**Transformers are costly and complex assets which require competent management in order to avoid costly and unexpected failures**

# Expert systems vs. human expert


## ABSTRACT

Expert systems have in recent years become an integral package of many online monitoring systems and diagnostic test equipment sold to transformer manufacturers, service providers and end users. They are also commonly used in oil laboratories for providing standardized reports with recommendations on dissolved gas analysis and oil quality tests results. This article discusses briefly the limitations of algorithms typically used in expert systems and in more detail their shortcomings. The article also provides examples of why expert systems have not and cannot replace the final review and assessment of the test results by a human expert considering that reports produced, automatically, by such expert systems will not cover the complex facts when important and costly decisions have to be made.



## KEYWORDS

expert system, human expert, limit values, reliability, credibility, intuition


## 1. Introduction

In most of the commercially available monitoring systems, it is now the current state of art for online or offline measuring systems to be supplied along with integrated expert systems. The big advantage is that results based on the established analysis algorithms and limit values are now available and can be provided in an auto-printed standard format report, in which case no further investigation may be necessary. That way, the user may believe that he has obtained an accurate condition analysis of his transformers. With the expert now inside the instrument, the user may wonder whether he still needs an external human expert at all.

It remains to be seen to what extent such expert systems can replace a specialist who will not only have many years of experience, but also an intuition based on learning on how to go beyond standard responses in order to look for and find the true facts behind the data, and evaluate the total complex situation and the consequences.

The reliability of the various expert systems that are available remains quite controversial. What should the user do after receiving conflicting results on identical data from different expert systems? Should the view of the majority prevail, or is there a better approach?

**It is a classical headache for our scientific procedures that we are not trained to look at the complexity of multi-causal backgrounds**

In the following, relevant examples will be used to demonstrate that expert systems are only able to deliver standard answers, which eventually may mislead the user. A "flesh-and-blood" expert is absolutely indispensable in order to obtain true understanding of the facts and receive suggestions of the right measures to both understand the problem and correctly address the situation.

Transformers are costly and complex assets which require competent management in order to avoid costly and unexpected failures. It will be a long time before we see a truly reliable expert system working independently from human experts, possibly based on highly sophisticated fuzzy logic or similar systems.

Let's not forget: transformers are handcrafted by humans, making incalculable human behaviour inherent in the system at all times.

## 2. What are the expert systems based on?

There are evaluation methods specified for various measurements, and their combination is sold as expert systems. Sometimes, even analyses from standards are used, such as the water content analysis of transformers based on the new IEC 60422 [1, 2, 3]. Reflections on the value of this system have been published in the past. Even the assessment of gas content in transformers of different design types under the IEC and IEEE has met with critical appraisal, showing that the gas exchange behaviour is more or less the same in open and closed systems, even if this is discussible from the physical point of view and must be regarded as wrong. Even against these facts, which can rightfully be called weak, it would appear presumptuous to "automatically" derive diagnoses or recommendations for action from innately critical data. It should be recalled that Michel Duval, for example, when presenting his indisputably brilliant triangle, made it obvious that all other evaluation methods (expert systems) suffer from a high error rate and frequently fail to shed light on the transformer's true condition [4]. Evaluation methods such as DGA had to be developed out of sheer necessity since it is only possible to identify the gas content taking a random sample, but not the gas production (as aimed by different evaluation methods). Although repeated attempts have been made to crack the secret of how to identify gassing behaviour based on gas content, lasting success has remained elusive.

The reluctance of the governing standards to associate the differences in exchange behaviour with the atmospheres of different transformer designs (open/closed) makes it all the more difficult and complicated to obtain a meaningful analysis. In addition, to go even further and cram these complex relationships into an automated and, necessarily, harmonized analysis seems hardly the most expedient approach.

The problem could be mitigated by having a look at a few examples where even the human analysts did not take the most expedient approach, and where it seems highly doubtful that an "automated" method would have yielded answers that are more reliable.

It is, of course, particularly important to assess the origin of the data and their accuracy. The first step for every human expert is to check the plausibility of the data. Incorrect data occur at various sources along their chain of generation.

## 3. The human expert must evaluate the complete picture

It is a classical headache for our scientific procedures that we are not trained to look at the complexity of multi-causal backgrounds and relations when we see any data and results. To arrive to a well-based diagnosis and understanding of the transformer condition we must look as far as possible into the past and evaluate the trends and movement of the data. There are different reasons for this indispensable practice, which is essential for obtaining reliable results. By looking back, we can see whether the data is sustainable long term and if we can confirm this, the trends can be analysed and integrated in the long-term understanding of the actual condition and its development. Taking into account all available information, we are able to paint the complete picture and truly understand the actual condition.

There is information and data of the whole history that must be put in the context and considered, using of course the algorithms behind the expert systems to get a better understanding of the ideas behind, and last not least, to understand the weak points as well.

It must be understood that all these evaluation schemes are based on the experience of the people who introduced it in the past. However, it must also be considered that this past is now long gone and we have new developments. These algorithms are based on a certain stage of technology development, and not to

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forget, on some regional backgrounds, which is often evident in the differences between the IEC and the IEEE world. Very often these are not technical differences, but rather the differences in the mental and philosophical ways of thinking. The experience of a human expert is that he has to learn with every new project. Therefore, there are no static databases that could really cover the dynamic development of the reality.

## 4. Errors not detected by an expert system

The first error source is the sampling location as such. Inappropriate layouts and sampling access points often preclude the generation of correct data right from the outset.

The second error source is sampling per se as manual sampling presents an inherent error risk, although major improvements have been made in terms of equipment, and hence sampling quality.

The third error source is the processing of the samples either on site or in a lab, where serious errors are likely to be made and the blame shifted to the samplers. An undesirable consequence is the dissolved atmospheric gases $N_2$ and $O_2$. It has been the author's personal experience that these gases are incorrectly stated in more than 50 % of cases. Unfortunately, things are not always as clear-cut as the cases where up to 500,000 ppm of $N_2$ are "measured", or 50,000 ppm of $O_2$. Matters are even worse in cases where the values, although theoretically feasible, are out of context and not logical. This means that a specific thermal load on one hand, as evident from the $CO_2$ and CO values, in combination with the relevant hydrocarbons and signs of oil stressors on the other, must also show the associated oxygen consumption. That results in a significant oxygen decrease to under 20,000 ppm for open design types and typically $O_2=0$ for closed design types. It is the sum total of all these considerations that tells the user whether or not the data are reliable, or in what form they will be useful; or should they be considered only after correction. If no other data are available or can be generated, for example after a serious failure, what is left is a mixture of detective work, prior experience, and, last but not least, an intuition in order to come up with a halfway reliable diagnosis.

It has to be admitted, however, that under everyday conditions, and especially given the usual cost pressures, the diagnoses printed as appendices to the inspection reports are likewise typically "automated" and are by that very fact usually inferior to the more detailed and sophisticated digital analyses produced by expert systems. At the end of the day, even these diagnoses require the corrective hand of an expert in order to ensure their logical reliability.

In conclusion of this chapter, we should realize that simple standardized analysis will not yield the degree of necessary reliability for a number of reasons, especially as the data to be assessed requires a critical examination itself before it can be allowed to undergo further processing.

## 5. How to evaluate the difference between using a human expert and using an expert system as a tool

Firstly, we need to examine what is behind the expert system, and what can be provided only by a "flesh and blood" expert. In best-case scenario, the expert system contains the long-term experience and knowledge of the people who fed the information into it and installed it (mostly many years ago). Applying the commonly used algorithms and limit values from different sources (IEC and IEEE), the point of knowledge and experience may be covered by these communities, but the actuality of these data is questionable. Any knowledge or experience that is not continuously updated will lose its real relation to the present developments.

Also, the idea of traffic light warnings where limit values are indicated in red or green must be considered as absolutely dangerous. For example, a BDV (breakdown voltage) of 31 kV may be marked as green and 29 kV as red. However, in the worst-case scenario even 50 kV can be a "red" value! Similarly, the "health index" idea often gives the same false sense of security.

The human expert, deserving the title, must not only have the knowledge which is up to date, but also a long-time hands-on experience, and something that a "system" will never be able to provide: an intuition! This feature cannot even be transferred to other humans, let alone installed in a "system".

So, how can a human expert take advantage of a machine-based expert system? The expert system should be used as a tool to reduce any routine work and to filter the cases needing deeper analysis from the uncritical ones. Nevertheless, even here it is not sufficient to use only the criteria of the system. A human expert must have his own criteria to filter out the cases of interest. Based on commonly used limit values, the system will accept a condition as green, and the human expert must judge whether the condition is worthy of a comment or action. Only if the human expert knows well the knowledge base of the expert system, can he evaluate the results being aware of the weak points and where he has to conduct deeper investigation. The typical behaviour of a good human expert is not to give the answer immediately, like a printout from an expert system, but to delay making the decision until the following day, when after a careful thought he will eventually reveal his findings.

## 6. Procedure's goal and results

Both human and machine experts mostly perform condition assessment which should be used as a diagnosis on which further actions are based. If no further actions are envisaged, then all previous actions were unnecessary and money was spent in vain. While monitoring is an indispensable prerequisite, it is not a solution for a well-managed transformer population.

For condition assessment all facts available must be used and the diagnosis should be based on:

- Longitudinal DGA results, preferably for the entire lifetime of the transformer

- Oil quality (breakdown voltage, moisture in oil/at what temperature, tan δ, resistivity, interfacial tension, acidity, colour, particles)
- Service life, loading, ambient and oil and winding operating temperatures, age, past exposure to through faults and lightning strikes events
- Any major repairs, overhaul
- Any re-claiming, re-conditioning or changes of oil (fluids)
- The overall condition of the transformer and its ancillaries
- Any defects which require action(s) to be remedied

Based on this data, the necessary actions and remedies must be planned. There are three possible basic results:

- The transformer is in optimal condition – no action is required!
- There are some actions recommended or even necessary in order to maintain reliability and security of service
- The transformer is in the technical or economical end-of-life condition (EOL)

**The reliability of the various expert systems that are available remains quite controversial**

The second condition is most interesting, with two areas to consider:

- Transformer condition, such as winding, tap changer, bushings, tank, cooling equipment, etc.; and
- Oil condition, mainly acidity and IFT

As detailed in other papers [3, 5], IEC 60422 leads to a misunderstanding of the transformer and oil conditions. So, non-compliance with the requirements of this standard provokes frequently wrong (and mostly automated) recommendations (i.e. change of oil due to low BDV).

Only high acidity and low IFT (Interfacial tension) in oil require some action, either regeneration or change of oil. Regeneration is typically the preferred action while oil purification provides no improvement and mostly has adverse results.

Low BDV and/or high water content are transformer problems, which cannot be resolved by oil treatment or oil change. Looking at BDV, if there is a case of low BDV with coinciding high water content in the cellulose (depending on the sampling temperature and water content in oil), then any transformer drying method will be an adequate action.

BDV lower than the related water content is a severe case indicating aged cellulose and a high content of cellulose fibres. In the worst case, this is classical EOL criteria.

The question of how the proceed with a certain transformer cannot be answered generally. After evaluating the above condition of the whole unit, the following factors must be considered:

- Transformer application (e.g. GSU, industrial, transmission)
- Risk evaluation
- Cost evaluation

Based on these considerations, the final recommendation may be different. In case of a GSU transformer with a very high risk (where a daily production loss may sum up to €1 million and the lead time will be about two years), a replacement may be recommended.

In case of an industrial transformer, often a good solution might be to do a complete refurbishment including rewinding, especially if the design had proved its quality over the years. In this case, the only risk is the workmanship risk and there is no design risk, which is typically very high for special transformers.

For transmission transformers, sometimes the risk of accepting a break-down on site is also a possible option.

Making such complete analysis is the classical goal of a human expert. However, the result will not always be the same, even with identical technical data. Finally, the commercial and economic backgrounds must also be considered as part of the whole procedure.

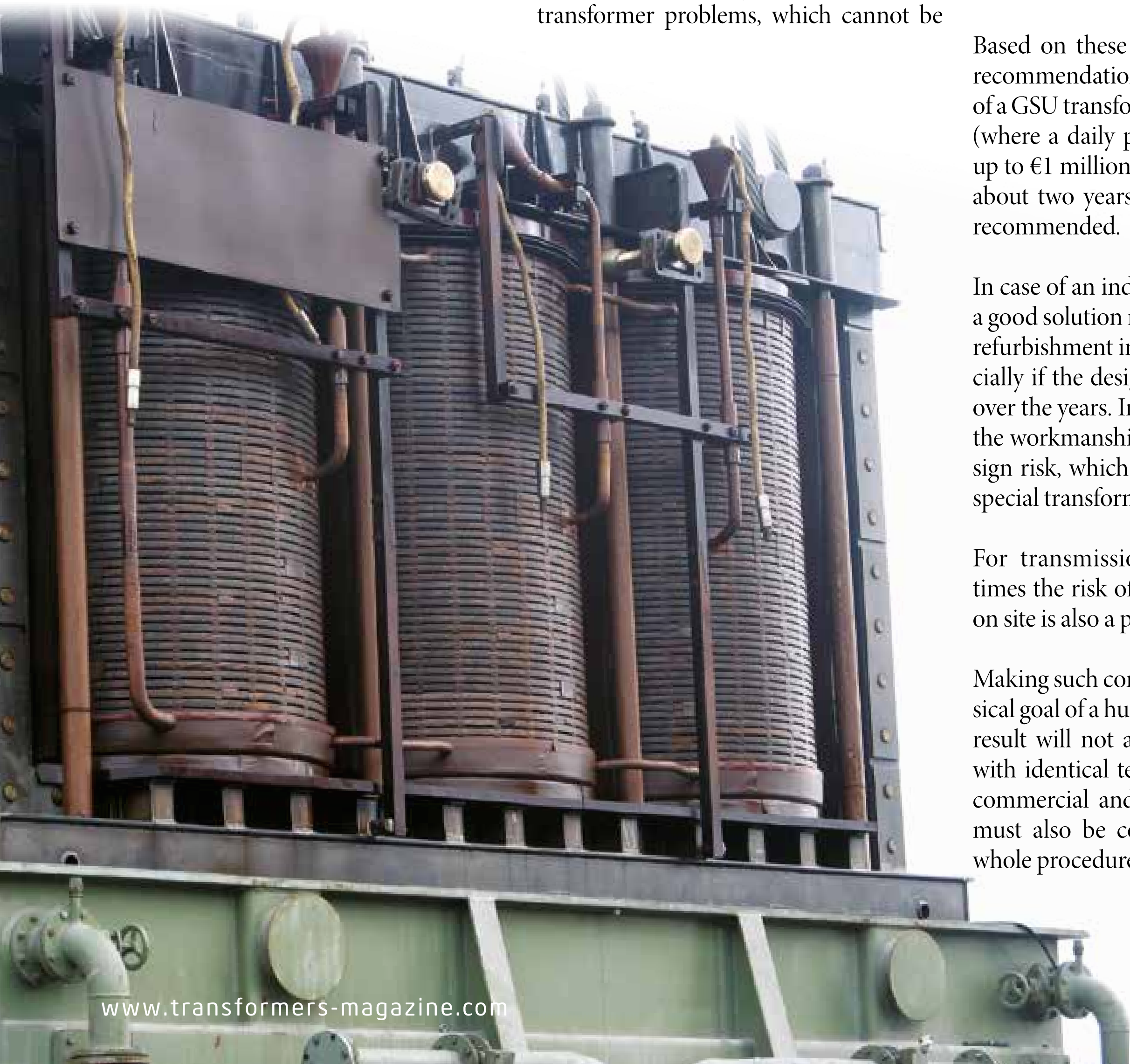

Figure 1. Transformer at the end of its lifetime

**It must be understood that all evaluation schemes used in expert systems are based on the experience of the people who introduced it in the past**

Table 1. Unit 1 DGA results (DIN EN 60567)

| | |
|---|---|
| Hydrogen | <10 ppm |
| Oxygen | <1000 ppm |
| Nitrogen | 13871 ppm |
| Carbon monoxide | 167 ppm |
| Carbon dioxide | 2837 ppm |
| Methane | 3 ppm |
| Ethane | <1 ppm |
| Ethylene | <1 ppm |
| Acetylene | <1 ppm |
| Propane | <1 ppm |
| Propylene | <1 ppm |
| Total gas content | <1.78 vol % |
| Solution pressure (calculated) | <178 mbar |

Table 2. Unit 2 DGA results (DIN EN 60567)

| | |
|---|---|
| Hydrogen | <10 ppm |
| Oxygen | <1000 ppm |
| Nitrogen | 37669 ppm |
| Carbon monoxide | 207 ppm |
| Carbon dioxide | 3697 ppm |
| Methane | 14 ppm |
| Ethane | 11 ppm |
| Ethylene | 2 ppm |
| Acetylene | <1 ppm |
| Propane | <1 ppm |
| Propylene | <1 ppm |
| Total gas content | <4.25 vol % |
| Solution pressure (calculated) | <463 mbar |

## 7. Examples

### 7.1. Example 1: Four GSU transformers 470 MVA 23/500 kV

In this example, the task at hand was to assess the reliability and criticality of all four units of a power plant.

#### Generator transformer 1

For this transformer, the gas values were without any pathological findings, so during the condition assessment an expert system would not have identified any problems, especially since no furans were detected. An expert system would have classified this transformer as being in mint condition and not afflicted by any problems.

**BUT!** The transformer was 30 years old (in 2012) and was sustaining oil temperatures in excess of 70 °C every single day. Is it possible to accept these findings at face value (even if measured without a doubt)? Here is where the human expert comes in, to voice doubts and to reinvestigate matters. Reinvestigation showed that the questionable sampling had yielded "critical" values, based on which the oil was purified at short intervals, with the result showing that nothing was left in the oil. The analysis of the internal data showed that $CO_2$ resaturation was very rapid, which in combination with $O_2$=0 indicated highly accelerated ageing.

#### Generator transformer 2

Similar behaviour was detected in Unit 2, where the oil had been purified a longer time ago, making the resaturation of $N_2$ and C…. gases significantly more apparent.

#### Generator transformers 3 and 4

Perhaps even more interesting was the development seen in Units 3 and 4, which were three years younger. Although basically identical to Units 1 and 2, some three tons of oil were "saved", resulting in the marked production of temperature-caused gases (130-400 °C), indicating an area of elevated temperatures. On the face of it, Unit 3 would appear more critical, but when taking into account the higher degasification level of Unit 4 and the very high and fast $CO_2$ restoration, there can be no doubt that the latter transformer was in the worse condition.

Assessing the reliability and criticality of all four units, after careful deliberation and with due consideration of all data available, Units 1 and 2 were classified as sufficiently reliable, whereas Units 3 and 4 were classified as significantly at risk. Unit 4 was diagnosed as being in the most critical condition. It should be noted that, subsequently, Unit 4 was the first to fail, three years ago, followed by Unit 3, which failed two years ago. Units 1 and 2 remain in operation as at the time of writing.

An expert system would not have identified a problematic condition for any of the units, least of all for the most critical Unit 4. It was recommended to the client to procure at least one spare transformer at short notice in order to limit block downtime to the replacement time in case of either transformer‘s failure. These recommendations were followed. Tables 1 to 4 present the last DGA data. To understand the final conclusion, the solution pressure showing the resaturation stage must be set in relation to the gas contents, which indicate, as in the case of Unit 4, the worst condition.

### 7.2 Example 2: A root cause analysis

Let us consider a case in which a 100 MVA 150/70 kV transformer fails and catches fire. What the user wants to know is: Why was this condition not recognized in time through conventional monitoring and a 500 MW supply shortfall prevented? In actual fact, the standard assessment based on the equipment‘s history failed to show any useful evidence of problems.

Even the "human expert system" at the lab had classified the transformer‘s condition as "normal". Besides, the bushings and tap-changers had been inspected in an ordinary sequence. After analysis of all these data, applying the usual limit values, no critical condition was determined.

There were, however, two factors, which were particularly striking:

1. The entire DGA analysis should be considered unlikely inasmuch as the "measured" nitrogen value of 176,183.00 ppm alone casts some doubt on the quality of the laboratory work.

   The other data are likewise not very trustworthy, and it is interesting to note that no hydrogen was detected. The only gas to appear distinctive was

**A human expert, deserving the title, must have the up-to-date knowledge and a long-time hands-on experience**

Table 3. Unit 3 DGA results (DIN EN 60567)

| | |
|---|---|
| Hydrogen | <10 ppm |
| Oxygen | <1000 ppm |
| Nitrogen | 31376 ppm |
| Carbon monoxide | 235 ppm |
| Carbon dioxide | 3614 ppm |
| Methane | 76 ppm |
| Ethane | 206 ppm |
| Ethylene | 8 ppm |
| Acetylene | <1 ppm |
| Propane | 182 ppm |
| Propylene | 13 ppm |
| Total gas content | <3.56 vol % |
| Solution pressure (calculated) | <382 mbar |

Table 4. Unit 4 DGA results (DIN EN 60567)

| | |
|---|---|
| Hydrogen | <10 ppm |
| Oxygen | <1000 ppm |
| Nitrogen | 9501 ppm |
| Carbon monoxide | 113 ppm |
| Carbon dioxide | 5327 ppm |
| Methane | 16 ppm |
| Ethane | 22 ppm |
| Ethylene | 1 ppm |
| Acetylene | <1 ppm |
| Propane | <1 ppm |
| Propylene | <1 ppm |
| Total gas content | <1.57 vol % |
| Solution pressure (calculated) | <126 mbar |

**Both human and machine experts mostly perform condition assessment which should be used as a diagnosis on which further actions are based**

methane, at 97.68 ppm, otherwise all hydrocarbons equalled 0.

2. The lack of hydrogen, however, can be partly explained by the sampling location and procedure. It is, of course, a common but generally bad idea to take an oil sample from the deepest point of the tank because this is usually a dead zone, especially in ON-cooled transformers, where the oil mixes either very slowly or not at all with the transformer's circulating live oil. In the case at hand, there was also a long tube present, which most certainly contained only dead oil. The usual procedure on location, which is to allow a maximum of two litres of oil to flow out before oil sampling, barely serves to empty the tube and the associated large valve. The hydrogen most likely disappeared from that oil a long time ago.

**Conclusion by the lab:** As the only hydrocarbon gas in the sample, which was methane, was below the "standard limit" of 120 ppm, everything appeared to be normal. No account was taken of the fact that this gas showed up in a DGA for the first time ever, and, given the above-mentioned conditions, at much higher levels than likely according to the measurements. Assuming that the hydrogen disappeared, massive partial discharging seems to have occurred.

Based on these considerations, it is also necessary to assess the SFRA measurement, which suggested a marked deviation in the winding area for the "R" phase. Obviously, this was not necessarily problematic per se inasmuch as no fingerprint existed and it might have been fine as it was. In combination with the partial discharge, however, it was safe to presume the existence of a mechanical problem in this phase, especially since the fault started as a single phase in this phase and initially caused a single-phase earth fault.

Probably by this stage, and possibly caused by potential shift or electromagnetic influx, the 220 V DC system was so crippled as to render any additional protective interventions useless. Therefore, the 150 kV circuit breaker was not tripped, missing the tripping signal at that point, causing 29 kA to be fed into the fault for another six seconds, which had by that point turned into a three-phase earth fault and short circuit, until an overriding protection was triggered which shut down the entire plant. By that time, the tank had torn open and the oil had caught fire.

Figure 2. Failed transformer

Even in that case, an expert system would not have issued a warning because no limit values had been exceeded, at least not initially.

### 7.3 Example 3: Stray gassing

A new transformer, in service for one year, is showing very unusual gassing behaviour, which, according to the classic view based on $CO_2$/Co relation, suggests accelerated ageing. One of the labs involved found furans and this in a virtually new transformer this was the base to calculating for this transformer having a remaining service life of 70 %. Obviously, the user was alarmed and started looking for explanations.

Controlled reference sampling and forwarding of the samples to two different laboratories finally helped to shed light on the matter. The oil had been contaminated with passivator, an additive that apart from not belonging in new oil is also causing stray gassing behaviour which resembles accelerated ageing. Incidentally, this product may be easily mismatched with furans by laboratories not working meticulously.

Interestingly, this case also helped to solve an older case where similar data had occurred. In both cases, the used oil was from non-established manufacturers. This makes it clear that a thorough inspection of the oil, including a test for unauthorized additives, is an important part of the FAT. In the aforementioned case, this was also corroborated by the fact that a virtually identical transformer, filled with oil from an established manufacturer, did not cause any problems whatsoever.

### 7.4 Example 4: Heat-generated gases and corrosive oil

In this example, all transformers in a power plant broke down within a five-year period. The diagnosis was corrosive oil. Upon closer examination, however, this was only half of the story. DGA data for all transformers showed heat-generated gases $C_2H_4$ and $C_2H_6$. The contents measured were significantly below the limit values, which may lead the expert system to the conclusion that the equipment's condition is not striking, let alone alarming.

However, the occurrence of these gases is an indicator of design problems, even in

Figure 3. Sampling device

cases when they are significantly below the threshold values, because these heat-generated gases occur only if some of the transformer's areas are experiencing temperatures significantly above 120 °C. What this means initially is that the service life of the insulating materials located in these areas is very limited (never forget the Montsinger rule). Transformers showing these symptoms typically have a limited service life of 15 years maximum. Add corrosive oil to the equation and you can expect the transformer to fail in less than five years, which is exactly what happened in this case.

It should, therefore, be a fundamental requirement that during normal operation heat-generated gases must remain below the limit of what is technically measurable. Limit values are completely irrelevant here!

## 8. Final remarks

The examples presented in this paper show beyond doubt that the accurate assessment of a transformer's condition depends, first and foremost, on the accurate collection of data. It all begins as early as the specification stage, where a suitable and easily accessible sampling device must be made mandatory. The commonly used sampling device located at the bottom of the tank, possibly close to the ground, can hardly be considered suitable. When errors sneak in right at the beginning of the chain, the remainder of the chain will be beyond remedy.

Equally indispensable is to run a critical study of the measurement results in order to ensure that the results intended for further use are indeed accurate, as any incorrect or illogical data will inevitably lead to incorrect and illogical conclusions. It may well be that in the future, well fed and sophisticated fuzzy logic systems will be able to identify even these problems.

What is for certain, however, is that unsuitable data collection and processing will lead to useless results. As of the time of writing, there is still an urgent need for intervention by human intelligence to identify the problem and salvage any data salvageable.

**Now more than ever, a human expert remains indispensable as the final authority to make a logical distinction between sense and nonsense**

## Conclusion

Expert systems are useful tools for assessing transformer condition. However, like any other tools, they belong into the hands of a human capable of using them in an appropriate manner. All too easily, we may find ourselves in the classic computer dilemma of "crap in, crap out".

It is entirely conceivable in practice for users working on site with expert systems to handle a large portion of standard tasks, albeit with the risk that the use of standard processes – which is what expert systems in fact are – may result in risks not being recognized, or recognized too late. This means that it is imperative for the results of these standard processes to be double-checked by a human expert who should intervene in time where deviations occur. In other words, while it is true that the use of expert systems makes the user's work easier and makes him less dependent on the more or less useful comments of his lab services provider, the user should also realize that even expert systems are standard applications whose results are unable to respond to individual problems or developments.

Now more than ever, a human expert remains indispensable as the final authority to make a logical distinction between sense and nonsense and to help the user achieve a reliable and uninterrupted use of his most perfidious asset – the transformer.

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