



IEEE Guide for Application of Monitoring Equipment to Liquid-Immersed Transformers and Components

IEEE Power and Energy Society

Developed by the
Transformers Committee

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STANDARDS

IEEE Guide for Application of Monitoring Equipment to Liquid-Immersed Transformers and Components

Developed by the

Transformers Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

Abstract: Identification of the key parameters that can be monitored for obtaining an indication of the condition of liquid-immersed transformers is covered by this guide. It also covers risk/benefit analysis, sensor application, and monitoring systems application. This guide does not cover interpretation of monitoring results.

Keywords: IEEE C57.143™, liquid-immersed transformers, monitoring equipment, online monitoring, transformer components, transformer monitoring

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Introduction

This introduction is not part of IEEE Std C57.143-2024, IEEE Guide for Application of Monitoring Equipment to Liquid-Immersed Transformers and Components.

For many decades, transformer users have sought ways to assess the general condition of electrical power apparatus and identify specific problems. Over the years, diagnostic tests have been developed, based on available technology. In the last few decades, sophisticated means have evolved for collecting a great deal of diagnostic information while the equipment is in service.

Periodic offline diagnostic tests still play an important role in industry. However, “continuous” or “online” monitoring can overcome some of the fundamental limitations of offline tests, in that it can provide early detection of performance degradation, increase performance and reliability of substation power apparatus, reduce maintenance costs, aid in optimization of apparatus operations and maintenance procedures, and help manage the growing risk of an aging population of transformers and their components.

This revision of the original 2012 guide presents a change in the philosophy of transformer monitoring, recognizing the use of integrated information systems coupled with appropriately selected monitoring devices to improve asset fleet management performance.

This guide includes recommendations for the following:

- Improved utilization of online continuous monitoring currently deployed on existing assets
- Online continuous monitoring specified for future implementation on existing or new assets
- Data and communications management to allow for derivation of useful and actionable information from the data

The first step in incorporating continuous online condition monitoring in an asset management program is to understand the technical and business context of the monitoring and to identify expectations: What value does monitoring bring, and how do we check that the monitoring is successful?

Once that discussion is in place, detailed expectations may be set for the following:

- What data is to be collected.
- Which analyses are to be undertaken.
- How the analyses will indicate a problem or deterioration of interest.
- How alerts are generated, and what are the responses within the organization should an alert be generated?
- Who will get the alerts and how are alerts communicated?
- How are alerts managed in terms of acknowledgment?
- Actions planned, and actions taken may differ, so a review of actions is required.
- Who should have access to the data.

Starting in the 1980s, industry and electric utilities shifted their strategies and resources from construction and expansion to maintenance and diagnostics for the plants that were built in the development boom of the 1960s and 1970s. Maintenance records were retrieved, tabulated, and analyzed; databases were created. Maintenance technology evolved through the following four levels:

- Corrective: Ensuring that equipment is operating and functional
- Preventive: Optimizing the performance of the equipment
- Predictive: Diagnosing impending downtime for maintenance
- Strategic/optimization: Operational controls and corporate wide asset management

Today, plant optimization systems have become fairly common, and the leading edge of technology is now focused on predictive maintenance systems. The monitoring of transformers and other electrical apparatus has received more widespread industry acceptance. The challenge for the end user is not so much about whether or not to invest in monitoring systems, but it is more about understanding the numerous different technologies available, how they align with industry understanding of the physics behind how failures develop, what can be monitored by one or several combined devices, and how best to leverage those technologies for optimal benefit.

This guide describes most of the continuous online monitoring and diagnostic methods that are in common practice at the time this guide was written, and updated from the original 2012 edition, and provides additional information in the case of developing techniques. This guide addresses various transformer operational parameters that can be monitored and describes the different technologies available for that purpose. It also provides specification considerations for monitoring hardware, software, and communication systems. For the purposes of this guide, the term *transformer* refers but is not limited to generator step-up transformers; autotransformers; phase-shifting transformers; regulating transformers; intertie transmission transformers; dc converter transformers; instrument transformers; retail, customer, or industrial service transformers; and shunt, series, and saturable reactors.

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IEEE Guide for Application of Monitoring Equipment to Liquid-Immersed Transformers and Components

1. Overview

Online monitoring of power transformers and associated accessories is an essential feature of electric utility systems. The justifications for online monitoring include the need to increase the availability of power transformers, improve strategies for time and/or operational-based maintenance to condition-based maintenance, asset and life management, catastrophic failure prevention, and failure cause analysis.

1.1 Scope

This guide covers identification of the key parameters that can be monitored for obtaining an indication of the condition of liquid-immersed transformers. It also covers risk/benefit analysis, sensor application, and monitoring systems application. This guide does not cover interpretation of monitoring results.

1.2 Purpose

The purpose of this document is to provide guidance to those who specify, apply, install, and use online monitoring equipment on liquid-immersed power transformers and their components.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

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⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60599-2022, Guide to the Interpretation of Dissolved and Free Gases Analysis.⁸

IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.^{9, 10}

IEEE Std C57.104™, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.

IEEE Std C57.113™, IEEE Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

IEEE Std C57.155™ IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers.

IEEE Std 1379™, IEEE Recommended Practice for Data Communications Between Remote Terminal Units and Electronic Devices in Substations.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

accuracy (of measurement): The closeness of agreement between the result of a measurement and the true value of the measurand. *See: measurand; precision of measurement; true value; uncertainty of measurement.*

adjustment of a measuring system: A set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured. Adjustment of a measuring system should not be confused with calibration, which is a prerequisite for adjustment.

calibration: An operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication. Calibration should not be confused with adjustment of a measuring system.

condition assessment: The comprehensive evaluation and analysis of the state, performance, and overall health of a piece of equipment, system, or infrastructure based on the collection of relevant data, measurements, and observations to determine the current condition of the subject and assess its suitability for continued operation.

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¹¹ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

continuous online monitoring: An enhancement of online condition monitoring (OLCM), where measurements are continuously tracked or supervised, typically using an intelligent electronic device (IED). They provide continuous measurement and control functions while the equipment remains energized and in service.

data acquisition unit (DAU): Collects data from one or more sensors and/or intelligent electronic devices (IEDs). Data acquisition includes signal conditioning and analog-to-digital conversion. The information from the DAU is passed on to be processed, or the DAU can be polled directly for its information. *See also:* **remote terminal unit (RTU).**

detection limit: Measured quantity value, obtained by a given measurement procedure, for which the probability of falsely claiming the absence of a component in a material is β , given a probability α of falsely claiming its presence. In practice, most often detection limit refers to the lower detection limit (LDL), which describes the lowest measured quantity of measurand that would be detectable with a sensor or detector within the uncertainties of measurement.

detector: Device or substance that indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded.

dissolved gas-in-oil analysis (DGA): A method of interpreting the quantities and type of gases that are dissolved in insulating liquids for the purpose of detecting incipient faults and aging mechanism.

expert system: Computer software that attempts to mimic the reasoning of a subject matter expert.

failure cause analysis (FCA): The diagnosis of failures or malfunctions. In terms of online monitoring, FCA uses the monitored parameters to draw a conclusion as to the cause of the failure or malfunction and thus replace or supplement the troubleshooting phase of corrective maintenance.

hysteresis: A variation in measurement induced by a direction change. Hysteresis is also a component of measurement uncertainty, which depends on a measurand's direction of change. The indication of an instrument may differ by a fixed and known amount according to whether successive readings are rising or falling.

intelligent electronic device (IED): A device with internal processing capabilities that can be described as a "smart sensor" providing monitoring and/or control functions, including communications.

intrusive: Opening and/or exposing the interior of a transformer or its components for the purpose of inspecting, maintaining, or installing sensors for data collection.

linearity (of measurement): The condition wherein the change in the value of one quantity is directly proportional to the change in the value of another quantity.

measurand: Quantity intended to be measured.

measurement error: A measured quantity value minus a reference quantity value.

measurement drift (instrumental drift): Continuous or incremental change over time of the instrument's indication, due to changes in metrological conditions.

measurement principle: Phenomenon serving as a basis of a measurement.

metrological: Relating to metrology, the science of weights and measures or of measurement.

monitor: A device that has a sensor that converts a physical input into an electrical output and digitizes the sensor signal to be both stored locally in a storage device and available to communications.

monitoring: Encompasses all aspects of performance management focused on tracking system activities to gather the necessary data for assessing performance.

non-intrusive: Without opening or exposing the interior of a transformer or its components.

offline: For transformers, offline generally refers to a state or condition in which a piece of equipment, system, or process is de-energized and not actively operating or functioning as intended. *See:* **offline monitoring/offline testing.**

offline monitoring/offline testing: Refers to techniques or processes used to assess the condition of a transformer or other equipment when it is not in active operation. Unlike online condition monitoring (OLCM), offline monitoring or testing involves inspections, tests, or measurements conducted during scheduled downtime or when the equipment is intentionally taken out of service for maintenance or assessment purposes.

online: For transformers, online generally refers to a state or condition in which a piece of equipment, system, or process is energized and is operating or functioning as intended. *See: online monitoring/online testing.*

online condition monitoring (OLCM): Refers to a technique, method, or measurement performed while the transformer is in active operation to gather information about the transformer's condition.

online monitoring/online testing: Refers to aspects where data can be collected while the equipment is electrically energized and in active service. This may include the collection of measurement data or samples, insulating liquid analysis, infrared thermal scanning, or simple observations such as monitoring oil levels in condenser bushings and conservators, while the equipment is operational, adhering to local safety regulations.

precision of measurement: The closeness of agreement between the results of repeated measurements carried out over a short period of time and under the same conditions. *See: accuracy of measurement; uncertainty of measurement.*

reference measurement procedure: Measurement procedure accepted as providing measurement results fit for their intended use in assessing measurement trueness of measured quantity values obtained from other measurement procedures for quantities of the same kind, in calibration, or in characterizing reference materials.

reference quantity value (reference value): A quantity value used as a basis for comparison with values of quantities of the same kind. A reference quantity value with associated measurement uncertainty is usually provided with reference to a reference measurement procedure.

remote terminal unit (RTU): Monitors the substation field digital and analog parameters and transmits data to the central monitoring station.

repeatability (of results of measurements): Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

reproducibility (of results of measurements): Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

resistance temperature detector: A sensor, typically made of platinum (Pt), nickel (Ni), or copper (Cu), with an accurate and repeatable resistance/temperature relationship that is used to provide an indication of temperature.

resolution: Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

response time (step response time): Duration between the instant when an input quantity value of a measuring instrument or measuring system is subjected to an abrupt change between two specified constant quantity values and the instant when a corresponding indication settles within specified limits around its final steady value.

selectivity (of a measuring system): Property of a measuring system, used with a specified measurement procedure, whereby it provides measured quantity values for one or more measurands such that the values of each measurand are independent of other measurands or other quantities in the phenomenon, body, or substance being investigated.

sensitivity (of a measuring system): Quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured. Sensitivity of a measuring system can depend on the value of the quantity being measured. The change considered in a value of a quantity being measured must be large compared with the resolution.

sensor: A device that detects or measures a physical property and records, indicates, or otherwise responds to it.

stability (of a measuring instrument): Property of a measuring instrument, whereby its metrological properties remain constant in time.

tan delta (Tan δ): A ratio of resistive current to capacitive current of the insulation system (tangent of dielectric loss angle).

time-based condition monitoring: A monitoring technique that involves periodic assessments and inspections of equipment or systems at scheduled intervals, as dictated by predefined time schedules. Unlike continuous online monitoring, which provides real-time data while the equipment is operational, time-based condition monitoring relies on planned intervals, such as weekly, monthly, or annually, to collect information about the equipment's condition.

time-based maintenance: A maintenance strategy that follows a calendar-based schedule for routine maintenance tasks. These tasks, including inspections, repairs, or component replacements, are carried out at specific time intervals regardless of the actual condition of the equipment. Time-based maintenance aims to ensure equipment reliability and longevity by addressing wear and tear and preventing failures based on predetermined schedules.

true value (of a quantity): Value consistent with the definition of a given particular quantity. This is a value that would be obtained by a perfect measurement. In the special case of a fundamental constant, the quantity is considered to have a single true quantity value.

uncertainty of measurement: A parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. *See: accuracy of measurement; measurand; precision of measurement.*

unit (of measurement): A chosen amount of a quantity, defined, and adopted by convention, with which other quantities of the same kind are compared in order to express their magnitudes relative to that amount.

3.2 Acronyms and abbreviations

AE	acoustic emission
ANN	artificial neural network
BPL	broadband over power line
CB	circuit breaker
CCD	charge-coupled device
CME	coronal mass ejection
CT	current transformer
DFT	digital Fourier transform
DGA	dissolved gas-in-oil analysis
DNP	Distributed Network Protocol
DP	degree of polymerization
DTS	distributed temperature sensor
FIR	far-infrared
FO	fiber optics
FPI	Fabry-Perot interferometer
FRA	frequency response analysis
FTIR	Fourier transform infrared
GC	gas chromatography

GIC	geometric-induced current
HF	high frequency
HFCT	high-frequency current transformer
HV	high voltage
IED	intelligent electronic device
IR	infrared
ISO	International Organization for Standardization
LED	light-emitting diode
LTC	load tap changer
LV	low voltage
MIR	mid-infrared
mV/g	parameter used by accelerometers to measure vibration, where acceleration, measured in units of gravitational constant g, is converted to voltage. $1\text{ g} = 9.81\text{ m/s}^2$
NEMA	National Electrical Manufacturers Association
NDIR	non-dispersive infrared
NIR	near-infrared
NIST	National Institute of Standards and Technology
OSI	Open Systems Interconnection
PAS	photo acoustic spectroscopy
PD	partial discharge
PF	power factor
PID	photoionization detector
PLA	piecewise linear approximation
PLC	programmable logic controller
ppm	parts per million
PTFE	polytetrafluoroethylene
RH	relative humidity
ROC	rate of change
RS	relative saturation
RTD	resistance temperature detector
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SPRT	standard platinum resistance thermometer
SSE	sum of squared error
TCD	thermal conductivity detector
TX	transformer
UHF	ultra high frequency
VT	voltage transformer

4. Motivations for transformer monitoring

4.1 General

There are a number of possible motivations to apply condition monitoring to power transformers, including, for example, detection and prevention of incipient failures, the identification and management of units in “distress” during an overload contingency, and determination of the need (or otherwise) for maintenance. Condition monitoring allows the collection of more data than would “normally” be available through regular testing, inspection, and maintenance practices.

Irrespective of the monitor type or role, without an action plan, the benefits of condition monitoring are unlikely to be realized.

The following basic questions should be addressed to achieve a successful condition monitoring application:

- Why is monitoring needed?
- What are the aims?
- How will it be determined that the intended result has been achieved?
- What parameters need to be monitored? How often, with what accuracy, and as a detector or a diagnostic?
- Who is responsible for choosing parameters, analyses, setting limits for alert generation, ensuring actions are in place to respond to alerts, and following up to make sure there was a response and that it was adequate in practice?

Figure 1 shows the “high-level” arrangement for monitoring.

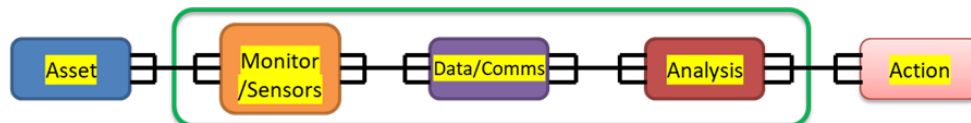


Figure 1—General relationship diagram of online transformer monitoring system

4.2 Understanding condition monitoring applications

In providing data, condition monitoring allows us to observe symptoms of potential failure modes from which it could be inferred the condition of the transformer—and thus its ability to perform its function.

Each transformer component could have one or several failure modes, and each failure mode is associated with some symptoms that could be measured. So, it could be inferred that by selecting a given symptom and monitoring it, we could then detect the onset of the associated component failure.

However, in practice, a given failure mode could produce several symptoms and a specific symptom could be associated with different components or failure modes.

For example, partial discharge (PD) (the failure mode) could generate hydrogen (the symptom). So, measuring hydrogen should in theory be enough to diagnose PD. However, hydrogen could also be generated by faults other than PD, such as arcing, stray gassing, core overheating, or corrosion. Therefore, from detecting hydrogen, we could not necessarily infer that it is caused by PD in a specific component (for example, the high voltage, HV, winding). The detected hydrogen could have been generated by another phenomena, such as overheating of a transformer or one of its components, for example.

PD could also generate acoustic phenomena and high-frequency current. In addition, PD could be produced by different incipient fault conditions such as insulation voids, excessive electrical field, excessive moisture, or design flaws.

Identification of a symptom being present could also be based on more than one measured parameter. For example, the carbon oxide ratio could be a diagnostic symptom of paper aging, but it is not something measured directly as it is calculated from two carbon oxide values.

Finally, a measured parameter could also be a symptom in itself: “High top oil temperature” is a measurable parameter, but it is also a symptom of several failure modes: loss of pumps, loss of fans, oil leak, and others.

This multiplicity of failure modes, symptoms, and measured parameters has to be considered when data is interpreted if a specific fault is to be identified.

4.3 Considerations for monitoring

A condition monitor provides data with an aim to support better decision-making. In general, an application may be as follows:

- a) “Fleet wide” with the aim of generating data to detect a wide range of possible symptoms and failure modes early and cost effectively.
- b) “Fleet wide” targeted on specific components, such as bushings with known failure modes and a higher failure rate than expected.
- c) Targeted on a specific transformer that has indications of early stages of deterioration in condition, or one needed for contingency loading.

In fleet wide or targeted monitoring, the process of justification and application requires the same attention to detail.

Examples of motivations or possible benefits from application of condition monitoring include the following:

- Improved utilization of assets through improved availability, reliability, and loading.
 - 1) Monitoring allows extra load to be carried while ensuring the transformer is not in distress or heading to imminent failure.
- Reduction in maintenance costs and outages by moving from time-based maintenance (TBM) to condition-based maintenance (CBM).
 - 1) Knowledge of condition allows for maintenance to be advanced/delayed and to reduce risk.
- Reduction in the risks associated with unexpected failures, including cost avoidance, time savings, avoidance of system interruption, and negative reputation impact.
 - 1) Knowledge of condition allows for alerts and alarms to be dealt with remotely.

- Reduction in the risk associated with unexpected failures, including cost avoidance, time wasted to time management, system interruption, and negative reputation impact.
 - 1) By identifying at-risk candidates in a more timely manner through identification of failure modes, in-service failures may be prevented and unplanned forced outages avoided.
- Life-extension, allowing transformers to be used past their nominal technical, design, and operational and financial “lives.”
 - 1) The use of monitoring allows for transformers that would otherwise be retired to remain in service without increasing their risk of unexpected failure.
- Supporting replacement planning and spare unit strategy by identifying locations of greatest need.
 - 1) Combining monitoring data with fleet and system planning to permit a reduction in the number of spare units held based on actual condition.
- Manage the transformer during contingency loading to prevent excessive overheating.
 - 1) Making sure a transformer under excess load does not have excess loss of life due to raised temperature.
- Detect abnormal operational conditions.
 - 1) Monitoring could reflect anomalous operating conditions: geomagnetically induced current (GIC), elevated ambient temperature, blocked pumps/fans, and so on.
- To learn about the capability and usefulness of the monitor itself.
 - 1) Often via a pilot to see if the monitor lives up to the requirements of the application.

4.4 Monitor selection—theory and practice

The process of selecting a monitor begins with the motivation (i.e., what is the decision to be made, or what is the motivation and the expected benefit?). The process is then, in theory, straightforward:

- Identify at the outset what the aim of the application of monitoring is meant to achieve.
- Identify what a successful application will yield, what measurable benefits are to be achieved, and what timescale will be used: How will it be determined that the intended result has been achieved?
- Identify possible measurable parameters to support the application and the decision-making process: Which failure modes to address, with what timeliness?
- Work out the accuracy, precision, update frequency, and other parameters of the data that allow the decision to be made with confidence. For example:
 - 1) Fault gases may take hours to reach the online sensor due to fluid flow rate and online sample schedule.
 - 2) PD sensors will respond immediately to a PD source but also to external noise sources outside of the transformer.
- Identify alerts that will be generated: how many and at what levels for parameters or diagnostic tools.
- Identify monitors that meet the requirements.
- Procure, install, support, maintain, and “apply” the monitor.

In practice, the process is quite complex:

- There may be many parameters of interest and monitoring; more than one or two could make the business case more difficult.
- There may be many options for data precision, accuracy, and update frequency. Is 20% accuracy on a dissolved gas-in-oil analysis (DGA) device sufficient to avoid false positives or false negatives? What is guaranteed in the field?
- There may be variations in monitor reliability. Some units, over the years, may be more prone to failure, have a need for maintenance/support, or need regular replacement components.
- The cost of the monitor is just the beginning: There is also the cost of installation, maintenance, support, communications, data security, and so on.
- Alert/alarm setting for the individual monitor may be a “detection” and not contribute to a “diagnostic” process but may require further data for the decision.
- Alerts/alarms and data will need to be available for the appropriate people to make decisions in a timely manner, in a format where contextual analysis data is also available: load, voltage, ambient temperature, tap position, and so on.
- Response plans are needed; if the monitoring does not, ultimately, stimulate timely and appropriate action, then there is little chance it will achieve its aim.

4.5 Setting alert levels and planning ahead

Alerts may be generated based on individual parameters or on diagnostic tools built within the monitor. Usually there are at least two levels of alert, low and high, but there may be more levels, “low, high, high-high,” for example, or “Info, Warning, Action.” The number of alerts and their configurability should be defined by the user.

For example, when a parameter such as hydrogen is monitored, there may be a plan to send alerts if hydrogen goes above 40 ppm, say, for low level and 90 ppm for high level.

NOTE—A repeated DGA measurement confirmation may be needed prior to alerting as validation. See IEEE Std C57.104-2019,¹² Table 1, and Table 2 for more typical gas concentration values. Table 3 and Table 4 on rates of change and increments do not apply to online DGA monitoring.

For alarm settings in transformers with natural ester and synthetic ester-immersed fluids, see IEEE Std C57.155.

Alert generation:

- Informing relevant parties: When the alert comes in, who gets it and what information does it contain? Is it an email, a text message? Should the alert be stored and an audit trail set up to indicate distribution and subsequent “acknowledgment?”
- Providing relevant information: The alert should indicate the asset, the monitor, and the sensor; it should state what the alert “cause” is and the associated measurement data; it should indicate the urgency of the alert and timescales for action.
- Data management: The informed parties should have access to relevant data: prior alerts for this asset, present monitoring, and operational data values.

¹² Information on references can be found in Clause 2.

A response plan is needed for a monitoring application: A defined plan for each level of alert for each sensor installed. Without the plan, when an alert comes in, there is always the possibility that while interested parties are contacted and brought together, the transformer fails, possibly catastrophically. It is a hallmark of good condition monitoring to have thought through what may happen, who needs to know, how they will be alerted, what data would be supplied, and what actions need to be taken.

Response planning:

- A list of individuals to receive the alert should be agreed upon by relevant stakeholders.
- Actions for an alert should be agreed upon by relevant stakeholders with accountable individuals and timescales for the action to be taken, with a means to record the actions actually taken, the date/time, the individuals responsible, and any relevant comments on the success of the response. The actions possibly include but are not limited to the following:
 - 1) Data review
 - 2) Offline testing
 - 3) Laboratory testing of newly sampled oil
 - 4) Mobilization of technical/engineering crew
 - 5) Implementation of a risk zone
 - 6) De-energization
- Response plan review: when actions are completed, and the alert dealt with, a review of response activities should be undertaken by relevant stakeholders to look for response improvement.

Response plan details will likely reflect the severity and urgency of the alert itself. The response plans for less urgent, less severe alerts may be less detailed.

Example of low-level alert:

Alert generation: A low-level alert is generated when online monitoring DGA rises above 40 ppm Ethylene; the alert is emailed to the substation manager and the condition monitoring coordinator.

Alert response: Condition monitoring coordinator reviews relevant DGA and operational data within 12 h and decides whether further investigation is necessary. If not, the coordinator acknowledges alert and decides whether resetting the alert level is necessary and informs relevant stakeholders of action.

Example of high-level alert:

Alert generation: A high-level bushing alert is generated when the daily power factor analysis exceeds the user-defined level for an individual bushing; the alert details are emailed to the head of operations, technical condition monitoring coordinator, substation manager, and other individuals. Operations also receive a “red light” relay alert on screen in the control room.

Alert response: System operations replaces transformer bushings that have a known high failure rate; engineering dispatches a team to test and assess the bushing; the condition monitoring team gathers and reviews relevant data.

Alert generation and response planning can be set up in a generic manner, looking at top oil temperature limits, for example, and also tuned to individual locations, assets, and applications. As an analogy, not all car tires will be expected to be within the same pressure range, and not all similar tires will receive the same operational experience of road, ambient conditions, and driver.

4.6 Successful application: common themes

Successful monitoring programs have the following:

- Clear aims that have “deliverables” that can be measured and managed
- Clear identification of what to monitor, which data to generate, with what accuracy, and with what update rate
- Clear identification of the data analyses for detection or diagnosis of failure modes
- Clear implementation of alert levels, alert response, action plans, and processes to review the response

Example of successful condition monitoring related to bushings:

A transmission company had 69 transformers with a type of bushing known to have a higher-than-expected failure rate, with the bushing exhibiting an elevated power factor as a symptom of insulation deterioration. A condition monitor was installed to record the individual bushing leakage currents, with subsequent derivation of both relative power factor and capacitance for each bushing. The engineering group set alert levels where low-level INFO alerts were issued frequently while they learned how the monitoring responded in each location—with variations in power factor being influenced by the presence of both long overhead lines and static var compensation. Initial response plans for the INFO alerts were to review data in detail, and as they became more familiar with the applications, they “loosened” those limits in some cases. Subsequently a written policy was agreed to by operations, engineering, asset management, and other stakeholders that required operations to switch out a transformer within 2 min of receiving a top-level ACTION alert, with subsequent offline testing to confirm the monitor result. The policy was instrumental in reacting to two alerts at different locations where suspect bushings were detected and subsequently confirmed through offline test, thus, saving two transformers.

5. Monitored parameters

This clause contains an overview of the parameters that are typically monitored for transformers and their components. A description is given for each parameter.

5.1 Online monitoring introduction

Transformer online monitoring equipment can vary depending on the number of parameters that are monitored, and the monitoring system may be limited by the desired accessibility of the data. At the most basic level, one can consider a temperature gauge to be a monitor. The measured parameter (temperature) is communicated via a visual observation for a substation inspector. Excessive temperatures are communicated via alarm activation. In contrast, sophisticated online monitoring systems can monitor many parameters simultaneously. These systems can be integrated into a complete substation system. Transformer problems, in the earliest stage, are communicated directly to the substation engineer. This clause describes a variety of such systems. The elements of an online transformer monitoring system typically consist of sensors, indication, electronic hardware, hardware interconnection, communication interface, and data processing.

Expert systems, supported by comprehensive data collection, provide a critical bridge between online monitoring and online diagnostics. In lieu of presenting the user with a voluminous amount of data requiring further analysis, an expert system approach is designed to inform if any intervention is required. To be useful, the online expert system's diagnostics should identify a wide array of problems in the incipient state. Diagnostic methods should distinguish between changes that are "noise," those of minor consequence, and those worthy of immediate attention. The diagnostic algorithms can be self-learning and not depend on the user to establish thresholds or employ average values from other nominally similar apparatus.

Table 1 shows the values that will be discussed later in this guide.

Selection criterion should be based on the priorities of the transformer owner. Operational reliability and costs normally are the main priorities of the transformer owner that will determine the selection criterion. A methodology to determine the specific requirements versus desired operational requirements needs to consider many factors. These requirements include the analysis of current operating costs and risk and consequences versus expected benefits. Once a determination has been made for operational requirements and associated risk, a decision can be made on the need/cost of online monitoring and/or offline monitoring requirements.

Table 1—Monitored parameters¹³

Clause	Category	Monitored value	Common sensor type	Comments
5.2	Transformer and Winding Temperature	Top Oil Temperature Bottom Oil Temperature Ambient Temperature Simulated winding hot spot Control cabinet temperature	RTD	Thermal wells Magnetic mount
		Direct winding temperature	Fiber Optic	Installed at time of manufacture
5.3	Transformer cooling control	Fan current	Interposing CT	Split core or fixed core
		Pump current		
		Pump flow indication	Flow sensor	
		Cooling contactor	Aux contact	
		Loss of cooling power	Loss of ac	
5.4	Transformer Loading	Load current	Interposing CT	Split core or fixed core
		Voltage	Voltage Transformer (VT, not part of the transformer)	
5.5	Load tap changer (LTC)	Tap position	Resistor Board Synchro Sensor	
		LTC oil temperature	RTD	
		LTC motor current	Interposing CT	Split core or fixed core
		Limit alarm	Low/High limit	
		Vacuum bottle fail	Leakage current sensor	Measured across vacuum bottle
		LTC control switch	Not in Auto	
		LTC oil level high/low	Level gauge	
		LTC pressure surge	Sudden Pressure Relay	
		LTC pressure relief activated	Pressure relief device (PRD)	
		LTC oil filter	Flow or pressure	
		LTC sequence timing	Cam switch	
5.6	Main tank sensors	Oil level high/low	Level gauge	Non-conservator designs
		Pressure Surge	Sudden Pressure Relay	
		Pressure relief activated	PRD	
		Gas accumulation	Gas accumulation relay	
		Tank pressure	Pressure sensor	
5.7	Conservator tank membrane	Oil level high/low	Level gauge	
		Conservator membrane rupture	Membrane leak sensor	
5.8	Dissolved gas-in-oil analysis (DGA)	Hydrogen	Key gas monitor, Multi gas monitor	
		Methane		
		Ethane		
		Ethylene		
		Acetylene		
		Carbon monoxide		
		Carbon dioxide		
		Nitrogen		
5.9	Moisture-in-oil	Oxygen		
		Dissolved water content	Capacitive sensor	

¹³ The numbers in brackets correspond to those of the bibliography in Annex A.

Clause	Category	Monitored value	Common sensor type	Comments
5.10	Bushing monitoring	Leakage current: RMS magnitude Relative phase Harmonic content	Bushing tap current sensor	Record current waveform to derive mag/phase/harmonics.
		Reference voltage	Voltage sensor	Record voltage waveforms to derive mag/phase/harmonics. Use voltage reference in power factor and capacitance calculations
		Power Factor		Power factor derived from relative phase, or with voltage reference.
		Relative	Bushing tap current sensor	
		True (offset)	Bushing tap current sensor, voltage sensor	
		Capacitance	Bushing tap current sensor, voltage sensor	Assume nameplate voltage if no reference available. Schering bridge use is uncommon
		Temperature	RTD	Temperature to allow correction of values to nameplate
			Thermal Imaging	Allows for multiple measurements simultaneously and detection of hot spots
5.11	Partial discharge	Amplitude (pC, mV, dB, mdB)	Antenna, HFCT, acoustic, bushing tap current sensor, transient earth voltages (TEV)	Check with standards such as IEC 60270 [B60] and guides such as CIGRE Technical Brochure #861 [B28]
		Repetition (pps)	Antenna, HFCT, acoustic, bushing tap current sensor, TEV	
		Spectrum (MHz-GHz)	Antenna, HFCT, bushing tap current sensor, TEV	
5.12	Geomagnetic induced current	Neutral current dc magnitude	Hall effect GIC sensor	Neutral/Ground on Wye-Wye connected transformer
		Current Harmonics Transformer Load	Interposing CT	Split core or fixed core
5.13	Online transient frequency response	Current	Current sensor	Via bushings, neutrals and in CTs
		Voltage	Voltage sensor	
5.14	Online impedance measurement	Current phasor	Disturbance recorder, digital relays	Configure a disturbance recorder to record the signals at steady operation
		Voltage phasor		

5.2 Transformer and winding temperature

5.2.1 Introduction

Continuous measurement of the top oil temperature is an important factor in maximizing transformer service life. Top oil temperature, ambient temperature, load (current), fan/pump operations, and direct reading winding temperatures (if available) can be combined in algorithms together with individual transformer thermal characteristics and time constants. Such algorithms could be used to create dynamic models that estimate hottest spot temperature and thermal aging based on defined operating conditions of ambient and load. They could therefore be used to manage the overall temperature profile of the transformer.

There is evidence that elevated winding temperature, cyclic loading, and overloading will reduce the overall service life of a transformer. The hottest spot temperature of the winding is one of a number of limiting factors for the loading capability of transformers. Insulation materials lose their mechanical strength with prolonged exposure to excessive heat. This aging process results in paper brittleness, possible tearing, and mechanical displacement that may lead to electrical failure for a lack of proper insulation during normal and abnormal operation.

Figure 2 has temperature at the top of the triangle with oxygen and moisture as the other two main components. The combination of these three parameters together with operations and maintenance profile are the key aspects that mostly influence transformer life.

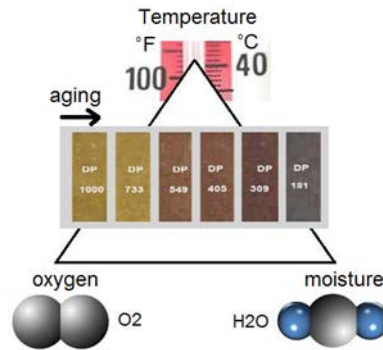


Figure 2—Triad of solid insulation aging showing the main parameters that affect paper aging rate

The actual aging occurs under the influence of those parameters and the by-products of the aging process, as well as operating in a closed cycle that feeds itself as illustrated in Figure 3.

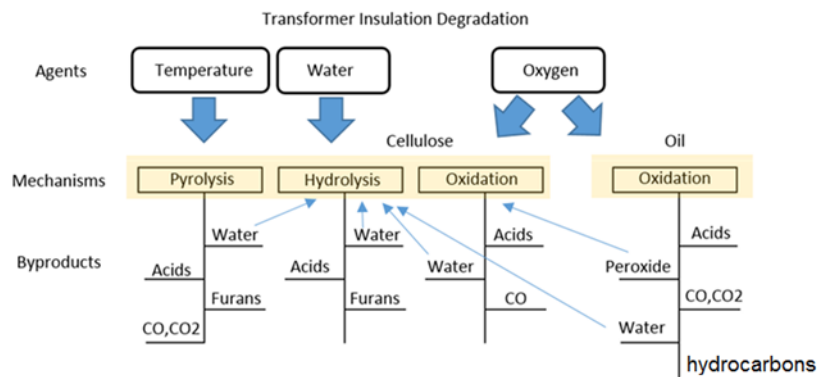


Figure 3—Complex process of paper aging in transformers with insulating liquids

5.2.2 Types of temperature sensors and their technologies

Winding temperature sensing:

In conventional analog winding temperature gauges, measurements are not made directly from the windings. The winding temperature measurement method is a simulated one, based on the temperature of a measurement probe installed in the top oil thermo-well to which a gradient temperature is added by a heater surrounding the well. The heater, in turn, is powered by the secondary current of a CT installed on one of the bushings and simulates winding hot spot temperature gradient over the top oil temperature. This method is described by Feser et al. [B44], Fox [B47], and IEEE Std C57.91.

Electronic temperature monitors (ETM):

A second method suitable for both new and existing transformers uses top oil temperature and winding load current to determine the winding hot spot temperature rise. These are commonly called electronic temperature monitors (ETMs). The ETM calculates winding temperature, based on IEEE Std C57.91 guidelines. One type of ETM is a digital display that provides a digital readout not subject to operator interpretation. Another option is a digital gauge type indicator that shows the winding temperature and liquid temperature in the same dial.

Transformer parameters can be used to determine thermal time constants. These time constants can be changed dynamically based on load and cooling conditions. Rate of change information can also be utilized to further improve the winding temperature accuracy. Depending on the sophistication of the temperature algorithm, accuracies close to embedded fiber sensors can be achieved in normal operating conditions.

A third method uses ETM with direct winding temperature measurement. This method can be used in conjunction with the second method to detect an abnormal condition such as when a drift occurs between the simulated and direct winding temperature. The following two direct winding temperature sensor types are available:

- Optical fibers that measure the temperature at one point. The main technologies used are GaAs (gallium arsenide), FBG (fiber Bragg grating), and fluorescence.
- Distributed optical fibers that measure the temperature along the length of the winding.

Point sensing fiber optic probes are much more common having matured in terms of cost and reliability since their early introduction in the 1980s. Signal conditioners are available for point optical sensors with the necessary hardened electronics and simplified optical components that survive online monitoring installations.

Distributed fiber optic temperature sensors can measure the temperature along the fiber as a function of distance. They may replace a large number of discrete sensors and allow a real-time measurement of the temperature distribution, but a standard method for easy installation in the winding has not yet been implemented.

5.2.3 Measurement response time

The response time of the analog method is affected by the transformer oil time constant and the well heating system delay. For the digital method, the winding temperature response time may be affected by the transformer oil time constant. The most impactful parameter for both methods is the transformer oil time constant that is given in hours. For the direct winding temperature, response time is affected only by the sensor thermal inertia, which is small.

5.2.4 Operating condition

For the conventional method, the gradient between liquid and winding temperature simulated by a thermal model must be adjustable according to the heat run test of the transformer. The temperature indication of all methods should simplify the visualization of the measurement. In cases of instruments without visible temperature indication, they can be located in any place. Set points for alarm and trip contacts must be adjusted or configured according to the service conditions of the transformer. Winding temperature indicators should withstand the environmental service conditions of the transformer with at least NEMA 3R type. All gaskets included with the equipment must withstand the ambient temperatures specified by the users. In cases of stainless-steel fittings, all of the stainless-steel parts must be properly passivated in order to avoid surface rust.

5.2.5 Signal requirements

Types of signal sourcing are as follows:

- Signals from existing sensors or transducers
- Combination of signals from existing sensors or transducers
- Signals from added non-intrusive sensors or transducers
- Signals from added intrusive sensors or transducers

Examples of existing sensors are those available from protection and control facilities: voltage, current, tap position indication, alarms, operation counters, transformer winding and top oil temperatures, and pump start commands. An example of an added non-intrusive sensor or transducer is a current transformer (CT) connected around the secondary of a bushing CT to measure load current, or the addition of a dissolved gas-in-oil monitor.

When adding intrusive sensors to existing equipment, caution should be exercised, and the original equipment manufacturer (OEM) should be consulted before any changes are implemented. For retrofit online condition monitoring applications, the first three signal types will be prevalent. In this regard, any upgrading of protective relay systems should take online condition monitoring needs into account. For future applications, all four signal types will be utilized, the intrusive transducers being factory installed.

The overall intent of signal source selection is to achieve the desired results from the fewest possible signals and requiring the least hardware and cabling. Allowance should be made for future modifications or additions.

5.2.5.1 Signal acquisition required for temperature monitoring

Signal acquisition is understood to include sensor selection and the signal transmission mode from the sensor to the monitoring hardware.

Sensor selection considerations include the following:

- **Parameter** to be measured: Input range and sampling rate.
- **Sensor type**: Active or passive, reliability, calibration needs, intelligence level.
- **Sensor output**: Voltage, current, digital, status (on/off), wireless, and so on. The signal should be configured as an isolated output without reference to ground. This is important from the point of view of electrical, isolation, and insulation levels.

Signal transmission considerations will include the signal type and the transmission medium as shown in Table 2.

Table 2—Signal type/transmission medium

Signal type	Output	Transmission medium	Comments
Analog	Current Voltage RTD (temperature measurement) Optical wavelength/decay (temperature)	Copper wire Fiber optic	Converted to digital at some point
Digital	Digitally encoded analog value	Copper wire or fiber optic RF/Wireless technologies	Serial connection, such as EIA232 (RS232, RS422, RS485), Ethernet, and others
Discrete (Status)	Voltage (on/off) Current (on/off) Contact (wet/dry)	Copper wire or fiber optic	On or Off state converted to digital at some point, usually copper wire connection

The choice of sensor may dictate the transmission medium in Table 2. Transmission of analog values either using current or voltage on copper wire will require one 2-conductor wire per signal. For analog transmission, consideration must be given to address signal attenuation. Digital transmission using fiber optic cabling will have some attenuation from the cable itself along with any and all splices used. Some modern IEDs use these technologies for communications into the monitoring hardware. Digital transmission on fiber optic cable is best suited for longer high-density transmission of continuous signals and remote communications.

5.2.6 Installation

Optical winding sensor installation with fiber optic temperature sensors are only installed during the initial manufacturing process or during refurbishment. The fiber optic temperature sensors should be installed in the winding at the expected hot spot locations. The windings hot spot is obtained by the transformer manufacturer's calculations and verifications on similar transformers. It is recommended to use multiple sensors to measure the temperature at the expected hot spot locations and around it. The single point fiber optic temperature sensors should be installed in the spacer, with the protective cable mechanically anchored in the spacer. Glue is not very efficient since the protective cables are mainly made in polytetrafluoroethylene (PTFE). The majority of point fiber optic temperature sensors manufacturers have developed an anchoring system. Care should be taken during all the installation steps of the sensors to respect the minimum bending radius of the fiber, keep the connectors clean, and limit unnecessary strain on the fiber optic cables.

For the distributed fiber optic sensors, no commercial solution is known at this time for installing the sensors. The trials that have been made consist of making a groove in the conductor, placing the sensing fiber in this groove, and then wrapping the conductor with transformer paper.

It should be noted that direct winding temperature sensors will only measure the temperature where the sensor is placed. Due to the difficulty in identifying the location of the hot spot, it is recommended to use multiple sensors to measure the temperature at the expected hot spot locations. Since the thermal model is the foundation for both calculated winding hot spot indication and for direct measurement sensor location, it should be recognized that the accuracy of any methodology is limited by the accuracy of the transformer manufacturer's thermal model.

5.2.7 Maintenance requirements

Transformer oil and winding temperature sensors, resistance temperature detectors (RTDs), indicating gauges, and electronic temperature indicators typically have no maintenance requirements, but it may be advisable to inspect analog gauges every 5 to 10 years for signs of deterioration, moisture ingress, and proper contact function. Many electronic temperature indicators have a watchdog feature that provides an alarm for malfunction of the device. Transformer oil and winding temperature sensors, RTDs, indicating gauges, and electronic temperature indicators should be tested and verified every 5 to 10 years to confirm that the data provided by these devices are accurate.

5.3 Transformer cooling control

5.3.1 Introduction

Having cooling control is important to make sure the transformer has the following:

- a) Acceptable temperature during normal and overload operation
- b) Even wear and tear of the cooling system
- c) Allows condition- versus time-based maintenance
- d) Future prediction to prepare for proper cooling in case of a heat wave or an overloading scenario or other contingencies

5.3.2 Control function

Information typically included in transformer monitoring systems may also be useful in some transformer control functions. For instance, load current information can be used to estimate winding temperatures. Cooling control may also be improved by making use of the measured parameters such as top oil temperature, transformer load current, winding temperatures, ambient temperature, fan and pump motor current, and cooling system health. Combined control and monitoring systems provide the ability to use the measured values for several purposes.

5.3.3 Types of sensors for cooling monitoring and their technologies

Table 3 shows a selection of sensors that could be used for cooling monitoring.

Table 3—Types of sensors for cooling monitoring

Parameter monitored	Type of sensor	Used for
Fan current	Interposing CT	— Detect fan(s) malfunction: — Detect fans that draw too much current — Detect loss of fans power supply
Pump current	Interposing CT	— Detect pump(s) malfunction: — Detect pump(s) that draw too much current — -Detect loss of pumps power supply
Pump flow	Flow switch, Flow sensor	— Detect the presence of flow — Detect flow rate in the cooling system
Cooling contactor	Contactors aux. contact	— Confirm contactor status
Loss of power supply	Voltage input or undervoltage relay	— Detect loss of power to the cooling system
Winding load current	Interposing CT	— Pre-cooling — Winding temperature calculation — Winding temperature prediction
Top oil temperature	RTD, fiber optic (FO) temperature sensor, Thermometer with analog output	— Pre-cooling — Winding temperature prediction — Cooling efficiency
Bottom oil temperature	RTD, FO temperature sensor, Thermometer with analog output	— Cooling efficiency
In/Out temperature of cooling system	RTD	— Cooling efficiency
Winding temperature	FO temperature sensor (Direct Measurement), RTD (oil) + Load Current (Calculated), Mechanical Thermometer with analog output (Simulated)	— Pre-cooling — Winding temperature prediction
Ambient temperature	RTD, FO temperature sensor, Thermometer with analog output	— Cooling efficiency — Pre-cooling — Adaptive setpoints based on ambient temperature

5.3.4 Operating condition

The most frequent failure mode of the cooling system is the failure of individual fans and pumps. The objective of continuous online monitoring of pumps and fans is to determine if they are running properly. This can be accomplished by monitoring the pump oil flow switches or measuring the current drawn by pump and fan motors against the typical load current and comparing them with their expected on/off status. Normal operational modes may indicate rotation of fan blades and correct rotation of pump impeller. Abnormal operational modes may be the result of improper control or power wiring or a mechanical issue with the motor's bearings or the fan blade or impeller that the motor is driving. Higher loads, above normal running current but below the motor's rated locked rotor current, are indicative of degradation that eventually may trip the motor's thermal protection device. A locked rotor condition should normally trip the motor's thermal protection device, fuse, and/or breaker protecting the branch circuit feeding these motors.

Pump failures due to malfunctioning bearings could be a source of metallic particles. The particles can be a potential dielectric hazard. Sensors that detect bearing wear or increasing motor currents are available. These use ultrasonic emitters and sensors embedded in the pump bearings and measure the thickness of the bearing based on travel time of emitted and then reflected high-frequency sound waves, thus, determining if metal loss is occurring.

Fan motor failure or inefficient operation may be caused by the following:

- A cooling system that is not operating frequently that causes the shaft bearing to seize
- Objects such as ice, snow, animal nests, snakes or other animals, and vines or sticks lodged in the fan cage preventing the fan blade from rotating to its full efficiency
- A loose or missing fan blade retaining screw, where the fan motor current is running lower than its normal running current

Furthermore, the online analysis should consider the following:

- The initial monitoring parameters should be set during commissioning cooling stages as actual air flow is dependent on numerous factors, including but not limited to any restrictions in air flow that are only known in the field. Also, these parameters may require adjustment if a fan motor and/or its blade is replaced.
- The maximum current, resolution, and accuracy of the current measurement should be based on whether the cooling stage(s) or the individual fan or pump motors are being monitored.
- If fan exercising is used, consideration should be given to command fan exercising when the ambient temperature is above 0 °C. When exercising pumps when the power transformer has cooling class ODAF, consideration should be given to the oil temperature as static electrification is possible. Consult with the transformer manufacturer for advice for the safe top oil temperature for pump motor exercising. If static electrification is of concern, online oil flow measurement might also be considered.

5.3.5 Installation

For new transformers, the complete system including sensors can be installed at the factory.

For existing transformers, except for the fiber optics (FO) temperature sensors, all other sensors can be retrofitted on an existing transformer. Some wiring and mechanical modifications may be needed to fit new sensors onto existing transformers if they have not been designed for addition of items such as a flow gauge, a bottom oil sensor, or in/out temperature sensors for the cooling system. For temperature sensors, a magnetic RTD can be used as an alternative to avoid an outage, or if no thermowell is available to fit a standard RTD.

5.3.6 Cooling failure mode detection

The most frequent failure modes are shown in Table 4.

Table 4—Cooling system failure mode detection

Component		Phenomenon leading to failure	Measured signals	Diagnostic interpretation
Cooling system	Fan(s) and/or pump(s)	Electrical failures of pump and fan motors Mechanical failure	Motor (fan, pump) currents Alarm contact for loss of pump flow Alarm contact for loss of fan Top oil temperature Winding temperature Dissolved gas-in-oil Pump bearing wear detector Fan or pump motor mechanical vibration Infrared scan Ambient temperature	Thermal Model Gas analysis Pumps/fans model
	Cooling controls	Failure or inaccuracy of temperature sensors Pumps and fans running in reverse	Ambient temperature Top oil temperature Winding temperature Load current Cooling control voltage Cooling supply voltage Cooling control contact status (on or off) Cooling control mode (manual or automatic)	Thermal model
	Radiators and coolers	Internal or external blocking of radiators resulting in poor heat exchange	Top and bottom oil temperatures Winding temperature Ambient temperature Load current Radiator inlet and outlet temperatures	Thermal model oil and winding temperature forecasting

5.3.7 Impact of sensors/diagnostics on transformer maintenance requirements

The application of various sensor technologies within the transformer cooling system, along with appropriate data analytics, can provide a positive impact toward optimization of the end user's maintenance program. For example, mechanical wear indication, current draw, and temperature data collected from cooling fans and pumps can provide trends that enable better prioritization and focus of maintenance resources onto marginal components before they reach the point of failure or before a more costly repair is needed. It is also possible to continuously monitor cooling system efficiency so that negative trends may be quickly identified. At the same time, unnecessary or untimely inspection and maintenance of cooling components that are performing satisfactorily can be minimized. Radiator and cooler diagnostics, for example, can detect radiators with blocked oil flow or perhaps cooler fins that are starting to collect debris, thus, allowing the end user to extend the interval between required inspections. Additionally, loss of significant transformer life may be avoided if cooling system problems are detected and addressed as early as possible.

5.4 Transformer loading

5.4.1 Introduction

Maximum loading of transformers is restricted by the temperature to which the transformer and its accessories can be exposed without excessive loss of transformer life or elevated risk of catastrophic failure. Continuous online monitoring of current and voltage coupled with temperature measurements can provide a means to gauge thermal performance. Load current and voltage monitoring can also automatically track the loading patterns and thermal response of the transformer for increased accuracy of

simulated computer load flow thermal models, as well as providing individual load profiles to assist in transmission and distribution system planning, aid in dynamically loading the transformer, and monitor the efficiency of the cooling system.

Load monitoring benefits can be further enhanced when combined with appropriately placed internal temperature sensors. For example, a temperature probe strategically placed within the transformer winding can enable direct measurement of the winding hot spot temperature. Data from loading and ambient temperature patterns, along with the thermal response of the oil and winding hot spot temperatures, can then be used to validate and improve the accuracy of the transformer thermal model. This arrangement can, for example, also be useful for monitoring the thermal response to geomagnetically induced current and harmonics. For these latter cases, however, it is also advisable to install temperature probes at other locations that may be affected within the transformer, such as flitch plates, yoke plates, T-beams, cores, and tank walls. The best location for these additional sensors should be determined during the transformer design review.

5.4.2 Load measurement technologies

The following measured parameters and types of sensors in Table 5 are used for measurement of normal load kW and kVar.

Table 5—Load measurement parameters

Monitored parameters	Type of sensor	Types	Used for
Current	Bushing current transformer (CT) on transformer (TX)	Magnetic core, metering class	Measurement of TX current
	Bushing CT on circuit breaker (CB)	Magnetic core, metering class	Measurement of circuit current
	Freestanding CT	Magnetic core, optical	Measurement of circuit current
	Current transducer	Transducer	Measurement of circuit current with voltage
Voltage	Voltage transformer (VT)	Magnetic core, capacitively coupled	Measurement of line voltage

5.4.3 Implementation and considerations

System load is the total resistive and reactive power consumed by the various users in a power system. Different types of transformers are located throughout the power system between the generation sources and the ultimate loads, and the system load power flows through them.

The transformer load can be referred to as the actual loading in kVA, kW, or load current. The load in kVA or MVA is the product of the output terminal voltages and phase currents. The impact of the load on the transformer depends on the voltage and current magnitude. Parameters including the power factor of the load and the excitation voltage level of the transformer can affect the transformer core excitation and the voltage drop in the transformer. The excitation voltage can correctly be determined using the terminal voltage, the current magnitude, and the power factor of the load. Load magnitude can affect the oil, active part, and tank temperatures, as well as its vibration and noise level. Transformers are designed to operate at nameplate ratings with minimum impact on the loss of life of the insulation. Excessive transformer load or loading beyond the transformer nameplate can accelerate the insulation aging and even lead to contact damage of any connection or oil bubbling that can lead to failure. IEEE Std C57.91 provides guidance on loading and the loss of insulation life associated with load magnitudes and time.

5.4.3.1 Load can be measured in several ways

Transformer terminal voltage is typically measured with instrument transformers measuring the voltage on the bus that is connected to the transformer. Currents can be measured directly with bushing current transformers in the transformer. Currents can also be measured with adjacent circuit breakers or free-standing current transformers located in the substation that may be conducting only the transformer current or a combination of the transformer and other loads. In the latter case, it may be necessary to analyze load data from multiple CTs in order to accurately determine the loading on the transformer itself.

Instrument transformers that measure substation voltages are typically capacitively coupled voltage transformers or wire-wound inductive voltage transformers that transform the system voltage to safe operating levels, typically in the 48 V to 240 V range.

Instrument transformers that measure phase currents are typically wire-wound inductive current transformers that transform the current to safe levels in the 0.5 A to 5 A range. Optical current transformers are also used in some applications that operate on the Faraday effect.

Non-sinusoidal voltages and/or currents can affect load measurement, and at high currents, inductive current transformers can saturate so they need to be selected with appropriate ratios and accuracy classes for proper operation during normal and expected overload operation.

The resistive and reactive components of load can be measured by the relative phase angle between the voltage and current and can be expressed in terms of Watts and Vars or kVA or MVA at a power factor. This is more a concern for revenue metering, but lower power factor values increase the regulation and decrease the output voltage.

5.4.3.2 Effect of online monitoring on overloading capability

The following additional measured parameters and available sensors in Table 6 can be used to monitor transformer overload capabilities.

Table 6—Additional load measurement parameters

Monitored parameters	Type of sensor	Types	Used for
Winding temperature	Electromechanical	Bourdon tube gauge with sensor heating element	Measurement of load adjusted oil temperature
	Electrical analog or digital	RTD with sensor heating element	Measurement of load adjusted oil temperature
	Fiber optics	GaAs, fluorescence, or fiber Bragg grating	Direct measurement of winding temperature
Dissolved gas in oil	Several, see 5.8		Measurement of CO, CO ₂ , and hot metal gases
Moisture in insulating liquids	Several, see 5.9		Measurement of percent moisture saturation and ppm moisture

It is generally recognized that the risks associated with overloading can be significantly reduced if the transformer conditions are closely monitored throughout the overload period (Bergman [B14], Farquharson [B43]). To quantify this benefit, the additional loading margin provided by monitoring needs to be stated. Field experience with transformer overloading is still limited, but it can be conservatively assumed that if the parameters mentioned below are properly monitored, the transformer may carry additional load with the same degree of confidence that would exist in operation without monitoring.

A comprehensive monitoring system comprising load, temperatures, dissolved gas-in-oil, and moisture sensors can provide a major support to the operator when the transformer faces the following overload conditions:

- An important limitation for transformer loading is winding hot spot temperature. The winding hot spot temperature is affected by many items, including load, ambient temperature, cooling system health, and transformer losses (which may change based on LTC position). Taking these elements into account, it is possible to calculate the maximum safe load the transformer can carry from a thermal perspective. This value is commonly referred to as the “dynamic rating” of the transformer. Using the time constant design details of the transformer, it is also feasible to calculate the time remaining until the winding hot spot temperature exceeds a defined limit.
- Continuous monitoring of hydrogen and carbon monoxide provides dependable detection of excessive overheating of leads, shields, structural parts, contacts, or bolted joints. It will also alert the operator if excessive circulating current is taking place in the core or in the tank, leading to arcing or overheating of contact points.
- The moisture sensor measures the relative moisture content of the insulating oil. Over time, the online monitoring system can use this information to infer the moisture content of the insulating paper, thus, allowing estimation of the bubble inception temperature. This temperature is compared to the hot spot temperature to indicate the safety margin prevailing during the overload. The moisture content of the insulating paper is also an important factor to consider when calculating the insulation’s loss of life.
- Although the thermal loss of life of the winding insulation cannot be prevented, online monitoring can provide a dynamic evaluation of insulation degradation. The relative loss of life can then be converted into cost if some hypotheses are set regarding normal life duration and transformer cost. The cost attributed to loss of life needs to be subtracted from the apparent benefits achieved from transmitting this extra load. The loss of life cost can also be useful when calculating the cost of transmitting this additional amount of energy.
- Due diligence is required because while the active part may be able to sustain an overload condition, some of the other components may well become the limiting factor, including the bushings, particularly resin impregnated paper (RIP) type bushings, and the LTC itself as an item that deserves attention when it comes to its overload capability.

5.5 Load tap changer (LTC)

5.5.1 General

Load tap changers on transformers have been a constant source of problems for most owners if not properly installed, operated, and maintained. High maintenance costs result from several causes. The reasons include misalignments, poor design, manufacturing defects, material defects, high loads, abnormal number of tap changes, mechanical failures, coking caused by contact heating, and moisture ingress. LTC failures account for a significant portion of transformer failures (Bengtsson [B9], Bengtsson et al. [B10]).

LTC contact wear occurs at LTCs with copper/copper tungsten contacts as the LTC operates to maintain a desired voltage with varying loads. This mechanical erosion is a normal operating characteristic, but the rate can be accelerated by improper application, faulty installation, wrong calculation of the resistors, and overloads. If an excessive wear situation is not corrected, the contacts may burn open or weld together. Monitoring a combination of parameters suitable for a particular LTC design can help avoid such failures.

LTCs with vacuum interrupters (resistive or reactive) in a perfect condition do not show wear of contacts since the vacuum interrupter is separated from the insulating liquid. The re-condensation of the metal, vapor plasma in the cell, would re-condense at its contacts, making the wear minimal. Monitoring a combination of parameters suitable for a particular LTC design can also help with those applications to detect upcoming failures in advance.

LTC failures can be combinations of mechanical, electrical, or thermal faults. Failures that are mechanical in nature include failures of springs, bearings, shafts, motors, and drive mechanisms. Faults that are electrical in nature and can result in a detectable thermal condition can be attributed to coking of contacts, burning of contacts and/or transition resistors, as well as insulation problems (Bengtsson [B9]).

Table 7 lists the major LTC components along with their associated failure mechanisms and the parameters that can be monitored online to detect abnormalities. Through manual analysis and/or automated analytics, the diagnosis of the failure mechanism may be made. This table is not all inclusive. Additional details are presented in later clauses.

Table 7—Load tap changer components, failure mechanisms, and measured signals

Component	Phenomenon leading to failure	Measured signals	Diagnostic interpretation
Diverter switch and/or Selector switch and/or Reversing switch	Overheating of contacts (coking) Excessive contact erosion Excessive mechanical wear/backlash Loose or broken parts Transitional impedance burn-out Barrier board tracking and cracking Bad synchronism diverter-tap selector	Direct contact temperature sensor Diverter switch compartment temperature Selector switch compartment temperature Main tank temperature Ambient temperature Line currents Tap position indication Vibro-acoustic Dissolved gas-in-oil Sudden pressure relay status Pressure relief device status	Temperature differential model Contact wear model Vibro-acoustic signature Gas trending Reversing switch inactivity Excessive LTC operations
Drive mechanism	Mechanical defect Broken linkage Binding of contacts Worn gears AC supply failure Defective brake Relay malfunction Weak Springs Geneva wheel adjustment Motor failure	Torque on the LTC driven shaft LTC motor torque LTC motor current Relay timing Direct Position Indication AC supply Motor run time	Torque analysis model Motor current index model Average motor current Excessive number of operations
Insulating liquid	Moisture contamination	Ambient temperature RS moisture in oil (including oil temperature at measured point)	Moisture model
	Arcing	Hydrogen Acetylene	Gas trending Gas ratio
	Partial discharge	Hydrogen Acoustical or electrical PD	Gas trending Gas ratio Vibration analysis PD model
	Overheating	Hydrogen Ethylene Methane Ethane	Gas trending Gas ratio
Oil filtration system/pump filter	Electrical failures of pump Plugged filter	Pump motor current Pressure differential Low flow	Filter clogged Leak Pump Binding/Failure

Component	Phenomenon leading to failure	Measured signals	Diagnostic interpretation
LTC control	Switch not in auto Loss of control power Control instrument failure Energizing in off-tap position Over/under current and voltage	Control switch position Control power supply Direct Tap position Knowledge counter Off tap sensor Voltage/current sensor	Excessive number of tap changes Return of voltage change Over/under voltage/current blocking and/or alarming
Bridging resistor	Overheating Arcing	Diverter switch compartment temperature Main tank temperature Hydrogen Acetylene Ethylene Rapid pressure rise	LTC differential temperature Gas trending Gas ratio

Several parameters that are monitored for LTCs include drive mechanism motor torque, temperature difference between the LTC compartment and the main tank, time since last through neutral, accumulated contact wear, and mechanism operating time. Monitoring a combination of parameters suitable for a particular LTC design can help avoid such failures.

5.5.2 Thermal diagnostics for load tap changers

5.5.2.1 General

Typical faults that are electrical in nature can be attributed to coking of contacts, burning of transition resistors, and insulation problems (Bengtsson [B9], CIGRE WG A2/C4.39 TB577A [B30]). An increase in the temperature difference between the LTC compartment and the main tank can be indicative of coking of contacts and problems of either thermal or dielectric nature. Coking of the reversing switch is often the result of the reversing switch contact remaining in the same position for too long. By monitoring the time since last through neutral, this potential cause can be identified.

5.5.2.2 Differential temperature

Differential temperature refers to the temperature difference between the main tank and LTC compartment. Typically, the top oil temperature in the main tank will be higher than the tap changer compartment temperature. This is referenced in Figure 4.

Many factors influence differential temperature. Excessive losses caused by misaligned, worn or defective contacts, or coking in the tap changer may be detectable. However, the LTC temperature can exceed the main tank temperature periodically under normal conditions through heated resistors (applicable for resistive-type LTCs). Hourly variations in electrical load, weather conditions, and cooling bank activation may result in a main tank temperature below the tap changer temperature.

It is recommended that a temperature range for oil temperature measurements of -40 to 120 °C be used, but different ranges may be needed particularly for use with high-temperature insulating liquids. The type of sensor normally used for this application is an analog sensor (e.g., RTD), but digital sensors are commonly used as well.

It is recommended that a thermometer pocket always be provided even if any supplied temperature sensor is not installed in the pocket. The measurement should be made at the top of the LTC diverter switch compartment. Where the main tank top oil measurement is not representative of the temperature of the oil next to the tap changer, an additional temperature measurement may be required to allow a more accurate differential temperature measurement to be used to detect thermal faults in the tap changer.

Care should be taken that oil temperature measurements are not unduly affected by local tank heating effects such as from eddy currents or by local ambient conditions. It should be noted that the temperature measured by a sensor in a thermometer pocket may be several degrees Kelvin below the actual oil temperature. This does not necessarily mean the thermometer pocket offers no value to the user, but it should be considered when analyzing thermal performance of the transformer.

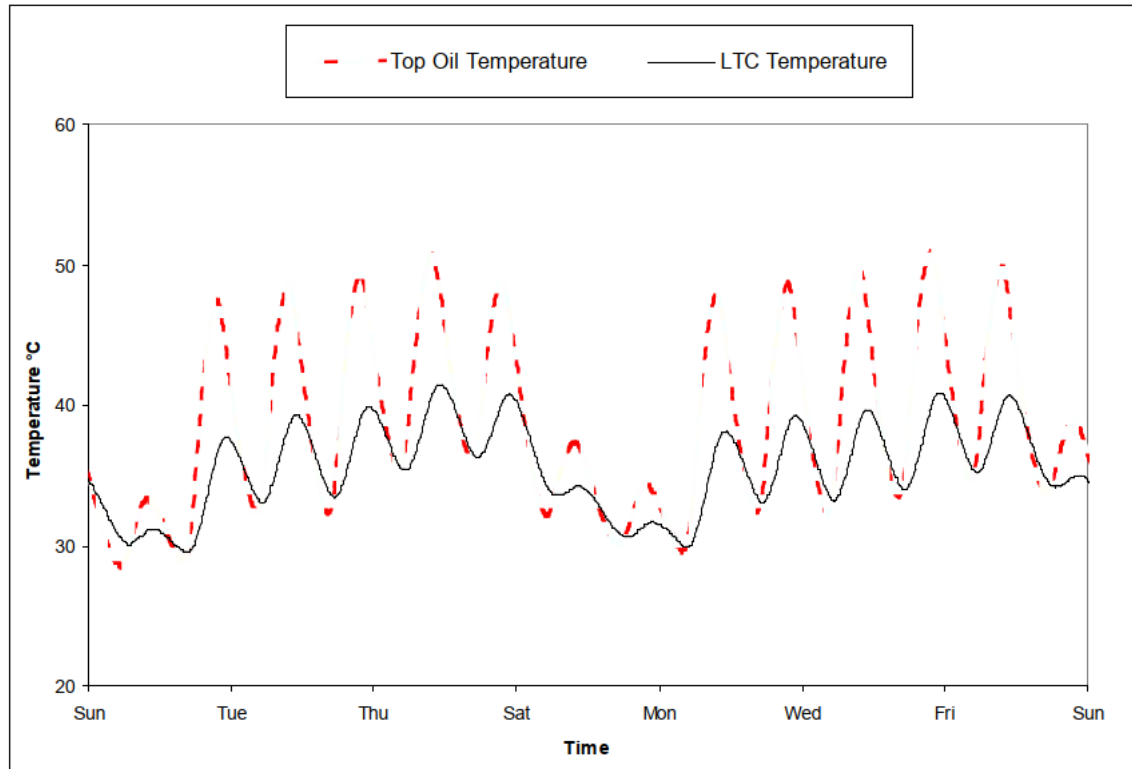


Figure 4—Example of variation of temperature in tank top oil and LTC

There are several methods to distinguish between normal and abnormal differential temperatures. Analytic techniques such as trending, slope, rolling averages, temperature index, timers, or similar methods may be used.

5.5.3 Vibro-acoustic signature

5.5.3.1 Introduction

The vibrations caused by various mechanical movements during a tap changing operation can be analyzed for signs of change. This gives continuous information of the transition time, as well as an indication of contact wear and detection of sudden mechanical faults (Bengtsson et al. [B10]).

Every operation of the tap changer mechanism produces a characteristic acoustic wave that propagates through the oil and structure of the transformer. The design structure of a transformer together with its core, windings, leads, and tank has a strong influence on the acoustic pattern. Due to these variations, some monitoring systems may be tuned to account for these variations. Field measurements show that in the case of a properly functioning tap changer, for a given operation, this vibration pattern proves to be very repeatable over time.

LTC operation can be analyzed by comparing the acoustic signature with the running average representative of recent operations. Experience has shown that electrical problems are detected more frequently than those that are mechanical in nature (Foata et al. [B46]).

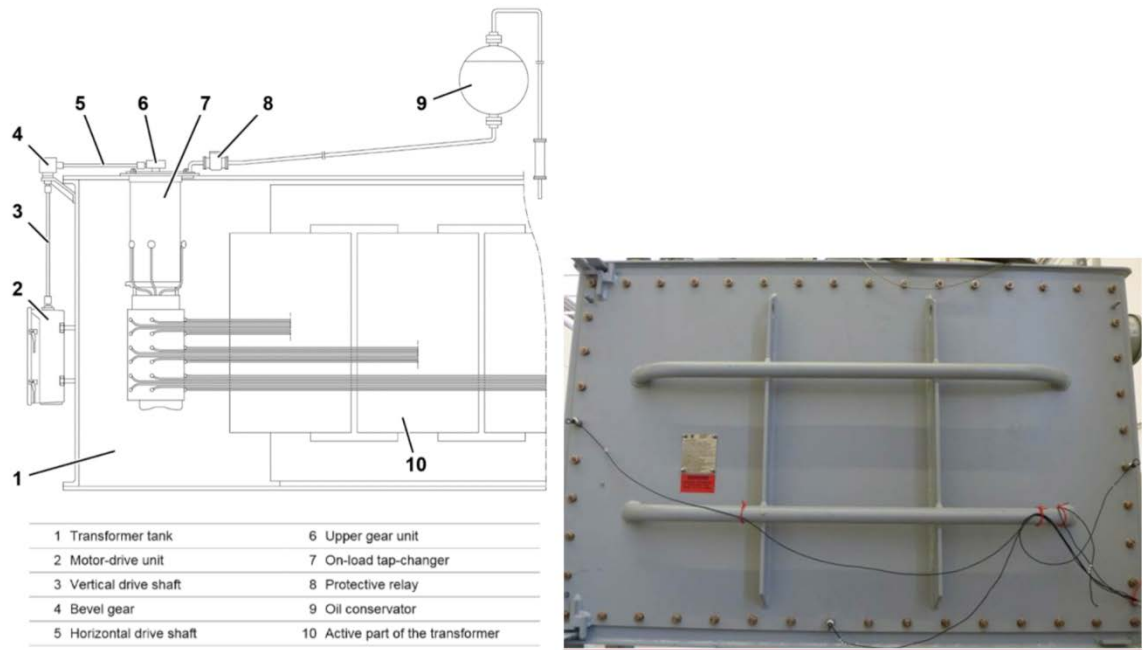
During a tap changer operation, a series of mechanical and electrical events produce distinctive vibration and noise patterns. Acoustic monitoring consists of listening to these vibrations and in detecting any changes in time that may be an indication of a developing malfunction or wear. It has been shown that both mechanical and electrical faults can be detected, as well as wear of contacts and changes in tap change switching time, independent of the LTC type.

5.5.3.2 Type of sensors

The vibro-acoustic probe is a piezoelectric accelerometer with a frequency range between a few Hertz up to about 100 kHz. The amplitude of the output signal typically lies within a range of ± 5 V with sensitivity of 100 mV/g. Vibration sensors with an IP67 rating (protected from immersion in water to a depth of up to 1 m (or 3.3 ft) for up to 30 min) are readily available from the market. The motor current sensor consists of a standard compensated current transducer that can be clamped on the supply cable to the motor.

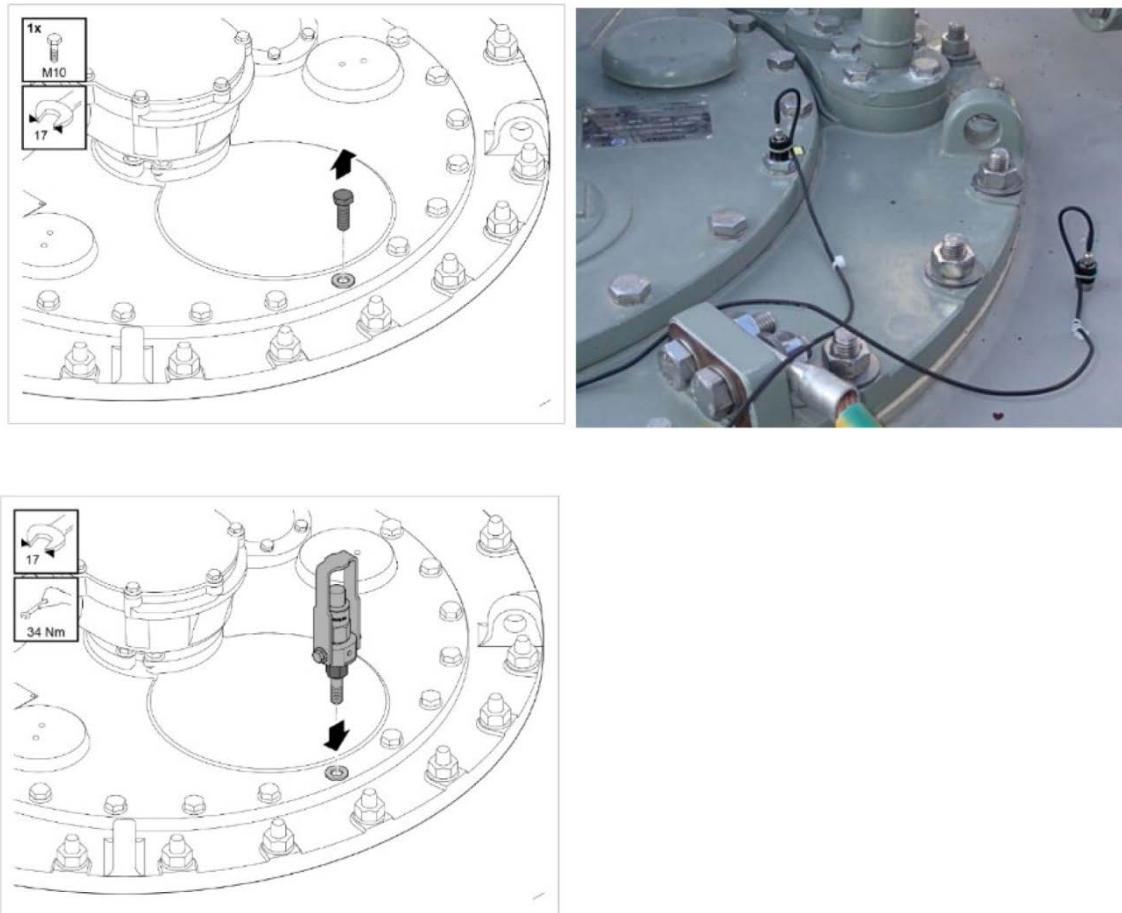
5.5.3.3 Operating condition

The tap changer vibro-acoustic monitoring sensor installation is illustrated in Figure 5 and Figure 6. The high-frequency accelerometer is mounted either on the tap changer compartment or, in the case of tap changers located in the main tank of the transformer, on the top of the LTC cover or on the side wall of the transformer.



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Figure 5—Suitable sensor locations for bolt-on LTC

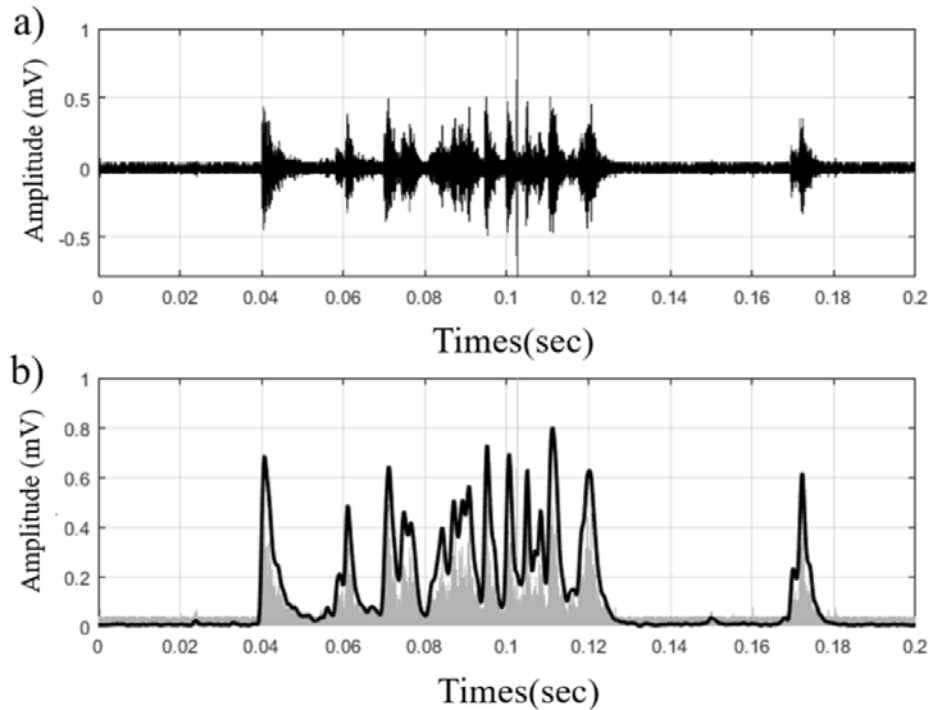


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Figure 6—Suitable sensor locations for in-tank LTC

The motor current signal is used primarily to start/stop the measurement but also serves for diagnostic purposes as it can give indications of certain types of mechanical and electrical faults in the drive mechanism.

Typical vibration signals measured on LTCs are complex non-stationary oscillatory patterns of overlapping transients. In order to extract the physical parameters of interest and to facilitate their trending, the vibration signal needs to be processed and converted into an envelope. Different schemes have been reported in literature, an example of which is illustrated in Figure 7 “Vibration signals transformation” for diverter switch operation. Upon processing, it can be seen that numerous details associated with contact or other mechanical events can be easily distinguished in a very short time span (about 0.2 s).

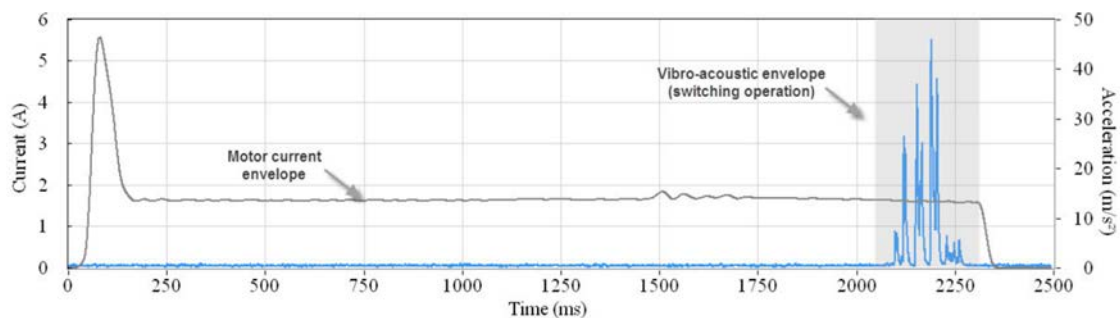


Vibration signals transformation into a waveform reflecting its original features of event time and amplitude and number of peaks; a) original vibration signals while OLTC's operation; and b) obtained vibration signal's waveform (bold black line) and positive side of original vibration signal (grey).

Source: Seo [B146].

Figure 7—Vibration signals transformation into a waveform

The vibro-acoustic signature consists of the envelope of the complete recording of both vibration and motor current signals such as illustrated in Figure 8.



Reprinted with permission from CIGRE, Gauvin et al. [B49].

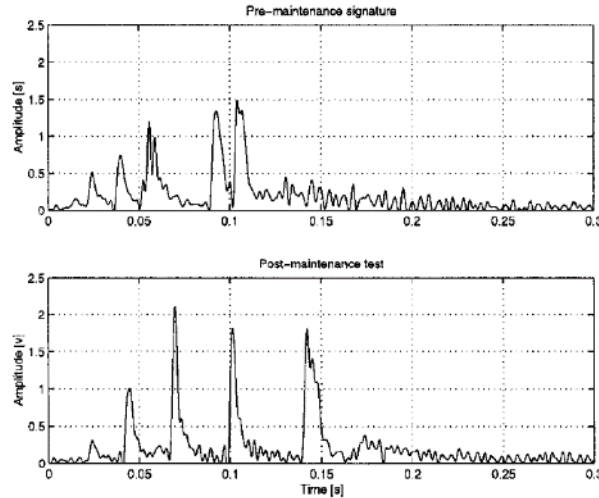
Figure 8—Typical LTC acoustic signature

5.5.3.4 Failure detection

Failure or wear detection is performed by observing changes in both the motor current and the vibration patterns. The use of statistics enables the full diagnostic potential of the method by compiling averages and deviations.

The following two monitoring schemes can be applied:

- a) Comparison with an original signature to monitor gradual changes related to wear and plan maintenance. Figure 9 (Kang et al. [B96]) illustrates the obvious differences that can be observed on the vibro-acoustic sensor
- b) .Signature of a selector switch before/after maintenance due to excessive contact wear.



Comparison with a recent (running) average to detect rapid degradation and prevent imminent failures.

Source: Kang et al. [B96].

Figure 9—Signatures before and after maintenance from tap 9 to 10

5.5.4 Dissolved gas-in-oil analysis (DGA)

Users have found DGA to be very useful in identifying just-in-time LTC maintenance needs, and many have developed databases to correlate gases with “before” and “after” maintenance for their particular LTC population. Increased “hot-metal gases,” methane, ethane, and especially ethylene, which are produced in problem LTCs, can be measured and used to identify incipient faults in LTCs. When arcing occurs, temperatures are high enough to produce acetylene (plus hydrogen) from breakdown of the oil. Oil acts as a coolant, and the oil temperature drops rapidly as distance from the arcing site increases. At lower temperatures, hot-metal gases are produced. Thus, all of the fault gases, hydrogen, methane, ethane, ethylene, and acetylene are produced when arcing occurs. Total gas concentrations are design, load, and operation-count dependent and vary with time. Loss of gases to the atmosphere also has a major impact on individual gas concentrations. Gas concentration ratios are thus a more reliable indication of an incipient problem than are individual gas concentrations. See IEEE Std C57.139™ [B87].

5.5.5 Motor drive

5.5.5.1 Introduction

LTC failures are frequently dominated by faults that are mechanical in nature. These typically include failures of springs, bearings, shafts, and drive mechanisms. Deviations in the drive mechanism’s motor torque, current, or operating time could be indicative of certain types of mechanical faults.

A variety of diagnostic algorithms for LTCs can be implemented using drive motor torque or motor current information. Mechanical and control problems can be detected because additional friction, contact binding, mechanical brake operation, extended LTC operation times, and other anomalies significantly impact torque and current.

A signature, or event record, can be captured each time the tap changer moves to a different tap. This event record can be either motor torque or motor current as a function of time. The signature can then be examined by several methods to detect mechanical problems. The following mechanical parameters can be analyzed.

5.5.5.2 Torque

The real (active) power consumption of the tap-changer motor drive can provide useful monitoring information, in particular, the torque of the motor. It is recommended that space is provided to fit a real power transducer in the motor drive cubicle. It is not enough to measure only the motor current because this value does not correlate directly with motor torque, which is the critical value for mechanical monitoring of the tap-changer mechanism. Direct measurement of the motor torque using a torque sensor can be used as an alternative.

Initial current inrush and starting torque are related to mechanical static friction and backlash in the linkages. Monitoring this peak value and duration of the event can provide a useful diagnostic. Consistently changing values over a period may be cause for concern.

Running current or torque provides a measure of dynamic friction and helps detect binding. Motor current measurement is most effective for those LTC types in which the motor directly drives the mechanical linkages. Torque or force sensors measuring drive force will yield the desired information.

It is also possible to determine the torque curve by measuring the active power of the motor. Figure 10 is a sample torque curve for a resistance-type tap changer for a motor in acceptable operating condition. Anomalies in the torque curve can be detected by using a system that performs a separate assessment of the individual functions of a switching operation.

Some LTC designs employ a motor to charge a spring that may supply energy to move the linkages during a tap change. In this case, the motor current measurement will only detect problems with the motor and/or spring charging mechanism.

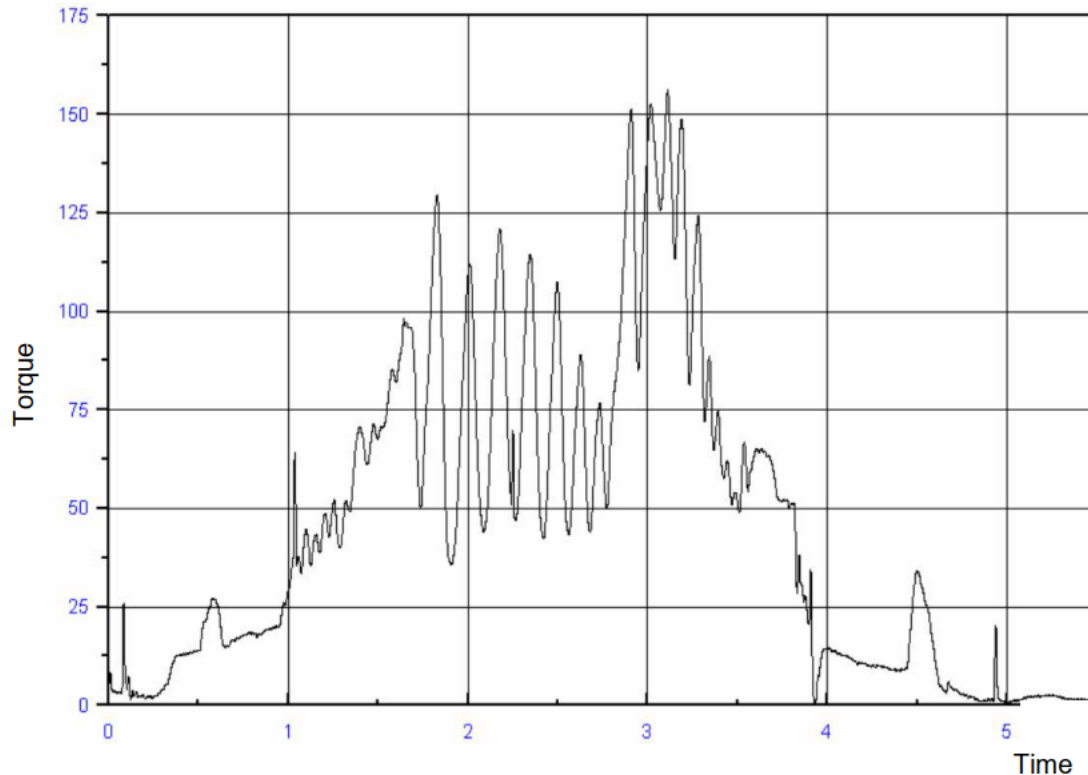


Figure 10—Sample torque curve

5.5.5.3 Motor current index

The area under the motor current curve is called the “motor index.” This index characterizes the initial inrush, average running conditions, and total running time. A similar index based on torque can be used. Not all types of tap changer operations have similar index values. An operation through neutral can have a significantly higher index as the reversing switch is operated. Similarly, tap changer raise or lower operations can have different index values depending on whether the previous operation was a raise or a lower. This is related primarily to linkage backlash. Figure 11 shows an example of the motor current curve for an LTC, and Figure 12 shows an example of the motor current index.

Sequential controls and other operational issues should also be considered. For example, the index will be very large if the tap changer moves more than one step during an operation. The index will be very small if the controls call for a tap change and then rescind the request before seal-in. All of these situations should be considered when performing diagnostics based on motor current or torque measurements.

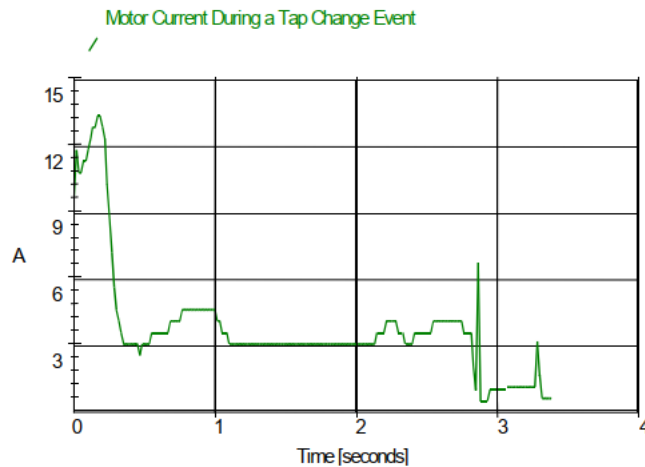


Figure 11—Sample load tap changer motor current during a tap changing event

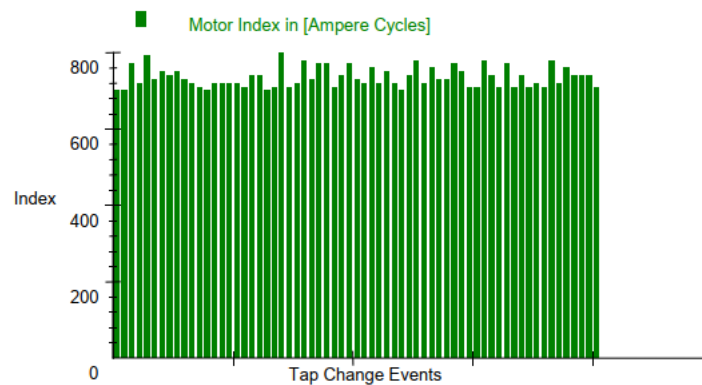


Figure 12—Sample motor current index curve

5.5.5.4 Operating time

The operating time of the tap changer motor drive can be derived from the diverter position switches. It is recommended that for new transformers, two switches are provided that may be driven directly or indirectly to indicate that the end position of the diverter switch travel has been reached. The operation time of the diverter can be deduced from this information. This method provides real-time indication once the threshold is exceeded and is suitable for both new and existing transformers. The switches should operate according to Figure 13.