

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

IEEE Power and Energy Society

Sponsored by the
Transformers Committee

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

Sponsor

**Transformers Committee
of the
IEEE Power and Energy Society**

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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, transformer monitoring

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Introduction

This introduction is not part of IEEE Std C57.143-2012, IEEE Guide for Application for 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 years, a sophisticated means has evolved for collecting a great deal of diagnostic information while the equipment is in service.

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

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. However, the monitoring of transformers and other electrical apparatus has several challenges: the reliability of the electronic equipment, cost of the monitors, continuing development of the sensors and monitoring systems, performance under harsh field conditions, lack of availability of field expertise, data collection, and interpretation.

This guide describes most of the continuous on-line monitoring and diagnostic methods that are in common practice at the time this guide was written, and provides additional information in the case of developing techniques. This guide addresses transformer operational parameters that can be monitored and the risks and benefits of the monitoring. 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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1. Overview

On-line monitoring of power transformers and associated accessories is becoming an essential feature of electric utility systems. The justification for on-line monitoring is driven by the need to increase the availability of power transformers, re-direction of time and/or operational-based maintenance to condition-based maintenance, asset and life management 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 on-line monitoring equipment on liquid-immersed power transformers and their components.

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, Guide to the Interpretation of Dissolved and Free Gases Analysis.¹

IEEE Std C37.90.1™, IEEE Standard Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus.^{2, 3}

IEEE Std C37.90.2™, IEEE Standard Surge Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers.

IEEE Std C57.13.3™, IEEE Guide to Grounding Instrument Transformer Secondary Circuits and Cases.

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

IEEE Std C57.148™, IEEE Standard for Control Cabinets for Power Transformers.

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

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3. 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.⁴

data acquisition unit (DAU): A data acquisition unit (DAU) collects data from one or more sensors and/or 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).**

data warehouse: A data warehouse provides data storage functions for future reference and can also provide a source of information to maintenance, work management, other programs and systems, and advanced system analysis.

de-energized tap changer (DETC): Tap changer designed to be operated only when the transformer is de-energized.

diagnostic: Interpretation of the data supplied by the monitoring system.

dielectric phase angle: The angular difference in phase between the sinusoidal alternating voltage applied to a dielectric and the component of the resulting alternating current having the same period as the voltage.

dissolved gas-in-oil analysis (DGA): A method of determining the quantities and type of gasses that are dissolved in insulating fluids for the purpose of determining incipient faults.

dissipation factor: (A) The ratio of energy dissipated to the energy stored in an element for one cycle. (B) (Dielectric) The cotangent of the phase angle between a sinusoidal voltage applied across a dielectric (or combination of dielectrics) and the resulting current through the dielectric system. (C) The tangent of the dielectric loss angle.

NOTE—For small values of dielectric loss, angle dissipation factor is virtually equal to the insulation power factor (PF). *See* IEEE Std C57.19.03.⁵

failure cause analysis: Failure cause analysis (FCA) is the diagnosis of failures or malfunctions. In terms of on-line 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.

intelligent electronic device (IED): An IED is a device with internal processing capabilities and can be described as a “smart sensor” providing monitoring and/or control functions.

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.

load tap changer (LTC): A selective switch device, which may include current interrupting contactors, used to change transformer taps with the transformer energized and carrying load. *Syn:* **on-load tap changer** (IEC). *See* IEEE Std C57.12.80, IEEE Standard Terminology for Power and Distribution Transformers.

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

on-line: While equipment or system is electrically energized.

on load tap changer (OLTC): *See* **load tap changer**.

partial discharge (PD): An electrical discharge that only partially penetrates or bridges the insulation between electrical components and may or may not occur adjacent to a conductor.

power factor: The cosine of the dielectric phase angle (or the tangent of the dielectric loss angle).

⁴IEEE Standards Dictionary Online subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

⁵Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

remote terminal unit (RTU): An RTU is a device that collects data, codes the data into a format that is transmittable and transmits the data back to a central station, or master. An RTU can also collect information from the master device and implements processes that are directed by the master.

tan delta: The tangent of the dielectric loss angle (power factor).

tap changer under load (TCUL): *See: load tap changer.*

4. Surveillance needs of high-voltage transformers and accessories

4.1 General

The surveillance needs defined in this clause includes both power transformers and instrument transformers. Although the materials, failure modes, and diagnostic methods are similar, the size and cost differences can present unique issues.

4.2 Power transformers

Transformer problems can be characterized as those that arise from manufacturing defects, those derived from deterioration processes, and those induced by operating conditions that exceed the capability of the transformer. These conditions may take many years to develop into a problem or failure. However, in some cases undesirable consequences may develop rapidly.

Deterioration processes relating to aging are accelerated by mechanical, thermal, and voltage stresses. Elevated temperature, along with oxygen content, moisture content, and other contaminants significantly contributes to accelerated insulation degradation. The rate of deterioration may be compounded by the presence of contaminants and by mechanical or electro-mechanical wear. Characteristics of the deterioration processes include sludge accumulation, weakened mechanical strength of insulation materials such as paper wrapped on conductor, and shrinkage of materials that provide mechanical support.

Overheating of insulation that has high water content can cause gas bubbles in the insulating fluid. The bubbles can cause serious reduction in dielectric strength of the insulating structure, which could result in an eventual dielectric failure.

Continuous monitoring permits timely remedial action. Premature action could result in wasted valuable maintenance resources; late action could result in costly consequences (e.g., equipment failure). Higher loading may be tolerated, as continuous automated evaluation may alert users of conditions that could result in failure or excessive aging of critical insulation structures and/or transformer components.

Degradation processes and/or operating conditions also play a significant role in premature failure of transformer ancillary components. Such items include bushings, load tap changers (tap changers under load), and de-energized tap changers.

Table 1 lists the major transformer components along with their associated failure mechanisms and the parameters that can be monitored on-line to detect abnormalities. Thorough 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 1—Main transformer components, failure mechanisms, and measured signals

Component		Phenomenon leading to failure	Measured signals	Diagnostic interpretation
Magnetic circuit	Legs Yokes	Overheating of laminations and/or core joints	Top and bottom temperatures Ambient temperature Excitation currents Hydrogen or multi-gas Gas accumulation relay Infrared scan	Temperature analysis PD model Gas analysis
	Core ground lead Magnetic shield	Loss of core ground Unintentional core and shield grounds create problems and discharges	Hydrogen or multi-gas Gas accumulation relay Core hotspot Acoustical and electrical PD Infrared scan	Gas analysis PD model
Winding insulation	Major: phase-to-phase winding-to-winding winding-to-ground	General overheating	Winding temperature Top and bottom oil temperatures Ambient temperature Line currents Hydrogen or multi-gas Gas accumulation relay Infrared scan	Direct measurement Thermal model Gas analysis
		Local overheating	Hydrogen or multi-gas	Gas analysis
	Minor: turn-to-turn layer-to-layer disk-to-disk	Excessive moisture	Top and bottom oil temperatures Ambient temperature Moisture in oil Oil temperature at moisture measurement location Line current Winding Temperature	Moisture analysis
		Bubble generation	Winding temperature Top and bottom oil temperatures Ambient temperature Total percent dissolved gas-in-oil Electrical PD Acoustical PD Line Currents Moisture in oil Oil temperature at moisture measurement location	Moisture and thermal model Gas models
		Overloading of transformer	Line currents Winding temperature Moisture in oil Oil temperature at moisture measurement location Top and bottom temperatures Ambient temperature Line currents Infrared scan	Moisture and thermal model
		Partial discharge	Hydrogen or multi-gas Gas accumulation relay Acoustical and electrical PD	Gas analysis PD analysis
Liquid insulation		Moisture contamination	Top and bottom oil temperatures Ambient temperature Moisture in oil Oil temperature at moisture measurement location	Moisture model
		Arcing	Hydrogen Acetylene Gas accumulation relay	Gas analysis
		Partial discharge	Hydrogen or multi-gas Gas accumulation relay Acoustical or electrical PD	Gas analysis PD model

**Table 1—Main transformer components, failure mechanisms, and measured signals
(continued)**

Component		Phenomenon leading to failure	Measured signals	Diagnostic interpretation
Cooling System	Fan(s) and/or Pump(s)	Electrical failures of pumps and fans Mechanical failure	Motor (fan, pump) currents Pump flow Top oil temperature Winding temperature Dissolved gas-in-oil Bearing wear detector Standard 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	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 Line currents Inlet and outlet radiator temperatures	Thermal model Oil and winding temperature forecasting
Main Tank	Gaskets Weld seams	Oil level drops, exposing the windings Moisture contamination	Oil level Nitrogen pressure	Oil leak detection Nitrogen consumed or leak detection
Bushings	See Table 2			
LTC	See Table 3			

4.3 Instrument transformers

4.3.1 General

As used in this guide, the term “instrument transformers” includes oil-filled current transformers, voltage transformers, and capacitive coupled voltage transformers (CCVT) since the degradation processes, failure mechanisms, and parameters that are monitored are similar for all three classes of equipment. The techniques available to monitor instrument transformers on-line may be focused on fewer possible degradation mechanisms than those that can be monitored on power transformers.

4.3.2 Failure mechanisms associated with instrument transformers

While the failure rates of instrument transformers around the world are generally low, failures are often catastrophic, leaving little evidence to determine the cause of the fault. Nevertheless, mechanisms listed in 4.3.2.1 through 4.3.2.4 have been observed and identified as probable causes of failure.

4.3.2.1 Moisture ingress

Moisture ingress is commonly identified as a cause of failure of instrument transformers. The ingress of moisture into the instrument transformer may be through loss of integrity of a mechanical seal (e.g., gaskets). The moisture migrates into the oil and oil/paper insulation (which increases the losses in the insulating materials) and failure then follows. This would appear to be a particular problem if the moisture penetrates to certain high stress regions within the instrument transformer. The increase in the dielectric losses will be detected as a change in the power factor of the material and will also appear as increased moisture levels in oil.

4.3.2.2 Partial discharge

The insulation of instrument transformers may have voids within it. Such voids will discharge if subjected to a high enough electric field. Such partial discharges may produce aggressive chemical by-products that then enlarge the size of the void causing an increase in the energy of the discharge within the void. Eventually, these small partial discharges may degrade individual insulation layers resulting in dielectric breakdown. Such a developing fault may be detected in two ways. The first is the observance of a change in the capacitance of the device (through the shorting of one stress grading layer), which may also reflect as a change in tan delta; and the second is an increase in the partial discharge levels associated with the failing item.

4.3.2.3 Overvoltages

Overvoltage produced by induced lightning surges is also a failure mechanism, particularly due to a close lightning strike. More recently, the observance of fast rise time transients ($T_{\text{rise}} \sim 100$ ns) in substations during disconnect switch operations has led to concerns that these transients may cause damage to the insulation of current transformers. There is significant speculation that current transformers do not perform well when exposed to a number of disconnect switch operations in quick succession. Switching operation generated fast transients are a suspected cause of failures. More needs to be understood about the stress distribution within the current transformer under these conditions. Switching overvoltages are a further source of overstressing that may lead to insulation failure.

In order to address failures due to the mechanisms outlined above, experience seems to indicate that incipient faults are probably detectable and preventable while instantaneous faults due to damage caused by lightning strikes will be difficult to prevent.

4.3.2.4 Through faults

Another possible cause of damage to current transformer insulation is high primary current due to through faults. It is currently not known whether damage is caused to current transformers under these conditions and additional information is required before this mechanism may be considered a probable cause of failure.

4.3.3 Instrument transformer on-line monitoring methods

4.3.3.1 General

On-line techniques for the measurement of relative tan delta and relative capacitance by comparing individual units against a larger population of similar units have been utilized by a number of utilities with reports of some success in identifying suspect units. On-line partial discharge measurement techniques may provide important additional information as to the condition of the insulation within the instrument transformer. This subclause reviews applicable methods to on-line monitoring of instrument transformers.

4.3.3.2 Relative tan delta and relative capacitance measurements

Off-line partial discharge and tan delta monitoring are well established techniques. On-line monitoring techniques are available that replicate off-line testing to measure relative tan delta and capacitance and partial discharge under normal operating conditions.

One method for obtaining these parameters on-line is the sum current method. The sum current method uses the sums of the voltage and current phasors. This sum is zero in a symmetrical three-phase system. The analysis of condition can be performed by vectorially adding currents from the capacitance or power factor taps. If the system voltages are perfectly balanced, the sum current will equal zero. Compensation circuits are used to make adjustments if there are differences in designs and specifications for the individual instrument transformers.

On HVCTs and CCVTs, test taps are usually present to perform off-line power factor and capacitance tests. Sensors can be installed at these test taps and provide the signals necessary for on-line monitoring.

On electromagnetic PTs, voltage signals from the secondary of the PTs can be summed to monitor the turns ratio. The vector sum should be zero. Changes in the turn ratio, core problems, etc. can then be detected. Use of the proper sensor can also allow periodic or continuous partial discharge measurements.

4.3.3.3 On-line gas analysis

Some dissolved gas monitoring technologies that have been applied widely to power transformers where the oil is in circulation may also be applied to instrument transformers. However, in instrument transformers the oil is confined and limited in volume, which affects sensor selection and operation. Installation may require factory modifications, depending on the type of sensor that is installed (Boisseau and Tantin [B9], Boisseau, Tantin, and Despiney [B10], Cummings, et. al.[B18]).

4.3.3.4 On-line partial discharge measurements

On-line partial discharge detection methods used with power transformers are also applicable to instrument transformers.

4.3.3.5 Tank pressure measurement

Due to partial discharge activity inside the tank, gases can be formed that result in a pressure increase after the gases saturate the oil. A threshold pressure switch may be used to perform this measurement. The operation of this sensor is possible with an inflatable bellows that is placed between the expansion device and the enclosure. The installation of the device typically requires factory modification. In some applications, pressure sensors take a considerable amount of time (on the order of months) to detect any significant pressure change. The sensitivity of this type of measurement is less than that of hydrogen and partial discharge sensors (Boisseau and Tantin [B9]). Pressure sensors are also available that mount on the drain valve (Cummings, et. al. [B18]).

4.4 Bushings

4.4.1 General

Bushings are subjected to high dielectric and thermal stresses, which may lead to bushing failures. Bushing failures cause outages and many times transformer failures. The methods of detecting deterioration of bushing insulation have been well understood for decades and are addressed in IEEE Std C57.12.90.

Traditionally off-line diagnostics are very effective at discovering problems. The challenge facing a maintenance engineer is that some failure modes can develop and occur between scheduled test intervals. Since on-line monitoring of power-factor and capacitance can be performed continuously, and with the same sensitivity as the off-line measurement, deciding whether to apply an on-line system is reduced to an economic exercise of weighing the direct and strategic benefits with the cost. On-line monitoring of the bushings provides data during all weather conditions, loads, and at rated voltage, with the same sensitivity as an off-line measurement.

The two most common bushing failure mechanisms are moisture contamination and partial discharge. First, moisture usually enters the bushing via deterioration of gasket material, loose terminals, or cracks, resulting in an increase in the dielectric-loss and insulation power factor. The first indication of this type of problem is an initial increase in power factor. As the deterioration progresses, increases in capacitance will be observed. Second, tracking over the surface or burning through the condenser core is typically associated with partial discharge.

Measurement of power factor and capacitance is a useful and reliable diagnostic indicator. A very sensitive method for obtaining these parameters on-line is the sum current method. The basic principle of the sum current method is based on the fact that the sums of the voltage and current phasors are zero in a symmetrical three-phase system. Therefore, analysis of bushing condition can be performed by vectorially adding currents from the capacitance or power factor taps. If the bushings have the same specifications and the system voltages are perfectly balanced, the sum current will equal zero.

On-line monitoring techniques are available that replicate off-line testing to measure relative tan delta under energized conditions. Current comparator capacitance bridges and other commercial instruments are available that are suitable for both grounded specimen and ungrounded specimen measurements under field conditions. Another method of testing bushings on-line is the sum current method using leakage currents from monitored bushings.

Details on two techniques used for on-line monitoring of high-voltage bushings are discussed in detail in Annex B.

Table 2—Bushings failure mechanisms and measured signals

Component	Phenomenon leading to failure	Measured signals	Diagnostic interpretation
Condenser Core	Moisture ingress Poor oil impregnation Wrinkled paper Delaminating of paper	Sum of currents Tan Delta/Power Factor Temperature dependency PD	Change in power factor
Oil	Moisture Contamination Thermal degradation	Sum of currents Tan Delta/Power Factor Temperature dependency	Increase in bushing power factor
Internal Porcelain Surface	Aging Deposits settling in lower porcelain	Sum of currents Tan Delta/Power Factor PD Negative temperature correlation	Change in power factor Change in capacitance as layers short
Taps	Grounded tap ungrounded Shorted electrodes	Sum of currents Tan Delta/Power Factor PD	Change in capacitance
External Porcelain Surface	Contamination Surface discharge	Sum of currents Tan Delta/Power Factor PD	Change in power factor
Conductor	Loose connections on top and/or bottom of bushing Circulating currents in head Cracks in conductor	Sum of currents Tan Delta/Power Factor Temperature dependency	Change in power factor

4.5 Load tap changers

4.5.1 General

Maintenance costs for load tap changers (LTC) 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 [B4], Bengtsson, et al. [B5]).

LTC contact wear occurs 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, 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.

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, and insulation problems (Bengtsson [B4]).

Table 3—On-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 wear Loose or worn contacts Transitional impedance burn out Barrier board tracking and cracking	Direct contact temperature sensor Diverter switch compartment temperature Selector switch compartment temperature Main tank temperature Ambient temperature Line currents Tap position indication Dissolved gas-in-oil Sudden pressure relay status Pressure relief device status	Temperature differential model Contact wear model Gas trending Reversing switch inactivity Excessive LTC movements
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 Position Indication AC supply Motor run time	Torque analysis model Motor current index model Average motor current Excessive number of operations
Insulating fluid	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
LTC control	Switch not in auto Loss of control power Control instrument failure Energizing in off-tap position	Control switch position Control power supply Tap position/counter Off tap sensor Current sensor	Excessive number of tap changes
Bridging resistor	Overheating Arcing	Temperature Hydrogen Acetylene Ethylene Rapid pressure rise	LTC differential temperature Gas trending Gas ratio

4.5.2 Mechanical diagnostics for load tap changers

4.5.2.1 General

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 a vibro-acoustic pattern and motor current as a function of time. The signature can then be examined by several methods to detect mechanical and, in the case of vibro-acoustic patterns, electrical (arcing) problems. The following mechanical parameters can be analyzed.

4.5.2.2 Initial peak torque or current

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 of time may be cause for concern.

4.5.2.3 Running torque or motor current

Running current or torque provides a measure of dynamic friction and also 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 1 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.

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

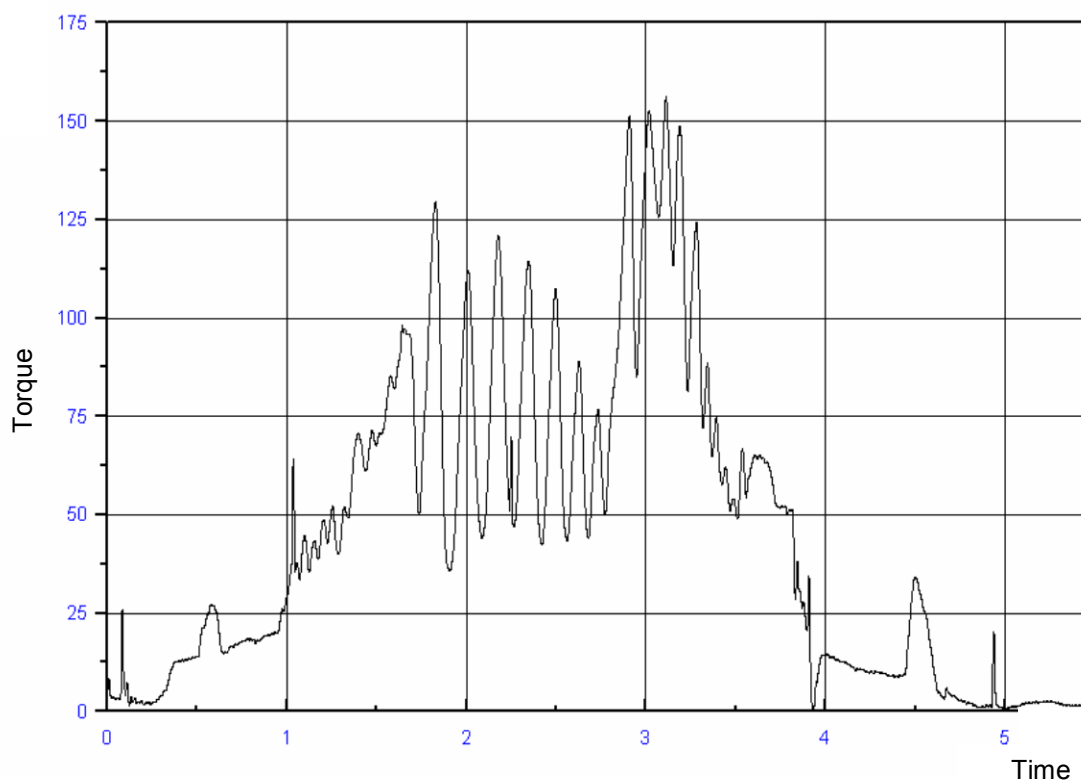


Figure 1—Sample torque curve

4.5.2.4 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 2 shows an example of the motor current curve for a LTC, and Figure 3 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.

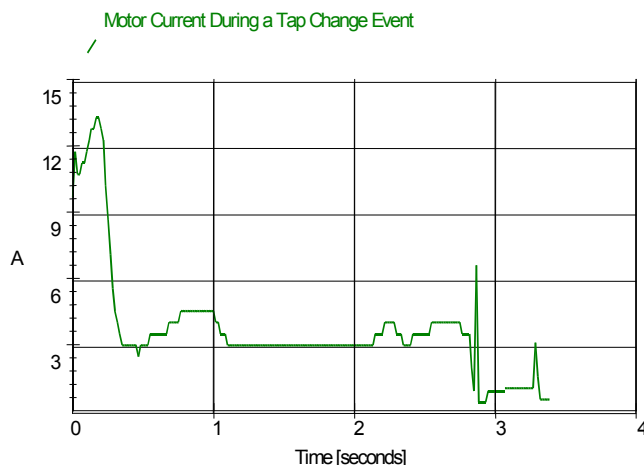


Figure 2—Sample load tap changer motor current during a tap changing event

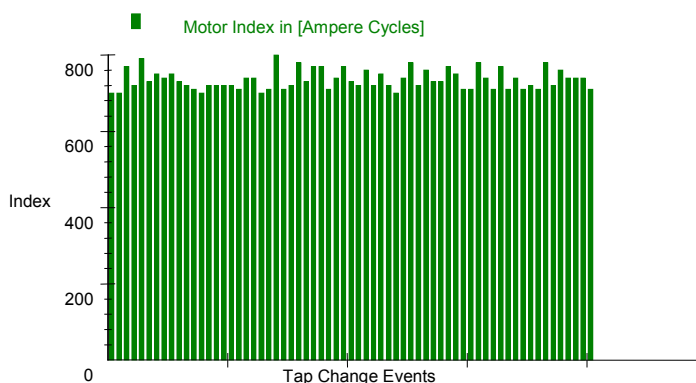


Figure 3—Sample motor current index curve

4.5.2.5 Contact wear

Contact wear can be monitored if tap changer current is known. Contact design and the material differences between contact suppliers can impact expected contact wear. Various algorithms that incorporate tap current are used to quantify contact wear.

As the contact wear in the diverter switch is dependent to a large extent on the transformer tap current to be switched, information on the tap current has to be provided (e.g., bushing-type current transformer).

4.5.2.6 Position and operating range determination

Technologies are available to determine the exact position of the tap selector switch. This information could be used to determine if an operation through neutral has occurred or if control problems exist.