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Prediction of Remaining Life of Transformer at PLTU Suralaya Unit 6 Using Tan Delta Method at 1 mHz and Degree of Polymerization Calculation

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Abstract

Assessing the insulation condition of power transformers is crucial for maintaining the reliability of electrical power systems. This research aims to predict the remaining life of the transformer at PLTU Suralaya Unit 6 by integrating the measurement of the dissipation factor (tan δ) using Dielectric Frequency Response (DFR) testing at ultra-low frequency (1 mHz = 0.001 Hz) and estimating the Degree of Polymerization (DP) through empirical correlation. The DFR measurements were performed with the OMICRON DIRANA device (frequency range 0.1 mHz–1 kHz) and validated against tan δ measurements at 50 Hz using OMICRON CPTD equipment. The dissipation factor at 1 mHz was extracted and converted to an estimated DP value through a validated regression model. Results show a DP value of approximately 302, indicating advanced degradation of the cellulose insulation. This corresponds to an estimated remaining life percentage of 29.68%, equivalent to an operational lifespan of roughly 11.87 years before reaching the end-of-life threshold. The study confirms that ultra-low-frequency DFR testing combined with DP estimation provides a non-destructive and effective approach for transformer remaining life prediction. It is recommended to implement condition-based monitoring and supplement with oil chemical analysis (e.g., furan compounds) and other diagnostic methods to enhance prediction accuracy and support proactive asset management.

Keywords: *Degree of polymerization; Dielectric Frequency Response; Dissipation factor (tan δ); Remaining life; Transformer*

Introduction

Power transformers are among the most critical components in electrical power systems, particularly in steam power plants such as PLTU (Steam Power Plant), where their reliability directly affects the continuity of electricity supply (IEC, 1993). Over time, transformers undergo material degradation, especially within the insulation system, which can lead to declining performance and potential failure. The insulation structure mainly consists of insulating oil and cellulose-based paper, with cellulose being the most vulnerable to thermal, moisture-induced, and oxidative aging (IEC, 2007a). One of the primary parameters used to determine transformer insulation condition is the Degree of Polymerization (DP), which represents the average length of cellulose polymer chains. The DP value decreases progressively as the insulation ages; new insulation paper typically has DP values of 1200–

1400 and is considered to reach end of life at DP values around 200, when its mechanical tensile strength becomes severely weakened (Mehta & Jariwala, 2012).

Direct DP measurement is destructive because it requires physically removing insulation paper from inside the transformer, making the method unsuitable for operational equipment (IEC, 2007a). Therefore, non-destructive diagnostic techniques are needed. Frequency Domain Spectroscopy (FDS) has emerged as a promising method, measuring the dielectric dissipation factor (tan δ) across a range of frequencies. Studies demonstrate a strong relationship between tan δ at ultra-low frequencies (such as 1 mHz) and transformer insulation aging, including DP and tensile strength degradation (Xiaoguang et al., 2018). This correlation allows tan δ at low frequency to be used as an indirect estimator of DP, enabling prediction of transformer remaining life without dismantling the equipment.

Transformer design life is guided by international standards such as IEC 60076-15, which outline operational limits and expected service durations under specified thermal stresses (IEC, 2015). In addition, transformer construction and core materials—including grain-oriented steel—are regulated under material standards such as IEC 60404-8-7 to ensure reliable magnetic and mechanical performance during long-term operation (IEC, n.d.). Instrument transformers and measurement systems used in diagnostics also conform to standards such as IEC 61869-1, ensuring accuracy and consistency in dielectric and electrical assessments (IEC, 2007b).

At PLTU Suralaya Unit 6, scheduled maintenance periods provide an opportunity to conduct comprehensive transformer condition assessments. As part of this process, tan δ measurements at 1 mHz were performed. The collected data forms the basis of this research, which develops a predictive method for estimating transformer remaining life by correlating 1 mHz tan δ values with DP estimates and insulation aging characteristics (Mehta & Jariwala, 2012; Xiaoguang et al., 2018; IEC, 1993, 2007a, 2007b, 2015, n.d.).

Methods

A. Location and Time of Research

This research was conducted at the Suralaya Steam Power Plant (PLTU Suralaya) Unit 6, located in the Tangerang district, Banten Province, Indonesia. PLTU Suralaya is one of the largest power plants in Indonesia with a total capacity of 3,400 MW, consisting of 7 generating units connected to high-voltage transmission systems. The power transformer in this unit plays a critical role in stepping down the generator output voltage from 23 kV to the 10.5 kV self-use voltage, as shown in Figure 1.

Figure 1. PLTU Suralaya Power Plant

Data collection and measurements were carried out during scheduled maintenance from February 2 to 7, 2025. The testing period was chosen to ensure safe offline conditions without disturbance to plant operation. Measurements were taken under controlled ambient temperature conditions ranging from 25°C to 34°C to minimize the influence of temperature variation on dielectric testing results.

B. Research Object

The research object is the three-phase, oil-immersed Unit Service Transformer (UST) operating at PLTU Suralaya Unit 6. The transformer was selected as it has been operating for more than 20 years and was scheduled for overhaul maintenance, making it a suitable subject for aging assessment due to natural aging of the oil-paper insulation system. Given its critical role in the plant's operational reliability, thorough condition assessment and testing of the transformer are essential.

C. Transformer Specifications

The tested transformer has the following technical specifications show on Table 1:

Tabel 1. Technical specifications transformator

Manufacture	MITSUBISHI ELECTRIC CORPORATION
Type	CRB
Serial Number	9578091101
Year of Manufacturing	1996
Vector Grup	Dyn11
Cooling Method	OA/FA/FA
Rated Power	30/40/50 MVA
Frequency	50 Hz
HV Side	23 kV
HV Rated Current	753/1000/1260 A
LV Side	10.5 kV
LV Rated Current	1650/2200/2750 A

D. Data Used

Two primary types of data were used in this research:

A. Winding Dissipation Factor and Capacitance Measurement
Measured using OMICRON CPTD at 50 Hz frequency. Parameters measured include dissipation factor (tan δ) and capacitance (C) on the high-to-low (ICHL) and low-to-high (ICLH) winding sides.

B. Dielectric Frequency Response (DFR) Measurement
Conducted using OMICRON DIRANA over a wide frequency range (0.1 mHz to 1 kHz). Dissipation factor data at 50 Hz was used for validation before conversion to ultra-low frequency (1 mHz) values.

Additional formulas were used to calculate the Degree of Polymerization (DP) from the dissipation factor (tan δ) and to estimate the remaining life of the transformer from the DP.

E. Tools and Software

The tools or software has following specifications show on Table 2:

Tabel 2. Tools and software used

Tool / Software	Function
OMICRON CPTD	Measures tan δ and capacitance at 50 Hz for IEC-based assessment
OMICRON DIRANA	Performs Dielectric Frequency Response testing from 0.1 mHz to 1 kHz
Digital Thermometer	Measures ambient temperature
Oil Temperature Indicator	Measures transformer oil temperature
Winding Temperature Indicator	Measures transformer winding temperature
Laptop + OMICRON PC Software	Extracts, processes, and converts OMICRON CPTD and DFR data
Microsoft Excel	Data analysis, DP calculation, and remaining life prediction

F. Research Procedures

Figure 2 illustrates the flowchart of the research process:

1. Preparation
   a. Coordinate with PLTU Suralaya maintenance team.
   b. Ensure transformer is offline, properly grounded, free of residual voltage, and ready for testing.
2. Winding Dissipation Factor & Capacitance Testing (50 Hz)
   a. Conducted using OMICRON CPTD following specified test instructions (Figure 3).
   b. Parameters measured: tan δ and capacitance.
3. Dielectric Frequency Response (DFR) Testing
   a. Performed with OMICRON DIRANA as per instrument instructions (Figure 4).
   b. Provides frequency-dependent dissipation factor and capacitance data from 0.1 mHz to 1 kHz.

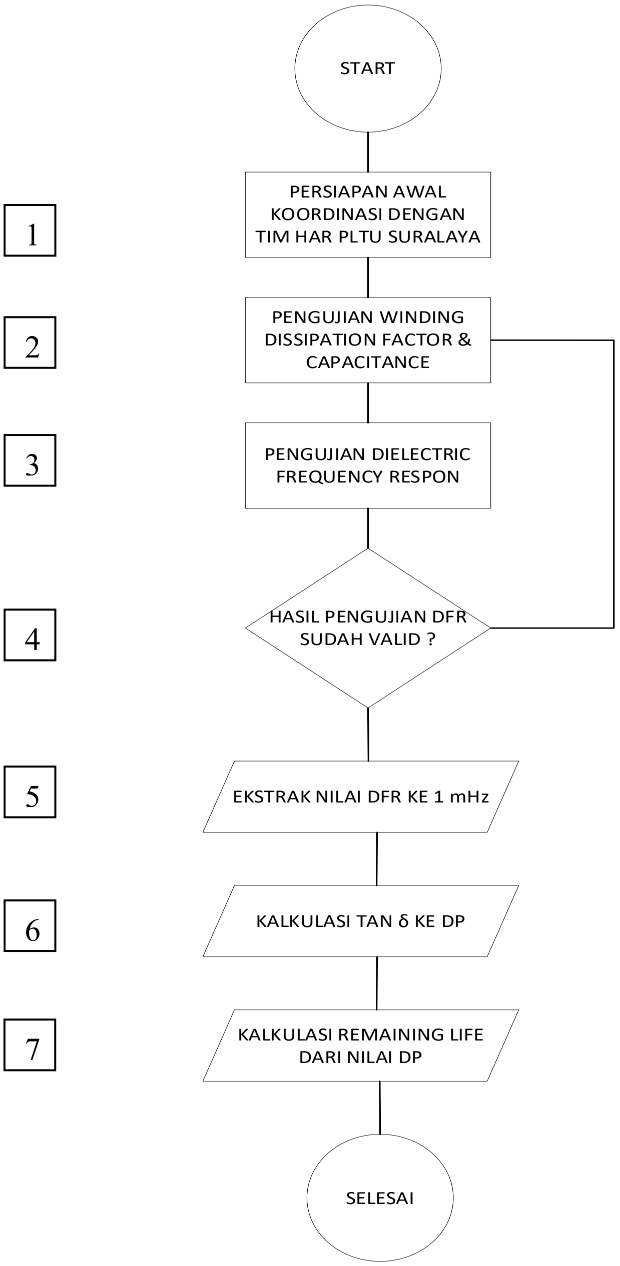

Figure 2. Research Procedure Flowchart

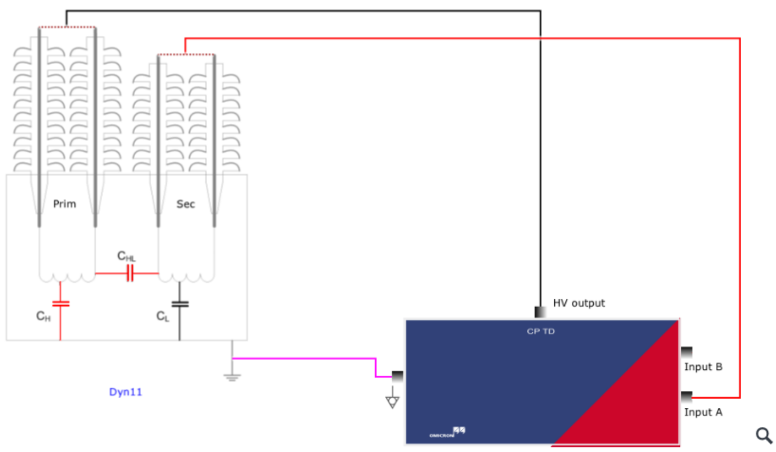

Figure 3. Test Instruction Winding DF & Capacitance Measurement

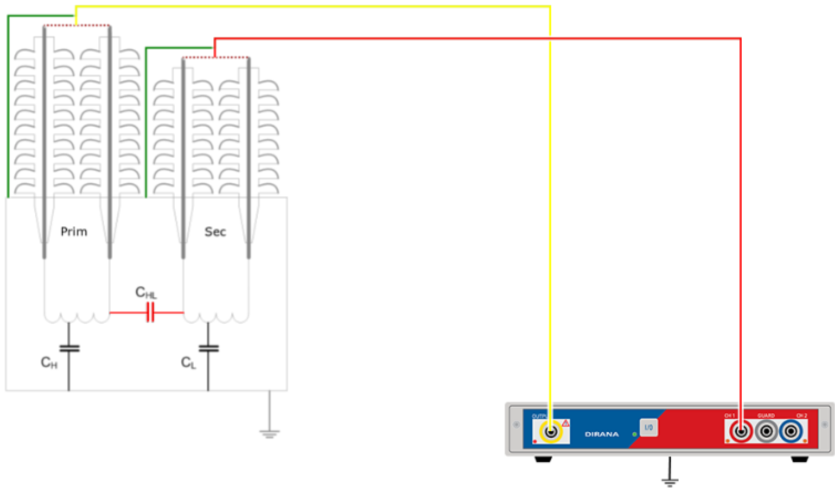

Figure 4. Test Instructions for DFR using OMICRON DIRANA

4. Data Validation
   Validated Tan δ results at 50 Hz from OMICRON CPTD against those from OMICRON DIRANA.
5. Extraction of Tan δ Value at 1 mHz
   Tan δ at 1 mHz frequency extracted from DFR curves using DIRANA software cursor feature. This ultra-low frequency is highly sensitive to moisture content and polymer degradation in cellulose insulation.
6. Degree of Polymerization Calculation
   Calculated based on the validated exponential regression model correlating Tan δ at 1 mHz with DP values.
7. Remaining Life Estimation
   Estimated transformer remaining life derived from DP values using empirically developed tables and logarithmic regression formulas.

G. Data Analysis

The analysis involved the following calculations:

1. Capacitance © derived from reactive current components measured by the test instruments, calculated by Equation (1):

$$C = \frac{I\ reaktif}{2\,\pi f V} \tag{1}$$

   Where IC is the capacitive current, f is the test frequency (50 Hz), and V is the measured voltage.
2. Dissipation Factor (DF or tan δ) is calculated as the ratio of resistive current to capacitive current, as shown in Equation (2).
3.

$$DF = tan\ \delta \frac{IR}{IC} \tag{2}$$

   Where IR is the resistive current derived from measured power losses.
4. Degree of Polymerization (DP) estimated from measured tan δ at 1 mHz using the validated exponential regression, as shown in Equation (3).

tan δ = 0,08979 + 36,179·e^(–0,01036·DP) (3)

Rearranged as Equation (4):

$$DP = -\frac{1}{0{,}01306}\, ln\left(\frac{\tan\delta - 0{,}08979}{36{,}179}\right) \tag{4}$$

5. Estimated Percentage of Remaining Life derived from DP by logarithmic equation: as Equation (5):

$$Y = 72{,}14.\, ln(x) - 382{,}27 \tag{5}$$

Where Y is the estimated remaining life percentage.

6. Estimated Remaining Life in Years calculated by Equation (6):

$$Remaining\ Life\ (years) = \left(\frac{Y}{100}\right) x40 \tag{6}$$

Results and Discussions

A. Measurement Results of Winding Dissipation Factor (tan δ) and Capacitance

The winding dissipation factor (tan δ) and capacitance data measured on the transformer UST A of PLTU Suralaya Unit 6 are shown in Table 1 and Table 2 (Figures 5). The measured tan δ values ranged between 0.14% and 0.53%, after correction with factor 0.77, resulting in values within 0.109% to 0.408%, which comply with IEEE Std 62 criteria. These results indicate that the insulation condition remains in good health. The measurements were performed for different winding configurations including ICH + ICHL (GST), ICH (GSTg-A), ICHL (UST-A), ICL + ICLH (GST), ICL (GSTg-A), and ICLH (UST-A). The calculated capacitance values were consistent and within expected ranges, reinforcing the validity of test results.

Block 1: injection at Prim

Corr. temperature	32 °C
Corr. factor	0.77
* Reference voltage	10.0 kV

No.	Meas.	Test mode	Freq.	V out	* I out	* Watt losses	DF meas	DF corr	Cap. meas	Assessment
1	ICH+ICHL	GST	50.00 Hz	10.00 kV	33.81 mA	874.04 mW	0.2585 %	0.1991 %	10757.3 pF	Pass
2a	ICH (V)	GSTg-A	50.00 Hz	10.00 kV	10.04 mA	533.15 mW	0.5309 %	0.4088 %	3193.4 pF	Pass
3a	ICHL (V)	UST-A	50.00 Hz	10.00 kV	23.76 mA	337.91 mW	0.1422 %	0.1095 %	7563.8 pF	Pass
Cross check: calculated ICHL					23.76 mA	340.88 mW	0.1434 %		7563.8 pF	Pass

Block 2: injection at Sec

Corr. temperature	32 °C
Corr. factor	0.77
* Reference voltage	10.0 kV

No.	Meas.	Test mode	Freq.	V out	* I out	* Watt losses	DF meas	DF corr	Cap. meas	Assessment
4	ICL+ICLH	GST	50.00 Hz	6.01 kV	57.47 mA	1503.06 mW	0.2616 %	0.2014 %	18288.6 pF	Pass
5a	ICL (V)	GSTg-A	50.00 Hz	6.00 kV	33.70 mA	1164.60 mW	0.3456 %	0.2661 %	10725.0 pF	Pass
6a	ICLH (V)	UST-A	50.00 Hz	6.00 kV	23.76 mA	336.46 mW	0.1416 %	0.1090 %	7563.7 pF	Pass
Cross check: calculated ICLH					23.76 mA	338.46 mW	0.1424 %		7563.6 pF	Pass

Figure 5. Measurement Results - Dissipation Factor (tan δ) and Capacitance

B. Dielectric Frequency Response (DFR) Test Results

Figure 6 presents the dielectric frequency response results measured by OMICRON DIRANA at 50 Hz, confirming a capacitance value of approximately 7.556 nF (7556 pF) and a dissipation factor (tan δ) of 0.14%.

Table 3 compares dissipation factor and capacitance obtained by conventional tan δ measurement (OMICRON CPTD) and frequency-varying DFR technique (OMICRON DIRANA). The close agreement (difference approximately 0.1%) validates the DFR measurement integrity.

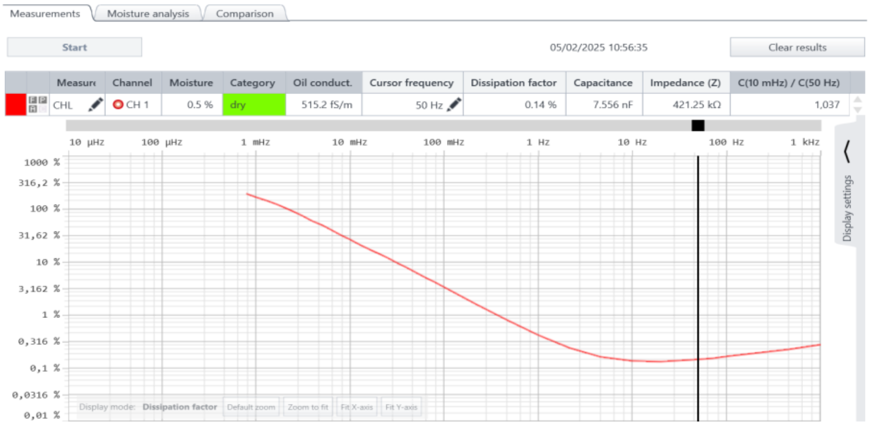

Figure 6. Dielectric Frequency Response at 50 Hz

Table 3. Comparison of Dissipation Factor and Capacitance Results

Parameter	Tan Delta (ICHL/ICLH)	DIRANA CHL	Remarks
Dissipation Factor (DF)	0.1422% / 0.1416%	0.14%	Valid (agreement)
Capacitance	7.564 nF	7.556 nF	Valid (0.1% diff.)
Measurement Frequency	50 Hz	50 Hz	Equal Frequencies
Test Method	High AC Injection	Variable Frequency	Different methods

C. Extraction of Tan Delta at 1 mHz

DFR results at ultra-low frequency of 1 mHz revealed a tan δ value of 167.75%, as seen in Figure 7. This high tan δ value at ultra-low frequency indicates advanced degradation in the cellulose insulation. This value forms the basis for estimating the Degree of Polymerization (DP) and thus the remaining life of the transformer.

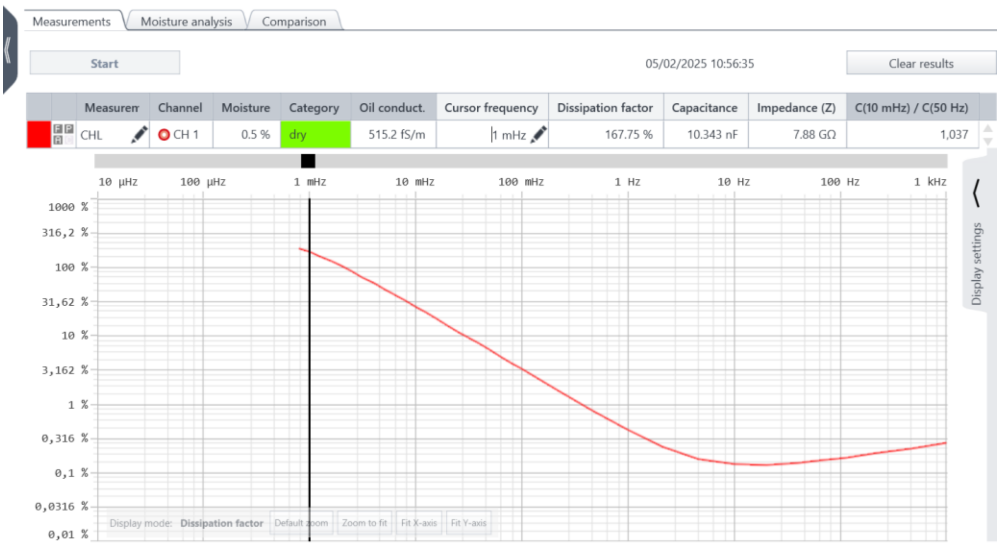

Figure 7. Dielectric Frequency Response at 1 mHz

D. Calculation of Degree of Polymerization (DP) from Tan Delta

Using the validated exponential regression formula as Equation (7):

$$DP = -\frac{1}{0,01306}\, ln\left(\frac{\tan \delta - 0,08979}{36,179}\right) \quad (7)$$

where tan δ is expressed as a decimal (tan δ = 1.6775 for 167.75%). Substituting as Equation 8.

$$DP = -\frac{1}{0,01306}\, ln\left(\frac{1,6775 - 0,08979}{36,179}\right) = 301,74 \approx 302 \quad (8)$$

This DP value signals advanced aging of the insulation paper.

E. Estimation of Remaining Life Percentage and Years

Using the logarithmic fitting formula as Equation (8) for remaining life percentage:

$$Y = 72,14.\, ln(x) - 382,27 \quad (8)$$

Substituting DP = 302 as Equation (9):

$$Y = 72,14.\, ln(302) - 382,27 = 29,68\% \quad (9)$$

Transforming this into estimated remaining life in years as Equation (10):

$$Remaining\ Life\ (years) = \left(\frac{Y}{100}\right) x40 = 11,87 \quad (10)$$

Conclusions

Based on the analysis of dielectric measurement results, Degree of Polymerization (DP) calculations, and remaining life estimations, the condition of the transformer at PLTU Suralaya Unit 6 shows clear indicators of aging. The calculated DP value of approximately 302 reflects that the cellulose insulation has entered an advanced stage of degradation, suggesting that the insulation paper has significantly lost its mechanical strength and thermal endurance. Furthermore, the estimated remaining life of the insulation, which is only 29.68%, indicates that a substantial portion of the transformer's service lifespan has already been consumed. This condition highlights the urgency for more intensive maintenance, monitoring, and consideration of long-term replacement planning to prevent unexpected failures. In addition, the projection of the transformer's remaining operational life, around 11.87 years, provides a quantitative reference that can assist asset managers in making informed decisions regarding refurbishment schedules, capital planning, and risk mitigation strategies. The analysis also demonstrates that the combined use of ultra-low-frequency (1 mHz) Tan Delta measurements with DP estimation serves as an effective non-destructive diagnostic approach for assessing transformer aging. This method offers superior reliability compared to traditional insulation testing techniques that rely solely on withstand voltage or capacitance measurements. The synergy of these diagnostic tools provides a more accurate depiction of insulation health and enables better predictive maintenance planning.

References

Mehta, D., & Jariwala, H. (2012). Predication of Life of Transformer insulation by developing Relationship between Degree of Polymerization and 2-Furfural. *International Journal of Scientific & Engineering Research*, *3*(7). Retrieved from http://www.ijser.org

Xiaoguang XI1, H. W. W. W. 1, Y. X. Q. L. W. L. (2018). *The Study on the Relationship of Frequency Domain Spectroscopy of Oil-paper Insulation with Degree of Polymerization and Tensile Strength*.

International Electrotechnical Commission. (1993). *IEC 60076-1: Power transformers – Part 1: General* (Ed. 2.1).

International Electrotechnical Commission. (2007). *IEC 60450: Measurement of the average viscometric degree of polymerization of new and aged cellulosic electrically insulating materials* (Ed. 2.1).

International Electrotechnical Commission. (2015). *IEC 60076-15: Power transformers – Part 15: Gas-filled power transformers*.

International Electrotechnical Commission. (n.d.). *IEC 60404-8-7: Specifications for individual materials – Cold-rolled grain-oriented electrical steel strip and sheet delivered in the fully-processed state*.

International Electrotechnical Commission. (2007). *IEC 61869-1: Instrument transformers – Part 1: General requirements*.