Determination of transformer board creep parameters under high-mechanical and thermal stresses

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Abstract
During operation of a transformer, all components inside the transformer begin to age and lose their performances due to various stresses. Among these components, transformer boards (TB) used between windings have an important role in terms of equipment reliability for being used for both insulation and cooling purposes. TBs are exposed to all sorts of specified stresses during operation and their physical structure deteriorates by creeping over time. This deterioration leads to a decrease in the gap between winding turns, and insulation failures occur due to insufficient cooling. In order to prevent these types of failures, it is quite important to specify creep characteristics of TBs before the production particularly for high-mechanical and thermal stresses. In this study, creep parameters (secondary creep rate, time to breakdown) of TB samples used in a typical power transformer under various loading and temperature are determined experimentally. In addition, gradient values are calculated for fitted lines and results obtained evaluated in terms of transformer operating conditions. Creep data obtained under high temperature (90, 100 and 110°C) and loading (30, 35 and 40 kg) makes an important contribution to literature and will help transformer manufacturers in design and production stages.

1 INTRODUCTION
Transformers are among the most important and high-cost equipment of today’s power systems [1, 2]. This electric machine has a high-efficiency near 98% and is widely used particularly in energy transmission and distribution systems. Today, R&D studies are carried out to develop high-power and voltage-rated transformers in order to meet the increasing energy demand [3]. However, production of larger-capacity transformers in terms of power, voltage and size will also increase the electrical and economic effects caused by a transformer failure [4]. According to the data obtained from TMS, samples are taken periodically to measure the dielectric performance of the transformer oil if necessary [30, 31]. As a result of measurements, when a critical or significant change is observed insulation failures occur due to insufficient cooling. In order to prevent such failures, transformer monitoring systems (TMS), which can instantly monitor several critical performance parameters, have been designed and their usage has gained popularity recently [25–29]. According to the data obtained from TMS, samples are taken periodically to measure the dielectric performance of the transformer oil if necessary [30, 31]. As a result of measurements, when a critical or significant change is observed in the properties of the oil, necessary measures can be taken. In the literature, there are many methods and studies used to diagnose dielectric performance of transformer oils, and experience in this field has been standardized [32–40]. However, the situation of transformer boards (TB) used for both insulation
and cooling purposes is more complex than transformer oils. Since samples can be taken from transformer oil, they can be examined periodically and even can be replaced if necessary. On the contrary, it is not possible to perform periodic examination of TBs since it is not feasible to take samples after production or during operation. This is because TBs are located between winding turns for purposes such as pressboard, press ring, cylinder and so forth. Although there are many applications where fibre optic cables are used on TBs, the data obtained gives only the temperature information of winding region. While the performance of many components is monitored instantaneously with TMSs, electrical and physical properties of TBs cannot be monitored instantly during operation. Therefore, it is quite crucial to investigate electrical and mechanical properties of TBs accurately before design and production stage. Determining the creep characteristics of TBs that are exposed to extreme thermal and mechanical stresses are among the areas that should be primarily studied in terms of operational reliability of transformers.

The most critical function of a TB is providing space between winding turns as spacer, and two typical types, radial and axial spacers, are used in practice. The main function of these spacers is to provide necessary fluid-flow channels between the winding turns for natural cooling. However, considering the mechanical stress due to winding weights, ambient pressure and magnetic forces, these materials are deformed over time resulting to lose their physical functionality. In this way, TB creeps, oil circulation weaken and so the windings cannot be cooled properly. In this case, winding temperature increases and damages the enamel coating around winding resulting in short circuit and insulation failure. In [41], it is experimentally specified that the hottest spot in a transformer is usually the first cooling channel of high-voltage winding and 85% winding height. While the locations and temperatures of these critical points can be monitored with fibre optic sensors, TB replacement is not possible due to the closed structure of the transformer. For this reason, it is quite important to determine the creep characteristics of TBs before the production, particularly for extreme stress conditions [42–44]. Many studies on creep characteristics have been carried out in the literature. However, in most of these studies, especially the effects of mechanical stresses on the creep characteristics of TB are examined [45–47]. It is important to examine the thermal and mechanical stresses on the material, in order to investigate the deformation of TB more accurately, particularly for overloading conditions.

In this study, creep characteristic of TB is determined experimentally for critical temperature and mechanical loading which occur in the overloading of a power transformer. Experimental study is carried out in two stages: First, breakdown duration of TB is measured in cases of extreme mechanical loading. In the second stage, secondary creep values are measured for excessive thermal stresses. According to the results, it is seen that the creep rate of TB increases much more rapidly in temperature-rise above the nominal operating temperature. In addition, significant decrease is observed in the breakdown duration data obtained for the transformer's overload condition will be an important reference for transformer manufacturers to develop more reliable TBs.

In Section 2 of the study, methodology of the creep is presented. Details of the experimental studies and test setup are given in Section 3. The test results obtained and the evaluations are presented in Section 4. In Section 5, outputs of the study and the studies planned to be carried out in the future are specified.

2 | METHODOLOGY

In this section, creep theory and stages related with the study are introduced. As it is known, a solid material is constantly deformed when subjected to a constant load or mechanical stress. This deformation is the function of material properties, temperature, mechanical stress amplitude and duration of stress exposure. Depending on these stresses and their durations, deformation may become so large that the material may no longer perform its function. In literature, creep rate is defined as in Equation 1, the time rate of deformation of a material subject to stress at a constant temperature [48]:

\[
\frac{\partial \varepsilon}{\partial t} = \frac{C \cdot \sigma^m}{d^b} \cdot e^{-\frac{Q}{kT}}
\]  

In Equation 1, \( \varepsilon \) is the creep strain, \( \sigma \) is the creep constant of the material, \( m \) and \( b \) exponents dependent on the creep mechanism, \( Q \) is the activation energy of the creep mechanism, \( k \) is the stress applied, \( d \) is the grain size of the sample material, \( k \) and \( T \) are Boltzmann’s constant and sample temperature, respectively. Creep equations in literature generally focus on the secondary creep stage of the material. For this reason, stages of the creep is introduced below.

Basically, creep curves consist of three stages: Primary (transient), secondary (constant rate) and tertiary stages as given in Figure 1 [49]. The slope \( \partial \varepsilon / \partial t \) of this curve given in Figure 1 represents the creep rate. When the material is subjected to mechanical stress at the beginning, an instantaneous deformation occurs and after that the sample material begins to creep over time. In the first stage, initial strain occurs due to the elastic response to the applied load or stress. The secondary region (II) is
characterised by steady-state creep in which competing mechanisms of strain-hardening and recovery may be present. In stage III, tertiary creep occurs in which there is a rapid increase in creep rate due to the excessive increasing damage, which leads to creep rupture, and which may generally be experienced at high temperatures, stresses and in constant-load machines. In literature, function of typical creep curve is defined as Equation 2:

\[
\epsilon_i = \epsilon_0 + \epsilon \cdot (1 - e^{-m \cdot t}) + \epsilon_f \cdot t
\]  

(2)

Here, \(\epsilon_0\) is the instantaneous strain that begins with the instant application of load; \(\epsilon\) is the linear function of time, representing stage II; and the term \(\epsilon \cdot (1 - e^{-m \cdot t})\) represents stage I in which \(m\) is the exponential time parameter and \(\epsilon\) is the limiting transient creep strain (strain at end of that stage minus \(\epsilon_0\)). Among all these stages, the minimum creep rate, or slope of stage II of creep is the most important parameter investigating in literature.

The constant pressure is represented with a dashed line in Figure 1. In the beginning stages, this curve is generally identical. However, as the specimen extends, its cross-sectional area reduces leading to a rising stress. For this reason, there are significant differences between the constant-load and constant-stress creep tests. From an engineering perspective, the creep test at constant load is more important than the one at constant stress. The reason is that it is the load, not the stress, which is mostly kept constant in engineering applications. Therefore, all creep tests in this study are performed under constant load.

3 | EXPERIMENTAL STUDY

In this section, details of the tests performed and the samples used in these tests are introduced. Cellulose-based insulation materials are widely used in transformer production and constitute approximately 10% of total weight of the transformer. The electrical and mechanical properties of cellulose are quite sufficient for use in many industrial applications. The material to be used in a power transformer should have long operating life. In addition, it should be resistant to high-mechanical stress occurring in nominal and short-circuit conditions and also should be capable of operating without degradation at variable temperature and humidity. Thanks to these properties, cellulose-based materials are preferred to use in transformer production as spacer, pressboard, press ring, barrier and cylinder, cleats and leads purposes.

Among these sections, TBs used as spacer come to the fore since they provide insulation between winding turns and the required cooling volume. In practice, two types of spacer TBs are used as radial and axial. These materials enable the necessary space for circulation of the oil and help for cooling the transformer. In addition to the magnetic and electrical forces, TBs are exposed to excessive strain due to the effects of the physical forces caused by the weight of the windings and the ambient pressure which results in creep. The creeping of TB causes insufficient cooling and insulation failures due to overheating.

Therefore, examining the effects of the mentioned forces on the creep characteristics of TB is quite important in terms of transformer life, fault prediction and operational reliability.

In this study, creep parameters of TB used in a typical distribution transformer as spacer are determined experimentally for different mechanical loads and temperatures. The dimensions of TB used as test sample are given in Figure 2.

The length of the test sample (b) 12 cm, thickness (b) 0.5 cm and width (w1) 1 cm. The width of the tip parts of the sample (a) is set to 4 cm so that it can be easily attached to the creep measurement setup. The width (w2) of the sample is 0.5 cm and it is determined by experimental studies, taking into account the capabilities of the test setup and the test durations [50]. In addition, three TB samples used for each measurement for accurate results and means are presented.

In the recent study of the authors, details of the designed test setup are introduced [51]. With this designed mechanism, thermal, mechanical and chemical stresses that the insulation materials are exposed inside the transformer can be applied to TBs. For this purpose, different stresses can be applied to TB using different loads. In order to provide variable thermal stresses, resistances are used around the oil tank. In order to heat the oil homogeneously, the resistances are placed in circular form around the tank and the oil is circulated during the tests. In addition, iron, copper and paper pieces are added to the oil tank in order to provide the effect of other materials (core, copper winding, TB etc.) used in the transformer. The creep rates of the samples where all these strains are applied are recorded with a computer connected to the system. As a result of these tests, creep curves (characteristics) of the samples tested are obtained for various conditions.

In experimental studies, it is aimed primarily to investigate the effect of different mechanical loads on TB creep characteristics. For this purpose, creep tests are carried out using the loads in the “mechanical stress” section given in Table 1 and breakdown durations are recorded. Ultimate loading value for the test sample is 43.3 kg [47]. Considering the mechanical and thermal stress effects during tests, upper mechanical weight value is chosen as 40 kg. Tests at different loads are repeated for both temperatures of 100 and 110°C. In this way, it is aimed to examine...
the effect of oil temperature and pressure change on the creep characteristic of TB.

In the next test phase, it is aimed to determine the creep rate (secondary creep rate) for the temperatures given in the “thermal stress” section in Table 1. In this section, tests are carried out at 35 kg constant-mechanical load (about 55 MPa) in order to observe the effect of temperature change on creep.

The load and temperature values in Table 1 have been determined by considering experimental study limits to be reasonable especially in terms of test durations. It is a fact that breakdown durations at lower temperatures and weights increase significantly. For this reason, many pretests are performed before the temperature and load values are determined, and the test conditions given in Table 1 are specified. Ambient conditions during the tests are measured by Extech Instruments SD700 and the mean values are given in Table 2.

### RESULTS AND DISCUSSION

In this section, creep test results of the TB sample are presented and examined. Experimental studies are carried out in two stages, and first, the effect of mechanical load change on the time to breakdown is examined.

#### 4.1 Experimental results

In this section, three mechanical loads as 30, 35 and 40 kg are used. In order to simulate the overloading condition of the transformer, breakdown duration tests are performed at 100 and 110°C for each mechanical load. Breakdown duration results obtained are given in Table 3.

According to Table 3, it is seen that the breakdown durations decrease exponentially due to the increasing weight at constant temperature. For instance, in case of 40 kg loading at 110°C, breakdown duration of TB is nearly 1 min. However, at same temperature, when the loading is 35 kg, breakdown duration increases to 14 min. Similar increment trend is also seen when loading is decreased to 30 kg where the breakdown duration is measured as 8591 min. According to these results, it is concluded that the increase in mechanical load on TB causes the deformation rate to be increased rapidly. In addition, due to the exponential change in load-dependent breakdown duration, optimum mechanical load value is determined as 35 kg in terms of test durations for the tests depending on the temperature change to be carried out in the second stage. Another case to be examined in Table 3 is the case where the mechanical load is constant and the temperature increases from 100 to 110°C. For both 35 and 40 kg loading cases, breakdown duration of TB decreases by 75% when the temperature increases from 100 to 110°C. Although the test temperature barely increases by 10°C, the reduction in breakdown duration is more significant since the increase particularly occurs in case of an overloading condition. Based on this, it is concluded that TBs used as spacers will deteriorate much faster in case of overloading. However, when the mechanical load is 30 kg, decrease in the breakdown duration of TB becomes 23.06%. It can be concluded that high temperature values, which occur when the transformer is overloaded, have serious effects on the creep of TB. Besides, in this temperature range, it is observed that mechanical loading also had a significant effect on the breakdown duration of TB. Consequently, it is important that both thermal and mechanical stresses have serious deforming effects on the breakdown duration of TB, and therefore these stresses should be examined synchronously, particularly in overloading cases.

In the second stage of the experimental study, effects of temperature variation on TB are examined. For this purpose, secondary creep values of TB are measured for 90, 100 and 110°C and time-dependent creep changes are presented as in Figure 3.

Figure 3 shows the secondary creep values obtained for three different temperature values under constant 35 kg mechanical load. In order to reveal the secondary creep characteristic of the region clearly, lines are fitted with the help of Matlab curve fitting.
fitting toolbox. In the study, only data of the secondary creep region are studied to examine the creep characteristics of the test sample since primary and tertiary creep data only provide information about the temporary creep condition. The region that is critical for creep characteristics is the secondary region where creep extends over time.

Under constant load (35 kg), while the temperature is 90°C, total secondary creep duration is determined as 56 min. The mean value obtained from the creep data for 56 min is calculated as 0.00095 mm/min. The same data are determined as 0.00419 mm/min when the temperature is 100°C and 0.0435 mm/min when 110°C. The secondary creep durations of these measurements are 44 and 11 min for 100 and 110°C, respectively. As can be seen in Figure 3, the increase in creep data for all three temperature values is close linear. However, in certain periods of measurements, it is observed that the increase in creep is below and above the line that has been partially slowed and accelerated since the oil temperature is controlled within ±2°C during the test period. As a result, it is specified that there is an exponential increase in secondary creep rates in critical situations where the sample temperature rises above 90°C. This condition is quite critical for the cases where transformers are overloaded. For instance, when a transformer is 150% loaded for 2 h, the hot spot temperature value measured as 110°C [41]. Especially in peak loading periods, the occurrence of this level of temperature significantly increases the creeping speed of TBs.

5 | DISCUSSION

It is commonly acknowledged that ageing mechanism of paper insulation in transformers is caused by oxidation and carboxylic acids, which improve catalytic efficiency of the acids by promoting their dissociation. When the bonds in cellulosic chains are deformed, the polymerisation degree is reduced and CO and CO₂ gases are generated which cause the tensile strength of the paper to be decreased. Therefore, when the temperature is increased from 90 to 110°C, more gases are generated in the oil and secondary creep rate of the sample increases exponentially. Experiment results show that there is correlation between the temperatures above nominal conditions and the secondary creep rate for TB sample [44, 52–54].

In addition, kraft paper is a material with a high degree of heterogeneity containing an infinite number of micro cracks of different dimensions [55, 56]. With an increase in temperature, these cracks widen. In this way, mechanical strength of the sample weakens. While temperature increases from 90 to 110°C, mechanical strength drops down strictly as sample becomes brittle due to deformation in physical structure of the paper. Mechanical strength of a cellulosic paper depends mainly on strength of fibre bonds. For higher temperatures, several cracks arise at these bonds which lead to serious failure of the system [57, 58].

Kraft paper consists of fibres binding to each other creating a strong structure. The presence of large open pores allows for impregnability of the material but also causes mechanical weakness. This perspective is important for cellulose-based components, where the resistance to tensile stress is relevant for transformers. The reason of decrease in time to breakdown when mechanical load is increased from 30 to 40 kg, may be explained as weakening of paper structure due to interaction with acid molecules formed by stepping oxidation of oil. Higher the thermal and mechanical stresses, the more is the reaction with acid, and more decrease in mechanical strength is observed [58].

6 | CONCLUSION

In this study, creep characteristics of TBs used in transformers for spacer purposes are determined experimentally. Tests are carried out under high temperature and mechanical load, especially considering the overloading conditions of transformers. Experimental studies are carried out in two stages, first, breakdown duration of TB under mechanical load, and then secondary creep characteristics at high temperatures are examined. In this way, it is aimed to introduce the effects of high-mechanical and thermal stresses on the creep characteristic of TB.

In the first part of the study, it is determined that optimum mechanical load value for the test setup is 35 kg in terms of breakdown duration. When heavier loads are used in the tests, breakdown durations are significantly shortened and creep stages cannot be tracked accurately. In contrast, when weights less than 35 kg are used, test durations are considerably longer and a single test can take weeks or even months. Besides, it is determined that not only the mechanical load but also the sample temperature also had significant effect on the breakdown duration of TB particularly in case of overloading. Therefore, it has been understood that mechanical and thermal stresses should be examined together for cases above nominal conditions.

In the second stage, the secondary creep characteristics of TB are investigated at 90, 100 and 110°C and 35 kg constant-mechanical load. It is known that creep changes in the secondary region are basically linear. Therefore, in order to see the effect of temperature change accurately, lines are fitted for each temperature and the slopes of these lines are presented in Table 4.
According to Table 4, creep amount of TB increases exponentially with the increasing temperature above 90°C. Increasing creep speed at these levels is particularly critical for breakdown duration of cellulose-based material. For instance, at 90°C, total secondary creep of TB is 0.058 mm and its breakdown duration is 56 min. In contrast, total secondary creep of 0.435 mm at 110°C occurred in 11 min. Although the sample is more creeped at high temperatures, breakdown duration is much shorter. It has been understood that, for high temperatures, it is more important to analyse the breakdown duration of TB rather than creep amounts in terms of sample performance.

In the study, it is also observed that mechanical and thermal stresses have negative impact on breakdown duration and creep amount of TB. As the stress levels exceed the nominal operating values, the amount of unit creep increases and the breakdown durations decreases. These conditions may probably cause unexpected failures in the winding insulation of the transformer under similar loading conditions. For this reason, results obtained are quite worthy to perceive creep mechanism of TB especially for high mechanical and thermal stresses that occurred in overloading condition. As future studies, measurements can be made for more precise temperature and mechanical load ranges, and the findings obtained can be used for fault prediction and transformer ageing studies.

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REFERENCES
1. Fan, J., et al.: Power transformer condition assessment based on online monitor with SOFC chromatographic detector. Int. J. Electr. Power Energy Syst. 118, 105805 (2020)
2. Islam, M.M., et al.: Application of a general regression neural network for health index calculation of power transformers. Int. J. Electr. Power Energy Syst. 93, 306–315 (2017)
3. Mi, C.L., et al.: Design and application of exits insulation structure for EHV and UHV AC transformers. Gaodianya Jishu/High Voltage Eng. 36(1), 122–128 (2010)
4. Jongen, R., et al.: Statistical analysis of power transformer component life time data. In: Eight International Power Engineering Conference (IPEC 2007), Singapore, pp. 1273–1277 (2007)
5. Mehta, A.K., et al.: Development of a novel dual temperature model for insulation aging in oil immersed transformers. IEEE Trans. Dielectr. Electr. Insul. 22(5), 2723-2735 (2015)
6. Bičen, Y., et al.: Lifetime estimation and monitoring of power transformer considering annual load factors. IEEE Trans. Dielectr. Electr. Insul. 21(3), 1360–1367 (2014)
7. Robalino Vanegas, D.M., Mahajan, S.M.: Correlation between hot-spot temperature and aging factor of oil-immersed current transformers. In: 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, Pennsylvania, pp. 1–5 (2008)
8. Žarković, M., Stojković, Z.: Analysis of artificial intelligence expert systems for power transformer condition monitoring and diagnostics. Electr. Power Syst. Res. 149, 125–136 (2017)
9. Jürgensen, J.H., et al.: Individual failure rates for transformers within a population based on diagnostic measures. Electr. Power Syst. Res. 141, 354–362, (2016)
10. Sarajcev, P., et al.: Transformer insulation coordination using volt–time curve and limit–state surface formulation. Int. J. Electr. Power Energy Syst. 90, 256–266 (2017)
11. Abu-Elantien, A.E.B., Salama, M.M.A.: A Monte Carlo approach for calculating the thermal lifetime of transformer insulation. Int. J. Electr. Power Energy Syst. 43(1), 481–487 (2012)
12. Vinolina, S.: Development of lifetime data management algorithm for power transformers. In: 2014 5th International Conference on Intelligent Systems, Modelling and Simulation, Langkawi, Malaysia, pp. 452–457, (2014)
13. Kunicki, M., et al.: Data acquisition system for on-line temperature monitoring in power transformers. Meas. 161, 107909 (2020)
14. Taslak, E., et al.: Analyses of the insulating characteristics of mineral oil at operating conditions. Electr. Eng. 100(1), 321–331 (2018)
15. Rigatos, G., Siano, P.: Power transformers’ condition monitoring using neural modeling and the local statistical approach to fault diagnosis. Int. J. Electr. Power Energy Syst. 80, 150–159 (2016)
16. Sedighi, A.R., et al.: Life estimation of distribution transformers using thermography: A case study. Meas. 149, 106994 (2020)
17. Arabul, A.Y., et al.: Experimental thermal investigation of an ONAN distribution transformer by fiber optic sensors. Electr. Power Syst. Res. 155, 320–330 (2018)
18. Liang, Z., Parlikad, A.: A Markovian model for power transformer maintenance. Int. J. Electr. Power Energy Syst. 99, 175–182 (2018)
19. Gassner, H.P., et al.: The aging characteristics of laminated pressboard and laminated wood in oil cooled power transformers. In: Conference Record of the 2006 IEEE International Symposium on Electrical Insulation, Toronto, Canada, pp. 403–407 (2006)
20. Emsley, A.M.: The kinetics and mechanisms of degradation of cellulose insulation in power transformers. Polym. Degrad. Stab. 44(3), 343–349 (1994)
21. Emsley, A.M.: The influence of cellulose degradation on insulation life in power transformers. Cellulose and Cellulose Derivatives, Woodhead Publishing, Cambridge, pp. 115–124 (1995)
22. Pradhan, A.R., et al.: Effect of temperature on frequency dependent dielectric parameters of oil-paper insulation under non-sinusoidal excitation. IEEE Trans. Dielectr. Electr. Insul. 21(2), 653–661 (2014)
23. Ni, J., et al.: The actual measurement and analysis of transformer winding deformation fault degrees by FRA using mathematical indicators. Electr. Power Syst. Res. 184, 106324 (2020)
24. Malik, H., et al.: Make use of DGA to carry out the transformer oil-immersed paper deterioration condition estimation with fuzzy-logic Procedia Engineering, 30, pp. 569–576 (2012)
25. Tenbohlen, S., et al.: Diagnostic measurements for power transformers. Energies 9(5), 347 (2016)
26. Kasinathan, M., et al.: Hotspot monitoring in transformers using Fiber Bragg Grating. In: 2012 International Conference Fiber Optics and Photonics (PHOTONICS), Chennai, India, pp.21–23 (2012)
27. Djamali, M., Tenbohlen, S.: Malfunction detection of the cooling system in air-forced power transformers using online thermal monitoring. IEEE Trans. Power Delivery 32(2), 1058–1067 (2017)
28. Hou, D., et al.: Oil-immersed transformer online hot spot temperature monitoring and accurate life loose calculation based on fiber Bragg grating sensor technology. In: 2014 China International Conference on Electricity Distribution (CICED), Shenzhen, China, pp. 23–26 (2014)

### Table 4: Gradients of fitted line for various temperatures

| Temperature (°C) | 90 | 100 | 110 |
|------------------|----|-----|-----|
| Gradient Ratio $\Delta E/\Delta t$ (%) | 0.0976 | 0.338 | 4.420 |

**TABLE 4** Gradients of fitted line for various temperatures
1. Arabul, A.Y., Senol, I.: Development of a hot-spot temperature calculation method for use in an on-line monitoring and diagnostic system. IEEE Trans. Power Delivery 12(1), 249–256 (1997)
2. Kirkbas, A., et al.: Fault diagnosis of oil-immersed power transformers using common vector approach. Electr. Power Syst. Res. 184, 106346 (2020)
3. Kurtnský, J., et al.: Effect of magnetic nanoparticles on partial discharges in transformer oil. J. Magn. Magn. Mater. 496, 165923 (2020)
4. Susa, D., Lehtonen, M.: Dynamic thermal modeling of power transformers: further development—Part I. IEEE Trans. Power Delivery 21(4), 1961–1970 (2006)
5. IEC 60076-7:2005: Power transformers—Part 7: Loading guide for oil-immersed power transformers (2005)
6. Josue, F., et al.: Transformer hot-spot temperature estimation for short-time dynamic loading. In: 2012 IEEE International Conference on Condition Monitoring and Diagnosis, Bali, Indonesia, pp. 217–220 (2012)
7. Feng, D., et al.: Evaluation of power transformers’ effective hot-spot factors by thermal modeling of scrapped units. IEEE Trans. Power Delivery 29(5), 2077–2085 (2014)
8. Pradhan, M.K., Ramu, T.S.: Estimation of the hottest spot temperature (HST) in power transformers considering thermal inhomogeneity of the windings. IEEE Trans. Power Delivery 19(4), 1704–1712 (2004)
9. Li, J., et al.: Hot spot temperature models based on top-oil temperature for oil immersed transformers. In: 2009 IEEE Conference on Electrical Insulation and Dielectric Phenomena, Virginia Beach, Virginia, pp. 55–58 (2009)
10. IEEE-C57.92:1981: Guide for loading mineral-oil-immersed power transformers up to and including 100 MVA with 55 degrees C or 65 degrees C average winding rise (1981)
11. IEC: IEC 60156:2018 Insulating liquids–Determination of the breakdown voltage at power frequency–Test method, 61010–1 © Iec:2001 (2018)
12. ASTM D877-02: Standard test method for dielectric breakdown voltage of insulating liquids using disk electrodes (2012)
13. Arabul, A.Y., et al.: Experimental investigation on creep characteristic of the spacer between winding turns of power transformers. Trans. Inst. Meas. Control (2019)
14. Oria, C., et al.: State-of-the-art review on the performance of cellulose dielectric materials in power transformers: Mechanical response and ageing. IEEE Trans. Dielectr. Electr. Insul. 26(3), 939–954 (2019)
15. Rigdahl, M., et al.: Analysis of cellulose networks by the finite element method. J. Mater. Sci. 19(12), 3945–3952 (1984)
16. Emsley, A.M., et al.: Degradation of cellulosic insulation in power transformers. Part 3: Effects of oxygen and water on ageing in oil. IEEE Electr. Insul. Mag. 18(6), 12–25 (2002)
17. Emsley, A.M., et al.: Degradation of cellulose paper insulation in power transformers. Part 3: Effects of oxygen and water on ageing in oil. IEEE Proc.: Sci. Meas. Technol. 147(3), 115–119 (2000)
18. Verma, P., et al.: Effects on tensile strength of transformer insulation paper under accelerated thermal and electrical stress. In: Annual Report—Conference on Electrical Insulation and Dielectric Phenomena, CEIDP, Vancouver, Canada, 619–622 (2007)
19. Chen, Q., et al.: Analysis of mechanical characteristics of transformer windings under short circuit fault. In: Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials, Xi’an, China (2018)
20. Kalkan, G.: Structural integrity of power transformers, Dissertation, Imperial College London (2012)
21. Hosford, W.F.: Mechanical Behavior of Materials. Cambridge University Press, Cambridge (2005)
22. Beniwal, N.S.: Creep failure estimation of distribution transformers. VIVECHAN Int. J. Res. 1, 49–56 (2010)
23. Arabul, A.Y., et al.: Experimental test set-up design for acquiring creep curve of the spacer between the winding turns of power transformers. In: 2018 6th International Conference on Control Engineering and Information Technology, CEIT 2018, Istanbul, Turkey (2019)
24. Mirzaie, M., et al.: Thermal degradation of cellulose paper insulation in power transformers. In: 2007 International Conference on Solid Dielectrics, ICSD, Winchester, UK, pp. 673–676 (2007)
25. Yoshida, H., et al.: Degradation of insulating materials of transformers. IEEE Trans. Electr. Insul. EI-22(6), 795–800 (1987)
26. Wang, M., et al.: Review of condition assessment of power transformers in service. IEEE Electr. Insul. Mag. 18(6), 12–25 (2002)
27. Lesieutre, B.C., et al.: An improved transformer top oil temperature model for use in an on-line monitoring and diagnostic system. IEEE Trans. Power Delivery 12(1), 249–256 (1997)
28. Lundgaard, L.E., et al.: Aging of oil-impregnated paper in power transformers. IEEE Trans. Power Delivery 19(1), 230–239 (2004)
29. Chen, Q., et al.: Analysis of mechanical characteristics of transformer windings under short circuit fault. In: Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials, Xi’an, China (2018)
30. Abil, A., et al.: Development of a hot-spot temperature calculation method for use in an on-line monitoring and diagnostic system. IEEE Trans. Power Delivery 12(1), 249–256 (1997)
31. Arb, A.Y., Senol, I.: Development of a hot-spot temperature calculation method for use in an on-line monitoring and diagnostic system. IEEE Trans. Power Delivery 12(1), 249–256 (1997)
32. Susa, D., Lehtonen, M.: Dynamic thermal modeling of power transformers: further development—Part I. IEEE Trans. Power Delivery 21(4), 1961–1970 (2006)
33. Arab, A.Y., et al.: Experimental investigation on creep characteristic of the spacer between winding turns of power transformers. Trans. Inst. Meas. Control (2019)
34. Josue, F., et al.: Transformer hot-spot temperature estimation for short-time dynamic loading. In: 2012 IEEE International Conference on Condition Monitoring and Diagnosis, Bali, Indonesia, pp. 217–220 (2012)
35. Feng, D., et al.: Evaluation of power transformers’ effective hot-spot factors by thermal modeling of scrapped units. IEEE Trans. Power Delivery 29(5), 2077–2085 (2014)
36. Pradhan, M.K., Ramu, T.S.: Estimation of the hottest spot temperature (HST) in power transformers considering thermal inhomogeneity of the windings. IEEE Trans. Power Delivery 19(4), 1704–1712 (2004)
37. Li, J., et al.: Hot spot temperature models based on top-oil temperature for oil immersed transformers. In: 2009 IEEE Conference on Electrical Insulation and Dielectric Phenomena, Virginia Beach, Virginia, pp. 55–58 (2009)
38. Arabul, A.Y., et al.: An experimental test set-up design for acquiring creep curve of the spacer between the winding turns of power transformers. In: 2018 6th International Conference on Control Engineering and Information Technology, CEIT 2018, Istanbul, Turkey (2019)
39. Mirzaie, M., et al.: Thermal degradation of cellulose paper insulation in power transformers. In: 2007 International Conference on Solid Dielectrics, ICSD, Winchester, UK, pp. 673–676 (2007)
40. Yoshida, H., et al.: Degradation of insulating materials of transformers. IEEE Trans. Electr. Insul. EI-22(6), 795–800 (1987)
41. Oria, C., et al.: State-of-the-art review on the performance of cellulosic dielectric materials in power transformers: Mechanical response and ageing. IEEE Trans. Dielectr. Electr. Insul. 26(3), 939–954 (2019)
42. Wang, M., et al.: Review of condition assessment of power transformers in service. IEEE Electr. Insul. Mag. 18(6), 12–25 (2002)
43. Rigdahl, M., et al.: Analysis of cellulose networks by the finite element method. J. Mater. Sci. 19(12), 3945–3952 (1984)
44. Emsley, A.M., et al.: Degradation of cellulosic insulation in power transformers. Part 3: Effects of oxygen and water on ageing in oil. IEEE Proc.: Sci. Meas. Technol. 147(3), 115–119 (2000)
45. Verma, P., et al.: Effects on tensile strength of transformer insulation paper under accelerated thermal and electrical stress. In: Annual Report—Conference on Electrical Insulation and Dielectric Phenomena, CEIDP, Vancouver, Canada, 619–622 (2007)

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