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Study of Feasibility Assessment of Starting Transformer Operation Based on Analysis of Test Results at PLTU UP Gresik

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ABSTRACT

Power transformers are critical components in generation systems that are susceptible to degradation in insulation quality and structural damage to windings due to prolonged operational loads. Starting Service Transformer (SST) #3-4 at PT PLN Nusantara Power Unit PLTU Gresik, which was built by Toshiba Corporation in 1978 with a capacity of 20. 000 kVA, has been in operation for more than 40 years so it requires a thorough evaluation before being allowed to operate again after the maintenance process. The purpose of this study is to identify the current state of the transformer, analyze the suitability of the test results with applicable technical standards, and provide recommendations on the feasibility of operation based on the available evidence. The method used was a mixture with a single descriptive case study design. Data was collected through direct observation in the field, semi-structured interviews with UMRO (Unit Maintenance, Repair, and Overhaul) technicians of PT PLN Nusantara Power, and analysis of FMH-17 report documents. 2. 4. 007. Seven types of electrical tests were conducted off-line from March 2 to 4, 2026, including Insulation Resistance and Polarization Index, Winding Resistance, Dissipaction Factor, Excitation Current, Sweep Frequency Response Analysis (SFRA), Dielectric Response Analysis (DIRANA), and Turn-to-Turn Ratio (TTR). The results of the tests showed that all eight parameters met the acceptance requirements set by IEEE C57. 152-2013, IEC 60422:2013, DL/T911-2004, and NCEPRI. The insulation system is in excellent condition, as evidenced by the moisture level of the insulation paper of 0.3% (well below the limit of 2.2%), the minimum IR value of 7.01 GΩ, and the Dissipation Factor value in UST mode of 0.138%. The structural integrity of the windings was confirmed to be normal through a deviation of winding resistance close to zero (0.000% of the HV side; 0.003% of the LV side), a good HLH excitation pattern, a uniform TTR deviation below 0.09%, as well as the results of the HV side SFRA showing Normal Winding based on the NCEPRI method. SST #3-4 was declared fit to operate again without the need for any prior repairs. The data from the SFRA test results is set as a benchmark for future overhaul.

Keywords:
Assessment kelayakan; starting transformer; insulation resistance; idissipation factor; sweep frequency response analysis; dielectric response analysis; PLTU Gresik

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1. Introduction

Power transformers are elements that directly affect the continuity of electrical energy distribution in the generation system. Its role as a link between the generator and the transmission network makes it a very important part and should not be underestimated. The demand for the reliability of this element is increasing as the demand for electricity increases in the Southeast Asian region, especially in Indonesia. According to a report from the International Energy Agency (IEA), electricity consumption growth has averaged around 4.5% per year in the past decade. At the national level, data from the Central Statistics Agency shows that per capita electricity consumption in Indonesia in 2022 reached 1,123 kWh, an increase from 1,084 kWh in the previous year. This increase reflects increasing operational pressure on the entire generation infrastructure, including transformers [1]. In terms of capacity, the 2021–2030 Electricity Supply Business Plan (RUPTL) released by the Ministry of Energy and Mineral Resources shows that Steam Power Plants (PLTU) still supply more than half of the national power plant capacity, which is around 53% of the total installed capacity [2].

The dominance of coal-fired power plants in the national generation system places the main transformer and auxiliary transformer of the unit as elements that must operate under high thermal and electrical loads continuously. This condition is further aggravated by exposure to transient voltage due to switching maneuvers and network interference. Overall, these conditions can accelerate the aging process of the insulation system and reduce the mechanical integrity of the transformer windings. Research conducted by Situmeang *et al.*, [3] on power transformers in the coal-fired power plant environment showed that equipment operated without periodic condition assessments tended to experience insulation failures faster than the estimated lifespan that had been designed by the factory. In coal-fired power plants located in coastal industrial areas, such as PT PLN Nusantara Power Unit PLTU Gresik, this risk becomes even greater because the transformer is directly exposed to high humidity, corrosive particles from the industrial environment, and more extreme variations in environmental temperature compared to more protected areas [4]. In conditions like this, the starting phase, which is the process of restarting the transformer after maintenance or replacement activities, becomes a very crucial evaluation stage. At this stage, all electrical and mechanical parameters must be ensured to be within the established technical limits before the unit is allowed to operate again in the system.

The transformer under review, namely SST #3-4, is a three-phase power transformer made by Toshiba Corporation in Tokyo, Japan, and has been installed and operated at the Gresik Power Plant since 1978. This device functions as a power provider for internal needs (station service) in generation units 3 and 4 at PLTU Gresik, with a maximum capacity of 20. 000 kVA in ONAF (Oil Natural Air Forced) cooling mode. Since it has been in operation for more than four decades, regular assessment of the condition of these transformers is of great importance, especially ahead of the operation phase after maintenance.

Various previous studies have made significant contributions in understanding the state of transformers through specific test methods. Robbani *et al.*, [5] evaluated the isolation conditions of the 60 MVA transformer at the 150 kV Tegal Substation using the polarization index, delta tangent, and translucent voltage testing methods, which showed polarization index values in the range of 1.26 to 1.97, all of which were classified as safe according to the IEEE C57 standard. 152-2013. Irianto *et al.*, [6] examined the application of Sweep Frequency Response Analysis (SFRA) to detect mechanical problems in distribution transformers with a test frequency range between 20 Hz to 2 MHz, and successfully distinguished the frequency response pattern between normal conditions and mild interference conditions in windings. The SFRA analysis conducted on a 60 MVA transformer at the

150 kV Tasikmalaya Substation using the FRAX-101 tool gave an average deviation of calculation below 0.13% to the reference standard, which corroborates the accuracy of the method as a diagnostic tool for mechanical winding conditions [7].

On the other hand, Rianti et al. examined the feasibility of current transformers for protection functions in electrical systems through testing of insulation resistance, transformation ratio, and excitation current, with results showing that all units were in the category of viable for operation. Riski and Ramadhan analyzed the condition of the 30 MVA power transformer at the Padang Luar Substation which has been operating for more than ten years, and concluded that this device still meets technical standards based on IEEE, IEC, and CIGRE even though it has entered the final stage of its design life [9]. Aribowo examined the fault cases in the main transformer of the Muara Karang PLTGU through multivariable tests that included excitation current, leakage reactance, winding ratio, winding resistance, and oil gas analysis, which successfully identified the fault in the T-phase as the basis for the technical decision of unit replacement [10]. Ananto *et al*., [11] also examined the maintenance of the current transformer at the Tanjung Awar-Awar Babat PLTU with reference to PLN's internal operational procedures and previous historical test data, as part of an effort to build documentation of the continuous condition of the device.

Although these studies provide a fairly good basis in the diagnostics of transformer conditions, there are still some unrevealed scientific aspects. First, almost all existing studies focus on transformers in normal operational conditions or immediately after a disruption, while studies that specifically address the initial phase—i.e. feasibility assessment before activation after the maintenance or overhaul process—are still very few in the Indonesian electrical engineering literature. Second, the simultaneous use of seven test methods, which include Insulation and Polarization Resistance Index, Coil Resistance, Dissipation Factor (Tan Delta), Excitation Current, SFRA Meter, DIRANA Measurement, and Turn-to-Turn Ratio, has not been applied in an integrated evaluation framework in a domestic coal-fired power plant environment. Third, the DIRANA (Dielectric Response Analysis) method, which can estimate the moisture content and damage rate of insulation paper through frequency-based dielectric response analysis, is still rarely discussed in the context of coal-fired power plants in Indonesia. Fourth, there has been no research that combines quantitative data from the results of tool testing with qualitative evaluation of operational procedures to produce systematic and evidence-based starting decision recommendations on specific objects of the UP Gresik PLTU.

Transformer failure in a generation unit can lead to unexpected outages, which directly impact financial losses, disruption of electricity supply for customers, and decreased reliability of the Java-Bali interconnection system as a whole. Suwarno and Prasetyo [12] revealed that the costs incurred due to transformer failures that are not detected early far exceed the cost of conducting the planned periodic evaluation. This emphasizes that the feasibility assessment is more than just a technical procedure, but it is also a preventive measure that has clear economic and technical value. This study makes scientific contributions in three areas: first, developing an integrated analysis framework based on seven test parameters that can be an evaluation protocol for starting transformers in the coal-fired power plant environment; second, providing empirical data from real objects in PT PLN Nusantara Power Unit PLTU Gresik which can be used as a reference for similar studies in other PLTU units in Indonesia; and third, combining quantitative and qualitative approaches in a single research framework so that the resulting recommendations are not only based on numerical data, but also consider the real operational context in the field.

Based on the background and findings of research gaps that have been presented, this study sets three main objectives. First, identify the real state of the transformer at PT PLN Nusantara Power Unit PLTU Gresik based on the results of the test results of the Insulation and Polarization Resistance

Index, Coil Resistance, Dissipation Factor, Excitation Current, SFRA Meter, DIRANA Measurement, and Turn-to-Turn Ratio. Second, analyze the conformity of each of these test results with the current technical standards, which include IEEE C57. 152-2013, IEC 60422:2013, DL/T911-2004, as well as the internal maintenance SOP of PT PLN Nusantara Power. Third, formulate recommendations for the feasibility of starting transformer operations that are evidence-based and can be applied directly by the operational team in the field.

2. Methodology

2.1 Types and Approaches to Research

This study applies a mixed approach that combines quantitative and qualitative analysis at the same time in one integrated research framework. The quantitative method is used to process numerical data taken from seven electrical testing parameters, while the qualitative method is applied to assess the test implementation process, the state of the environment in the field, and the suitability of the results with applicable technical standards. The selection of these two methods is based on the understanding that decisions regarding the feasibility of starting transformers can not only be determined by numerical values, but also require an interpretive contextual assessment of the overall state of the device [13].

In terms of the type of research, this study is classified as a descriptive research with a single case study design, where the unit of analysis studied is Starting Service Transformer (SST) #3-4 at PT PLN Nusantara Power Unit PLTU Gresik. This design was chosen because the purpose of the study is to understand in depth the condition of a particular object based on actual test data, not to make statistical generalizations from a larger sample. The data collected are empirical and directly obtained through field testing, so the level of internal validity of this study is highly dependent on the accuracy of the test procedure, the calibration of the tool, and the consistency in recording environmental conditions during the test.

2.2 *Research Object*

The object that is the focus of this research is the Initial Service Transformer (SST) #3-4 installed at PT PLN Nusantara Power Unit PLTU Gresik, located on Jl. Harun Thohir No. 1, Gresik, East Java, Indonesia. This device is manufactured by Toshiba Corporation based in Tokyo, Japan, and functions as a power provider for internal needs (station service power supply) for generation units 3 and 4 at PLTU Gresik. With an operational age that has exceeded forty years since the year of manufacture in 1978, this transformer falls into the category of devices that need to be thoroughly evaluated in condition before being allowed to operate again after the maintenance process.

Fig. 1. Transformer (Source: PT PLN Nusantara Power UP Gresik)

Fig. 1. Transformer (Source: PT PLN Nusantara Power UP Gresik)

The complete technical specifications of SST #3-4 listed on *the unit nameplate* are presented in Table 1 and Table 2 below.

Table 1
Technical specifications of SST Unit 4-5 PLTU Gresika

Parameter	Value
Manufacturer	Toshiba Corporation, Tokyo, Japan
Type / Standard	Power Transformer JEC-204 (1978)
Location	PLTU Gresik
Serial Number	860900048
Installed Capacity	12,000 / 20,000 kVA
Frequency	50 Hz
Number of Phases	3 (Three)
Tegangan Primer (HV)	154.000 V
Secondary Voltage (LV)	4.160 V
Impedance Voltage	10,57% -- 20.000 kVA Base
Insulation Class	A
Temperature Rise	55 degC
Cooling Type	ONAN / ONAF
Vector Group	YY0
LV Side Current (Rated)	2.780 A
Usage	Outdoor

Table 2
SST tap changer position data #3-4

Tap	Voltage HV(V)	Arus HV (A)
1	F 161.700	71,4
2	F 157.850	73,2
3	R 154.000	75,0
4	F 150.150	76,9
5	F 146.300	78,9

This transformer works at a maximum capacity of 20. 000 kVA with ONAF (Natural Oil with Forced Air) cooling system, has an impedance value of 10.57% on a base of 20. 000 kVA. The position of the tap changer used as a reference for the test is tap 3, which means that the HV voltage reaches R154. 000 V with a current of 75.0 A, except for excitation current and DIRANA tests carried out on tap 4 in accordance with specified technical procedures. All tests were conducted off-line between March 2 and 4, 2026, with ambient conditions of room temperature of 29 to 30 degrees Celsius, top oil temperature of 28 to 29 degrees Celsius, and relative air humidity of 74 to 78 percent.

2.3 Data Collection Methods

Data collection in this study was carried out through two complementary methods, namely direct field observation and documentation study.

2.3.1 Technical interview

Interviews in a semi-structured format were conducted with technicians at the Maintenance Repair and Overhaul (UMRO) Unit of PT PLN Nusantara Power who were directly involved in the implementation of SST #3-4 testing. This method was chosen because it provides an opportunity for researchers to ask additional questions following the answers from the sources, so that the information obtained becomes more in-depth and related to the context compared to a fully structured interview. The interview guide has been created in advance as a reference, but the order and depth of questions can be adjusted to the dynamics of the discussion that takes place during the interview.

The interview focused on several important points, namely: (1) the technical steps in the implementation of each test method and the reasons for choosing certain test parameters; (2) the transformer's historical history based on experience and existing maintenance records; (3) technical problems or anomalies found during the testing process; and (4) technical considerations that are the basis for determining the acceptance criteria for each test parameter. The data obtained from the interviews are used as qualitative primary data that is useful to enrich the context in interpreting the quantitative data of the test results.

2.3.2 Literature and documentation studies

Literature studies are conducted against relevant global and local technical policies, including IEEE C57. 152-2013 on guidelines for diagnostic testing on transformers in use, IEC 60422:2013 on the supervision and treatment of insulating mineral oils in electrical devices, DL/T911-2004 as well as NCEPRI guidelines on frequency response analysis in power transformers, as well as IEEE C57. 149-2012 regarding the application and understanding guidelines of SFRA. The supporting literature also includes articles from scientific journals related to the diagnostic methods of transformer conditions that have been published, as a basis for comparison and validation of the methodology applied in this study.

A documentation study was carried out on the Electrical Assessment Report for Starting Service Transformer (SST) #3-4 issued by UMRO PT PLN Nusantara Power in 2026, with document number FMH-17. 2. 4. 007 Revision 03. The official document contains all data on the summary of test results as well as graph recordings and output tables of the instrument as an attachment for verification. The data from this report is used as secondary data and adjusted to the primary data obtained through observation and interviews to ensure consistency and completeness before the analysis is carried out.

2.3.4 Field observation

Field observations were carried out in person during the testing time span which lasted from March 2 to 4, 2026. Some of the elements that are systematically observed and recorded include: environmental conditions (ambient temperature, upper oil temperature, humidity levels, and weather conditions); the physical appearance of the transformer before testing, including the condition of the bushing after cleaning; the position of the tap regulator at each test session; the sequence and procedure carried out in each test method; and also the readable values on the instrument obtained directly from the test device screen. This observational data is used to verify the secondary data from the UMRO report and provide the field context needed to understand the results of the analysis.

2.4 Research Flow Diagram

This research was carried out through a series of organized and gradual steps as seen in Figure 3. The flowchart documents eight structured phases. Phase 1 is problem identification and research objective formulation, establishing the scope and boundaries of the assessment. Phase 2 is literature review, encompassing IEEE C57.152-2013, IEC 60422:2013, DL/T911-2004, NCEPRI, and IEEE C57.149-2012, as well as relevant published research from Indonesian transformer diagnostic studies [3, 5, 6, 7]. Phase 3 covers data collection through three parallel tracks: technical interviews with UMRO technicians, documentation study of the FMH-17.2.4.007 assessment report, and direct field observation during the testing period. Phase 4 is pre-test field preparation, which includes physical inspection of the transformer, bushing cleaning, recording of ambient conditions (temperature 29–30°C, humidity 74–78%), instrument calibration verification, and setting the tap changer to the test position. Phase 5 is the sequential execution of seven electrical tests in a fixed order: Insulation Resistance and Polarization Index → Winding Resistance → Dissipation Factor → Excitation Current → SFRA → DIRANA → Turn-to-Turn Ratio. Phase 6 is parameter-by-parameter evaluation against the applicable acceptance criteria of each standard. At this stage, a decision gate applies: if any parameter falls outside its acceptance threshold, the workflow branches to a supplementary investigation and consultation loop with UMRO engineers before a conclusion can be drawn. Phase 7, reached only when all parameters are accepted, is the cross-parameter integrative analysis that examines consistency and mutual support between the insulation-related parameters (IR, PI, DF, DIRANA) and the mechanical integrity parameters (WR, Excitation, TTR, SFRA). Phase 8 is the formulation of feasibility recommendations, preparation of the technical report, and drawing of conclusions for submission to the relevant operational authority [13].

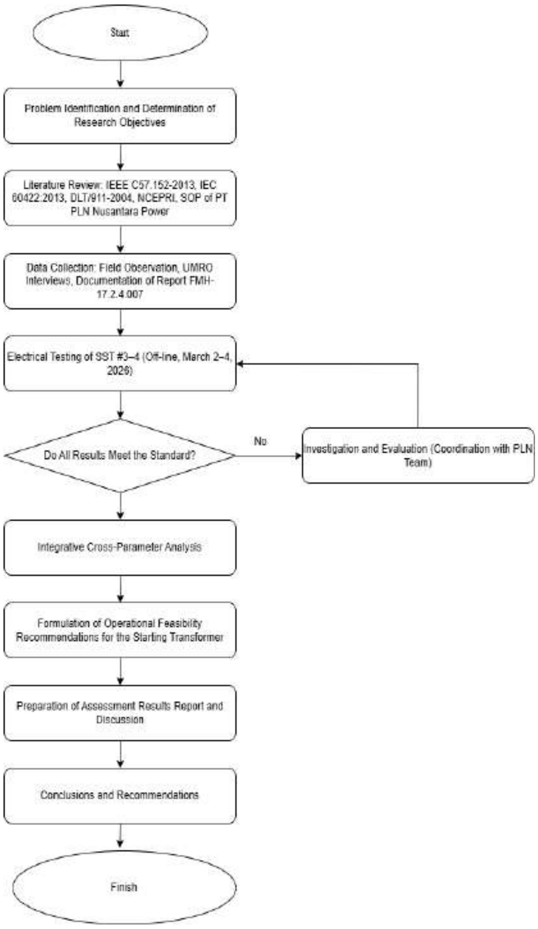

Fig 3. Flowchart

2.5 Data Analysis

Data analysis is carried out separately for each test parameter by comparing the measurement results against the acceptance standard based on applicable technical guidelines, then thoroughly integrated between the parameters to provide an assessment of the overall condition of the transformer. A summary of the acceptance criteria for all parameters is shown in Table 3. An explanation of the analysis method as well as the formula applied for each test is as follows.

Table 3
Acceptance requirements for all test parameters

Test Parameters	Admission Criteria	Reference Standards
Insulation Resistance	AND > 100 MOhm	IEEE C57.152-2013
Polarization Index	PI > 1.25 (min. Fair)	IEEE C57.152-2013
Winding Resistance	Inter-phase deviation < 5%	IEEE C57.152-2013
Dissipation Factor	DF < 0.5% (good); < 1.0% (acceptable, old transformer)	IEEE C57.152-2013
Excitation Current	Pola HLH (High-Low-High)	IEEE C57.152-2013
SFRA	Evaluation of 4 categories DL/T911-2004	DL/T911-2004 & NCEPRI
DIRANA	Moisture < 2.2% (Dry category)	IEC 60422:2013
Turn-to-Turn Ratio	Deviation < 0.5% thd. Nameplate	IEEE C57.152-2013

2.5.1 Insulation Resistance (IR) dan Polarization Index (PI)

IR analysis was performed by comparing the insulation resistance values obtained from measurements with the minimum value of 100 Mohm specified by IEEE C57. 152-2013 for all terminal configurations (HV-Ground, LV-Ground, and HV-LV). The Polization Index is determined by **Eq 1.**

$$PI = \frac{R_{10}}{R_1} \quad (1)$$

where R_{10} is the insulation resistance at the 10th minute and R_1 is the insulation resistance at the 1st minute. This formula and its classification thresholds are defined in IEEE C57.152-2013 and have been applied in similar transformer feasibility studies in Indonesia [3,5,9]. R_{10} R_1The interpretation of the results refers to the IEEE C57 classification. 152-2013: PI 4.0 is considered excellent. IR results before and after Dissipation Factor testing were also compared to identify changes in isolation conditions. IR results before and after Dissipation Factor testing were also compared to detect changes in isolation conditions.

2.5.2 Winding resistance

The winding resistance value measured at the test temperature T_{Meas} was converted to a reference temperature of 75$°C$ using **Eq 2**.

$$R_{75} = R_{Meas} \times \frac{(235+75)}{(235+T_{Meas})} \quad (2)$$

where is the resistance that has been adjusted at 75$°C$, R_{Meas} is the measured resistance, the measurement is the winding temperature when tested (28$°C$), and the number 235 is the constant for copper winding materials. The temperature correction factor used in this test was 1.179, calculated according to the correction constant for copper conductors as specified in IEEE C57.152-2013 and applied in prior assessments of power transformers in Indonesia [3, 5]. Furthermore, the deviation between phases is calculated with **Eq 3**:

$$Dev(\%) = \left[\frac{(R_{max} - R_{min})}{R_{avg}}\right] \times 100\% \quad (3)$$

Deviation results that do not exceed 5% are considered acceptable according to the IEEE C57 standard. 152-2013. Deviations exceeding this limit indicate the possibility of loose connections, damage to the windings, or problems with the tap replacement.

2.5.3 Dissipation Factor (Tan)Ω

The measured Dissipation Factor value is adjusted for a reference temperature of 20$°C$ using **Eq 4:**

$$DF_{20} = DF_{Meas} \times f_k$$
(4)

Where DF_{20} is the DF value corrected to 20 °C, DF_{meas} is the value obtained from the measurement, and f_k is the temperature correction factor (0.32 at a test temperature of 29 °C), which is derived from IEC 60422:2013 correction tables for mineral oil-impregnated transformers [12]. Assessment were performed on six components: CH+CHL, CH, CHL(UST), CL+CLH, CLH, and CLH(UST). Acceptance requirements: 0.5% DF < categorized as good condition; 0.5% ≤ DF < 1.0% are still acceptable for transformers that have been in operation for a long time; DF ≥ 1.0% requires further investigation. A comparison of values between GST and UST modes was performed to identify the source of the increase in delta tangents, whether they came from insulating oil, insulation paper, or bushings.

2.5.4 Excitation current

Excitation Flow Evaluation is carried out by paying attention to the flow pattern between phases. In transformers with a three-foot core, the normal state is observed from the High-Low (HLH) pattern, where the current in the middle phase (H2) is lower than the current in the two outside phases (H1 and H3). The storage percentage of the excitation current between phases is calculated using **Eq 5:**

$$Dev_{leks}(\%) = \left[\frac{(I_{max} - I_{min})}{I_{avg}}\right] \times 100\% \qquad (5)$$

Significant deviations from the HLH pattern or very large deviations in either phase could indicate a short circuit between the windings, damage to the core, or mechanical deformation of the windings. The evaluation was carried out qualitatively based on the relative flow patterns of the three phases according to IEEE C57 guidelines. 152-2013.

2.5.5 SFRA (Sweep Frequency Response Analysis)

SFRA analysis was carried out by two methods simultaneously. The DL/T9911-2004 method calculates the similarity index of the frequency response curve using **Eq 6**, **7**, and **8** for three frequency ranges:

$$RLF = 1 - \frac{6}{\pi^2} \times \frac{\sum_{i=1}^{n} (X_{1i} - X_{2i})^2}{\sum_{i=1}^{n} X_{1i}^2} \quad (1\ kHz - 10\ kHz)$$
(6)

$$RMF = 1 - \frac{6}{\pi^2} \times \frac{\sum_{i=1}^{n} (X_{1i} - X_{2i})^2}{\sum_{i=1}^{n} X_{1i}^2} \quad (10\ kHz - 100\ kHz)$$
(7)

$$RHF = 1 - \frac{6}{\pi^2} \times \frac{\sum_{i=1}^{n} (X_{1i} - X_{2i})^2}{\sum_{i=1}^{n} X_{1i}^2} \quad (100\ kHz - 1\ MHz)$$
(8)

Where is X_{1i} the frequency response value of the reference phase, while it is X_{2i} the frequency response value of the phase being analyzed. The NCEPRI method calculates the E index using **Eq 9:**

$$E = 1 - \frac{[|H_1(j\omega)| - |H_2(j\omega)|]^2}{|H_1(j\omega)|^2 + |H_2(j\omega)|^2}$$
(9)

Where $H_1(j\omega)\ and\ H_2(j\omega)\ is\ the$ transfer function of the frequency response of each phase. An index value close to 1 indicates a high similarity (normal condition), while a value that does not approach 1 indicates a deformation. Since SST #3-4 does not yet have historical data from SFRA, an inter-phase comparison is conducted in accordance with the NCEPRI and DL/T911-2004 standards, and the results of this test serve as a baseline reference for the next overhaul cycle [6,7,14]. The NCEPRI E-index formula above is widely referenced in Indonesian transformer diagnostic studies as a more nuanced method for capturing winding deformation compared to the simpler DL/T911-2004 correlation indices alone [6,7].

2.5.6 DIRANA (Dielectric Response Analysis)

The DIRANA analysis processed polarizing current (PDC) and capacitance spectrum data in the frequency domain (FDS) simultaneously. Polarizing currents as well as depolarization are formulated with **Eq 10** and **Eq 11:**

$$I_{pol}(t) = \frac{U}{R} + C_{\infty} \cdot \frac{dU}{dt} + U \cdot f(t)$$
(10)

$$I_{depol}(t) = U \cdot [f(t) - f(t + t_c)]$$
(11)

Where U is the test voltage, C_{∞} is the geometric capacitance, $f(t)$ is the dielectric response function of the insulation material, and t_c refers to the charging duration. The DIRANA software utilizes both types of data to estimate the moisture content in the insulation paper. The acceptance criteria refer to IEC 60422:2013, where a moisture content of ≤ 2.2% is considered dry and suitable for operation. The DIRANA results are evaluated together with IR and Dissipation Factor values to provide a comprehensive assessment of the insulation system condition.

1.1.1 Turn to Turn Ratio (TTR)

The measured ratio values on each terminal pair (R-r, S-s, T-t) compared to the nameplate ratio are 36.0629 (154,000 V/4,160 V). the percentage deviation is calculated using **Eq 12:**

$$Dev_{TTR}(\%) = \frac{TTR_{avg} - TTR_{nameplate}}{TTR_{nameplate}} \times 100\%$$
(12)

This deviation formula follows IEEE C57.152-2013 and has been applied in transformer assessment studies across Indonesian power plants [8,9,11]. According to IEEE C57.152-2013, deviations that do not exceed are $\pm 0,5\%$ considered acceptable. Deviations that cross this limit may indicate the possibility of a short circuit between the windings, insulation damage between the winding layers, or a fault in the connection at the tap changer terminal.

2.5.7 Cross-Parameter Integrative Analysis

After each parameter is assessed separately, a thorough analysis is carried out to find the consistency and relationship between the parameters. The main relationships studied: (1) the relationship between the results of DIRANA, IR, and Dissipation Factor which act as three indicators of insulation system conditions, DIRANA directly measures the humidity level and oil state, IR measures the overall insulation current leakage, and the Dissipation factor measures the dielectric loss; (2) the conformity between the results of the SFRA of the HV side and the LV side in assessing the mechanical integrity and winding; and (3) the relationship between the results of Excitation Current and TTR which are two parameters that are equally sensitive to the condition of the winding and the transformer core. The findings of this comprehensive analysis are the basis for formulating preliminary feasibility recommendations that are comprehensive and evidence-supported.

3. Result and Discussion

3.1 Insulation Resistance (IR) dan Polarization Index (PI)

Insulation Resistance (IR) testing was performed using a Megger MIT 1025 tool with a voltage of 5. 000 VDC for one minute for each terminal configuration. The test is performed twice—before and after the Dissipated Factor test, to identify possible changes in insulation conditions due to the voltage applied at that stage. All IR measurement results are presented in full in Table 4.

Table 4
SST insulation resistance test results #3-4

Terminal Configuration	Before DF (GΩ)	After DF (GΩ)	Change (GΩ)	Min. Limit (MΩ)	Status
HV – Ground	18,37	17,78	−0,59	> 100	✓
LV – Ground	7,25	7,01	−0,24	> 100	✓
HV – LV	14,85	12,55	−2,30	> 100	✓

All IR measurement results are presented in full in Table 4. All IR value results far exceed the minimum limit of 100 MΩ set by IEEE C57. 152-2013, with the lowest value found in the LV-Ground configuration of 7.01 GΩ after DF testing. The decrease in IR value after DF testing is small and reasonable, considering the residual effect of the capacitive charging voltage in the insulation system, so there is no deterioration in insulation quality.

The Polarity Index test was performed in conjunction with the IR test, by comparing the insulation resistance values at the 10th minute and the 1st minute. The PI results for all three terminal configurations are shown in Table 5.

Table 5
Polarization index test results #3-4

Configuration	R_1 (GΩ)	R_{10} (GΩ)	PI	Category	Status
HV – Ground	18,37	24,30	1,32	Fair	✓
LV – Ground	7,25	11,05	1,52	Fair	✓
HV – LV	14,85	25,10	1,69	Fair	✓

All three PI values exceed the minimum value of 1.25 (Fair category) according to the IEEE C57 standard. 152-2013. The PI value for HV-LV of 1.69 almost reached the Good category (PI > 2.0), indicating that the absorption capacity of the load between windings is still quite adequate. The PI values located in the Fair category in the HV-Ground (1.32) and LV-Ground (1.52) configurations correspond to the operational age of the transformer which has been more than forty years and does not indicate any major problems related to moisture contamination.

Taken together, the IR and PI results paint a picture that is not only acceptable but genuinely reassuring. The insulation system of SST #3-4, built in 1978 under JEC-204 standards, has withstood over four decades of thermal cycling, load variation, and ambient stress without experiencing the kind of cumulative degradation that typically leads to failure in aging transformers. The fact that IR values remain in the gigaohm range — far above the threshold — and PI values still fall within the

Fair-to-approaching-Good range suggests that the insulation material retains adequate dielectric strength. For the system as a whole, this means that re-energizing SST #3-4 does not introduce insulation-related risk to the generation unit, provided that standard pre-energizing procedures, including phasing verification and grounding checks, are properly observed.

3.2 Winding Resistance

The winding resistance test was carried out at the tap 3 position with a voltage configuration of 154/0.416 kV and a test current of 20 A. All measurements were carried out at a room temperature of around 28°C. On the high-voltage (HV) side, the resistance values obtained for each phase were 3,070 mΩ in the U-N phase, 3,086 mΩ in the V-N phase, and 3,075 mΩ in the W-N phase. Meanwhile, on the low voltage (LV) side, resistance values were recorded at 1,873 mΩ in the u-v phase, 1,854 mΩ in the v-w phase, and 1,827 mΩ in the w-u phase. When viewed from the difference between the phases, the deviation that appears is very small. On the HV side the deviation is around 0.002%, while on the LV side it is around 0.003%. The value indicates that the winding resistance in each phase is relatively uniform under the same measurement conditions. The results of the test can be seen in Table 6.

Table 6
SST winding resistance test results #3-4

Tap Changer				Winding Resistance Test					
				HV SIDE			LV SIDE		
Position	Former (KV)	Winding Temp (°C)	Test Current (A)	U-N (mΩ)	V-N (mΩ)	W-N (mΩ)	u-v (mΩ)	v-w (mΩ)	w-u (mΩ)
3	154 / 0,416	28	20	3,070	3,086	3,075	1,873	1,854	1,827
		75		3,619	3,638	3,626	2,208	2,186	2,154
Deviation (%)				0,002 %	0,002%	0,002%	0.004%	0.001%	0.004%

The winding resistance value is then corrected to a reference temperature of 75°C according to the IEEE C57.152-2013 standard so that the measurement results can be compared with the standard conditions, which can be seen in Table 7. After temperature correction, the resistance on the HV side for the U, V, and W phases became 3,619 mΩ, 3,638 mΩ, and 3,626 mΩ, respectively, with a maximum value of 3,638 mΩ and a minimum of 3,619 mΩ. On the LV side, the phase resistance values of u, v, and w are 2,208 mΩ, 2,186 mΩ, and 2,154 mΩ, with a maximum value of 2,208 mΩ and a minimum of 2,154 mΩ.

Table 7
Deviation after temperature correction 75°C

Sisi	Fasa	R measured (mΩ)	R 75°C (mΩ)	R max (mΩ)	R min (mΩ)	Dev (%)	Status
HV	U (H1-H0)	3,070	3,619	3,638	3,619	0,000%	✓ Accepted
	V (H2-H0)	3,086	3,638				
	W (H3-H0)	3,075	3,626				
LV	u (X1-X0)	1,873	2,208	2,208	2,154	0,003%	✓ Accepted
	v (X2-X0)	1,854	2,186				
	w (X3-X0)	1,827	2,154				

The deviation between the phases on the HV side is 0.000% and on the LV side of 0.003%, both well below the maximum limit set at 5% according to IEEE C57. 152-2013. This uniformity indicates that there are no loose connections, damage to the winding conductors, or problems with the tap changer connections.

From a system reliability standpoint, winding resistance deviations this small carry a clear implication: the current-carrying conductors in both HV and LV windings are electrically continuous, mechanically undisturbed, and thermally equivalent across phases. For a transformer that has been through overhaul and has been de-energized for a period, this result confirms that reassembly and maintenance activities have not introduced any new defects or contact resistance issues in the tap changer or winding terminals. Given that even a small resistance asymmetry between phases can produce sustained unbalanced currents and differential relay false trips during operation, a deviation this close to zero is an important positive indicator for the upstream protection system.

3.3 Dissipiation Factor (Tan Ω)

DF testing was carried out using OMICRON TESTRANO 600 and CP TD15 at a frequency of 50 Hz, involving six components in GST and UST modes, as well as voltage injection on the HV (10 kV) and LV (2 kV) sides. The DF value was adjusted to the reference temperature of 20°C using a correction factor of 0.82 at the test temperature of 29°C. The results of the test can be seen in Table 8.

Table 8
SST factor dissipation test results #3-4

Components	Mode	V (kV)	I (mA)	Loss (mW)	DF measurement (%)	DF 20°C (%)	Status
CH + CHL	GST	10,00	17,99	803,99	0,4470	0,3666	✓ Good
CH	GSTg-A	10,00	6,20	516,45	0,8333	0,6833	✓Accepted
CHL (UST)	UST-A	10,00	11,77	162,64	0,1382	0,1133	✓ Good
CL + CLH	GST	2,00	11,22	42,44	0,1892	0,1551	✓ Good
CL	GSTg-A	2,00	8,86	35,98	0,2030	0,1664	✓ Good
CLH (UST)	UST-A	2,00	2,35	6,47	0,1374	0,1127	✓ Good

Five of the total six components showed values below 0.5% (Good category). Meanwhile, the CH component in GSTg-A mode (0.8333%) exceeds the limit of 0.5% but remains below 1.0%, so it is classified as Probably Acceptable for older transformers. A higher CH value than CHL (UST) indicates that there is an increase in delta tangents from HV insulation oil or bushings, not from winding paper insulating materials. These findings are in line with DIRANA's results which show that moisture levels in paper are very low.

The practical implication of these DF results for system operation is significant. The UST mode values — which specifically isolate the winding paper insulation from the influence of oil and bushings — are consistently well below 0.5%, meaning the paper insulation itself contributes very little dielectric loss. This aligns with DIRANA results confirming 0.3% moisture in the paper. For the transformer system as a whole, low paper DF means that under normal operating voltage (154 kV / 4.16 kV), the insulation will not experience excessive dielectric heating, which in turn reduces the risk of thermal runaway or accelerated aging in the short to medium term. The CH component reading of 0.833% in GSTg-A mode, while slightly above the new-transformer threshold of 0.5%, is well within the acceptable range for aged units and is consistent with typical oil conductivity changes in transformers of this vintage.

3.4 Exitation Current

Excitation current testing was carried out at the tap changer 4 position (150.15 kV) using OMICRON TESTRANO 600 and CP TD15, with a test voltage of 10 kV at a frequency of 50 Hz. Measurement results are presented in Table 9.

Table 9
SST exitation current test results #3-4 (Tap 4, V test = 10 kV)

Fasa	V out (kV)	I out (mA)	Phase (°)	Power Loss (W)	Reactance (kΩ)	Pola
A (H1)	10,00	15,097	−19,50	142,308	221,113	High (H)
B (H2)	10,00	10,083	−14,62	97,566	250,398	Low (L)
C (H3)	10,00	15,099	−19,36	142,452	219,560	High (H)

The current excitation pattern forms a High-Low-High (TRT) configuration, where the middle phase of H2 (10,083 mA) is at a lower level than the outer phases of H1 (15,097 mA) and H3 (15,099 mA). This TRT pattern is a normal feature of transformers with a three-foot core in accordance with the IEEE C57 standard. 152-2013. The almost similar alignment of H1 and H3 currents (with a difference of 0.002 mA or 0.013%) suggests that the winding mechanism is highly symmetrical. No deviations in the pattern were found indicating the possibility of short circuits, damage to the core, or mechanical deformation of the windings.

The significance of the HLH pattern extends beyond a simple pass/fail check. For a three-limb core transformer like SST #3-4, the outer phases (H1 and H3) must magnetize through longer magnetic flux paths than the center phase (H2), which naturally results in higher magnetizing current at the outer positions. The nearly identical values of H1 (15.097 mA) and H3 (15.099 mA), differing by only 0.002 mA, indicate that the core geometry is fully symmetric — a result that would not hold if there were core delamination, inter-lamination shorts, or physical displacement of the core stack. Together with the winding resistance and TTR results, this gives a comprehensive three-parameter confirmation of mechanical and electrical integrity in the core-winding assembly.

3.5 Sweep Frequency Response Analysis (SFRA)

SFRA testing was conducted using OMICRON FRANEO 800 (SN: LN664B) in the frequency range of 20 Hz–2 MHz with 801 logarithmic measurement points, test voltage of 2.8 V. Since SST #3-4 does not yet have historical SFRA data, the analysis was conducted using an inter-phase comparison method using two methods simultaneously: DL/T911-2004 (RLF, RMF, RHF index) and NCEPRI (E index). The test results are shown in Figure 4, while the results of the HV and LV side analysis are presented in Table 10 and Table 11, respectively.

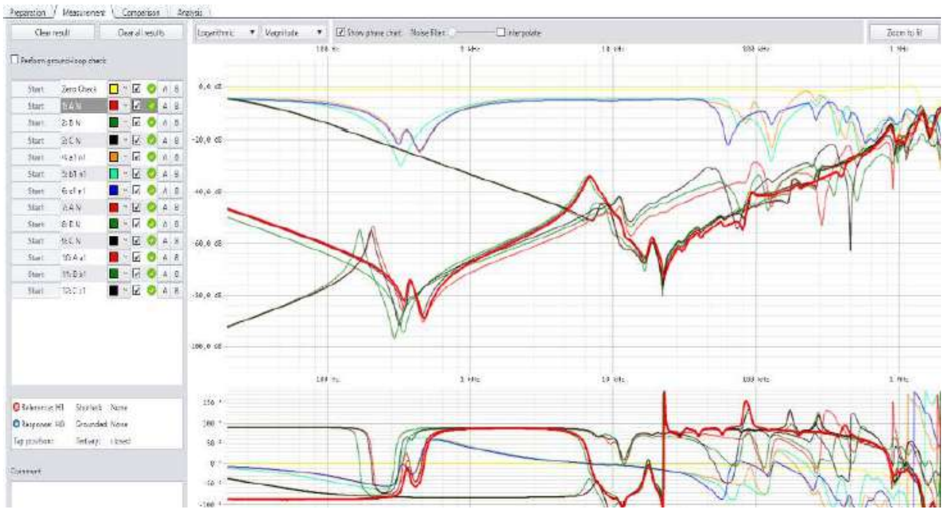

Fig. 4. Inter-phase frequency response curve (Source: Laporan Assessment UMRO PT PLN Nusantara Power)

Table 10
SFRA analysis results of HV SST side #3-4

Comparison	RLF	RMF	RHF	Assessm. DL/T911	E	Assessm. NCEPRI
H1H0 – H2H0	1,44	1,35	0,67	Slight deformation	2,19	Normal winding
H2H0 – H3H0	2,47	2,41	0,84	Normal winding	0,63	Normal winding
H1H0 – H2H0*	1,88	1,86	0,81	Slight deformation	1,26	Normal winding
H1H0 – H3H0	2,87	2,99	1,04	Normal winding	0,50	Normal winding
H2H0 – H3H0*	2,05	1,86	1,31	Normal winding	1,11	Normal winding
H1H0 – H3H0*	1,39	1,57	1,55	Slight deformation	2,24	Normal winding

Table 11
SFRA analysis results of LV SST side #3-4

Comparison	RLF	RMF	RHF	Assessm. DL/T911	E	Assessm. NCEPRI
X1X0 – X2X0	0,65	0,68	0,33	Obvious deformation	4,49	Slight deformation
X1X0 – X3X0	0,38	0,67	0,29	Severe deformation	4,76	Slight deformation
X2X0 – X3X0	0,33	0,49	0,65	Severe deformation	5,93	Slight deformation

The HV side shows that the Winding state is Normal consistently according to the NCEPRI method. Some comparisons show the existence of Slight Deformation using the DL/T911-2004 method which is only visible in the high frequency range (RHF). On the LV side, the DL/T911-2004 index value is lower (Obvious–Severe Deformation category), but the NCEPRI method always shows Slight Deformation results. The difference between these methods must be understood in the context of the absence of historical data as a reference; comparisons are made between phases, not against the same unit data from the past. The variation in LV winding geometry between phases on a three-leg transformer naturally causes differences in frequency response. There is no support from other mechanical parameters (Winding Resistance, Excitation Current, TTR) regarding the possibility of mechanical damage. This test data is recorded as a baseline reference for the next overhaul cycle.

Table 10 presents the SFRA inter-phase comparison results for the HV side (H1H0, H2H0, H3H0) using both DL/T911-2004 and NCEPRI evaluation methods. Reading across each row, the RLF, RMF, and RHF columns represent the frequency response similarity index at low (1–10 kHz), medium (10–100 kHz), and high (100 kHz–1 MHz) frequency bands, respectively, where a value closer to 1.0 indicates a higher degree of similarity between the two phases being compared. The first comparison, H1H0 versus H2H0, yields RLF = 1.44, RMF = 1.35, and RHF = 0.67, which under DL/T911-2004 falls into the Slight Deformation category due to the RHF value dropping below the normal threshold. However, the same pair evaluated by the NCEPRI E-index gives E = 2.19, which corresponds to Normal Winding. The discrepancy is expected: the H2 phase sits on the center limb of the three-limb core and carries a shorter magnetic flux path than the outer H1 and H3 limbs, producing a naturally different high-frequency response that DL/T911-2004 interprets as a geometric anomaly rather than actual damage. The H2H0 versus H3H0 comparison produces RLF = 2.47, RMF = 2.41, and RHF = 0.84, classified as Normal Winding under DL/T911-2004 and confirmed as Normal Winding by NCEPRI (E = 0.63). The H1H0 versus H3H0 comparison — both on outer limbs and therefore geometrically equivalent — returns RLF = 2.87, RMF = 2.99, RHF = 1.04, categorized as Normal Winding by both methods (NCEPRI E = 0.50). This outer-limb comparison is the most structurally meaningful because it eliminates the center-limb geometry effect; both methods agreeing on Normal Winding here strongly confirms the absence of mechanical deformation on the HV winding.

Table 11 presents the SFRA inter-phase comparison results for the LV side (X1X0, X2X0, X3X0). The DL/T911-2004 index values are noticeably lower than the HV side, with the X1X0–X2X0 comparison yielding RLF = 0.65, RMF = 0.68, RHF = 0.33 (Obvious Deformation), the X1X0–X3X0 comparison yielding RLF = 0.38, RMF = 0.67, RHF = 0.29 (Severe Deformation), and the X2X0–X3X0 comparison yielding RLF = 0.33, RMF = 0.49, RHF = 0.65 (Severe Deformation). At first glance, these values appear concerning. However, the NCEPRI E-index evaluation tells a consistently different story: all three LV comparisons return E-values of 4.49, 4.76, and 5.93 respectively, all falling in the Slight Deformation category rather than Severe. This divergence between the two methods on the LV side is not unusual and must be understood in two key contexts. First, the LV winding of SST #3-4 operates at 4.16 kV and is wound in a different configuration from the HV side, making inter-phase geometric dissimilarity more pronounced. Second, and most critically, this is the very first SFRA measurement ever recorded for this transformer — there is no historical baseline from a prior healthy state to serve as the proper reference. Under DL/T911-2004, the inter-phase comparison implicitly assumes that all phases should be identical, which is an idealization that real transformers with physically distinct limb geometries do not satisfy. The NCEPRI E-index, which is a normalized energy-based metric, is more tolerant of this natural asymmetry and yields a more reliable assessment in the absence of historical data. Given that winding resistance deviation on the LV side is only 0.003%, excitation current pattern is perfectly HLH, and TTR deviations are below 0.09%, there is no corroborating mechanical evidence of actual deformation. The LV SFRA data is therefore logged as a baseline reference for the next overhaul cycle.

Taken together, Tables 10 and 11 confirm that the SFRA results are consistent with the mechanical integrity conclusion drawn from the other three mechanical parameters. The HV side gives an unambiguous Normal Winding result under both evaluation standards. The LV side, while showing lower DL/T911-2004 index values, is better understood as a geometric artifact amplified by the absence of baseline data, not as evidence of structural damage. The multi-method approach applied in this study — using both DL/T911-2004 and NCEPRI simultaneously, and cross-validating with winding resistance, excitation current, and TTR — is precisely the best-practice methodology recommended for transformers undergoing first-time SFRA assessment, as established in IEEE C57.149-2012 and corroborated by Indonesian transformer diagnostic literature.

3.6 DIRANA (Dielectric Response Analysis)

The DIRANA test was conducted using the DIRANA OMICRON in UST mode at the tap changer 4 location, with an FDS voltage of 100 V and a PDC of 200 V. DIRANA software combines information from PDC and FDS to assess the moisture level of the insulation paper as well as the state of the insulating oil. The results of this test can be seen in Table 12.

Table 12
DIRANA SST test results #3-4

Parameter	Value	Remarks
Moisture in Cellulose	0,3 %	Dry (< 2,2% — IEC 60422:2013)
Moisture Saturation	0,6 %	—
Oil Conductivity	750 fS/m	—
Oil Category	Very Good	—
Bubbling Inception Temp.	189 °C / 372 °F	Safe thermal margin
Tan δ @ 50 Hz	0,142 %	—
Capacitance @ 50 Hz	3,7481 nF	—
Barriers / Spacers	45 % / 14 %	—
Moisture Category	Dry	Accepted

The moisture level in the insulation paper reaching 0.3% is well below the limit of 2.2% in the Dry category according to IEC 60422:2013, indicating that the paper insulation system is in very dry conditions even though the transformer has been in operation for more than forty years. The condition of the oil was declared Very Good with a conductivity of 750 fS/m, which indicates the absence of significant pollution. The initial temperature of the bubble formation reaches 189°C providing a sufficient level of thermal safety. The results from DIRANA reinforce and explain the findings of IR and DF: high IR values and low DF UST values (CHL: 0.138%) are in line with very minimal paper moisture levels.

3.7 Turn to Turn Ratio (TTR)

The winding ratio test was carried out using the OMICRON TESTRANO 600 with a test voltage of 120 V at a frequency of 50 Hz, tap changer position 3. The reference nameplate ratio is 36.0629 (154,000 V / 4,160 V). The test results are presented in Table 13.

Table 13
SST turn to turn ratio test results #3-4 (Tap 3)

Fasa	V prim (V)	V sec (V)	TTR Measure	TTR Nameplate	Deviation (%)	Status
R (U-u)	119,97	3,33	36,0629	36,0629	−0,09	✓ Pass
S (V-v)	119,97	3,33	36,0621	36,0629	−0,09	✓ Pass
T (W-w)	119,97	3,33	36,0644	36,0629	−0,08	✓ Pass

TTR deviations in all three phases were in the range of −0.09% to −0.08%, well below the ±0.5% limit per IEEE C57.152-2013. The uniform consistency of the deviation between the three phases indicates the absence of short circuits between the windings, insulation damage between the winding layers, and errors in the terminal connection of the tap changer.

3.8 Cross-Parameter Integrative Analysis

A summary of all test results and acceptance conditions is shown in Table 14 as a basis for a thorough analysis.

Table 14
Recapitulation of SST testing results #3-4

No	Electrical Test	Results	Standard	Conclusion
1	Insulation Resistance	Before DF test results: HV-G = 18,37 GΩ LV-G = 7,25 GΩ HV-LV = 14.85 GΩHoD Test Results: HV-G = 17,78 GΩ LV-G = 7.01 GΩ HV-LV = 12.55 GΩ	IEEE C57.152 – 2013 IR > 100 MΩ	*Accepted*
2	Polarization Index	HV-G = 1.32 LV-G = 1.52 HV-LV = 1.69	IEEE C57.152 – 2013 PI > 1.25	*Accepted*
3	DC Resistance Test	Dev HV: 0,000 % Dev LV: 0,003 %	IEEE C57.152 – 2013 Deviation < 5%	*Accepted*
4	Dissipation Factor Overall	CH + CHL = 0.4470 % CH = 0.8333 % CHL (UST) = 0.1382 % CL + CLH = 0.1892 % CL = 0.2030 % CLH (UST) = 0.1374 %	IEEE C57.152 – 2013 Tanδ < 0.5 for new transformers Tanδ < 1 for old transformers	*Accepted*
5	Excitation Current Analysis	H_1: 15.097 mA (H) H_2: 10,083 mA (L) H_3: 15.099 mA (H)	IEEE C57.152 – 2013 High-Low-High (HLH) pattern	*Accepted*
6	Sweep Frequency Response Analysis	Normal winding (*Used as Reference data*)	NCEPRI / DL/T911- 2004 & IEEE C57.149TM-2012	*Accepted*
7	Dielectric Response Analysis	CHL = *Dry* Oil Category = Very Good	IEC 60422.2013 – 01 Moisture dry: ≤ 2.2 %	*Accepted*
8	Turn to Turn Ratio	R – r = -0,09 % S – s = -0,09 % T – t = -0,08 %	IEEE C57.152 – 2013< 0,5 %	*Accepted*

From the point of view of isolation conditions, the three variables that directly assess the isolation system, IR and PI, DF, and DIRANA, provide a consistent and mutually supportive picture. The high IR level (at least 7.01 GΩ), very low paper moisture (0.3%), and DF value for UST mode (CHL: 0.138%) which is well below 0.5% together confirm that the insulation system is in excellent condition. The higher CH value in the GSTg-A mode (0.833%) is in line with the conductivity of the DIRANA oil (750 fS/m), indicating that the increase in delta tangents comes from the insulation oil and not from the paper damage.

In terms of the mechanical condition of the winding, three parameters: Winding Resistance, Excitation Current, and TTR, provide a very clear reinforcement of the mechanical integrity. Deviations in the winding resistance of almost zero, perfect HLH excitation patterns, and uniform TTR deviations below 0.09% indicate the absence of structural changes in the windings. The results of the normal HV side SFRA reinforce this conclusion. The assessment from the LV side using the DL/T911-2004 method cannot be used as a reference to identify mechanical damage due to the absence of historical baseline data and the absence of support from other mechanical parameters.

4. Conclusions

This study has conducted an operational feasibility assessment for the starting SST #3-4 of PT PLN Nusantara Power Unit PLTU Gresik through seven integrated electricity testing methods, which will be carried out offline on March 2-4, 2026. Based on all the results of the tests and analyses that have been described, there are three main conclusions that can be drawn.

First, the condition of the SST #3-4 isolation system was declared to be very good. All parameters directly related to the isolation condition, i.e. IR and PI, Dissipation Factor, and DIRANA, meet the accepted standards set coherently and support each other. The measured moisture level of insulation paper of 0.3% is well below the maximum limit of 2.2% (IEC 60422:2013), which indicates that there is no insulation degradation due to moisture even though the transformer has been in operation for more than forty years since 1978. The PI values included in the Fair category (1.32–1.69) are in line with the operational age of the device and show no signs of imminent threat of isolation failure.

Second, the mechanical integrity of SST #3-4 windings was confirmed under normal conditions. Very small winding resistance deviance (0.000% for the HV side and 0.003% for the LV side), perfect HLH excitation current pattern, and uniform TTR deviation below 0.09% overall indicate no structural changes in windings, loose connections, or short circuits between windings. The results of the HV side SFRA which are categorized as Normal Winding based on the NCEPRI method reinforce this conclusion. The assessment of Visible to Heavy Deformation in some LV side comparisons according to DL/T911-2004 cannot be considered an indication of mechanical malfunction given the absence of historical baseline data and lack of support from other mechanical parameters.

Third, SST #3-4 was formally declared fit and worthy of re-operation. All eight electrical test parameters achieved Accepted status under their respective technical standards without exception. From the isolation side, the insulation paper moisture content of only 0.3% against a maximum permissible limit of 2.2% (IEC 60422:2013) reflects a transformer whose paper insulation has been exceptionally preserved despite more than four decades of continuous service. The minimum IR value of 7.01 GΩ — roughly 70,000 times the minimum threshold of 100 MΩ — and the DF in UST mode of 0.138% together confirm that no meaningful dielectric degradation has occurred. From the mechanical side, the near-zero winding resistance deviation (0.000% on HV, 0.003% on LV), the textbook High-Low-High excitation current pattern with only 0.013% asymmetry between outer phases, and the uniform TTR deviation of less than 0.09% across all phase pairs collectively confirm that the winding structure remains physically intact. The SFRA result on the HV side, evaluated as Normal Winding under the NCEPRI method, further reinforces this conclusion. The apparent anomaly in LV-side SFRA readings under DL/T911-2004 is attributable to the absence of historical baseline data and receives no corroborating support from any other mechanical parameter, and therefore cannot be treated as an indication of genuine mechanical damage.

For future research, several directions are recommended based on the gaps and opportunities identified in this study. First, establishing a complete SFRA baseline database immediately following this re-energization is strongly advisable. Since this assessment was the first time SFRA measurements were recorded for SST #3-4, future overhaul cycles will now be able to employ time-based comparison rather than inter-phase comparison alone, which will substantially improve diagnostic sensitivity for detecting early-stage LV winding deformation. Second, incorporating dissolved gas analysis (DGA) alongside electrical testing in subsequent assessments would enable a more comprehensive condition picture, capturing thermal and arcing fault signatures that offline electrical tests alone cannot detect. Third, partial discharge (PD) measurement and extended frequency-domain spectroscopy (FDS) should be explored for transformers in this age category, where localized insulation defects may be present even when bulk parameters remain within acceptable limits. Fourth, it is recommended that PT PLN Nusantara Power formalize the assessment framework demonstrated in this study into a standardized starting transformer evaluation protocol applicable across all PLTU units, thereby enabling consistent documentation and cross-unit benchmarking over time.

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