CONDITION ASSESSMENT OF POWER TRANSFORMERS TROUGH MONITORING OF PARTIAL DISCHARGES AND GASSES DISSOLVED IN INSULATING OIL

Aleksandar Vladimirov, *University of Mining and Geology "St. Ivan Rilski", Sofia, BULGARIA*
Evtim Ruychov Kyrtselin, *University of Mining and Geology "St. Ivan Rilski", Sofia, BULGARIA*
Georgi Tsonev Velev, *Technical university of Gabrovo, Gabrovo, BULGARIA*
Vasile Cozma, *"Constantin Brâncusi" University of Târgu Jiu, ROMANIA*

ABSTRACT: The paper inhere presents the use of data from measurements regarding partial discharges in insulation and dissolved gasses in insulating oil as diagnostic indicators for condition assessment of power transformers.

KEY WORDS: Power transformer, partial discharge, dissolved water, insulation diagnostics.

INTRODUCTION

Determining transformer condition is useful itself for making short-term decisions regarding operation and maintenance of power transformers. Assessing transformer condition through diagnostic techniques is also important for conducting asset management studies in order to clarify the need of transformer replacement. Transformer condition is an important input to an engineering and economic model used to determine the most cost-effective alternative for power transformer rehabilitation (i.e., continued operation, refurbishment, or replacement). On-line diagnostic techniques are necessary for establishment of condition based maintenance methods.

Dissolved gas analysis (DGA) is the most important method in determining the condition of a transformer. It is the first indicator of a problem and can identify deterioration in insulation and oil, overheating, hot spots, partial discharges, and arcing. The health of oil is reflective upon the health of transformers.

Partial discharge measurement (PD - measurement) is a non-destructive method used to evaluate the condition of a transformer's insulation system. The goal of partial discharge measurement is to certify that no harmful PD-sources exist within the insulation.

Since transformer insulation is designed to withstand operational voltage levels as well as system and lightning overvoltages, its condition determines the remaining life span of the transformer. Both tests – PD-measurements and DGA are sensitive to insulation condition and are able to detect incipient faults inside the transformer without use of expensive transformer internal inspections and losses as a result of power outages during off-line diagnostics. For implementation of both methods there are commercially available instruments that can be used, depending on the financial abilities of the investor. Also it is possible PD-measuring system to be installed for a particular transformer, and DGA samples to be taken and sent to an accredited laboratory for testing on regular basis by the staff that is responsible for transformers' maintenance.

PD – MEASUREMENTS

All PD measuring methods are based on the detection of PD current impulses *i(t)* circulating in parallel connected capacitors C_k (coupling capacitor) and C_t (test object capacitance) via measuring impedance Z_m. The basic equivalent circuit for PD measurements is presented in figure 1 [1], where: C_k – coupling capacitance; C_t test object capacitance; *G* – voltage source; *i(t)* – PD pulses; $i_{\sim k,\sim t}$ – displacement currents; *Z* – voltage source connector; *q* – transferred charge; U_t – voltage at parallel-connected capacitors; Z_m – measuring impedance; A, B – winding connection to bushings.

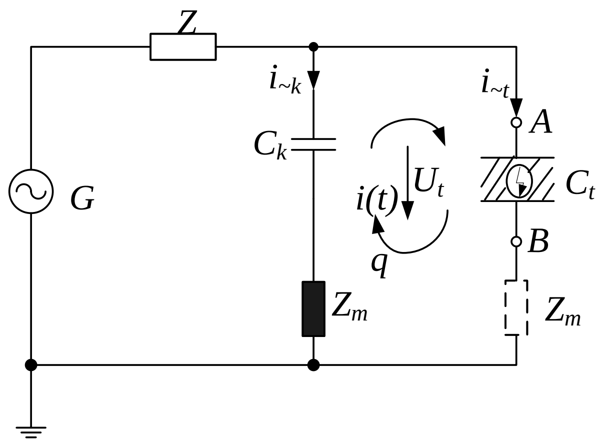

Figure 1. Equivalent circuit for PD measurements

The measuring impedance Z_m can be connected in series with coupling capacitor C_k or with test object capacitance C_t (see fig.1).

Present standards IEC [2, 3], IEEE [4], and GOST [5,6] have both established rules for measuring and evaluating electric signals caused by partial discharges together with specifications on permissible magnitude.

The IEC approach for processing of recorded electric signals is different form the IEEE approach. IEC transforms the signal to an apparent charge generally measured in picocoulombs (pC), while IEEE transforms the signal to a Radio Interference Voltage RIV, generally measured in microvolts (μV). The detection of apparent charge in pC is the proffered method now in use in IEEE Std.C57.113 [7].

For detection of apparent charge the integration of the PD-current impulses *i(t)* is required.

Integration of the PD current impulses can be performed either in the time domain (by digital oscilloscope) or in the frequency domain (by band-pas filter).

For duration of currents (ns-range) the test voltage source is practically decoupled from measuring circuit (parallel connection of C_k and C_t by the inductive impedance *Z* (step-up transformer connections).

For HV-components without any capacitive bushing an external coupling capacitor C_k must be connected in parallel with the test object C_t, see figure 2 [1]. On this figure *U~* is test voltage; PDS – partial discharge test system.

For power transformers the measuring impedance usually is connected between bushing measuring tap and earth.

The registration of PD signals could be performed in short or long term measurement mode.

Short term measurement mode by itself is a PD testing mode, where total time of one measurement cycle is less than the duration of the intervals between test cycles. Typical examples for short term test of PD properties are measurements made after remedial works on electrical equipment having a goal to check quality of the insulation rehabilitation.

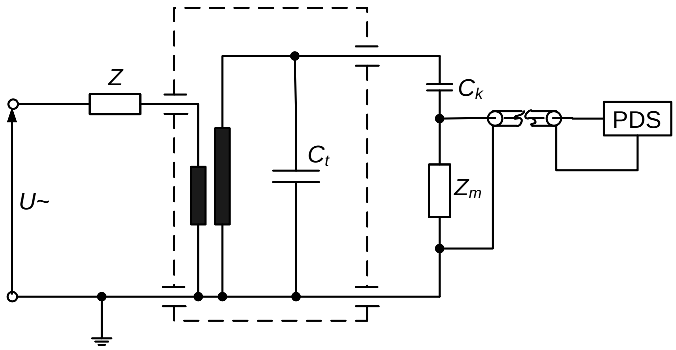

Figure 2. Connection of the measuring impedance in test circuit without available measuring tap in the HV bushings

Long term measurement mode is such a mode, where the total time of the PD measurement is long enough to eliminate large dispersion of the data in case of a stochastic nature of PD occurrence.

After recording of PD data, a results processing is performed:

- On first stage of the processing the PD signals are separated by the interference signals, analyzing the results from measurements with the aid of specialized software;
- The second stage of processing is to determine quantity and location of the most intense discharges;
- On third stage, analysis of the results from the PD measurement is performed; expert evaluation for the fault type and its severity is provided.

The type of the fault is determined on the base of many factory and in-service tests, after checking transformer's technical specifications. For an objective assessment of test data, additional data recorded by other methods could be used, e.g. acoustic and/or electromagnetic, as well as DGA tests of oil samples.

In case PD source detection inside the main insulation of a transformer, the following limits of maximal apparent charge could be used to determine severity of the fault [8]:

- There is no fault, pC.......…………….<100;
- Normal condition, pC....…………….≤1000;
- Condition required clarification of the causes for occurrence of PD, pC – from 1000 to 25000;
- Faulty condition, nC…….......from 5 to 25;
- Possibility of irreversible fault (creeping discharge), nC…………...…………….≥25;
- Critical (dangerous) condition, nC…..>100.

In case of detection of PD source inside high voltage bushings, the numbers above should be reduced with one order.

DISSOLVED GAS ANALYSIS

One reasonable method for monitoring of insulation material deterioration in power transformers includes calculation of the total released combustible gases. The amount of released total combustible gasses is an indicator for the level of the incipient fault.

The testing of transformer oil samples on regular basis reveals changes in the insulation condition with time. Equation (1) can be applied in order to determine the volume, in liters, of generated combustible gasses dissolved in the insulating oil [9]:

$$TDCG_V = \left(\frac{FG(V)}{10^6} \right) \tag{1}$$

where:

FG – sum of concentrations of H_2, CH_4, C_2H_6, C2H4 and CO, [μl/l (ppm)];

V – volume of the oil in a transformer;

$TDCG_V$ – total volume of combustible gas.

This simple method is useful for completely filled with oil transformers (with conservator for the oil) in case when small quantities of combustible gas are generated.

The generation of small amounts of combustible gas is a good reason for continuous monitoring of transformer's insulation, since up to that particular moment the type and the character of the supposed incipient fault could not be defined clearly according to the available methods for insulation condition assessment, based on analysis of the type and quantity of the individual gasses obtained. This method continues to be helpful during the initiation and development of the fault. As advantage it allows consecutive observation of the insulation deterioration despite of all measures taken in order to process and degas the oil.

It is hard to determine whether a transformer is performing normally or not if there are not available previous records for dissolved gasses concentration. Also, different opinions are available with regard to the classification "Normal transformer" considering the permissible levels of gases concentration.

In the IEEE standard [9] a system of four concentration levels is presented, which classifies the risk of transformer faults, when there are no available records for the total amount of dissolved gasses and individual concentrations of combustible gasses, during the continuous operation of the equipment. The criteria for different insulation condition assessment are built as regard to the total amount of combustible dissolved gasses and their individual concentrations in oil according to table 1 [9]:

- Condition 1: Concentration of total combustible gasses below this level is indicator that transformer works satisfactory. Any of the individual gases exceeding this level, this is a sign for additional investigation for the source of the problem;
- Condition 2: Concentration of total combustible gasses above this level is indicator that gasses are generated at rate higher than usual. Any of the individual gases exceeding this level is a sign for additional investigation for the source of the problem. Actions should be taken to establish trend line over the time;
- Condition 3: Concentration of total combustible gasses above this level is indicator for accelerated degradation of the insulation. Actions should be taken immediately to establish trend line over the time. There is a high probability for presence of a fault;
- Condition 4: Concentration of total combustible gasses above this level is indicator for excessive degradation of the insulation. Continuing the operation of this transformer can result in breakdown.

In table 1 are presented data for individual and overall concentration of dissolved gases in transformer oil (excluding CO_2) for conditions from 1 to 4. The data in table 1 is for initial evaluation of faults, associated with gas generation for new and recently refurbished transformers or it can be applied to transformers without recent oil insulation test history. The concentration levels presented inhere are consensual and based on the experience of many companies.

Table 1

Status	Limits of key gases concentrations (µl/l (ppm))							
	Hydrogen (H_2)	Methane (CH_4)	Acetylene (C_2H_2)	Ethylene (C_2H_4)	Ethane (C_2H_6)	Carbon monoxide (CO)	Carbon dioxide (CO_2)	TDCG
Condition 1	100	120	1	50	65	350	2500	720
Condition 2	101-700	121-400	2-9	51-100	66-100	351-570	2501-4000	721-1920
Condition 3	701-1800	401-1000	10-35	101-200	101-200	571-1400	4001-10000	1921-4630
Condition 4	>1800	>1000	>35	>150	>200	>1400	>10000	>4630

The condition of a transformer is evaluated regarding the highest measured concentration - of individual gasses or total amount of combustible gasses dissolved in insulating oil. New transformers (in service one year or less) usually contain level of gasses much less than the values described for condition 1 and does not contain traceable (detectable) levels of acetylene. This, as well as service lifetime of the transformer should be taken into consideration when a decision is based on table 1 data.

It should be taken into account, that acetylene is generated in three different cases of incipient faults, including: high temperature overheating of oil; partial discharges (discharges with low energy); arcing (discharges with high energy). In case of overheating the acetylene will be a small part of the total hydrocarbon gasses. In case of partial discharges, high concentrations of hydrogen will be produced with respect to acetylene; this will be a cause for concerns even if the level of total combustible gasses is below the acceptable level. The worst case is arcing. When high energy arcing occurs, the acetylene and hydrogen usually are with same concentrations, as the other hydrocarbon gasses. If condition with active arcing is detected, immediate attention to the equipment is a must.

At a sudden rise of dissolved gasses' concentration in oil of a transformer under operation, as a result of a supposed internal fault according to table 1 for operating conditions 2 to 4, it is required to check table 2 for the respective time interval between sampling and operational procedures [9].

Table 2 gives the required initial sampling time intervals that have to be kept and operational procedures which should be performed for detected different concentration levels of total combustible gasses [in µl/l (ppm)]. Increasing concentration of gasses is indicator for incipient faults and the time intervals between individual samples should be shortened.

When source which generates gasses is detected trough analysis and after an assessment of the risk, engineering decision should be taken to determine the final sampling period with the respective operational procedure.

In standard IEC 60599 [10] typical concentrations of gasses for transformers under operation are given. That data is collected form 15 different independent networks for more than 15000 transformers; this information is summarized in tables 3 and 4 in form of 90% concentration limits. Above those levels, monthly concentrations of the individual gasses should be monitored. If gas concentration rises with more than 10% monthly above a typical concentration, this means that incipient fault is present inside the transformer. Higher concentrations in the range of 50% per week/month are considered as a serious problem.

Similar data is presented in the Russian document RD 153-34.0-46.302-00[10], as summarized in table 5.

Table 2. Time intervals between the samples and operating procedure depending on TDCG levels

Status	TDCG level (µl/l)	TDCG rise (µl/l per day)	Interval between the samples and operating procedure	
			Sampling	**Operating procedure**
Condition 4	>4630	>30	Daily	Consider removing from service. Advice the manufacturer.
		from 10 to 30	Daily	
		<10	Weekly	Operate with high caution. Perform analysis of the individual gasses. Plan the removing form service. Advice the manufacturer.
Condition 3	from 1921 to 4630	>30	Weekly	Operate with high caution. Perform analysis of the individual gasses. Plan the removing form service. Advice the manufacturer.
		from 10 to 30	Weekly	
		<10	Monthly	
Condition 2	from 720 to 1920	>30	Monthly	Operate with high caution. Perform analysis of the individual gasses. Check load dependency.
		from 10 to 30	Monthly	
		<10	3 Months	
Condition 1	≤720	>30	Monthly	Operate with high caution. Perform analysis of the individual gasses. Check load dependency.
		from 10 to 30	3 Months	Continue normal operation
		<10	Yearly	

Table 4. Typical concentrations of gasses for transformers under operation with communicating tap changer

Gas	90% concentration limit µl/l	10% per month µl/l	50% per month µl/l
H_2	75-150	7,5-15	37,5-75
CH_4	35-130	3,5-13	17,5-65
C_2H_2	80-270	8-27	40-135
C_2H_4	110-250	11-25	55-125
C_2H_6	50-70	5-7	25-35
CO	400-850	40-85	200-425
CO_2	5300-12000	530-1200	2650-6000

Table 5. Typical concentrations under operation for voltage ratings between 110 and 500 kV

Gas	90% concentration limit µl/l	10% per month µl/l	50% per month µl/l
H_2	100	10	50
CH_4	100	10	50
C_2H_2	10	1	5
C_2H_4	100	10	50
C_2H_6	50	5	25
CO	500*/600	50*/60	250*/300
CO_2	6000(2000)*/8000(4000)	600(200)*/800(400)	3000(1000)*/4000(2000)

*for CO in the numerator the given values are for transformers with nitrogen protection or with rubber bag inside conservator, in the denominator – for free breathing transformers; for CO_2 in the numerator the pointed values are for free breathing transformers under operation of 10 years, in the denominator – above 10 years, in parentheses is given the same data for transformers with nitrogen protection or with rubber bag inside the conservator.

CONCLUSIONS

The methods described inhere for monitoring of PD and gas concentrations are for initial assessment of transformers' insulation condition. On-line gas detectors are very helpful for detection of sudden and atypical rates in concentration of dissolved in oil gasses, which could occur in minutes, hours or weeks. In such cases sampling at a monthly or yearly schedule is not relevant for insulation condition assessment. Along with that when a rise in gas concentration is detected it is necessary to perform a complete DGA in a certified laboratory to confirm transformer's insulation state. When a fault is suspected it is always a good practice an extended diagnostics for the respective transformer to be made.

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