Power Quality and Utilisation Guide

Leonardo ENERGY

# On Line Diagnostic Monitoring for Large Power Transformers


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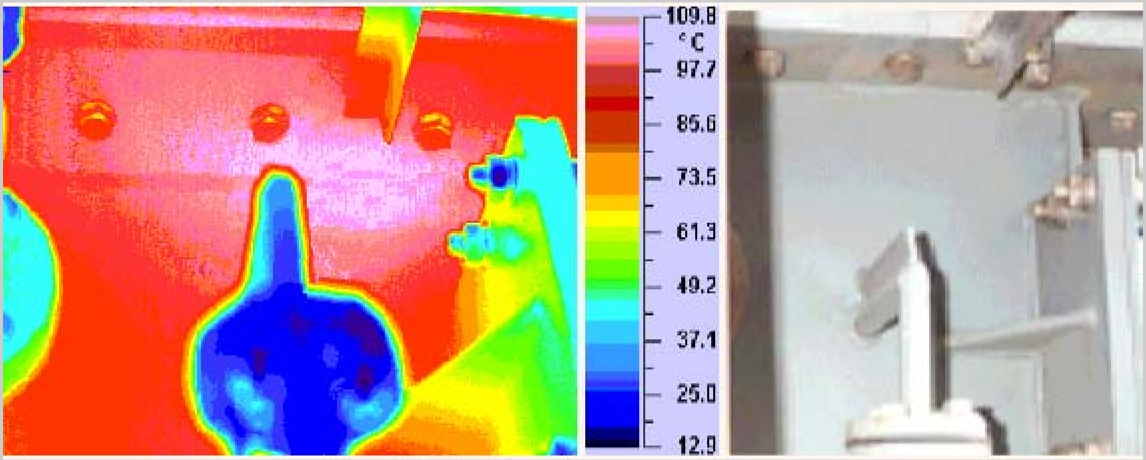


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## Introduction

In industrial plants, power transformers are expensive components of high strategic importance. Unavailability due to faults generally results in high costs, both in relation to repair work and in terms of lost production.

Efficient diagnostic monitoring capable of highlighting incipient faults and therefore able to reduce the fault rate and downtime of the transformer within considered physiological limits are generally of extreme interest for maintenance departments.

This article introduces a number of general considerations on fault statistics, and explains the main on-line diagnostic monitoring approaches.

## Fault Statistics

Fault statistics available for large transformers are rather controversial, probably due the different definitions which can be given to the faults themselves. While manufacturers only consider events that require the removal of the transformer from its station, users define all events that make the transformer unavailable as faults, with the exception of routine maintenance.

Since the figures can also vary by an order of magnitude, it is necessary to adopt a consistent approach from the outset to be able to make comparisons.

In the absence of data specifically relating to the industrial sector and with reference to a proposal relating to transformers of electricity companies from a number of years ago by a Working Group of CIGRE Technical Committee 12, any event which involves the transformer being put out of operation within 30 min of its occurrence must be defined as a fault.

From this perspective, the average annual fault rate for transformers for networks with $U_m$ between 145 and 420 kV is on average 2 percent, with higher values for higher voltage transformers.

As a rule, transformers with on-load regulators are at a disadvantage. The downtime can vary from a few hours to more than 12 months, depending on the circumstances.

However, it should be noted that such statistical data relate to transformers which are often more than thirty years old.

### Faults in the windings

#### Ageing of the insulation

The lifetime of large transformers is principally linked to the natural thermal ageing of the impregnated paper insulation of the windings.

The paper ages as a result of temperature, and this breaks the bonds between the glucose chains. This phenomenon, which becomes serious at temperatures in excess of 100°C, is accentuated by the presence of humidity, which makes the paper fragile and decreasingly resistant to mechanical stress.

The most critical points are normally located in the upper part of the coils, in the connections and in the joint points, especially in windings with very high rated currents.

In the first case, it is necessary to take into account that the oil is hotter in the upper part and at the same time the specific losses are highest due to the greater radial component of the magnetic leakage field.

### Failure due to electro-dynamic stress

Overcurrents in general and short-circuits in particular can cause deformation of the windings and related connections.

Every transformer should naturally be capable of withstanding the overcurrents assumed at the time of installation but, especially for older transformers, this condition is not always fulfilled, since short-circuit currents tend to increase over time.

A transformer with deformed windings can remain energized without apparent problems if the internal insulating distances and the insulation between coils, although reduced, are still sufficient.

Yet in any case this is a critical situation, since if the paper insulation is fragile due to thermal ageing even slight electro-dynamic stresses can result in complete failure.

## Faults in the magnetic core

Faults in the magnetic core are primarily caused by failure of the insulation between the laminations or tension rods. The resulting localized losses lead to such overheating to result in combustion of the oil and sometimes even fusion of the magnetic laminations.

These types of fault, although quite rare, usually result in very long down times.

## Faults in the on-load tap changer

A good percentage of total failures are linked to the presence of the on-load tap changer. Fortunately, 90 percent of these are mechanical problems in the control mechanism, and the necessary repairs normally cause only limited downtime.

Dielectric-type failures are rarer and are usually linked to errors in the tap changer design or selection.

## Faults in the feed-through insulators

Faults in the high voltage feed-through insulators are usually of dielectric origin, due to superficial contamination.

## Ageing and contamination of the insulating oil

Mineral oil tends to lose its original characteristics as a result of contaminants (humidity, atmospheric gases, glues, resins) and temperature.

The presence of corrosive sulphur can lead to the formation of conductive compounds (predominantly sulphides), which can have a negative effect on the dielectric seal of the insulation between the coils over time.

This effect increases with temperature, so that transformers which operate at full load for long periods end up in more critical conditions.

### Faults in the tank

Faults in the tank and the accessories affixed to it are generally related to losses of oil due to seal defects in the valves and gaskets, the presence of humidity in the conservator, mechanical blockages of valves and locks, etc.

Localized overheating may occur at times; this may be related to losses resulting from leakage flux which affect the tank and cover and which can damage the gaskets.

This type of fault usually has modest consequences, since it can normally be repaired without putting the transformer out of operation or during the course of ordinary maintenance.

### Faults in the cooling system

Faults in the cooling system are generally related to the functional failure of forced systems (ONAF, OFAF, OFWF).

## Diagnostic Monitoring

Diagnostic monitoring can be divided into on-line, if performed with the transformer in normal operation (this article is dedicated to such monitoring) and off-line, if they require the transformer to be powered down.

They can be used to:

- detect faults at an early stage and enable corrective measures in order to prevent degeneration into catastrophic phenomena;
- monitor the ageing process of the insulating systems.

Table 1 shows the main on-line diagnostic monitoring and indicates the necessary frequency, at least for the most critical transformers.

Table 1 - Main monitoring on high-power transformers

| **Type of check** | **Frequency** |
|---|---|
| Dielectric rigidity of the oil | annual |
| Water content in the oil | annual |
| Chemical characteristics of the oil | annual |
| Presence of corrosive sulphur in the oil | two-yearly |
| Chromatographic analyses of gases dissolved in the oil | annual |
| Analysis of gases collected in the Buchholz relay | six-monthly |
| Thermometric check of hot points | continuous |
| Measurement of tank vibrations | three-yearly |
| Measurement of acoustic emissions | three-yearly |
| Check of the cooling system | six-monthly |
| Tank monitoring | six-monthly |
| Check of other accessories | six-monthly |

## Analysis of gases dissolved in the oil

The analysis of gases dissolved in the oil is considered to be one of the most effective diagnostic monitoring methods for assessing the presence of partial discharges in the oil and the state of the paper/oil system as an alternative to other measurements (tensile breaking load and degree of depolymerisation), which would require the collection of insulation samples from the transformer.

It is based on the phenomenon in which cellulose paper and oil, when thermally stressed, emit gases whose nature changes with the temperature, and the fact that these same gases mainly accumulate in the oil.

The concentration and nature of the gases can thus be determined with chromatographic analyses of oil samples.

The interpretation of the results of the analyses can be based on the following criteria (not universally recognised):

- nature of the dissolved gases;
- concentration of the individual gases;
- formation speed of the individual gases;
- ratio between the concentrations of different pairs of gas.

Table 2 shows the main gases of interest and the minimum temperatures at which they start to form.

Table 2 - Diagnostic gases and temperatures at which they form

| Gas | Temperature (°C) | Gas | Temperature (°C) |
|---|---|---|---|
| Hydrogen ($H_2$) | 50¸100 | Acetylene ($C_2H_2$) | 900¸1000 |
| Methane ($CH_4$) | 50¸100 | Carbon monoxide (CO) | 110 |
| Ethane ($C_2H_6$) | 150¸200 | Carbon dioxide ($CO_2$) | 110 |
| Ethylene ($C_2H_4$) | 600¸700 | - | - |

Other gases are also normally found dissolved in the oil, but these are of little interest and can actually result in errors, such as for example:

- gases present in the atmospheric air (nitrogen, carbon dioxide and hydrogen) which are absorbed by the oil to a varying extent, depending on the system provided for the oil-atmosphere contact;
- gases, with notable presence of acetylene, produced by the arcs of the switch of the on-load tap changer, if not perfectly sealed;
- gases produced by materials used in the manufacture of the transformers (resins, glues, paints).

In normal conditions, all of the gases mentioned in Table 2 are present to a quite considerable extent with the exception of acetylene ($C_2H_2$) which, even in small traces, is an indicator of dangerous conditions.

With regard to the analysis of the concentrations, the situation is more complex, since there are various uncertain factors:

- the presence of the on-load tap changer;
- it is difficult to clearly define risk thresholds, since the formation of the various gases is progressive;
- the concentrations are drastically reduced by treatment of the oil under vacuum and when the total quantity of gases absorbed tends towards saturation.

Table 3 shows indicative values taken from the IEC 60599 Guide and from other experiences [21], which show how the concentration of acetylene increases notably when the on-load tap changer is present.

The rate of formation of the gases, for which Table 4 shows the limits proposed by the mentioned IEC guide, is certainly more significant for diagnostic purposes.

Table 3 - Concentration thresholds (indicative values)

| Type of transformer | $H_2$ (ml/l) | CO (ml/l) | $CO_2$ (ml/l) | $CH_4$ (ml/l) | $C_2H_6$ (ml/l) | $C_2H_4$ (ml/l) | $C_2H_2$ (ml/l) |
|---|---|---|---|---|---|---|---|
| Without on-load tap changer | 0.20 | 0.90 | 12.0 | 0.15 | 0.10 | 0.30 | 0.05 |
| With unsealed on-load tap changer | 0.25 | 0.90 | 12.0 | 0.20 | 0.10 | 0.30 | 0.25 |
| Furnace | 0.20 | 0.80 | 12.0 | 0.15 | 0.15 | 0.20 | 0.10 |

Table 4 - Critical values for rate of gas formation

| Gas | According to IEC 60599 (ml/day) |
|---|---|
| Hydrogen ($H_2$) | 5 |
| Methane ($CH_4$) | 2 |
| Ethane ($C_2H_6$) | 2 |
| Ethylene ($C_2H_4$) | 2 |
| Acetylene ($C_2H_2$) | 0,1 |
| Carbon monoxide (CO) | 50 |
| Carbon dioxide ($CO_2$) | 200 |

If the speed of gas formation exceeds the indicated limits, it is probable that degenerative phenomena are in progress in the transformer.

A further refinement of the interpretation of the analyses regards the type of process underway, depending on the gases which form (Table 5).

Table 5 - Degenerative processes depending on the gases formed

| Process | Gases which form | | | | | | |
|---|---|---|---|---|---|---|---|
| | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ | CO | $CO_2$ |
| Decomposition of cellulose | | | | | | x | x |
| Low energy discharges in the oil | x | x | x | | | | |
| High energy discharges in the oil | x | x | x | x | x | | |
| Overheating of paper and oil | x | x | x | x | | x | x |
| $H_2$: hydrogen $CH_4$: methane $C_2H_6$: ethane $C_2H_4$: ethylene $C_2H_2$: acetylene<br>CO: carbon monoxide $CO_2$: carbon dioxide | | | | | | | |

The thermo-oxidation of paper can also lead to the formation of furanic compounds (beyond 130°C) which, if analysed, can provide information on the degree of depolymerisation of the paper.

In transformers in operation, furanic compounds are found in concentrations up to 20 mg/kg of oil and they can be determined using the method of Standard IEC 61198.

Table 6 shows the ratios between the concentrations of pairs of gas.

Table 6 - Concentration ratios between gases (IEC 60599 Guide)

| Case | Characteristic fault | $C_2H_2/C_2H_4$ | $CH_4/H_2$ | $C_2H_4/C_2H_6$ |
|---|---|---|---|---|
| PD | Partial discharges | (*) | < 0.1 | < 0.2 |
| $D_1$ | Low energy discharges | > 1 | 0.1¸0.5 | > 1 |
| $D_2$ | High energy discharges | 0.6¸2.5 | 0.1¸1 | > 2 |
| $T_1$ | Thermal fault (< 300°C) | (*) | (*) | < 1 |
| $T_2$ | Thermal fault (300¸700°C) | < 0.1 | > 1 | 1¸4 |
| $T_3$ | Thermal fault (>700°C) | < 0.2 | > 1 | > 4 |

(*) Not significant

Note: In some countries, the ratio $CH_4/H_2$ is used instead of $C_2H_4/C_2H_6$.

With the exception of truly glaring cases, or the presence of acetylene not originating from the on-load tap changer, gas chromatographic analyses do not provide definitive results. Therefore, it is not a good idea to make hurried decisions about putting transformers out of operation.

The rate of growth is very important, so that it is a good idea to perform periodic analyses in order to verify the trend of the concentrations. In case of doubt, it can also be useful to repeat the analyses a few hours later in order to confirm that the measurements have been carried out correctly.

Until the problem has been clarified, it is also possible to increase the frequency of subsequent periodic analyses (even at monthly intervals).

## Thermometry with infrared rays

Thermometry with infrared rays is a very useful investigation tool for showing the presence of high-temperature sections since these are visible through the camera lens.

## Temperature check of hot points in the windings

According to the IEC 356 Guide, the temperature that can be continuously tolerated by the insulating systems is 98°C.

Two fundamental techniques can be used to check the temperature of hot points in the windings: thermal image and the insertion of sensors applied to the windings.

The thermal image consists of an oil-filled container, whose temperature is practically the same as the upper layers of the liquid in the tank, in which a model of the windings is created, into which currents proportional to those of the transformer are injected by means of appropriate transformers.

For direct measurement of the temperature of the hot points, sensors applied to the windings and connected to the measuring instrument by means of optic-fibre cables must be inserted in the construction phase.

A luminous pulse produced by an LED is transmitted to a photo-luminescent sensor which, when energized, produces a reflection of the luminous signal with a different wavelength to that of the incident signal. The temperature is measured on the basis of the delay time of the reflected signal.

Figure 1 shows an example plan of insertion of the sensors in the axial insulating spacers provided on the windings.

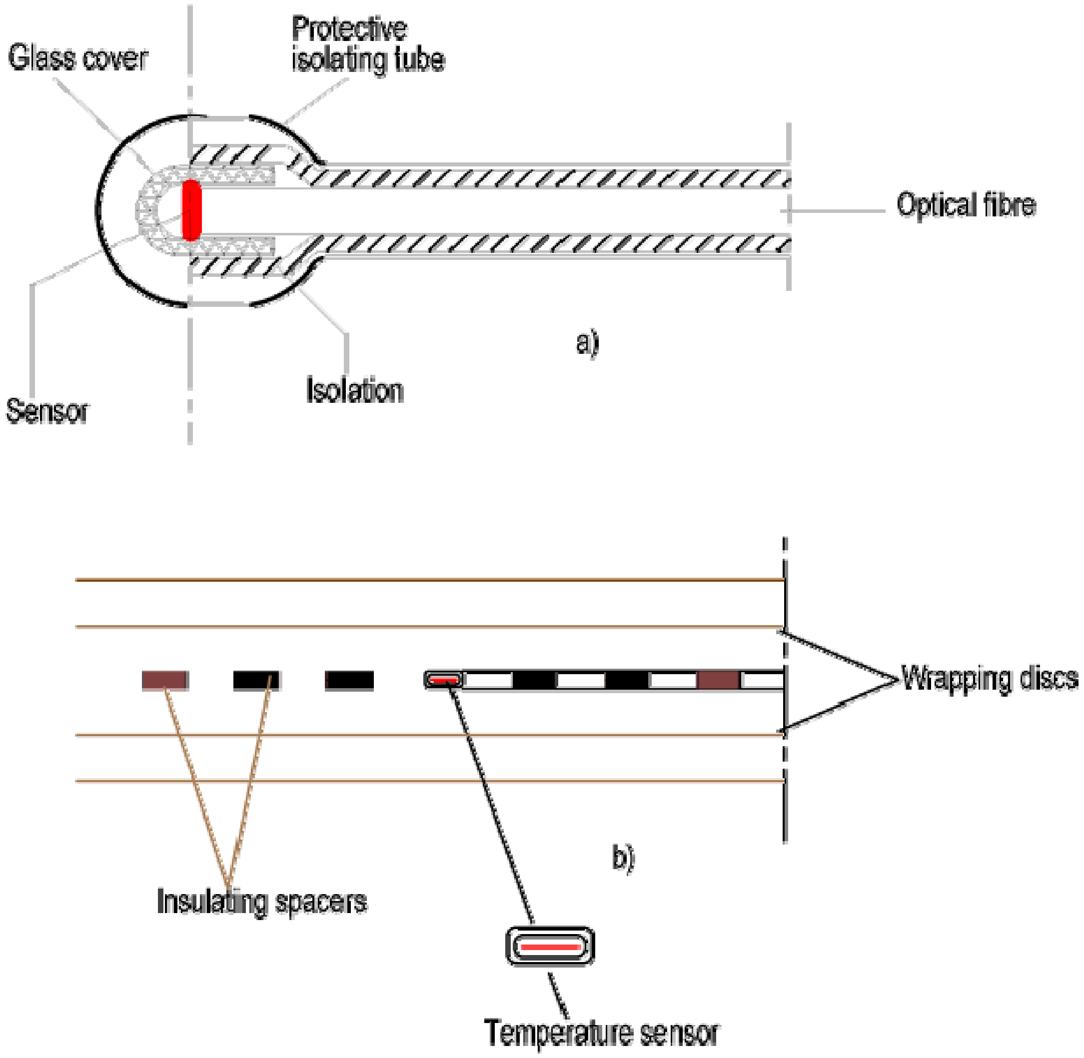


Figure 1 - Thermal probe with fibre-optic cable and respective mounting on the head of a disk winding.

The direct temperature measurement essentially brings the following advantages:

- it is possible to monitor the ageing of the insulating system, allowing the transformer management to be optimised, also from an economic viewpoint;
- the transformer can be overloaded in steady or transient condition since the temperature limits considered dangerous are not exceeded.

The thermal image method, on the other hand, only provides rough information, given the difficulties in achieving a reliable model.

### Check of the physical-chemical characteristics of the oil

Monitoring of the characteristics of the oil of the transformers in operation is carried out on oil samples taken from the bottom of the tank through specially prepared taps.

The tests to which the oil can be subjected during operation are included in those prescribed by the IEC Standard for new oil (Table 7).

Table 7 - Characteristics of oil of transformers in operation

| Characteristic | Unit of | Test results | |
|---|---|---|---|
| | measure-ment | Average value | Limit value |
| Dielectric rigidity (IEC) | kV | 50 | 40 |
| Dissipation factor (tan d) at 90°C | - | 0.010 | 0.05 |
| Water content | mg/kg | 5 | 12 |
| Neutralization number (IEC) | mgKOH/g | 0.05 | 0.20 |
| Total sulphur | mg/kg | 400 | 800 |
| Corrosive sulphur (test ISO 5662) | - | exceeded | exceeded |
| Particle diameter >15 mm | number | 10 | 100 |
| Water | mg/kg | 8 | 20 |

It is advisable to remember that the dielectric rigidity test has little significance for detecting the presence of humidity since its value is not strongly influenced by water content up to 2% mass (20 mg/kg). In conditions of equilibrium, water is actually predominantly accumulated by the paper (to a ratio of around 50/1).

Vice-versa, it can indicate the presence of solid contaminants (increasing the dispersion between the rigidity values determined with tests repeated on the same sample).

The check for the presence of corrosive sulphur is particularly important.

When the temperature of the hot points continuously exceeds 98°C (maximum limit indicated by the IEC 354 Load Guide), the test performed with the method of Standard ISO 5662 may not be sufficient to guarantee the non-hazardousness over time of the corrosive sulphur content since the test temperature and the induction time specified

(140°C for 19 hours) are not adequate for this purpose. For this check, it is advisable to increase the test severity (for example, 140°C for 48 h).

## Measurement of the tank vibrations and the acoustic emissions

Measurement of the vibrations and the acoustic emissions (Standard IEC 60551), although not very selective, can highlight loosening in the lamination clamping system and damage to the core due to localized overheating.

Care must be taken to ensure that the vibrations are not amplified by the tank, and the results must be compared with those found at the time of installation (possibly on the basis of induction), assumed as reference.

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