanical strength of the paper insulation and hence it becomes susceptible to mechanical forces where faults occur. Therefore, assessing transformer health indices and monitoring the mechanisms of insulation degradation under different load conditions are an important field of research to prevent untimely failure of the system and to guarantee the stability of power systems [12].

The remaining service life of the transformer insulation systems was performed on laboratory experiments of accelerated thermal aging tests under a static condition. Most studies in conventional academic literature make an assumption of a constant heating temperature in order to take into account the rate of degradation and mathematical service life models. In the studies by Istiqomah et al. and Duanaputri et al., kraft paper and mineral oil degradation was studied at constant temperature of 150°C after 30 days [13]-[14]. In a similar vein, the high-constant-temperature experiment by Duanaputri et al. employed the use of static aging at an even higher temperature 160°C for 30 days—to observe accelerated tensile strength degradation [15].

The present paper therefore proposes and experimentally validates a quicker method of thermal ageing with dynamic distributions of hot-spots. The key feature of the proposed technique compared to other more traditional constant-temperature ageing techniques [16]-[17] the use of load curves analysis to direct the actual thermal behavior of transformers, allowing a more realistic analysis of insulation degradation and transformer life where photovoltaic solar power penetration is possible.

II. Research Contribution and Novelty

The key contribution of this study is the experimental implementation and confirmation of the dynamic profiles of the hot-spots temperature when the realistic distribution transformer loading conditions are applied to an accelerated thermal ageing chamber. Most past studies used unvarying ageing temperatures which were not reflective of the real transformer operating conditions. The recommended methodology fills the gap between thermal modelling of power systems and insulation ageing experiments, allowing a more realistic lifetime analysis framework of distribution transformers under solar PV penetration.

III. Methodology

In this section, the experimental procedure to be used in establishing the accelerated thermal ageing process of the distribution transformer insulation will be outlined based on the dynamic hot-spot temperature profiles. It has

several main steps: the preparation of the insulation material, the dynamic heating cycle in accordance with the load curve of the transformer and mechanical and electrical characterization of the aged samples.

A. Materials and Equipment

The key insulation materials were 0.05-mm kraft paper and Shell Diala B 13.3:1 (oil to paper) mass ratio of mineral oil to reflect the actual conditions in a distribution transformer. The kraft paper and the mineral oil used in this study are shown in Fig. 1 and Fig. 2, respectively.



Fig. 1. Kraft paper 0.05 mm



Fig. 2. Shell Diala B mineral oil

An oven was used to carry out the accelerated simulation of thermal ageing. Temperature variations with transformer loading were reproduced in the oven in controlled laboratory conditions. The oven used for the ageing test is shown in Fig. 3.

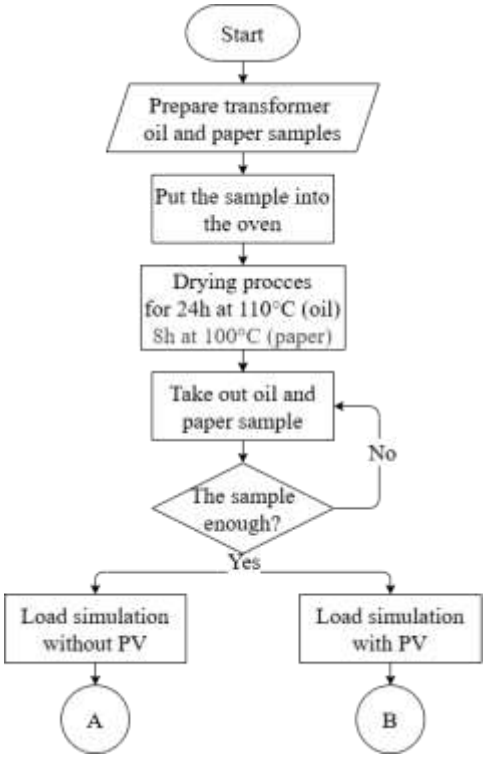


Fig. 3. Oven

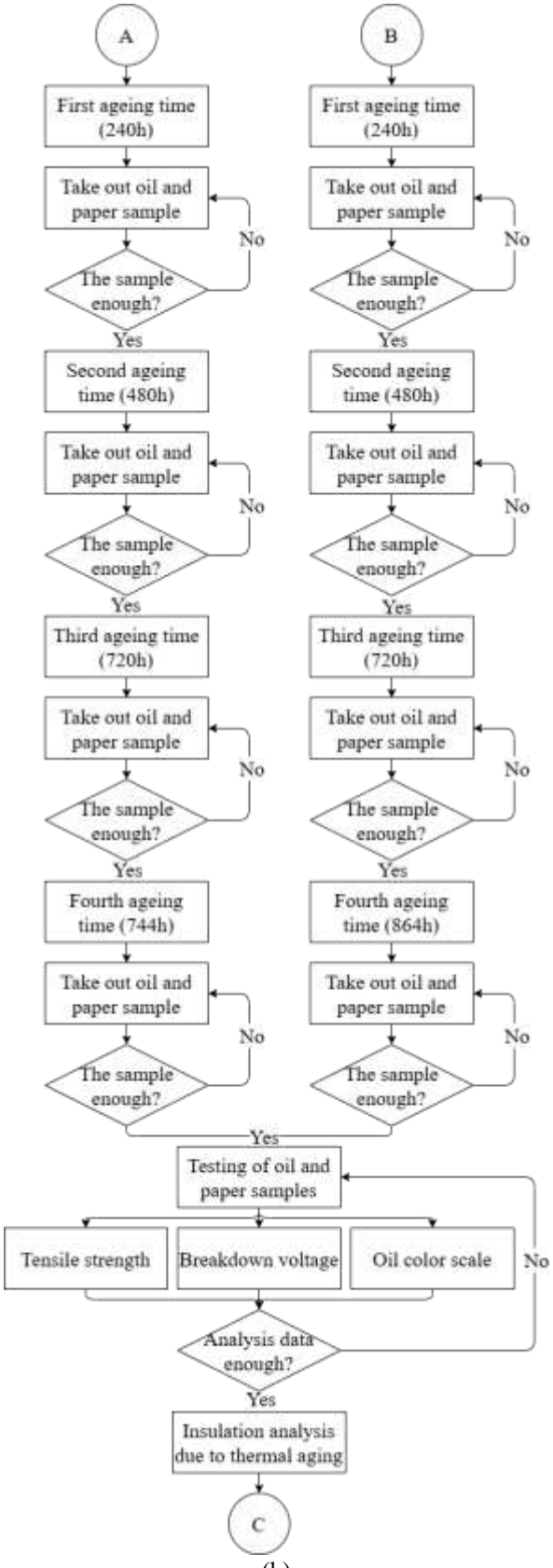
The breakdown voltage threshold was determined with an oil breakdown tester by conducting electrical property tests such as the breakdown voltage (BDV) [18]. The tensile strength of the paper was measured after ageing [19]. A traditional destructive testing apparatus, which was used to perform this test, was a Universal Testing Machine [20].

B. Research Flowchart

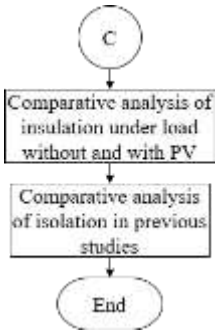
The workflow of accelerated thermal ageing consists of three main stages that consider accurately the working conditions of a transformer: sample preparation, dynamic heating, and thermal duration control. The complete research flowchart is presented in Fig. 4.



(a)



(b)



(c)

Fig. 4. Research flowchart of dynamic thermal ageing: (a) Sample preparation and initial load simulation; (b) Ageing test procedure and data collection; (c) Comparative data analysis

The procedures will be described step-by-step according to the flowchart of the research as follows:

- Preparation of insulation materials
  It started by preparing a transformer insulating oil and kraft paper, which was rolled on copper conductors in a mass ratio of 13.3:1 of oil to paper [21].
- Sample grouping
  To make sure that the ratio was constant during the process of the tests, the materials that were produced were divided into two groups that were to represent the three stages of the sample collection.
- Filling the test oven and heating
  Duran bottles were used to put the oil samples and kraft paper rolls and heat them at a given temperature.
- Drying process
  The drying process for the oil was carried out for 24 hours at 110°C, and for the paper, it was carried for 8 hours at 100°C to reduce moisture content [13]-[14].
- Thermal ageing tests
  The samples were collected in the same sequence during ageing conditions of 240 hours, 480 hours, 720 hours and the final ageing condition of 744/864 hours at non-PV and PV conditions.
- Sample testing
  The BDV and color change of the insulating oil were tested. The tensile strength of the paper was experimented.
- Data processing and analysis
  The degradation was compared to find out the level of degradation in comparison to the previous constant-temperature studies.

C. Ageing Test Procedure

The calculation of the ageing temperatures was done based on the Hot Spot Temperature (HST) calculations obtained through the daily load curve of a 160 kVA transformer. As the primary parameter to assess the level of degradation and estimate service life of the insulation, the temperature of the hot-spot can be taken into consideration [22]. The HST is given by: [17]-[23] as per Equation (1):

$$\theta_h(t) = \theta_a + \Delta\theta or \cdot \left(\frac{1 + RK^2}{1 + R}\right)^x + H \cdot gr \cdot K^y \quad (1)$$

where,

$\theta_h(t)$ = Hotspot temperature (°C)
θ_a = Ambient temperature (°C)
$\Delta\theta or$ = Top-oil temperature rise (°C)
R = Ratio of load loss at rated load to no-load loss
K = Transformer load ratio
x = Oil exponent
H = Hotspot factor
gr = Hotspot to top-oil temperature gradient
y = Winding exponent

In order to determine the service life that a transformer has left to operate, the Loss of Life (LOL) formula is calculated as illustrated in Equation (2) [17]-[23]:

$$\%LOL = \frac{F_{EQA} \times t \times 100}{\text{Normal Insulation Life}} \quad (2)$$

where,

F_{EQA} = Age factor
t = Time (h)

The load curve without PV contribution, presented in Fig. 5, shows that all the electricity requirements are supplied directly by the transformer [17]. This condition keeps the current load at a comparatively high level during the day, constant during the day and increasing at night with the peak load occurring. The discussion can be subcategorized into four main sections:



Fig. 5. Daily load curve of the distribution transformer without PV

- Section 1 (00:01–06:59)
  During the early morning hours, the PV is not operating and thus, the entire system load has to be borne by the transformer.
- Section 2 (07:00–16:59)
  The load of the transformer is relatively high during the day as there is no other power generated by PV, so the temperature of the transformer does not vary significantly.
- Section 3 (17:00–22:59)
  The maximum system load is in the afternoon and evening when all the electricity is switched to the transformer and causes it to reach the maximum.
- Section 4 (23:00–00:00)
  The operating condition remains the same by the end of the day with no contribution of PV and the load is again fully supported by the transformer.

The load curve with PV contribution in Fig. 6 illustrates the effects of PV on the electrical grid whereby the load of the power generated may vary based on the daily solar cycle [17]. The discussion is broken down into four parts:

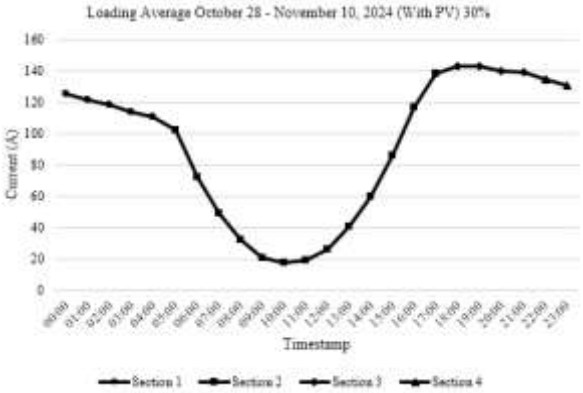


Fig. 6. Daily load curve of the distribution transformer with PV

- Section 1 (00:01–04:59)
  During the morning hours the PV will not generate any electricity because there will be no sunlight therefore the entire load will be substituted by the grid.
- Section 2 (05:00–16:59)
  At 05:00 PV gradually begins to produce electricity, reaches its peak at 11:00 and begins to decrease slowly until it stops producing electricity at 16:59.
- Section 3 (17:00–22:59)
  Later afternoon and evening PV is not contributing and the system load is at peak demand.
- Section 4 (23:00–00:00)
  PV ceases to work during the end of the day and the entire load is once again fully carried by the grid.

Using the obtained data on the load curve, the next step is to calculate the input parameters to compute the hot-spot temperature i.e., the load percentage and ambient temperature. The values of the load ratio and average temperature of each load curve are as follows:

TABLE I
TABLE OF LOAD RATIO AND AVERAGE TEMPERATURE VALUES ON THE LOAD CURVE OF A TRANSFORMER WITHOUT PV

Section	Power (kVA)	Power used (kVA)	Load used (kVA)	Average temperature (°C)
1	160	77.88	49	27
2	160	74.51	47	31
3	160	96.60	60	32
4	160	90.25	56	27

TABLE II
TABLE OF LOAD RATIO AND AVERAGE TEMPERATURE VALUES ON THE LOAD CURVE OF A TRANSFORMER WITH PV

Section	Power (kVA)	Power used (kVA)	Load used (kVA)	Average temperature (°C)
1	160	81.51	51	27
2	160	37.08	23	30
3	160	96.59	60	32
4	160	90.25	56	27

Table I and II give the parameters that are used as inputs to calculate the hot-spot temperature (HST). Using Equation (1) an estimated HST value in each load section is determined and the HST value multiplied by 2.37 to give an HST value that is comparable to that of the accelerated ageing temperature reference. The results of the calculations are given in Table III:

TABLE III
TEMPERATURE VARIATION VALUE FOR TRANSFORMER LOADING WITHOUT AND WITH PV

Section	Transformer loading without PV		Transformer loading with PV	
	Results of the HST formula calculation (°C)	Final value of temperature variation (°C)	Results of the HST formula calculation (°C)	Final value of temperature variation (°C)
1	59.08	140	61.12	145
2	62.05	147	48.31	114
3	73.37	174	73.37	174
4	65.21	155	65.21	155

The Equation (2) of the load on the two sections can be used to calculate the time of the test using the LOL calculation. So based on the outcome of the calculation as per this equation we can determine the test time as follows:

TABLE IV
LOL DURATION OF TRANSFORMER LOADING WITHOUT AND WITH PV

Secti-on	Transformer loading without PV			Transformer loading with PV		
	Temperat-ure variation (°C)	LOL (%)	Valid-ation (days)	Temperat-ure variation (°C)	LOL (%)	Valida-tion (days)
1	140	3.27	30.49	145	2.84	35.19
2	147			114		
3	174			174		
4	155			155		

Based on the above calculations, it is noted that the insulation material will be at LOL after 30.49 days or rather 31 days when the accelerated aging conditions are taken without the PV loading but when the accelerated aging conditions are taken with the PV loading, the insulation material will reach LOL after 35.19 days or rather 36 days. Thus, accelerated aging test was done in the loading conditions at no PV in 31 days, loading conditions at PV in 36 days. All the test scenarios have the following durations:

- Scenario without PV, simulated for 31 days with temperature variations of 140°C, 147°C, 155°C, and 174°C, based on the duration of each load section.

TABLE V
TEMPERATURE VARIATION AND TIME DURATION FOR TRANSFORMER LOADING WITHOUT PV

Section	Temperature variation (°C)	Time (hours)
1	140	7
2	147	10
3	174	6
4	155	1

- Scenario with PV (30% penetration), simulated for 36 days with temperature variations of 114°C, 145°C, 155°C, and 174°C.

TABLE VI
TEMPERATURE VARIATION AND TIME DURATION FOR TRANSFORMER LOADING WITH PV

Section	Temperature variation (°C)	Time (hours)
1	145	5
2	114	12
3	174	6
4	155	1

A penetration rate of 30% was selected based on the results of a previous study, the study showed that an average PV penetration rate of 30% resulted in a reduction in transformer HST of up to 49%, increasing the service life of the insulation. Furthermore, transformer degradation remains very low at penetration rates up to 30%, but on 40% PV penetration rate can accelerate degradation and shorten the transformer's operational lifetime. Therefore, a 30% PV penetration was selected for this experimental simulation [24]-[25].

D. Sample Collection and Storage Techniques

After the complete ageing process, material property testing was performed. Hence, sample storage steps should be adhered to in order to ascertain the accuracy of data. Paper samples of insulation are removed and put in containers that are tightly sealed out of the oil. The oil samples are stored in glass bottles which are tightly filled and, covered with aluminum foil. They are stored at room

temperature (25°C - 30°C) and away from direct sunlight. This method is applied to:

- The hygroscopic (absorbs water) feature of the insulating paper and water can decrease the dielectric strength of the oil, exclude moisture in the surrounding air.
- Prevent additional oxidation and destruction by UV light (photooxidation) during sample waiting to be tested.

E. Insulation Characteristics Testing

Periodical sampling was done. The evaluations included:

- Tensile strength
  The tensile strength test was conducted on a universal testing machine (Fig. 7), according to IEEE C57.91. A general criterion for knowing the end of service life is when the tensile strength which is half that of the original strength [23]. Equation (3) was used to obtain the tensile strength:

$$\sigma = \frac{m \times a}{A} \tag{3}$$

where,

σ = Tensile strength (MPa)
m = Mass (Kg)
a = Gravity acceleration (m/s)
A = Area (mm²)



Fig. 7. Universal testing machine

- Breakdown voltage (BDV)
  Measured using oil breakdown voltage tester (Fig. 8) according to IEC 60422. Permission limit: The transformer oil must have a BDV that is over 40 kV [26].



Fig. 8. Breakdown voltage tester

- Oil color scale
  Determined with a color scale instrument (Fig. 9) which is related to IEC 60422 and ASTM D1500. The good condition should not have a color value above 4.5 [26]-[27]-[28].



Fig. 9. Color scale instrument

IV. Result and Discussion

A review of experimental evidence of accelerated thermal ageing experiments will be included in this section. Three areas are discussed where mechanical degradation of kraft paper can be measured, the dielectric performance of the mineral oil and the change in the color scale of oil, in the absence of PV penetration, as well as in the presence of PV penetration of 30%. In addition, it compares it with the conventional constant-temperature ageing methods to show the effectiveness of the proposed dynamic profile.

A. Mechanical Characteristics of Kraft Paper

Ageing is a kind of process, which alters the cellulose structure through weakening of the mechanical bonds of the material [29]. Equation (3) was used to determine tensile strength of kraft paper at 100% to be 164.64 MPa. Table VII gives the summary of the degradation of the mechanical strength of the paper during the period of the

simulation. The tensile strength degradation trends of both scenarios are compared in Fig. 10.

TABLE VII
COMPARISON OF KRAFT PAPER TENSILE STRENGTH BETWEEN SCENARIOS

Ageing time (days)	Without PV		With PV		IEEE C57. 91 (%)
	Tensile Strength (MPa)	Percentage (%)	Tensile Strength (MPa)	Percentage (%)	
0	164.64	100	164.64	100	50
10	139.16	84.5	143.08	86.9	
20	115.64	70.2	121.52	73.8	
30	99.96	60.7	109.76	66.7	
31	86.24	52.4	-	-	
36	-	-	86.24	52.4	

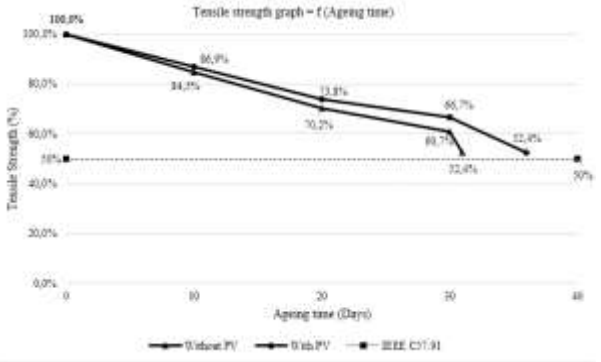


Fig. 10. Comparison of tensile strength degradation

In the no PV factor, tensile strength was decreased by 84.5%, 70.2% and finally by 52.4% on day 10, 20, and 31. At the same time, in PV, degradation was less rapid with tensile strength of 86.9% on day 10, 73.8% on day 20 and 52.4% on day 36. These results indicate that the PV penetration reduces the operating temperature of the transformer when the sun is bright, reducing slower the degradation of the paper insulation.

B. Electrical Characteristics of Mineral Oil

The first breakdown voltage (BDV) of the oil was 47.36 kV. Table VIII gives the data of dielectric strength degradation with time, and Fig. 11 compares the BDV trends of both scenarios.

TABLE VIII
COMPARISON OF BREAKDOWN VOLTAGE (BDV) BETWEEN SCENARIOS

Ageing time (days)	BDV without PV (kV)	BDV with PV (kV)	IEC 60422 (kV)
0	47.36	47.36	40
10	41.09	46.32	
20	33.84	43.68	
30	24.63	30.38	
31	24.38	-	
36	-	28.20	

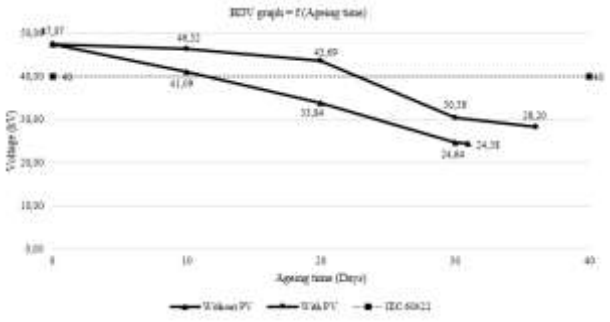


Fig. 11. Comparison of BDV

The breakdown voltage on day 10, day 20 and day 31 was decreased to approximately 41.09 kV, 33.84 kV, and 24.38 kV respectively in the sample where no PV was added. This implies that without PV oil decays more quickly and the risk of insulation breakdown (lower than the 40 kV standard) is more likely. Conversely, the sample with PV was much more stable in the values of the breakdown voltages, being 46.32 kV on day 10, 43.68 kV on day 20, and it continued to be constant, at around 28.20 kV on day 36.

C. Oil Color Scale

Physical evidence of oxidation and thermal ageing is the darkening of the oil color. Table IX indicates the relative color scale progression, which is also illustrated in Fig. 12.

TABLE IX
COMPARISON OF OIL COLOR SCALE BETWEEN SCENARIOS

Ageing time (days)	Oil color scale without PV	Oil color scale with PV	IEC 60422
0	0.5	0.5	4.5
10	0.5	0.5	
20	2.5	0.5	
30	4.0	2.5	
31	4.0	-	
36	-	4.0	

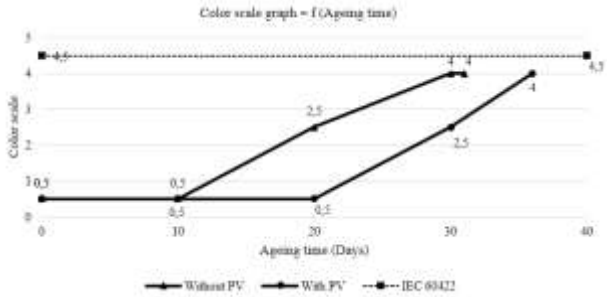


Fig. 12. Comparison of oil color scale

When PV was not used, the oil color drastically rose to level 2.5 on the 20 th day and 4.0 on the 30 th day. In the case of the PV system, the color of the oil was clear until day 20, increased to a scale of 2.5 on day 30 and not until

day 36 did the color attain a scale of 4.0. The results also show that in the test samples of oil with PV, the color of the oil was changing slowly than in the ones without PV.

D. Comparative Analysis: Dynamic vs Constant Temperature Ageing

The parameters of traditional tests at constant temperature were compared to the ageing outcomes obtained by using dynamic load curves, to ascertain the realism of the testing [13]-[15].

TABLE X
COMPARISON OF TRANSFORMER INSULATION DEGRADATION BASED ON A TEMPERATURE APPROACH

Reference	Test methode (Temp.)	Ageing Parameter		
		Remaining tensile strength of paper	Oil breakdown voltage	Oil color scale
Istiqomah et al.; Duanaputri et al. [13]-[14]	Constant (150 °C)	Decreased to 52% over a period of 30 days	Decreased gradually from 11.17 kV to 2 kV (30 days)	2.0 (in 30 days)
Duanaputri et al. [15]	Constant (160 °C)	Decreased to 38.14% over a period of 30 days	not discussed	not discussed
Current research	Dynamic (load curve without PV)	Decreased to 52.4% over a period of 31 days	Decreased from 47.36 kV to 24.38 kV (31 days)	4.0 (in 30 days)
	Dynamic (load curve with PV)	Decreased to 52.4% over a period of 36 days	Decreased from 47.36 kV to 28.20kV (36 days)	4.0 (in 36 days)

In previous studies that also focused of isolation aging, most of them used a constant simulated aging temperature. The studies by Istiqomah et al. [13] and Duanaputri et al. [14] were conducted at a constant temperature of 150 °C to evaluate the performance of kraft paper and Thermally Upgraded Paper (TUP) immersed in mineral oil and natural ester oil. Meanwhile, the study by Duanaputri et al. [15] was conducted at constant temperature of 120 °C and 160 °C to evaluate the performance of 0.8 mm kraft paper immersed in Shell Diala B mineral oil. This study used 0.05 mm kraft paper immersed in Shell Diala B mineral oil, simulated with dynamic temperature based on the transformer's daily load curve.

Continuous heating at a constant high temperature, as used some previous studies, can result in material degradation that does not accurately reflect the operational conditions of transformer insulation material in actual use. However, the dynamic heating used in this study can produce varied material degradation due to temperature fluctuation caused by changes in transformer load. These temperature changes more accurately reflect the condition experienced by the transformer's insulation material, as well as the impact of load changes caused by PV penetration.

By applying this more realistic dynamic thermal profile, the benefit of PV penetration on transformers can be accurately determined. The reduction in load during the day resulting from PV penetration directly reduces thermal stress, resulting in slower rate of degradation of the transformer's insulation material. The improvement in insulation material performance resulting from PV penetration is shown in Table XI.

TABLE XI
IMPROVEMENT OF INSULATION PERFORMANCE DUE TO PV PENETRATION

Parameter	Without PV	With PV	Improvement
Equivalent ageing duration	31 days	36 days	16.13%
BDV above IEC 60422 limit	10 days	20 days	100%
Oil color scale reaching 4.0	30 days	36 days	20%

V. Conclusion

The current study was in a position to authenticate the fact that the dynamic hot-spots temperature profiles could be applied in the accelerated thermal ageing experiment to estimate lifetime of the distribution transformers. The results indicated that the transformer insulation subjected to dynamic temperature profiles that were founded on actual load curves exhibited degradation behaviors that were far more realistic of actual operating conditions, than the conventional constant-temperature ageing methods. The 30 percent solar PV penetration and reduced thermal stress resulted in a 31-36 days equivalent ageing period increase, and reduced the insulation degradation. Oil breakdown voltage exceeded IEC 60422 standard minimum under the PV penetration on the 20th day, but exceeded the IEC 60422 standard minimum on the 10th day without PV penetration, and the oil color scale was 4.0 on day 36 with PV penetration, and was 4.0 on day 30 without PV penetration. These findings support the fact that the dynamic profile-based accelerated thermal ageing of hot-spots are realistic and practical models of the study of transformer life under varying conditions of the distribution network on a higher rate of penetration by renewable energy. The subsequent research can take this

approach into account and include a number of PV penetration levels and different transformer ratings to be able to generalise the proposed framework.

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Conflict of Interest

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Author Contributions

Rohmanita Duanaputri: Conceptualization, resources, data curation, formal analysis, supervision, funding acquisition, validation, investigation, visualization, methodology, writing – original draft, project administration, writing – review & editing; Galuh Prawestri Citra Handani: Data curation, formal analysis, validation; Rahman Azis Prasojo: Validation, investigation, methodology; Hanifiyah Darna Fidya Amaral: Investigation, visualization; Bustani Hadi Wijaya: Resources, validation; Firdaus Bayu Aqila: Data curation, formal analysis, visualization, writing – original draft, writing – review & editing; Nur Alvi: Data curation, formal analysis, visualization, writing – original draft, writing – review & editing.

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