

Maintenance and Testing of Power Transformers

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Abstract - Power transformers are critical assets in the electrical power transmission and distribution network, ensuring efficient voltage conversion and continuity of power supply. Their reliable operation is vital for maintaining system stability and performance. Over time, transformers are subjected to electrical, thermal, and mechanical stresses that can degrade their components and compromise performance. Therefore, regular maintenance and testing are essential to extend transformer life, prevent unexpected failures, and ensure safety. This paper presents a comprehensive overview of the maintenance strategies and testing methodologies used in power transformers. It covers routine maintenance practices categorized into daily, weekly, monthly, and annual tasks, as well as key diagnostic tests such as Breakdown Voltage (BDV), Moisture Content Analysis, Neutralization Number (Acidity), Interfacial Tension, Dissolved Gas Analysis (DGA), and Dielectric Dissipation Factor (Tan δ). The paper also covers constructional features, standard ratings, and performance parameters of power transformers. The integration of modern monitoring systems and diagnostic techniques has enhanced the ability to detect incipient faults before they escalate, minimizing downtime, improving operational efficiency, and reducing long-term costs.

Index Terms - Power Transformer, Transformer Maintenance, Transformer Testing, Insulating Oil, Dissolved Gas Analysis, Buchholz Relay, Breakdown Voltage, Dielectric Testing, Tap Changer, Temperature Rise Test.

I. INTRODUCTION

The phenomenal growth of the Indian power transmission system has resulted in the formation of One Nation One Grid — one of the largest single synchronous grids in the world. The transmission system establishes the vital link between the generating source and the distribution system connected to the ultimate consumer. A robust, reliable, and optimally planned transmission network facilitates cost-effective delivery of power and provides 24×7 quality power for all consumers at affordable rates.

The complexity of the Indian power system has increased manifold over the years. With the operation of multiple agencies — State Utilities, Central Utilities, and Private players — high availability and reliable operation assume tremendous importance. Major assets such as power transformers play an important role not only in terms of capital investment but also in terms of availability and reliability of the system.

The transformer and reactor are vital and expensive assets in a power system. Transformers fail much before their expected life span of approximately 35 years due to poor quality of raw material, workmanship, manufacturing techniques, or due to electrical, thermal, and mechanical stresses during operation. Restoration of a failed transformer typically takes 3 to 6 months after major repair, while procurement of a new unit requires 6 to 10 months depending on the voltage class.

The objective of this work is to present a standard document outlining the critical technical parameters, maintenance strategies, and testing procedures for power transformers. Standardisation offers the following key advantages:

- The procurement process is simplified and delivery time is reduced, resulting in early project completion.
- Frequent design reviews are avoided due to standard designs.

- Standard ratings and civil foundation blocks facilitate interchangeability across manufacturers.
- Standard fittings, accessories, and reduced inventory requirements lower operational costs.

II. ROLE AND TECHNICAL SPECIFICATIONS OF POWER TRANSFORMERS

A. Electrical Ratings

The key electrical specifications of a power transformer include: Rated Power (Capacity) in kVA or MVA (e.g., 10 MVA, 100 MVA); Primary and Secondary Voltage (e.g., 132 kV / 33 kV); Frequency (50 Hz); Number of Phases; Vector Group (e.g., Dyn11, Yyn0, Yd1) indicating winding connections and phase displacement; and Impedance Voltage typically in percentage (e.g., 8%, 10%).

B. Insulation and Dielectric Strength

Insulation class (e.g., Class A, B, F, or H) defines the thermal capability of the insulation system. The Impulse Withstand Voltage (BIL) for a 132 kV transformer is typically 325 kVp. The Power Frequency Withstand Voltage for a 33 kV winding is approximately 70 kV rms.

C. Cooling Type

The cooling method determines the transformer's thermal performance. Common designations include ONAN (Oil Natural Air Natural), ONAF (Oil Natural Air Forced), OFAF (Oil Forced Air Forced), and ODAF (Oil Directed Air Forced). The cooling system capacity is specified in kW or kVA.

D. Temperature Rise and Losses

Winding temperature rise is typically 55°C or 65°C over ambient. No-load (iron) losses are measured in kW at rated voltage. Load (copper) losses are measured at rated current and

temperature (typically 75°C). Efficiency typically exceeds 99.5% at full load.

E. Tap Changer

Transformers are equipped with either an Off-Load Tap Changer (OCTC) or an On-Load Tap Changer (OLTC). A typical tap range is $\pm 10\%$ in steps of 1.25%, providing 17 tap positions to regulate voltage under varying load conditions.

F. Protection and Monitoring Devices

Standard protection and monitoring equipment includes: Buchholz Relay, Oil Temperature Indicator (OTI), Winding Temperature Indicator (WTI), Pressure Relief Device (PRD), Silica Gel Breather, Sudden Pressure Relay, and Magnetic Oil Level Gauge.

III. STANDARD RATINGS OF POWER TRANSFORMERS

Table I presents standard power ratings of transformers along with their high-voltage (HV) and low-voltage (LV) configurations and typical applications in the Indian power grid.

TABLE I. Standard Ratings of Power Transformers

Rated Power	HV Side	LV Side	Typical Application
25 kVA	11 kV	0.433 kV	Rural / Small Distribution
63 kVA	11 kV	0.433 kV	Distribution Transformer
100 kVA	11 kV	0.433 kV	Urban / Suburban Distribution
250 kVA	11 kV	0.433 kV	Commercial / Industrial
1 MVA	33 kV	11 kV	Substation Step-Down
10 MVA	110 kV	33 kV	Grid-Level Step-Down
50 MVA	220 kV	66 kV	Regional Grid Transmission
100 MVA	220 kV	66 kV	EHV Grid Transformer
315 MVA	400 kV	220 kV	Extra High Voltage (EHV)

Source: Standard Specifications and Technical Parameters for Transformers and Reactors

IV. PERFORMANCE OF POWER TRANSFORMERS

The performance of a power transformer is a critical aspect that determines its operational efficiency, reliability, and suitability for power system applications. Power transformers typically exhibit very high efficiency, often exceeding 98%, especially at full load. This efficiency is influenced by both no-load losses (core or iron losses, which remain constant regardless of load) and load losses (copper losses, which increase with the square of the load current).

Voltage regulation refers to the change in secondary voltage when the load varies from no-load to full-load. Good voltage regulation ensures consistent voltage delivery to connected equipment, minimizing voltage fluctuations. Short-circuit impedance, expressed as a percentage, affects voltage drop and fault current levels, playing a significant role in protection coordination and load sharing.

Temperature rise in the windings and oil is a key performance criterion. The permissible temperature rise is typically in the

range of 50–65°C, depending on the cooling method and insulation class. Accordingly, the cooling performance — whether through ONAN, ONAF, or OFAF — is essential to prevent overheating and sustain prolonged service.

V. CONSTRUCTIONAL DETAILS OF POWER TRANSFORMERS

A. Tank and Tank Cover

The tank shall be of proven design of either Bell type with bolted/welded joint or conventional with bolted/welded top cover. The tank shall be designed so that the transformer can be rested on a concrete plinth foundation directly or on a roller assembly, and shall be pressure-tested to ensure no oil leakage under service conditions.

B. Conservator

The conservator of the main tank shall have an air cell type constant oil pressure system to prevent oxidation and contamination of oil due to contact with moisture. It shall be fitted with a magnetic oil level gauge with potential-free high and low oil level alarm contacts, and a prismatic oil level gauge for direct reading.

C. Dehydrating Silica Gel Filter Breather

The silica gel breather filters and dehydrates the air entering the conservator. The silica gel crystals absorb atmospheric moisture and change colour from blue to pink/white when saturated, indicating that regeneration or replacement is required. A transparent oil seal at the base prevents moisture ingress during non-breathing periods.

D. Pressure Relief Device (PRD)

The pressure relief device is designed to open at a set pressure to protect the transformer tank from internal pressure buildup caused by faults. It is typically set to operate at 70 kPa and is fitted with a visual trip indicator and an electrical contact for remote alarm signaling.

E. Buchholz Relay

The Buchholz relay is a gas-actuated protection device installed in the pipe connecting the main tank to the conservator. Under normal conditions, it is filled with oil. Slow gas accumulation due to minor internal faults triggers an alarm; a severe fault causing rapid oil displacement trips the transformer circuit breaker.

F. Core and Windings

The magnetic core is constructed from high-grade cold-rolled grain-oriented (CRGO) silicon steel laminations to minimize hysteresis and eddy current losses. High-voltage (HV) and low-voltage (LV) windings are wound concentrically on the core limbs, insulated with high-quality kraft paper and pressboard, then vacuum-dried and oil-impregnated to improve dielectric strength.

VI. MAINTENANCE OF POWER TRANSFORMERS

A. Introduction

Maintenance and testing of power transformers are preventive measures that safeguard the integrity of the entire power system. Failure to maintain these high-voltage assets can lead to catastrophic consequences such as blackouts, equipment

damage, fire hazards, and significant loss of revenue. Transformer maintenance is broadly classified into three types: (1) Preventive Maintenance — scheduled at fixed intervals; (2) Predictive Maintenance — based on condition monitoring and diagnostic data; and (3) Corrective Maintenance — carried out after a fault or failure.

B. Routine Maintenance Schedule

Table II summarises the routine maintenance activities categorised by frequency, along with the key parameters to be monitored at each stage.

TABLE II. Recommended Maintenance Schedule for Power Transformers

Freq.	Maintenance Activity	Key Parameters
Daily	Check oil level, load current, OTI / WTI readings	Oil level, temperature indicators
Weekly	Inspect silica gel breather, check for oil leaks, clean surroundings	Silica gel colour, visual oil inspection
Monthly	Inspect bushings, check Buchholz relay gas, inspect cooling radiators	Gas volume, bushing condition, radiator fins
Annual	Oil sampling for BDV/DGA, check gaskets and tap changer, paint inspection	BDV \geq 60 kV, moisture $<$ 5 ppm, Tan $\delta <$ 0.5%

C. Insulating Oil Maintenance

Insulating oil serves as both a coolant and dielectric medium. Oil degradation products — including moisture, dissolved gases, acids, and sludge — must be monitored through periodic sampling and laboratory analysis. Regeneration by Fuller's Earth filtration removes polar contaminants and restores oil properties. Oil replacement is recommended when the Neutralization Number exceeds 0.5 mg KOH/g or the BDV consistently falls below acceptable limits.

D. External Component Maintenance

External maintenance covers inspection and servicing of bushings, cable boxes, cooling radiators, conservators, oil gauges, valves, bolts and fasteners, dehydrating breathers, Buchholz relays, temperature indicators, sealing gaskets, and paintwork. Bushings should be cleaned to remove dust and pollution deposits that can cause tracking or flashover. Cooling radiators should be checked for blockage or corrosion to maintain optimal heat dissipation.

VII. TESTING OF POWER TRANSFORMERS

A. Introduction

Testing plays a vital role in assessing the internal health of the transformer without dismantling it. Tests are classified as routine tests (performed on every unit), type tests (performed on representative units to qualify the design), and special tests (performed on specific request). Table III provides a comprehensive summary of the key diagnostic tests performed on power transformers.

TABLE III. Key Diagnostic Tests for Power Transformers

Test Name	Purpose	Acceptance Criteria
Breakdown Voltage (BDV)	Measures dielectric strength of transformer oil	\geq 60 kV (new oil); \geq 40 kV (service oil)
Moisture Content	Detects water contamination in insulating oil	$<$ 5 ppm (new); $<$ 15 ppm (service)
Neutralization No. (Acidity)	Assesses oil oxidation and degradation level	$<$ 0.03 mg KOH/g (new oil)
Interfacial Tension (IFT)	Indicates polar contaminants and sludge formation	\geq 40 mN/m (new); \geq 25 mN/m (service)
Dissolved Gas Analysis (DGA)	Detects incipient faults from gas generation in oil	H ₂ $<$ 100 ppm; C ₂ H ₂ $<$ 1 ppm (IEC 60599)
Dielectric Dissipation Factor (Tan δ)	Measures insulation quality and ageing	$<$ 0.5% at 90°C (oil); $<$ 0.4% (bushings)
Insulation Resistance (IR / PI)	Measures DC resistance of windings to earth	PI \geq 1.3 (10 min / 1 min ratio at 5 kV DC)

B. Breakdown Voltage (BDV) Test

The BDV test determines the dielectric strength of transformer oil by applying an increasing AC voltage between two electrodes immersed in the oil sample until breakdown occurs. A low BDV value (below 40 kV for in-service oil) indicates the presence of moisture, carbon particles, or contaminants that reduce insulating capability and require immediate oil filtration or replacement.

C. Dissolved Gas Analysis (DGA)

DGA is one of the most powerful diagnostic tools for identifying incipient faults in oil-filled transformers. The Duval Triangle method and the Rogers Ratio method interpret gas concentrations to diagnose fault types: partial discharge, thermal faults below or above 700°C, or electrical arcing. Hydrogen (H₂) and acetylene (C₂H₂) are key fault gases. DGA should be performed before and after heat run tests and dielectric tests as per IEC 60567 sampling procedures.

D. Insulation Resistance and Polarization Index

DC insulation resistance is measured between each winding to earth and between windings at 5000 V DC. The Polarization Index (PI) is the ratio of the 10-minute insulation resistance to the 1-minute insulation resistance at constant voltage. A PI value of 1.3 or above is recommended. Low PI values indicate contaminated or moisture-saturated insulation.

E. Temperature Rise Test (as per IEC 60076)

The temperature rise test verifies that the transformer's thermal performance meets the specified limits. The test is conducted at the tap position giving the worst combination of loading losses for top oil. Headspace extraction and gas chromatographic analysis on oil are conducted before, during, and after this test as per IEC 60567.

F. Dielectric Tests

Dielectric tests are performed in the following sequence as per IEC 60076-3:2013 — Lightning Impulse Tests (LIC, LIN), Switching Impulse (SI), Applied Voltage Test (AV), and Line Terminal AC Withstand Test (LTAC). For 400 kV class transformers, the transfer surge at the tertiary winding should not exceed 250 kVp under any condition.

G. Overload Testing

For 765 kV class transformers, overload testing is conducted using the short-circuit method. In Testing Option 1, the unit is pre-loaded at 100% full-load current until top oil temperature stabilises, then increased to 120% overload for 4 hours. In Testing Option 2, loading is increased to 130% for 2 hours. Infrared thermal images are recorded at regular intervals and hot-spot temperatures are measured and recorded throughout the test.

VIII. TESTING OF NEUTRAL GROUNDING REACTORS

In addition to standard routine tests listed in IEC 60076, neutral grounding reactors require a volt-current characteristics test on each unit, preferably up to the short-time rated current. Lightning impulse voltage withstand tests and ohmic resistance measurements are also mandatory. Measurement of insulation resistance and Polarization Index is carried out at 5000 V DC. Tan delta of winding insulation shall not exceed 0.5% at ambient temperature. The two-hour excitation test is conducted at rated voltage to measure reactance, losses, and vibration. DGA tests are performed before and after heat run tests and dielectric tests in accordance with IEC/CIGRE/IEEE guidelines.

IX. RESULTS AND DISCUSSION

The integration of preventive and predictive maintenance strategies — combined with modern diagnostic techniques such as DGA, BDV testing, and online partial discharge monitoring — provides a comprehensive framework for assessing and assuring transformer health throughout their service life.

The BDV test remains the most commonly performed field diagnostic test due to its simplicity and direct relevance to oil condition. A BDV value below 40 kV for in-service oil is a strong indicator of oil contamination requiring immediate corrective action. DGA, as the most powerful incipient fault detection technique, enables utilities to detect thermal faults, partial discharge, and arcing at an early stage - well before catastrophic failure. Gas generation rates and the Duval Triangle diagnosis provide actionable guidance on the urgency and type of maintenance intervention required.

Routine maintenance activities such as daily temperature checks, weekly breather inspections, monthly Buchholz relay checks, and annual oil sampling form the foundation of a sound maintenance programme. Components such as bushings, cooling radiators, sealing gaskets, and the on-load tap changer are particularly susceptible to wear and ageing and must receive focused attention during scheduled maintenance.

The standardisation of transformer ratings, specifications, and test procedures as outlined in this paper simplifies procurement, reduces lead times, enables interchangeability across

manufacturers, and lowers the total cost of ownership. For the Indian power system — operating as one of the world's largest synchronous grids — the adoption of standardised maintenance and testing protocols is essential to achieving the national goal of 24×7 reliable power supply.

X. CONCLUSION

Power transformers are essential components in the transmission and distribution of electrical energy. They play a pivotal role in ensuring the efficient, safe, and stable delivery of power over long distances. Due to their critical function in electrical power systems, it is imperative that transformers are maintained and tested regularly to ensure reliable performance over their service life.

This paper has provided a detailed analysis of both the maintenance procedures and testing methodologies necessary for power transformers. A structured and timely maintenance schedule — covering daily inspections, weekly checks, monthly tests, and annual overhauls — forms the foundation of a sound maintenance programme. Diagnostic tests such as BDV, DGA, Tan δ , and Polarization Index provide deep insight into the condition of the insulating oil and winding insulation without requiring transformer shutdown.

The integration of modern monitoring systems, online diagnostic techniques, and standardised test procedures has significantly enhanced the ability to detect incipient faults before they escalate. Transformer maintenance and testing are indispensable for ensuring the reliability, safety, and longevity of power systems, and the standardisation of ratings and procedures further strengthens the resilience of the national grid.

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