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Assessing the lifespan of power transformers considering the frequency and magnitude of short circuit currents

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Abstract

Power transformers are among the main electrical energy transmission equipment. During the period of operation, these equipment's are exposed to different types of stresses. Short-circuit currents are one of the main causes of damage to the winding and insulation of the transformer during the period of operation. When a short-circuit current passes through a power transformer, Certain parts of the winding inside the transformer are under excessive pressure, which in extreme cases leads to the destruction of the winding insulation. One of the ways to detect damage to the insulation of power transformers is to check the results of the transformer oil test. In this paper, based on the oil test results of power transformers, as well as examining the number and intensity of short-circuit currents passing through transformers during 11 years, the effect of the number and intensity of short-circuit currents on the life of power transformers has been evaluated. And for the first time, the relationship between the number and intensity of short-circuit currents passing through power transformers and the life of these equipment's is expressed, and it is determined that as the frequency of short-circuit currents with higher intensity increases, the lifespan of power transformers decreases more strongly.

Keywords: Dissolved gas analysis, power transformers, short-circuit currents, transformer lifetime, furfural
2020 MSC:

1 Introduction

The lifespan of a power transformer is expressed in terms of its insulation lifespan [20]. Various factors can affect the insulation lifespan of a transformer. During the operation of a transformer, its insulation system is subjected to electrical, thermal, mechanical, and environmental stresses, each of which contributes in some way to the aging and eventual degradation of the insulation system [6].

One of the factors influencing the insulation lifespan of power transformers is the presence of abnormal currents passing through the transformer. In fact, any current exceeding the nominal current range of the transformer is

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considered an abnormal current for that transformer. Short-circuit currents fall into the category of abnormal currents, as they generate transient electromagnetic forces in radial and axial directions, imposing severe electrical and mechanical stresses on the core and windings [22]. This phenomenon can lead to damage to the core, windings, and their insulation, significantly reducing the operational lifespan of power transformers.

When a short-circuit current passes through a power transformer, radial and axial electromagnetic forces are induced due to radial and axial leakage magnetic fields, respectively. Figures 1 and 2 illustrate, respectively, the axial and radial leakage magnetic fields and the radial and axial electromagnetic forces produced by these leakage fields during a short-circuit condition. In these figures, **Fr** represents the radial force acting on the winding, **Ba** denotes the axial leakage magnetic field, **Fa** indicates the axial force acting on the winding, and **Br** represents the radial leakage magnetic field. The magnitude of the forces exerted on the transformer windings and insulation is directly related to the intensity of the short-circuit current. The higher the short-circuit current, the greater the forces acting on the transformer windings and insulation, thereby increasing the likelihood of transformer damage [19].

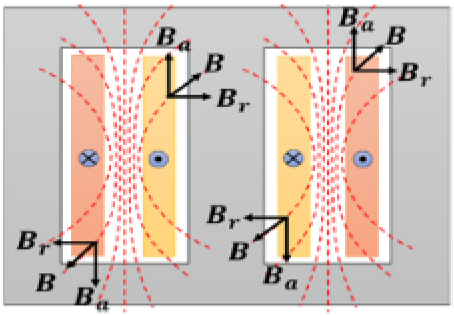

Figure 1: Axial and radial leakage fields [19]

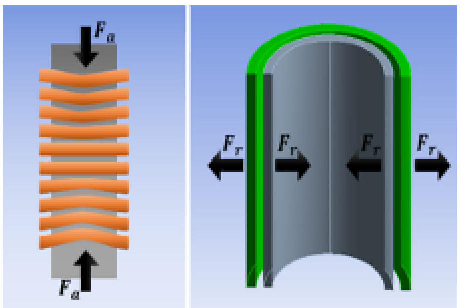

Figure 2: Radial and axial electromagnetic forces in short circuit current state [19]

Research on the performance, health, and insulation systems of power transformers has gained significant attention in recent years, particularly due to the growing demand for enhanced reliability and longevity of electrical infrastructure. Numerous studies have been conducted globally to investigate the impact of various factors, such as oil treatment, load effects, moisture, and cellulose degradation on transformer life assessment and insulation health. This paper builds upon the foundations laid by key research efforts that have contributed substantially to the understanding of transformer condition monitoring and maintenance. Below are some notable studies in this field: Duanaputri et al. [5], The article titled The Influence of Load on the Oil Index for Treatment Recommendations explores how varying load conditions influence the oil index and the associated recommendations for treatment. This study underlines the crucial role of transformer load in determining the oil's degradation rate and informs the development of more accurate diagnostic tools for assessing transformer health. By integrating load conditions into the oil treatment recommendation process, the authors propose a framework to extend transformer life by optimizing oil maintenance strategies. Adekunle et al. [1] In their review article Performance Assessment of Cellulose Paper Impregnated in Nanofluid for Power Transformer Insulation Application, Adekunle and colleagues investigate the application of nanofluids as insulating materials in power transformers. This paper presents a comprehensive evaluation of cellulose paper impregnated with nanofluids, highlighting their potential to enhance the dielectric properties of transformer insulation and improve the overall performance and reliability of power transformers. The study provides a critical overview of recent advancements in transformer insulation technology and presents a detailed comparison of the performance of traditional insulating materials versus nanofluid-impregnated cellulose. Islam et al [9] The article Power Transformer

Health Condition Evaluation: A Deep Generative Model Aided Intelligent Framework introduces a novel approach to evaluating the health of power transformers using deep learning models. The study leverages a generative model to predict the transformer's health condition, which can aid in detecting early signs of deterioration in insulation or other critical components. This intelligent framework promises to enhance decision-making in transformer maintenance by providing real-time condition assessments, thus reducing the risk of unexpected failures and extending transformer service life Liang et al. [12] Innovative Transformer Life Assessment Considering Moisture and Oil Circulation by Liang and colleagues presents an innovative approach to transformer life assessment, incorporating both moisture content and oil circulation. The study emphasizes the importance of monitoring moisture levels and oil flow in transformers, as these factors significantly influence the aging process of the insulation materials. The authors propose a combined moisture-oil circulation model to predict the transformer's remaining useful life more accurately, thus optimizing maintenance schedules and reducing operational costs. Prasojo et al. [15] In their article Assessment of Power Transformer Solid Insulation Condition Using a Composite Index, Prasojo et al. introduce a composite index for evaluating the condition of solid insulation in power transformers. The study focuses on using this index to assess the integrity of solid insulation materials, such as paper, under various operational conditions. The authors apply their proposed index to a case study of the UIT-JBM population, demonstrating its effectiveness in providing a more comprehensive and reliable assessment of transformer insulation health. Prasojo et al. [16] Another paper by Prasojo et al., An Evaluation and Correlation Study of Oil and Solid Insulation in Power Transformers Using Composite Index Considering Operating Age, investigates the relationship between oil insulation and solid insulation performance. By considering the operating age of transformers, the study aims to correlate the aging processes of oil and solid insulation materials to better predict transformer health. The use of a composite index allows for an integrated analysis of both insulation systems, providing a more holistic view of transformer aging and helping to optimize maintenance protocols.

Prasojo et al. [17] In Assessing Transformer Insulation Aging through Oil Treatment Index: A Comparative and Correlation Study of 150 kV Power Transformers, Prasojo and colleagues focus on the aging process of transformer insulation. They introduce the oil treatment index (OTI) as a key parameter for assessing insulation degradation over time. The study compares the performance of 150 kV transformers with different oil treatment histories and presents a correlation between oil aging and insulation degradation. This research aids in understanding the factors contributing to transformer aging and provides insights into improving transformer life expectancy through better oil management. Prasojo et al [18] Another work by Prasojo, Implementasi Metode Scoring Matrix dalam Menentukan Indeks Kondisi Minyak Isolasi pada Transformator Daya 150 kV (Implementation of Scoring Matrix Method for Determining the Oil Insulation Condition Index of 150 kV Power Transformers), explores the application of a scoring matrix to evaluate the condition of oil insulation in power transformers. The paper presents a systematic methodology for assessing oil quality, using a scoring matrix that combines various oil parameters to determine the overall condition of transformer oil. This approach helps in identifying potential risks to transformer insulation and ensures timely interventions to maintain transformer health.

These studies represent a broad spectrum of research focused on power transformer health, insulation systems, and life assessment techniques. They highlight advancements in diagnostic tools, material science, and deep learning applications for monitoring transformer conditions. The ongoing efforts in this field are paving the way for more efficient and predictive maintenance strategies, contributing to the overall improvement of power transformer reliability and performance. The integration of moisture, oil analysis, and advanced modeling approaches is expected to revolutionize how utilities manage transformer health, ensuring longer service life and reduced downtime.

This paper initially discusses the insulation lifespan of power transformers. In this section, paper and oil insulation are examined, along with an analysis of dissolved gases in oil using Dissolved Gas Analysis (DGA), introducing the dissolved gases in transformer oil. The next section focuses specifically on furfural dissolved in oil and its relationship with the lifespan of power transformers. Subsequently, a case study is presented, analyzing the number and severity of short-circuit currents passing through two power transformers in a high-voltage substation, as well as the variation in furfural concentration in oil samples taken at each sampling period for the two transformers.

The final section of this paper is dedicated to concluding the relationship between short-circuit current severity and the lifespan of power transformers.

2 Insulation lifespan of power transformers

The insulation system of a power transformer is categorized into oil insulation and paper insulation. If the oil insulation deteriorates, it can be purified or even replaced. However, accessing paper insulation is challenging, and repairing or replacing it is not considered a viable option. Consequently, the limiting factor in a transformer's lifespan is the lifespan of its paper insulation.

2.1 Paper insulation

Transformer paper insulation is composed of cellulose molecules. The strength of a cellulose molecule depends on the number of glucose bonds it contains. A schematic representation of a cellulose molecule is illustrated in Figure 3. Each cellulose molecule consists of a chain of glucose rings. The average number of glucose bonds in a cellulose molecule is known as the Degree of Polymerization (DP). For a new transformer, the DP value typically ranges between 1000 and 1250. According to a common standard, when the DP value decreases to 200, the paper insulation reaches the end of its useful lifespan [21].

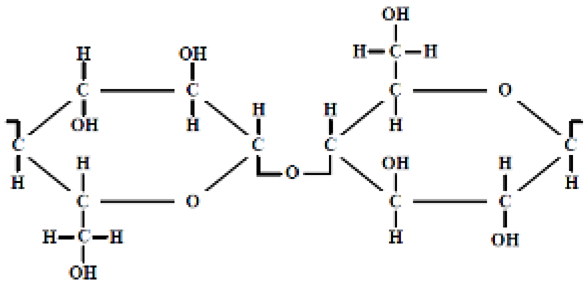

Figure 3: Chemical structure of a cellulose molecule [21]

To determine the degree of polymerization of paper insulation, a sample of the paper is tested in a laboratory to measure the number of glucose bonds. However, in practice, this method is not feasible for power transformers. Therefore, in recent years, various methods and equations have been developed to estimate the DP value [3, 14].

2.2 Oil insulation

Mineral oil is widely used in high-voltage equipment as both an insulating and cooling medium. The base material of mineral oil used in power transformers is classified into paraffinic and naphthenic types. As illustrated in Figure 4, paraffins consist of chain molecules without double bonds, whereas naphthenes are cyclic hydrocarbons without double bonds [11].

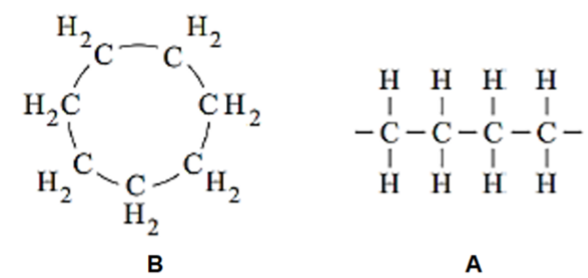

Figure 4: Basic chemical structure of mineral oil. a) paraffin-b) naphtan [11]

The presence of foreign substances in transformer oil is considered contamination. Some of these contaminants can affect the electrical properties of the oil. These contaminants are categorized into soluble and insoluble types. The quantity of these contaminants provides valuable insights into the operational condition of the power transformer.

2.3 Dissolved gas analysis (DGA)

One of the diagnostic methods that provides insights into the thermal and electrical stresses experienced by oil-immersed power transformers is Dissolved Gas Analysis (DGA). Since DGA detects early transformer faults, it can help prevent further damage. The process begins with sampling oil from an active power transformer, followed by gas chromatography analysis in the laboratory to identify the dissolved gases in the oil. These gases include:

- Acetylene (C_2H_2)
- Ethylene (C_2H_4)

- Ethane (C_2H_6)
- Methane (CH_4)
- Carbon monoxide (CO)
- Carbon dioxide (CO_2)
- Nitrogen (N_2)
- Oxygen (O_2)
- Hydrogen (H_2)

In addition to dissolved gases, parameters such as water content, oil acidity, breakdown voltage, and Total Combustible Gas (TCG) are also measured. Several analytical approaches have been developed to interpret the significance of these gases, including:

- Key Gas Method
- Dornenburg Ratio Method
- Rogers Ratio Method
- International Electrotechnical Commission (IEC) Method
- Duval Triangle Method

These methods are outlined in IEEE Standard C57.104 and have been compared for their effectiveness in transformer condition assessment in [8]. All of these techniques help detect internal transformer faults, which can accelerate insulation degradation in power transformers.

3 Power transformer lifetime

The flow of short-circuit currents through high-voltage substation equipment can affect their lifespan [13]. A large short-circuit fault current is one of the major threats to the safety and stability of power systems [4].

Several factors influence power transformer aging, all of which are functions of temperature, humidity, and oxygen levels. One of the key factors impacting these parameters is the deformation of transformer windings. This deformation is caused by electromagnetic forces, leading to structural changes in the windings. Such structural changes can result in internal faults within the transformer.

Not all protection systems have the sensitivity, speed, and accuracy required to detect internal transformer faults. If these faults remain undetected, they can severely damage transformer insulation and, consequently, the power system, significantly reducing the transformer's lifespan.

3.1 Furfural

Furfural is a furan derivative that is produced exclusively from molecular degradation of cellulose insulation. Other furan compounds in transformer oil are unstable and gradually convert into furfural over time.

To isolate furfural, High-Performance Liquid Chromatography (HPLC), in accordance with IEC 61198, is used alongside gas chromatography. The amount of furfural dissolved in oil provides critical insights into the extent of cellulose insulation degradation. The key advantage of using furfural for estimating cellulose insulation lifespan is that it cannot be produced by oil itself—it is solely a byproduct of cellulose aging [7].

3.2 Relationship between degree of polymerization and furfural concentration

The degree of polymerization (DP) is a key indicator of cellulose insulation lifespan. In recent years, researchers have considered using furfural concentration in oil to estimate DP values. Equation (3.1) expresses the DP value as a function of furfural concentration [2]:

$$DP = a + b * \text{furfural} + c * \text{furfural}^2 + d * \text{furfural}^3. \tag{3.1}$$

In this equation, the coefficients a, b, c, and d depend on the type of transformer oil base and are selected from Table 1. Since DP reflects the mechanical strength of cellulose insulation, it serves as a reliable criterion for estimating the remaining lifespan of transformer insulation.

Table 1: Formula parameters (3.1) based on the type of power transformer oil

Parameter	Naphthene base oil	Paraffin base oil
a	634.95605	608.57587
b	-0.076591657	-0.08562357
c	3.097411×10^{-6}	$-5.9920883 \times 10^{-6}$
d	0	$-1.426611 \times 10^{-10}$

3.3 The relationship between power transformer lifespan and the number and intensity of short-circuit currents

The forces generated by short-circuit currents either directly damage part of the cellulose insulation or create conditions for internal faults [10], which accelerate the aging of the transformer's cellulose insulation. To investigate and study the effect of short-circuit currents passing through power transformers, the number of short-circuits occurring in each oil sampling period of the transformers has been extracted.

To establish a meaningful relationship between the intensity of short-circuit currents and the lifespan of power transformers, the short-circuit current at one and a half times the minimum rated current of the power transformer has been chosen as the base value, and values lower and higher than this threshold have been categorized separately. To better understand the aging of cellulose insulation, the variations in the concentration of dissolved furan compounds in the oil as well as the changes in the degree of polymerization during each transformer oil sampling period have been analyzed. High-voltage station power transformers, provided they are not subjected to electrical stresses beyond their tolerance limits, undergo oil sampling once per year. The dissolved gases in the oil and the extracted furan concentration are analyzed afterward. By considering the number and intensity of short-circuit currents passing through the transformer in each oil sampling period, the relationship between the number and intensity of short-circuit currents passing through power transformers and their lifespan is examined.

4 Lifetime evaluation based on data from two real transformers

To examine the relationship between the lifespan of power transformers and the number and intensity of short-circuit currents, a case study has been conducted on two transformers in a high-voltage substation.

4.1 Case study sample

The two parallel transformers, with specifications listed in Table 2, are located in a high-voltage substation with a main and auxiliary busbar configuration, as shown in Figure 5.

4.2 Oil sampling

The results of the oil tests for the two studied power transformers over a period of 11 years are presented in Tables 3 and 4. It should be noted that the oil purification of Transformer 2 was performed on **December 1, 2010**, and the oil purification of Transformer 1 was conducted on **October 27, 2010**.

Table 2: Characteristics of studied transformers

Transformer Name	Transformer Type	Year of Operation	Cooling System	Transformation Ratio (kV)	Primary Current (A)	Secondary Current (A)
Transformer 1	Oil-Immersed (Naphthenic)	1999	ONAF	63/20	206/275	650/866
Percentage Impedance (%)	Vector Group	Maximum Ambient Temperature (°C)	Maximum Short-Circuit Current (kA)	Maximum Short-Circuit Duration (s)	Rated Power (MVA)	
13.44	Ynd11	45	2.3/6.1	2	30	

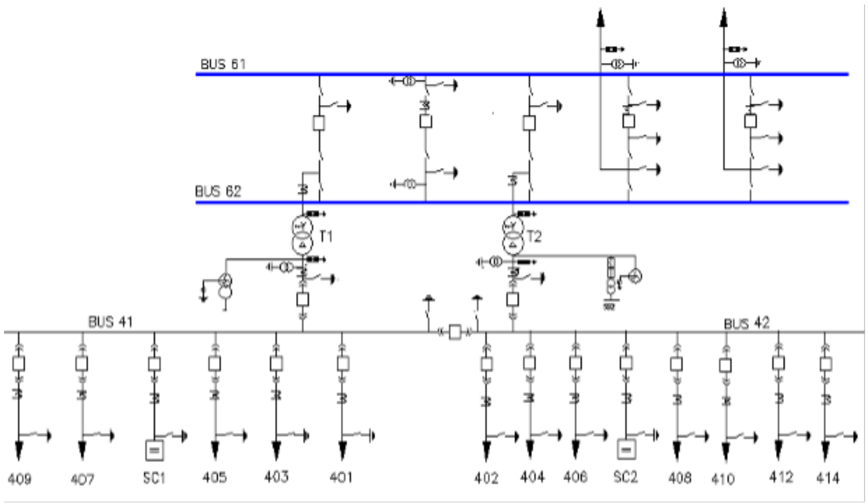

Figure 5: The location of the studied transformers in the substation

Table 3: The results of testing transformer oil 1 during 11 years

Oil sampling date	water content (PPM)	break down voltage (kV)	acidity	CO (PPM)	CH4 (PPM)	CO2 (PPM)	C2H4 (PPM)	C2H6 (PPM)	C2H2 (PPM)	H2 (PPM)	O2 (PPM)	N2 (PPM)	TCG (PPM)	FURFURAL (PPM)
April 13, 2011	1.1	91	0.013	34	21	110	8	2	1	3	10034	51231	89	0.6133
April 12, 2012	1.9	87	0.021	48	36	287	13	4	4	8	11908	67543	109	0.7938
April 23, 2013	2.1	86	0.042	68	22	315	16	5	6	11	12408	72340	121	0.9239
June 2, 2014	2.7	82	0.055	81	53	362	19	6	7	13	15471	81235	152	1.0141
May 12, 2015	3.3	79	0.064	92	61	481	21	8	9	15	13098	79651	178	1.1636
April 10, 2016	3.9	77	0.053	100	4	566	24	10	11	19	17978	91102	204	1.2737
March 15, 2017	3.6	87	0.082	184	16	406	29	19	10	17	25440	89343	275	1.3038
October 13, 2018	5.1	82	0.08	790	81	2639	42	13	11	42	15101	70763	979	1.5537
June 27, 2019	8.1	76	0.07	445	74	2307	50	14	16	49	13402	94941	648	1.6336
July 4, 2020	6.5	81	0.07	567	79	2415	45	14	14	57	27775	111939	776	1.7337
July 16, 2021	8.6	82	0.06	407	52	3269	45	12	22	65	15488	85577	603	1.7541
July 16, 2022	13	81	0.08	531	58	2610	62	37	15	184	9559	137387	887	1.8039

Table 4: The results of testing transformer oil 2 during 11 years

Oil sampling date	water content (PPM)	break down voltage (kV)	acidity	CO (PPM)	CH4 (PPM)	CO2 (PPM)	C2H4 (PPM)	C2H6 (PPM)	C2H2 (PPM)	H2 (PPM)	O2 (PPM)	N2 (PPM)	TCG (PPM)	FURFURAL (PPM)
April 13, 2011	2.3	89	0.024	21	16	102	3	0	0	0	24129	47802	64	0.6178
April 12, 2012	2.7	81	0.032	32	24	238	8	3	2	1	26013	59054	70	0.8182
April 23, 2013	3.1	86	0.045	39	31	302	11	4	4	3	27031	71230	81	0.9781
June 2, 2014	3.4	81	0.052	49	38	328	15	5	5	3	29910	69012	97	1.0979
May 12, 2015	3.9	77	0.056	52	28	391	17	7	6	4	28709	78612	112	1.2781
April 10, 2016	4.2	65	0.05	58	25	415	20	8	7	6	30806	88625	124	1.4278
March 15, 2017	5.5	80	0.029	241	65	1756	32	19	10	24	23679	90918	391	1.468
October 13, 2018	5.9	86	0.05	615	63	2160	37	11	6	87	16480	67901	819	1.7479
June 27, 2019	6.1	73	0.03	409	46	1847	40	12	9	26	10882	90697	542	1.8479
July 4, 2020	5.4	78	0.04	462	51	1794	33	11	6	40	31911	116916	603	1.9778
July 16, 2021	6	86	0.04	294	58	2372	29	8	8	38	12508	85541	435	2.0079
July 16, 2022	6.1	84	0.05	333	35	1679	29	19	0	125	4107	129460	541	2.0884

4.3 Short-circuit currents

Over a period of 11 years, all short-circuits that occurred, causing fault currents to pass through the studied transformers, were collected, and their number was categorized based on whether the short-circuit current was less than or greater than one and a half times the minimum rated current of the transformer. It should be noted that due to the parallel arrangement and identical specifications of Transformers 1 and 2, the short-circuit current passing through both transformers is equal. By having the oil sampling times of the transformers, the amount of furan generated from each oil sample, the occurrence time of the short-circuit, and the short-circuit current values, the variations in furan concentration and the changes in polymerization number during each oil sampling period are presented according to the number and intensity of short-circuit currents in Table 5.

Table 5: Changes of furfural and degree of polymerization with the number and intensity of short circuit current in each oil sampling period

Time Interval Between Oil Sampling Dates	Total Number Short Circuits	Number of Short Circuits Less Than 975A	Number of Short Circuits Greater Than 975A	Furan Changes Transformer 1 (ppm)	Furan Changes in Transformer Transformer	DP Changes in Transformer 1 (ppm)	DP Changes in Transformer Transformer
From April 13, 2011 to April 13, 2012	110	94	16	0.1805	0.2004	13.0381	14.4576
From April 12, 2012 to March 23, 2013	96	84	12	0.1301	0.1599	9.2724	11.3573
From April 23, 2013 to February 22, 2014	124	115	9	0.0902	0.1198	6.3671	8.4053
From February 22, 2014 to February 11, 2015	105	92	13	0.1495	0.1802	10.4420	12.4756
From February 11, 2015 to January 11, 2016	106	95	11	0.1101	0.1497	7.6016	10.2111
From January 11, 2016 to March 14, 2017	57	55	2	0.0301	0.0402	2.0651	2.7184
From March 14, 2017 to July 2, 2018	215	171	44	0.2499	0.2799	16.9284	18.6499
From July 2, 2018 to April 25, 2019	41	34	7	0.0799	0.1000	5.3309	6.5454
From April 25, 2019 to April 3, 2020	30	20	10	0.1001	0.1299	6.6228	8.4100
From April 3, 2020 to July 14, 2021	15	14	1	0.0204	0.0301	1.3421	1.9338
From July 14, 2021 to July 16, 2022	36	31	5	0.0498	0.0805	3.2654	5.1443

4.4 Relationship between furfural changes and the number and intensity of short-circuit currents

Figure 6 shows the relationship between the changes in furfural and the number and intensity of short-circuits that occurred in Power Transformers 1 and 2. To better understand the subject, the total number of short-circuits that occurred, as well as the number of short-circuits with intensities less than and greater than one and a half times the minimum nominal current of the power transformers, are arranged in ascending order, and the corresponding furfural changes are plotted. As can be seen, there is only a meaningful relationship between the increase in the number of short-circuits with an intensity greater than one and a half times the minimum nominal current of the transformer and the furfural changes. In other words, as the number of short-circuits greater than one and a half times the minimum nominal current of the transformer increases, the amount of furfural produced in the power transformer increases.

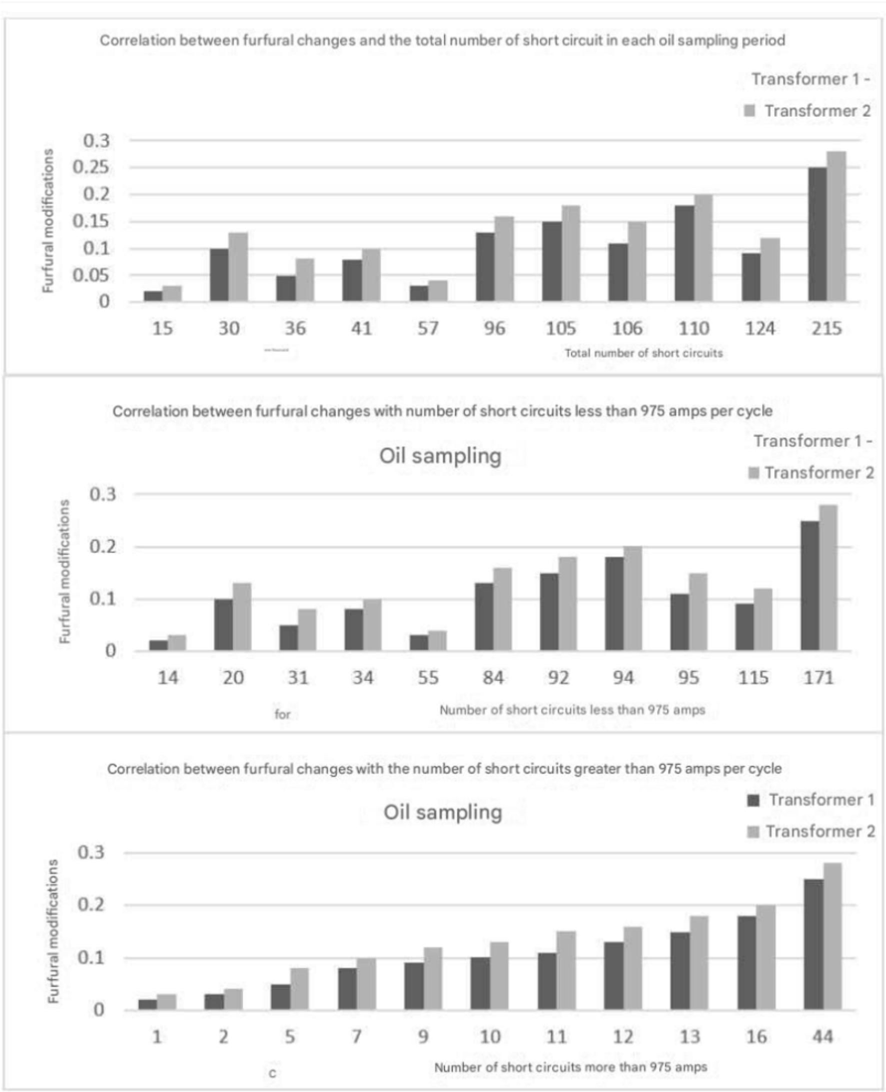

Figure 6: Correlation between furfural changes in each oil sampling period of transformers 1 and 2 with a) the total number of short circuit. b) The number of short circuits is less than 975 amperes. c) The number of short circuit more than 975 amperes

4.5 Relationship between changes in polymerization number and the number of short-circuit currents

Figure 7 shows the relationship between changes in polymerization number and the number and intensity of short-circuits that occurred in Power Transformers 1 and 2. To better understand the subject, the total number of short-circuits that occurred, as well as the number of short-circuits with intensities less than and greater than one and a half times the minimum nominal current of the power transformers, are arranged in ascending order, and the corresponding changes in polymerization number are plotted. As can be seen, there is only a meaningful relationship between the increase in the number of short-circuits with an intensity greater than one and a half times the minimum nominal current of the transformer and changes in the polymerization number. In other words, as the number of short-circuits greater than one and a half times the minimum nominal current of the transformer increases, the polymerization number decreases more significantly, and consequently, the cellulose insulation life of the power transformer decreases more rapidly.

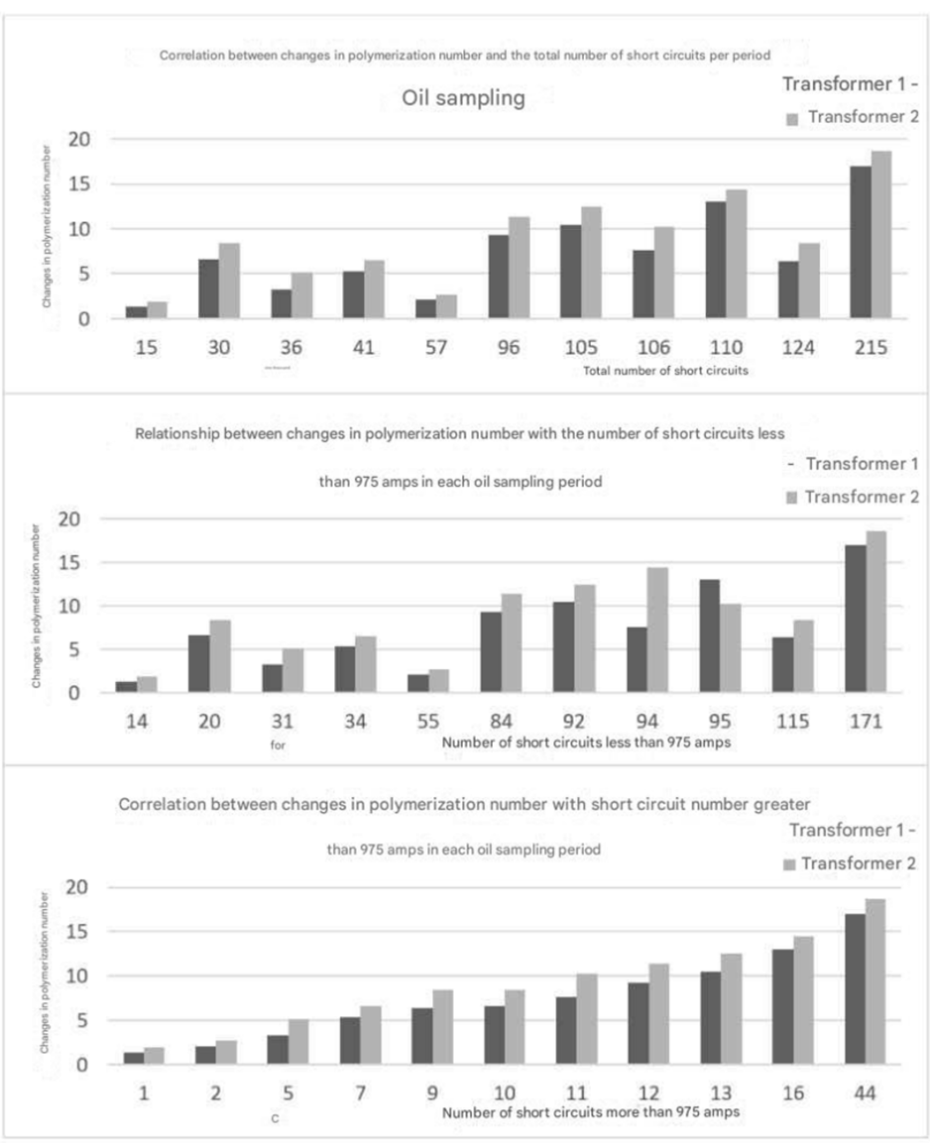

Figure 7: Correlation between changes in degree of polymerization in each oil sampling period of transformers 1 and 2 with a) the total number of short circuits. b) The number of short circuits is less than 975 amperes. c) The number of short circuit more than 975 amperes

5 Conclusion

In this study, the amount of furfural obtained from the oil test of two power transformers and, accordingly, the degree of polymerization of the power transformers in each oil sampling period at a high-voltage substation over a period of 11 years was examined. In parallel, the number of short-circuit currents passing through the power transformers, as well as the severity of these short-circuit currents during each oil test period, were also analyzed. The results indicate that the variation in furfural content in each oil test period has a direct correlation with the severity of the short-circuit currents passing through the power transformer during the same period. In other words, as the number of short-circuit currents with higher intensity passing through the power transformer (in each oil test period) increases, the furfural variation observed in that period also increases. Consequently, this leads to a greater reduction in the degree of polymerization of cellulose, ultimately accelerating the reduction of the power transformer's lifespan.

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