A revolution in progress

From the transformer monitoring to the predictive maintenance

The world of power transformers follows this revolution process with a delay, typical for the conservative electrical sector, where the reliability of available technologies is preferred over innovations and new technologies

ABSTRACT

We live in an era where technology is advancing at an unprecedented velocity. The offering of online sensors measuring multiple physical parameters has increased immensely. Moving from traditional maintenance (age-based) to on-time maintenance based on monitoring systems may not be painless. It will be necessary to adopt data collection systems that are reliable and include automatic data processing that helps with data interpretation. This evolution, accompanied by the availability of automatic data processing and Artificial Intelligence (AI), determines a further push of "Industry 4.0" in "Smart Grid."

KEYWORDS:

predictive maintenance, monitoring, dissolved gas analysis (DGA), power transformers


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Introduction

We live in an era where technology is advancing at an unprecedented velocity. The offering of sensors, with affordable prices, measuring multiple physical parameters has increased immensely. This evolution, accompanied by the availability of automatic data processing and also through Artificial Intelligence (AI), determines a further push of ***"Industry 4.0"*** *in the field of power systems and is leading what we call the "Smart Grid."*

In this situation, we need to handle the exponential growth of data and leave the old criteria of Operation and Maintenance.

The world of power transformers follows this revolution process with a delay, typical for the conservative electrical sector, where the reliability of available technologies is preferred over innovations and new technologies.

While the development of construction technologies and materials has long been in a saturation curve, the criteria of Operation and Maintenance today are under stress due to the ongoing industrial revolution.

Where we are today

The attention to the installed assets is traditionally different across the different end users and also depends on the size of the company. For example, utilities with a large fleet have determined the maintenance strategy based on periodic visual checks to verify the status of accessories, insulation, and dissolved gases. In addition, extraordinary events in the operations significantly increased the use of special electrical diagnostics (for example, in the case of short-circuit currents).

Industrial users and some minor OEMs (Original Equipment Manufacturers) do not have an adequately equipped maintenance structure and rely just on periodic visual checks and simple electrical tests. They delegate the most specialized periodical tests, often limited to oil analysis only, to external service companies.

However, the best practice is to combine the results of the electrical tests with the oil analysis to obtain a complete status of the transformer's health.

The chemical-physical diagnostics made through the dissolved gas analysis (DGA) have evolved, allowing more detailed evaluation today. The DGA analysis is based on the principle of the generation of different combustible gases depending on the temperatures reached by the oil. The diagram in Fig. 1 represents the results of research carried out on this phenomenon.

IEEE [1] and IEC [2] standards guide the interpretation of dissolved gas analysis by defining scenarios such as:

R: Catalytic reaction
PD: partial discharges
S: Stray gassing at temperatures < 200 °C,

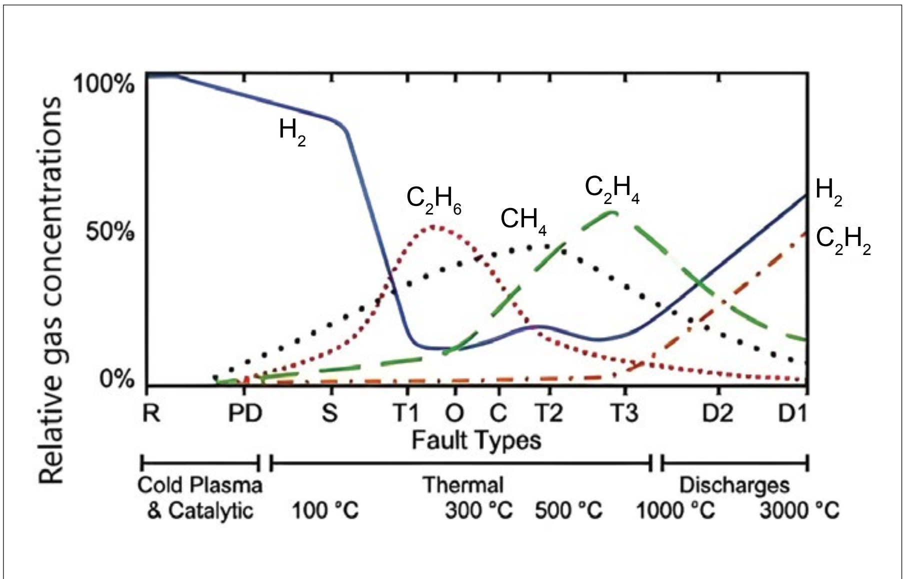

Figure 1. Relative concentration of gases generated by fault temperature

O: Overheating < 250 °C without carbonization of paper
C: Possible paper carbonization
D1: Low energy discharges
D2: High energy discharges
T1: thermal failure < 300 °C
T2: thermal failure 300÷700 °C
T3: thermal failure > 700 °C

To better correlate electrical test results with DGA results, it would be extremely useful to have more DGA results over time (trend analysis) and relate them with the load profile and the electrical test outcomes.

The results become interesting when the analysis performed on the oil (chemical-physical tests and DGA) gives results that deviate from those considered "normal" by the standards. Therefore, the need to give meaning to what has been detected is triggered, but there is not enough historical data to support it. Therefore, necessarily a phase of closer surveillance follows with more frequent monitoring of the oil to acquire a "trend" that was not available before.

The information gathered in the past could only inform us about serious problems, such as overheating windings or significant oil leaks

Which parameters are accessible today for asset monitoring?

Historically, few parameters were monitored and not always by remote:

a) Top-oil temperature with pre-settled alarm signals
b) Load

The operator can use a tool to define the overload capacity of the transformer time after time with a precise definition of the immediate risk and the risk related to the ageing of the insulation

c) Oil level
d) Buchholz Relay gas accumulation
e) Cooling system efficiency (inlet and outlet temperatures, fans and pumps motors current, etc.)

Today the new sensors enable an expansion of monitored parameters and allow remote data transmission, adding:

f) Bottom-oil temperature
g) Ambient temperature
h) Hot spot temperature (direct or calculated)
i) Humidity
j) Gases dissolved in oil [3]
   1. Combustible gases: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2)
   2. Carbon oxides: carbon monoxide (CO), carbon dioxide (CO_2)
   3. Atmospheric gases: oxygen (O_2), nitrogen (N_2)
k) Oil colour
l) Oil permittivity
m) Oil conductivity
n) Other parameters from bushings
   1. Dielectric Dissipation Factor (DDF or tan δ),
   2. Capacitance
o) Partial discharge

The availability of more detailed information enables a wider evaluation of both asset operation and maintenance strategy.

The information gathered in the past could only inform us about serious problems, such as overheating windings or significant oil leaks. To get more detailed information, it was necessary to refer to specific tests or to oil samplings to be analyzed in the laboratory.

Effects on the operation: a new concept of load guidance

Until today, it was used to establish fixed load parameters, with a direct link to the detection of the maximum oil temperature and, therefore, also assuming a fixed temperature gradient between maximum oil temperature and hot spot temperature.

This methodology does not avoid risks and false alarms.

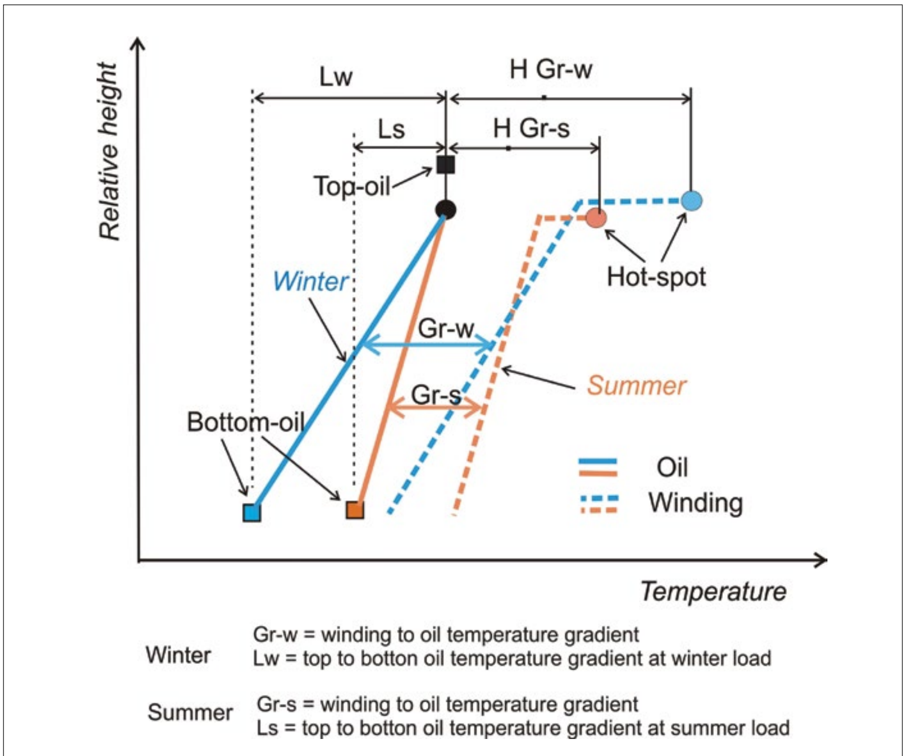

Figure 2. The trend of oil and windings temperatures in the two opposite operating conditions: winter and summer

The data availability, if processed according to experience, allows a maintenance approach increasingly oriented towards "condition-based" actions, considering also actions aimed at extending the asset life or "life extension"

In the summer, the maximum oil temperature can be reached easily due to the high ambient temperature, even with load currents below the nominal load and with a much lower hot spot temperature gradient, forcing an excessively reduced current. In the winter, the opposite situation arises. It is necessary to have an overload and, therefore, a greater hot spot gradient to reach the maximum oil temperature. It leads to a risk of premature ageing. It is an unlikely but not excludable load situation.

Fig. 2 refers to the IEC guidelines [4] and illustrates what was stated above. The blue tracked line represents the winter condition, while the red one represents the summer condition with reference to the same top-oil temperature. This shows that the criterion adopted so far for the

The monitoring of the main parameters related to the transformer operation and any signs of development of anomalies allows the operator to know the margins of operation and the level of reliability of the asset

thermal protection of the transformer is incorrect.

A correctly determined hot spot temperature can limit the transformer operation more reasonably. This is possible when parameters such as the top-oil temperature, the oil temperature at the bottom of the tank, the environmental temperature, and the load are known. Combining these data in the thermal model of the transformer with oil exponent (x), winding exponent (y), and the ratio of losses, we can define hot spot temperature.

The thermal model of the transformer may be provided by the manufacturer, detected during the acceptance tests, or simply determined by the IEC [4]-IEEE [5] guidelines.

Well-proven studies show that solid insulation ageing depends on the temperature, so the ageing of insulation can be evaluated. This criterion has been incorporated into the Directive, which has therefore issued specific guidelines.

This criterion is even more effective if the presence of humidity inside the transformer is known. In theory, with temperatures above 100 °C, "bubbling" phenomena can occur, i.e., the generation of vapour bubbles at a humidity value close to saturation. This phenomenon can be dangerous and lead to the discharge of insulation oil.

The operator can therefore use a tool to define the overload capacity of the transformer time after time with a precise definition of the immediate risk and the risk related to the ageing of the insulation and a reduced life expectancy.

Effects on the maintenance

The information that has an impact on the life of the transformer is the most interesting for the maintenance plan. This information is related to the status of the health of the accessories, insulation, and the electrodynamic performances of the windings.

Extended monitoring enables a significant leap in the quality of the asset maintenance strategy. The data availability, if processed according to experience, allows a maintenance approach increasingly oriented towards "condition-based" actions, considering also actions aimed at extending the asset life or "life extension" [6]. The overall maintenance cost reduces, and, especially, the life of the transformer can be extended, improving the total cost of ownership.

It is necessary to adopt this new maintenance strategy and the ability to process a lot of data on the performance of the transformer and its correct interpretation. It requires precise

knowledge of the transformer behaviour and, if possible, having also reference to transformers of the same type, leaving the classic methods valid for all types of transformers. The directive should follow this new path.

Two approaches for continuous monitoring

1) Basic monitoring

It consists of maximizing the cost/benefit parameter without complicating the data flow too much with immediate effect on both the Operation and the Maintenance.

This type of monitoring is limited to the following parameters:

Hydrogen (H_2)

The presence of hydrogen dissolved in the oil is monitored. As shown in Fig. 1, this gas is always present in the degenerative phenomena of internal insulation, whether it is due to partial discharges, overheating, or high-energy discharges. Gas generation is monitored by establishing the alarm thresholds on a maximum value and the rate of change.

A complete diagnosis on the single cause of the increase cannot be performed, but it is just a warning for the end-user to collect an oil sample and perform a more detailed analysis of all dissolved gases and therefore get a complete diagnosis.

Humidity (H_2O)

This is an important parameter that affects the performance of internal insulation, both solid and oil. It is also an indicator to verify the proper functioning of the oil protection system (use of a transformer with a conservator that breathes through salts or hermetic systems). The standards establish the limits that must be respected.

Temperature

To have complete control of the thermal operation of the transformer, it is necessary to detect both the top-oil temperature (under the tank cover), as well as the ambient temperature.

This mapping allows a significant leap in quality in the management of transformer operation if it is also combined with the knowledge of the thermal model of the transformer, as mentioned above.

2) Advanced monitoring for detailed diagnostics

To perform a detailed diagnosis almost in real-time, it is necessary to broaden the visibility, especially regarding dissolved gases, therefore, to the main gas H_2, have to be added the monitored gases listed at point j) above.

The monitoring systems available today are distinguished according to the number of gases monitored and the principle of gas detection [3].

The goal is to get a detailed analysis comparable to the one obtainable through an oil sample processed by a laboratory. The main advantage consists of having data in real-time and avoiding errors caused by the collection and transport of the sample. However, there is still a risk

that the analysis is not as reliable as the one performed in the laboratory.

Compared to the analysis conducted in the laboratory on the oil samples, there is the considerable advantage of knowing the temporal trend of the development of gases, even if the magnitude is less precise.

What is the right choice?

Below we evaluate the possible monitoring choices and define the most convenient usage boundaries.

(a) Basic monitoring

The measurement of H_2, temperatures, load current, and humidity turn out to be the relatively economical solution valid for all transformers, including distribution transformers.

The same applies to the transformers for solar and wind power applications, basically, for all transformers with Pn ≥ 1MVA.

Thanks to the basic monitoring solution, the operation of the transformer is enhanced with detailed control of the thermal balance, the overload capacity, and the ageing of the main insulation. The minimum monitoring of dissolved gases is also guaranteed by establishing alarm thresholds for further investigation and tracing the gas development. Finally, useful diagnostic information is also obtained for maintenance purposes.

(b) Advanced monitoring

Detailed dissolved gas analysis is added to the basic monitoring. DGA monitoring solutions are usually costly. The cost can be justified for larger transformers or medium-sized transformers that must be continuously observed, as they have already given signs of anomalies that must be diagnosed in detail.

Extensive monitoring gives the end-user the advantage of following the trend of gas development over time. Combined with the necessary electrical tests made on-site, the end-user can get a detailed diagnosis of the origin of the anomaly and therefore define a precise maintenance plan.

Conclusions

The technological development of sensors has allowed an increased diffusion of monitoring systems in all industries. Automotive is one of the most emblematic examples. The traditionally conservative electrical engineering industry is only now adapting to this trend. The costs of monitoring systems are progressively decreasing. It makes the question of how to monitor the grid and its most important components even more actual, both from the point of view of operation and investments. Surely, power transformers are at the forefront of this analysis.

The monitoring of the main parameters related to the transformer operation and any signs of development of anomalies allows the operator to know the margins of operation and the level of reliability of the asset.

The adoption of simplified monitoring we have defined as basic grants full control of the main parameters and allows a qualitative leap in the management of the protection towards the maximum temperature that the insulation can withstand. Any anomalies caused by gas development would still be monitored as a temporal trend to be investigated with specific DGA analysis.

The advanced monitoring with the integration of the DGA analysis on individual gases is justified on the most important assets where a fast diagnostic and a detailed trend over time are needed.

Moving from traditional maintenance to maintenance with monitoring systems may not be painless. It will be necessary to adopt reliable data collection systems and include automatic data processing that helps with data interpretation. In addition, it would be advisable to make this monitoring system dialogue with the transformer protection and control system and adjust the asset maintenance according to this new information.

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PEER REVIEWED

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