Transformers in Electrical Substations

Overview

Transformers are one of the most critical components in electrical substations. Their primary function is to transfer electrical energy between circuits through electromagnetic induction, allowing voltage to be stepped up for transmission or stepped down for distribution. They ensure efficient power delivery across long distances while minimizing losses.

Working Principle of a Transformer

A transformer is a static electromagnetic device that transfers electrical energy between two or more circuits through electromagnetic induction. It enables the transmission and distribution of electrical power at varying voltage levels, minimizing losses and ensuring efficient energy flow across the substation network.

Transformers in substations primarily function as step-up or step-down devices:

* Step-up transformers increase generator output voltage for long-distance transmission (e.g., 11 kV → 220 kV).
* Step-down transformers reduce high transmission voltages to safer distribution levels (e.g., 220 kV → 33 kV → 11 kV → 415 V).

Principle of Electromagnetic Induction

The transformer operates on Faraday's law of electromagnetic induction, which states that any change in the magnetic flux linking a coil induces an electromotive force (EMF) in it.

Mathematically:

E=−NdtdΦ

where,

* E = Induced EMF (Volts)
* N = Number of turns in the winding
* Φ = Magnetic flux (Weber)

When alternating current (AC) flows through the primary winding, it generates an alternating magnetic flux in the laminated steel core. This flux links both primary and secondary windings and induces a voltage in the secondary winding due to mutual induction.

Voltage and Current Relationship

The voltage transformation ratio is directly proportional to the turns ratio:

V2/V1=N2/N1

where,

* V_1, V_2 = Primary and secondary voltages

* N_1, N_2 = Number of turns in primary and secondary windings

The corresponding current relationship is inversely proportional:

$I2/I1=N2/N1$

This ensures power balance (neglecting losses):

$V1I1=V2I2$

Thus, while voltage changes according to the winding ratio, the overall power remains nearly constant.

Magnetic Core and Flux Path

The core serves as the magnetic circuit that provides a low-reluctance path for the flux. It is typically made of cold-rolled grain-oriented (CRGO) steel laminations, insulated from each other to minimize eddy current losses.

* Core Type Transformers: Windings are placed on two limbs of the core.
* Shell Type Transformers: Both windings are wound on the central limb with flux returning through outer limbs.

Flux leakage is minimized by using tight magnetic coupling between primary and secondary coils.

Losses and Efficiency

Two major losses affect performance:

* **Core (Iron) Losses:**
  * Hysteresis Loss: Due to magnetization and demagnetization of the core during each cycle.
  * Eddy Current Loss: Induced circulating currents within the laminations.

Reduced using CRGO steel and thin laminations.

* **Copper Losses:**
  * Caused by I^2R losses in the windings.

Managed through optimal conductor sizing and temperature monitoring.

Overall efficiency (η) is expressed as:

η=(Output Power / Output Power + Losses) x 100

Typical efficiency for power transformers ranges from 98%–99.7%.

Cooling and Temperature Regulation

Since losses convert into heat, temperature rise must be controlled for reliable operation. Transformers employ several cooling techniques:

* ONAN (Oil Natural Air Natural): For distribution transformers.
* ONAF (Oil Natural Air Forced): Fans increase air circulation.
* OFAF (Oil Forced Air Forced): Pumps circulate oil actively.
* OFWF (Oil Forced Water Forced): For high-capacity transformers.

Cooling ensures the winding temperature remains below 105°C (Class A insulation limit).

Protection and Monitoring Systems

Transformers are equipped with protective and diagnostic devices:

* Buchholz Relay: Detects gas accumulation from internal arcing.
* Pressure Relief Device (PRD): Prevents tank rupture.
* Oil Temperature Indicator (OTI) and Winding Temperature Indicator (WTI): Monitor thermal conditions.
* Silica Gel Breather: Maintains dry air in conservator tanks.
* Differential and Overcurrent Relays: Detect fault currents.

These systems are integrated into Supervisory Control and Data Acquisition (SCADA) systems for real-time monitoring and predictive maintenance.

Standard Measuring and Operating Values

Parameter	Typical Value / Range	Remarks
Efficiency	98–99%	Depends on load and design
Insulation Resistance	>1000 MΩ for HV winding (at 5 kV test)	Indicates insulation health
Winding Temperature Rise	< 65°C (oil), < 80°C (winding)	Based on IEC 60076-2
Oil Breakdown Voltage (BDV)	> 60 kV (for new oil)	Measured per IEC 60156
Turns Ratio Error	Within ±0.5%	Checked during ratio test
Load Losses	< 1% of rated power	Checked as per IEC 60076-1

Transformer Maintenance Practices

Proper maintenance ensures reliability, minimizes breakdowns, and extends service life.

a) Routine Maintenance:

* Visual inspection for oil leaks, rust, loose connections.
* Checking oil level in conservator tank.
* Ensuring proper functioning of Buchholz relay and temperature indicators.
* Cleaning bushings and radiators.
* Monitoring load and temperature trends.

b) Preventive Maintenance:

* Periodic oil filtration and testing (BDV, moisture, acidity, dielectric loss).

* Insulation resistance (IR) measurement using a 5 kV megger.
* Tightening of terminals and inspection of gaskets.
* Cooling system check (fans, pumps, radiator valves).

c) Predictive Maintenance:

* Dissolved Gas Analysis (DGA) for detecting incipient faults.
* Partial Discharge (PD) measurement.
* Thermal imaging for detecting hotspots.

Transformer Testing Procedures

Testing ensures the operational reliability, dielectric strength, and mechanical integrity of transformers. These tests are divided into routine, type, and special tests as per IEC 60076 and IEEE C57.12.90 standards.

Insulation Resistance (IR) Test

* Purpose: To assess the health of insulation between windings and between windings and the core.
* Method: A 5 kV Megger is used to apply DC voltage across the windings.
* Typical Values:
    * HV-LV: >1000 MΩ
    * HV-Ground: >1000 MΩ
    * LV-Ground: >500 MΩ
* Interpretation: A decreasing trend in IR over time indicates insulation deterioration or moisture ingress.

Turns Ratio (TTR) Test

* Purpose: To confirm that the transformer's voltage ratio corresponds to its design turns ratio.
* Procedure: Apply a low AC voltage to the primary winding and measure secondary voltage; compare measured ratio to nameplate value.
* Acceptable Deviation: ±0.5% from nominal.
* Indication: Any deviation indicates possible shorted turns, open circuits, or incorrect winding connections.

Winding Resistance Test

* Purpose: Detects loose connections, shorted turns, or contact resistance in tap changers.
* Method: Apply DC current through each winding and measure voltage drop using a micro-ohmmeter.
* Acceptable Range: Uniform resistance across phases; significant variation (>2%) indicates issues.
* Standard: IEC 60076-1 / IEEE C57.12.90.

Vector Group Test

* Purpose: To confirm phase displacement between primary and secondary windings and ensure correct vector group configuration.
* Procedure: Apply voltage to one phase and measure induced voltages on secondary windings; verify against phase diagram.
* Importance: Incorrect vector group leads to parallel operation issues and phase mismatch.

Magnetization Current Test

* Purpose: To identify core defects such as shorted laminations or residual magnetism.
* Procedure: Apply rated voltage to primary winding with secondary open; measure current.
* Typical Results: Symmetrical and low magnetizing current indicates healthy core; asymmetry implies core problems.

Oil Dielectric Breakdown Voltage (BDV) Test

* Purpose: To assess the insulating strength of transformer oil.
* Procedure: Measure breakdown voltage by increasing AC voltage across 2.5 mm electrode gap until spark-over occurs.
* Typical Values:
  * New Oil: ≥ 60 kV
  * In-Service Oil: ≥ 40 kV
* Low BDV: Indicates contamination or moisture presence.

Dissolved Gas Analysis (DGA)

* Purpose: To identify internal faults through gas composition in transformer oil.
* Method: Gases such as H_2, CH_4, C_2H_2, C_2H_4, and CO_2 are measured using gas chromatography.
* Key Interpretations:
  * H_2, CH_4: Partial discharge
  * C_2H_4, C_2H_6: Overheating of oil
  * C_2H_2: Arcing or high-energy discharge
  * CO, CO_2: Insulation paper decomposition
* Standard Reference: IEC 60599, IEEE C57.104.

Tan Delta / Power Factor Test

* Purpose: To evaluate insulation aging and dielectric losses.
* Procedure: Measure the phase angle between applied voltage and current through insulation.
* Acceptable Value: Tan $\delta \leq 0.5\%$ for new insulation.
* High Tan Delta: Indicates contamination, aging, or moisture in insulation.

Sweep Frequency Response Analysis (SFRA)

* Purpose: Detects mechanical movement or deformation of windings due to short circuits or transportation stresses.
* Method: Apply low voltage sweep (20 Hz–2 MHz) to windings and plot frequency response.
* Interpretation: Comparison with baseline signature identifies mechanical anomalies.

Transformer Failure Modes and Corrective Actions

Transformers, though designed for high reliability and long operational life, are susceptible to various failure modes due to electrical, thermal, and mechanical stresses. One of the most common causes of failure is insulation degradation, which occurs over time because of excessive heating, moisture ingress, or contamination of the insulating oil. This deterioration leads to reduced dielectric strength and eventual insulation breakdown between windings or core laminations. Overloading and hot spots within windings accelerate this process, potentially resulting in short circuits or inter-turn faults. Another major issue arises from winding deformation, which can occur due to mechanical stresses during short-circuit events or vibrations, leading to displacement and eventual failure.

Oil contamination and leakage are also critical concerns; transformer oil serves both as an insulator and coolant, and the presence of moisture, dissolved gases, or oxidation products can severely compromise its performance. Dissolved Gas Analysis (DGA) is often employed as a diagnostic tool to detect early-stage failures such as arcing, overheating, or partial discharge by analyzing the types and concentrations of gases dissolved in the oil. In addition, bushing failures and tap changer malfunctions can lead to catastrophic breakdowns if not addressed promptly. Bushings, being the interface between the transformer windings and external circuits, are prone to surface tracking, moisture absorption, and cracking, while on-load tap changers (OLTCs) are subject to contact wear, carbonization, and mechanical fatigue due to frequent switching operations.

Cooling system failures also pose a serious threat, as blocked oil passages, fan or pump malfunctions, or inadequate cooling can lead to abnormal temperature rise, accelerating insulation aging and increasing internal pressure. Similarly, core faults, such as localized heating due to lamination shorting or poor grounding, contribute to efficiency loss and eventual equipment damage. External factors such as lightning surges, switching transients, and improper earthing can also cause dielectric failures or flashovers, especially in high-voltage substations.

To mitigate these failures, preventive and predictive maintenance strategies are implemented. Regular monitoring of temperature, oil quality, and load conditions helps detect abnormalities early. Corrective actions include oil filtration or replacement, tightening of electrical connections, drying of insulation systems, and rewinding or core repair when necessary. For mechanical issues, vibration analysis and frequency response analysis (FRA) are conducted to detect displacement or structural deformation. In the case of major internal faults, the transformer is taken offline for detailed inspection, repair, or replacement.

Adopting condition-based monitoring systems integrated with IoT and AI analytics further enhances reliability by predicting potential failures before they occur. This proactive approach, combined with adherence to international standards such as IEC 60076 and IEEE C57.104, ensures safe, efficient, and prolonged operation of transformers within substations, thereby minimizing downtime and maintaining grid stability.