# Impact of Vacuum treatment on DGA

Dipl.-Ing. J. Altmann

## 1. Introduction

State of the art for the diagnosis of undesired changes in the Insulating Systems of oil-immersed transformers is DGA - Dissolved Gas in oil Analysis [L1]. By the detecting variations of the individual gases over longer periods, it is possible to estimate the type, the size and in certain cases the localisation of the damage. The introduction of new vacuum treatment methods for transformers has raised worries weather results of DGA would not be deteriorated or changed in an unwanted manner.

## 2. Analysis of the saturation-mechanism of oil inventory of the transformer

To evaluate the plausibility of DGA in general, it has to be estimated with which precision at all such measurement can work.

The quantity of gases dissolved in transformer oil is influenced by the following events:

- Fault(s) inside of the transformer
- Diffusion external gases from the atmosphere into the transformer
- Diffusion of gases from the transformer into the atmosphere
- Accumulation of gases in the oil-filling of the main tank
- Intensity of the oil circulation between the main tank and conservator
- Transformer temperature and loading

The presence of a faults is generally determined by the presence of a typical “fault” gases in the transformer oil. The increase or decrease of  specific gas contents in the oil inventory of the transformer is then interpreted as a increase or decrease of the size or intensity of given fault in the transformer. The similar relations can be used for the oxygen aging of insulating materials  and inflow of gases from the atmosphere. The samples of oil for DGA are always taken from the oil inventory of the main tank of the transformer.

Simplified  Oil System of a transformer is shown in Fig 1.:

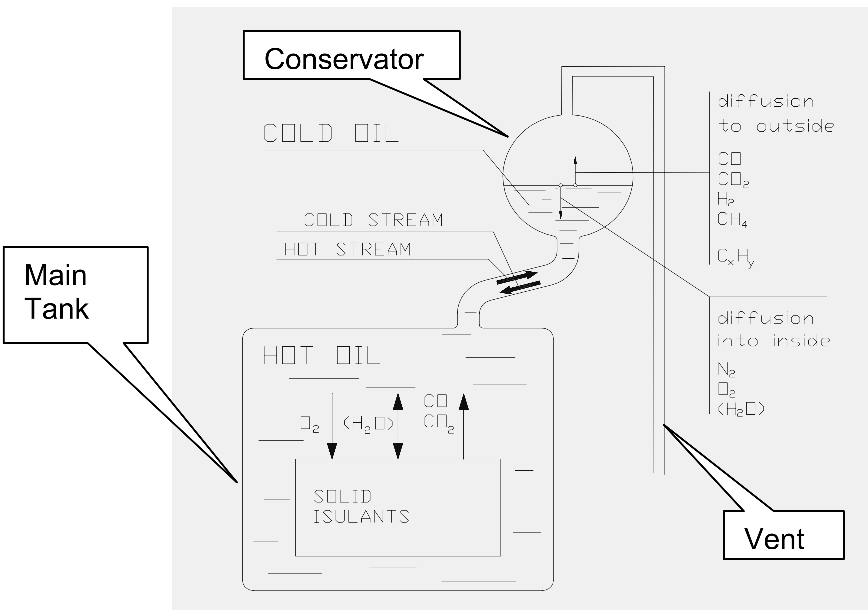


Fig. 1 The oil system of power transformer

For a satisfying understanding of the gas–movements in the  oil system, it is sufficient to introduce a hydraulic analogy.

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The simpler one describes the movement fault gas (and the oil), which is created in given systems and its production thereof is independent of oxygen.

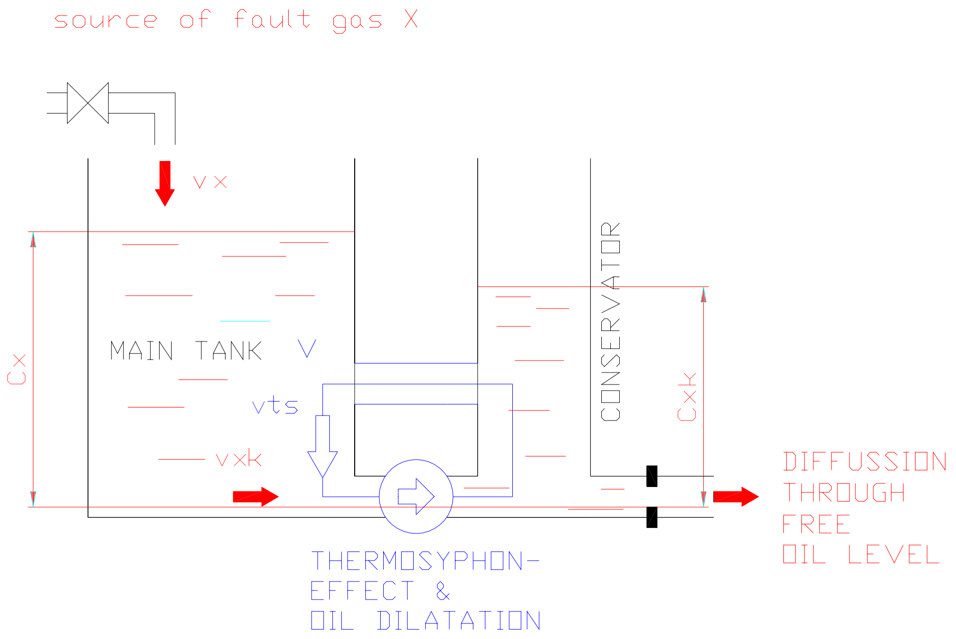


Fig 2: Hydraulic Analogy of the movement of the fault gas X and the oil in the transformer

The gas (**X**), which will be generated by an internal fault of the transformer, "flows" in the oil-filling of the main tank and is diluted in the oil. The size and intensity of a an internal fault determines the gas flow **v**x into the main tank. The fault gas (X) is stored in the oil inventory of the main tank and its actual concentration level **C**x depends on the inlet value **v**x and outlet value **v**xk. Because of the flow of oil **v**ts between the main tank and the conservator , the in-oil diluted gas with the concentration **C**x is permanently (or semi-permanently) transported into the conservator. There, the gas (**X)** then partially diffuses into the atmosphere over an oil-level in the conservator (by a open-transformers) and the oil with lowered concentration **C**xk is transported back into the main tank.

The discharge flow **v**xk of gas X from the main tank into conservator is then determined as follows:

(1) **v**xk = **v**ts . ( **C**x – **C**xk)

the discharge intensity of the gas (**X**) from the main tank is therefore a **product of volumetric oil flow vts , and the concentration drop Cx – Cxk between the main tank and the conservator.**

The transformer oil works there as a porter. The "circular" movement of oil between both vessels is in our analogy represented by a virtual circular pump (or a conveyor) which transports the oil from the main tank to the conservator and back.

We can therefore teoretically presume that:.

- if our virtual circular pump stops and the intensity of fault X remains the same, will the content of gas X (in the oil inventory of the main tank) inevitably linearly grows until the saturated condition will be reached. The classical DGA will then interpret an arbitrarily small fault X as a big one.

- on the other hand, if our virtual circular pump will run on full speed, the biggest fault will be most probably produce only very low Cx-level in the main tank and DGA will be interpret the big fault X as a small one.

Conclusion:

The reading of DGA in any transformer is generaly affected by:

- a size or intensity of the internal faults
- a “rotation speed” of our virtual circular pump
- a intensity of the diffusion process in the conservator

The first a main question is, what processes in the transformer determines the intensity of the oil circulation between the main tank and the conservator.

2. The Thermosyphon-Effect

The thermosyphon- or natural circulation cooling effect is induced by the temperature difference between the hot oil in the top of the main tank and the cold oil in the conservator and usually results in an intense exchange of oil between the both vessels.

Hot oil from the main tank transports an in-oil-dissolved gases into the conservator, where it diffuse into the atmosphere. Simultaneously the same amount of cooled oil (at constant transformer temperature) with considerable lowered fault gas levels, will move back into the main tank, mix with the hot oil, and will therefore reduce the gas content in the main tank.

The velocity of oil created by this thermosyphon-effect can be calculated as follows:

(2) $$U \approx \sqrt{2\ g\ H\ \beta\ \delta T}$$

where:

| | | |
|---|---|---|
| $U_{te}$ | …. | Velocity of the oil flow induced by thermosyphon efect |
| $H$ | … | the vertical distance between top of the main tank and bottom of the conservator |
| $\delta T$ | … | the temperature difference between top of main tank and conservator |
| $\beta$ | … | the dilatation coefficient of the oil |

Even though taking into consideration a moderate height of the thermosyphon H = 1m and a temperature difference only about 20°C a theoretical velocity of $U_{te}$ ~ 0,3 $ms^{-1}$ will be achieved.
If, for example the main tank is connected with two 2” pipes to the conservator, and a height of H = 0.80 m, as typical for a medium size transformers, the oil-throughput can be higher than $50 m^3/24$ h.

With the main tank volume ca 20 $m^3$, the whole oil inventory of the main tank will then be transported into conservator and back in less than 24 hours, and a considerable amount of the fault gases will have been diffused into the atmosphere.

For the one-pipe connections is typical a presence of the counterflow in the connecting pipe. The oil then flows simultaneously in the both directions, in the top part of the pipe cross-section the hot oil flows from the main tank upwards (hot stream) in the conservator, and in the lower part fows the cold oil from the conservator downwards (cold stream) into the main tank - See Fig. 1.

Of course, this permanent counterflow reduces the teoretical flow-velocity $U_{te}$, and the quantity of oil throughflow will be reduced more than 2/3 of the theoretical value.

Neverheless can be already concluded, that not only the size and intensity of the fault(s) decides about the absolute results of DGA.

The one-pipe connection will limit the velocity of oil to 1/3 of the theoretical value or even more, but the measured gas-content in an oil-sample from the main tank will be nevertheless influenced by temperature differences between the main tank and the conservator. The same conclusion is valid for a construction-design of the pipe connection(s) between main tank and conservator.

The construction design can be seen as a fixed and stable value, but its impact on the counterflow intensity can be very strong. The short connecting pipe will by the same temperature difference will induce a strong thermosyphon effect → strong counterflow, and on the other hand, very long heat-uninsulated pipe between the main tank and the conservator, under virtually constant temperatures of the transformer, results in a reduction or even stand-still of the flow between both vessels.

If the temperature difference (between main tank and conservator) decreases, i.e. by longer load reduction, sun-heating of the conservator, the thermosyphon effect will be reduced. In this case the content of fault gases in the main tank will be higher, even if the quantity of gas-production remains the same or be even lower.

The typical case is a summer – winter DGA deviations. Most users have detected that at cold temperatures e.g. in the winter, that the measured fault gas-contents are lower and the oxygen content is higher (the temperature difference main tank – conservator is higher), and vice versa, in the summers at higher temperatures (the temperature difference main tank – conservator is lower) the levels of measured fault gases are higher and the oxygen level in the oil is lower. Reason and background thereof just has been described.

The present diagnostic methods are trying to partially solve that problem by introducing Ratio Analysis Methods [1], which should take into consideration the similar conditions. This normalization of test results can a certain degree suppress the systematic errors, caused by the changing boundary conditions of a transformer system, but the basic problem of the dependency of classical DGA on this conditions can be never completely eliminated.

Pure theoretically the whole effort looks a little useless and desperately, because the good and precise diagnostic method must always ab initio have a quantitative character - the fault X must be described as a flow of the gas X in the standard physical units (m3 s-1, kg s-1).

### 3. Dilatation of the oil-filling of the main tank

Compared to the thermosyphon effect, the temperature dilatation of the oil in the main tank will probably contribute to the transport relations only to a minor extend. We can imagine its yourself as a circular pump which transports by increasing temperature the oil from the main tank into the conservator, if the temperature in the main tank remains constant the pump stops, and by the decreasing temperature is circular pump running in the reverse and delivers the oil from the conservator back in the main tank.

The transport relation can be described as follows:

**(3)** $v = V_o . \beta . \delta T . f$

where:

| | | |
|---|---|---|
| *v ts,d* | ….. | volumetric flow of oil flow induced by dilatation |
| *Vo* | …. | volume of the oil inventory of the main tank |
| $\beta$ | ….. | dilatation coefficient of oil |
| $\delta T$ | ….. | max. temperature difference of loading cycle |
| *f* | …. | loading cycle frequency |

Example:

Transformer main tank volume = 20 $m^3$
Temperature difference = 20°C

Frequency of the temperature changes = 1 per hour

The amount of oil induced by the heat extension will only be 0,7 $m^3$ / 24 h, or slightly more than 10% of the volume flow which is created by the maximum thermosyphoneffect.

The falsifying effect of the oil-flow between main tank and conservator on the DGA results can easily be proved especially with the transformer with the two connecting pipes between the main tabk and conservator**.** Closing one of them will induce a considerable increase of the measured fault gases (and a slight reduction of the oxygen content in the oil) after opening the valve, the gas-levels will go back to the original values.

***By the simple manipulation of one valve, the classical DGA reading can be heavy influenced, without that any changes inside of the system alone would have occurred.***

## 4. Effect of the oil inventory degassing on the precision of DGA

As shown above, the argument that a degassing of the transformer can irreversibly or long-term deteriorate of DGA data is wrong. There is no major storage of the fault gases which could be emptied, with the exception of the oil inventory. Every fault gas in the system is permanently created, short-term "stored" in the oil inventory and permanently drained into the surroundings. An transformer system has therefore no " DGA long-term memory".

A radical degassing (i.e. standard high vacuum treatment with 4 to 6 $m^3$ oil / hour with a vacuum below 1 kPa) would not create any tragic impact in respect of DGA, because after about 1 month after the treatment, will be in the transformer reached the same fully saturated conditions as berefore. Only the proper timing of the sampling procedure is therefore important.

On the other hand, any changes of the boundary conditions will always result in different results of DGA, without, with, or after any oil- or transformer treatment.

## 5. DGA Gradient Method

The validity and a plausibility of the classical DGA is limited by the change of the boundary conditions, which are influencing:

- the intensity of oil movement between the main tank and the conservator
- the permanent escape of the all fault gases from the main tank and consequently into the atmosphere.

In order to achieve the desired reproducibility of a classical DGA results, identical boundary conditions need to be met in respect of load-changes, oil temperatures, ambient temperatures, air-flap-cooling positions, cooling conditions of the conservator – sun-influence, wind force, etc… There is no chance to met the similar requirements in the practice.

Therefore it is necessary to find a measurement method, which will be independent of the boundary conditions.

One of those methods is a DGA Gradient Method.

The method is based on measuring and evaluating the dynamic response of the observed system on a defined jump change of the system.

The dynamic behaviour of the content of the gas X in the oil inventory of the main tank can be described with a simple differential equation as follows:

$$V_o \frac{dC_x}{dt} = v_x - v_{ts} \left( C_x - C_{xk} \right) \quad (4)$$

where:

| | | |
|---|---|---|
| *Vo* | …. | volume of the oil inventory of the main tank |
| *Cx* | …. | concentration of the gas X in the main tank |
| *vx* | …. | gas production (Gas X) of given fault |
| *vts* | …. | oil flow induced by the thermosiphon effect or by the oil inventory dilatation |
| *Cxk* | …. | concentration of the gas X in the conservator |
| *t* | …. | time |

The formula (4) shows, that the real quantification of the source of the fault gas X means that we have to find the value vx [ $m^3 s^{-1}$ ] - the flow of the fault gas X into the oil inventory of the main tank.

The direct measurement of this value is obviously impossible, but we can easy read the linear increase of the content of the given gas X, if we are able to "insulate" the oil inventory of main tank such way that no "gas" will escape from a main tank into a conservator .

We must therefore eliminate either the oil throughflow between the main tank and conservator (our virtual circular pump must be stopped)

(5) $vts \rightarrow 0$

or to avoid of the gas-concetration difference between the main tank, and the conservator

(6) $Cx - Cxk \rightarrow 0$

The simple execution of the relation (5) is difficult – we cannot simply stop the oil movement between the main tank and the conservator e.g. by closing the cock between the main tank and conservator. The transformer oil is practically incompressible and any deviation of the oil temperature will therefore immediately induce heavy and dangerous pressure deviations in the main tank. A relatively new option to stop the circulation and the mixing processes in the main tank-conservator system offers TRAFOSEAL, but we must then to change the plumbing between both tanks.

But the problem can be easy solved by exploitations of relation (6). This way we get the same effect and moreover in the normal operational conditions, because this relation is always fulfilled immediately after an on-line degassing of the transformer – the concentration of the gas X in the main tank and in the conservator is then roughly the same

(7) $Cx \sim Cxk \rightarrow Cx - Cxk \rightarrow 0$

Fig. 3 shows a typical time-development of the concentration of the gas X in the oil filling of a transformer after a vacuum-drying process.

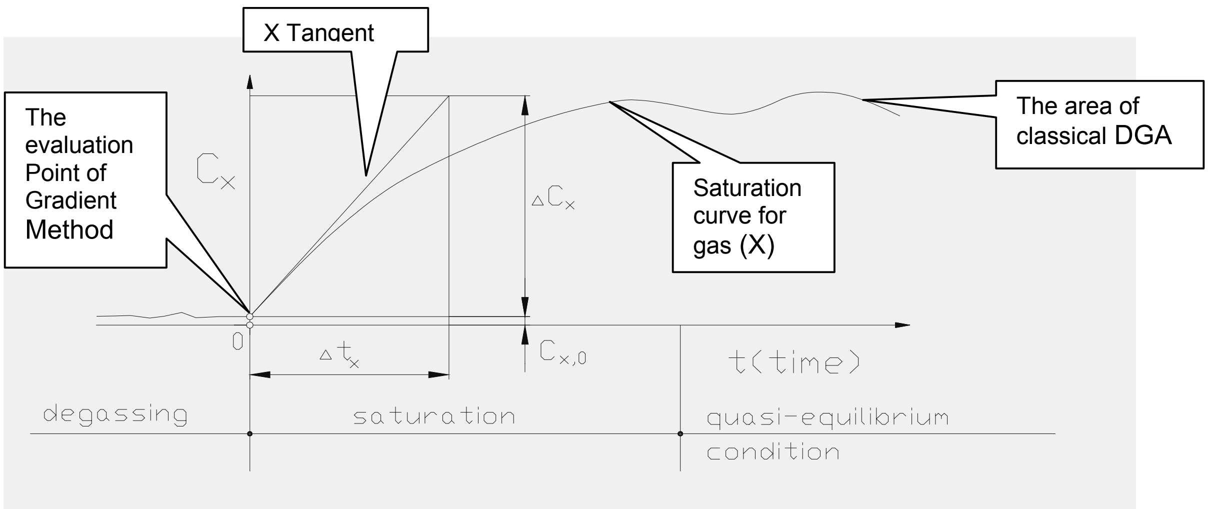

Fig. 3 Quantitative Evaluation a Gas(X) Source

The dynamic of the increase of the gas concentration *Cx* in the transformer's main tank (saturation curve) is a typical dynamic response of the system, caused by a sudden process change ( after the interruption of the transformer degassing process)

At t = 0 (end of vacuum-transformer treatment) the gas concentration *Cx* in the main tank and in the conservator is very low, condition (5) is therefore met, and equation (3) simplifies to:

$$\frac{v_x}{V_o} = \frac{\Delta C_x}{\Delta t_x} \tag{8}$$

The dynamic of our system at point t = 0 is similar to a linear behaviour of one-capacity closed system, with constant inflow of the gas X, but without a discharge of gas X into the surroundings.

The gradient of the measured *Cx*-value at starting point *Cx* (t=0) gives us directly the production of Gas X, normalized by the oil volume *Vo* of the main tank.

**Only this way is possible to eliminate the changes of the boundary conditions.**

Oil troughflow between main tank and conservator remains, but the oil flowing from the conservator to the main tank has at that moment the same very low content of diluted gases, and can thus not falsify our measurements.

Pure theoretically, the more it is possible to evacuate the transformer oil inventory the more precise diagnosis based on the gradient method can be established.

The DGA measurement of very low gas contents, directly at starting point, will be very difficult, but this problem can be simply solved by the evaluation of the saturation curve (X) - the tangent to the saturation curve at point t = 0 give us then a sufficiently precise gradient.

It stands to reason that for proper diagnostic of a given fault, that the saturation curves for the fault-typical gases should be established.

Not only one-point quantitative description of the fault can be established this way, more over we can get the relatively very precise time-trends of the development of the given fault.

The same way it is possible to calibrate e.g. the oxygen inflow into the transformer, and to quantify the process of oxidation aging of the insulating materials.

## 4. **Conclusion**

- an argument that the radical degassing of the oil inventory of the transformer would irreversibly deteriorate of DGA historical data is obviously wrong – system has no " DGA long-term memory".
- after a transformer degassing is a recovery of the fully saturated conditions for a classical DGA relatively short (maximal a month) and when the fault remains the same, we get the same reading again
- the standard DGA diagnostic of the fault in the transformer has primarily qualitative character – we can exactly determine if is the given fault in the transformer present or not, but classical DGA give us very little or no information about its real size.
- the precision of the standard DGA inevitably and strongly depends on the change of the boundary conditions of the transformer

- the DGA Gradient Method has an quantitative character and we can therefore exactly describe the size of given fault by a indirect measuring of gas flow(s) which this fault actually produce.
- the DGA Gradient Method eliminates the influence of boundary condition and we can evaluate a flow of gases from a fault into a oil inventory as a real physical value (kg s-1, m3 s-1).

**Literature:**

**[L1]** Myers, Kelly, Parrish
**A Guide To Transformer Maintenance**
**TMI** Transformer Maintenance Institute, Division, S.D.Myers, Inc., Akron, Ohio 1981