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Condition Monitoring in New Zealand Power Transformers

A short survey

S. N. Hettiwatte[1*] and H. A. Fonseka[2]
[1] Manukau Institute of Technology, Manukau, Auckland, New Zealand
[2] Transpower New Zealand Ltd, Greenlane, Auckland, New Zealand
*E-mail: Sujeewa.hettiwatte@manukau.ac.nz

***Abstract*— Transpower owns and operates New Zealand's high voltage electricity grid which includes approximately 725 in service power transformers [1]. Presently, condition monitoring of these units is routinely carried out by oil testing (moisture, acidity and dielectric breakdown) and using dissolved gas analysis (DGA), (every year), and winding resistance, insulation resistance, and bushing power factor tests (every four years). However, since the average age of a power transformer in New Zealand is nearly 40 years [1], it is considered that online condition monitoring of important transformers or transformers that have known issues is carried out to identify any incipient faults. The online condition monitoring in existing power transformers is hoped to minimize the risk of sudden failures and thereby prolong the in service life. It is equally important to decide on *what to monitor* in a power transformer and *how to monitor*, and these are also governed by the budgetary constraints. Transpower is in the process of acquiring online condition monitoring units for some of the new large power transformers it plans to purchase and will also retrofit such units to some old transformers as required. This paper presents the condition monitoring techniques currently used by Transpower on power transformers, and the online condition monitoring techniques for new and existing power transformers.**

Keywords -- power transformers;condition monitoring; dissolved gas analysis (DGA); online gas monitors, Roger's Ratio, Duval Triangle, winding resistance; insulation resistance; on load tap changers (OLTC), bushings.

I. INTRODUCTION

Power transformers play an important role in a power system. Once a new power transformer is installed and commissioned it is normally expected to operate 24/7 with minimum maintenance for its entire life span, which averages to be around 40 years. However, a power transformer can fail while in service without much warning. A sudden failure will incur massive losses in terms of capital cost of repair or replacement as well as other economic penalties due to the potential power outage. Condition monitoring has therefore become a common practice among the power utilities.

Transpower who owns and operates the New Zealand's high voltage electricity grid has around 725 in service power transformers [1]. This fleet of power transformers consists of both single-phase and three-phase units, out of which around 50% are three-phase. The age profile of these power transformers shows (Fig. 1) that most of the older units are single phase. The average age of the entire fleet was 39.8 years in 2009. These data [1] show that an average power transformer in service has completed its designed lifetime and some units are operating well beyond their designed lifetime. Therefore, condition monitoring is highly important to keep these transformers in service.

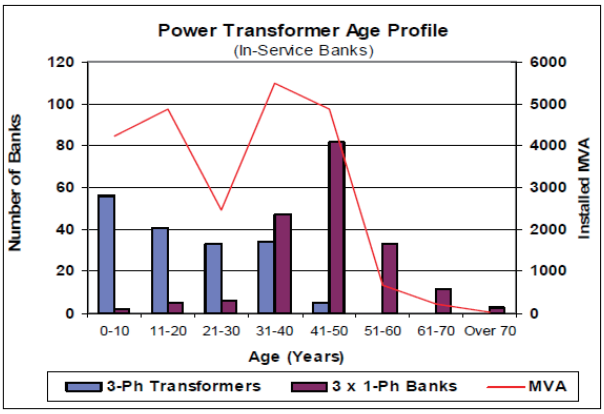

Figure 1. Transpower's power transfomer age profile [1]

At present, condition monitoring is routinely carried out on these units using dissolved gas analysis (DGA), and oil testing (moisture, acidity and dielectric breakdown) (every year), winding resistance measurements (every 4 years), winding insulation measurements (every 4 years), bushing power factor measurements (every 4 years), and by visual inspection of external condition and condition of ancillary equipment (every 4 years) such as radiators, coolers, off load tap changer drive mechanism and bushings. Even though condition monitoring can identify incipient faults, the interval of measurements is important. If this interval is too long, like 1 year, faults can develop, and may even lead to catastrophic consequences. On the other hand, if the condition is monitored online precise operating conditions can be obtained, and power utilities can move from time based maintenance scheme to a condition

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based maintenance scheme. However, this adds to the capital cost of monitoring equipment.

II. Condition Monitoring Methods

A. Dissolved Gas Analysis (DGA) Oil Testing

Dissolved gas analysis (DGA) oil testing is the single most important diagnostic test for a power transformer. This test enables to detect and estimate the composition of various gases (hydrogen, carbon monoxide, carbon dioxide, methane, ethane, ethylene, acetylene, etc), dissolved in transformer oil.

Gases inside an oil filled transformer are generated either by electrical discharges or from overheating of the transformer insulation under thermal and electrical stresses.

The detected gases and their composition are an indication of the incipient fault. For example, a high concentration of hydrogen indicates partial discharge activity, and a high concentration of carbon monoxide indicates overheating. DGA of transformer oil is by gas chromatography, and is carried out by Transpower according to the international standard ASTM D-3612-02 [2]. According to this standard [2], the following gases dissolved in electrical insulating oil may be identified and determined:

Hydrogen – H_2
Oxygen – O_2
Nitrogen – N_2
Carbon monoxide – CO
Carbon dioxide – CO_2
Methane – CH_4
Ethane – C_2H_6
Ethylene – C_2H_4
Acetylene – C_2H_2
Propane – C_3H_8
Propylene – C_3H_6

Transpower specifies [3] the allowable levels for each of these gases in parts per million (ppm), (except for propane and propylene), as Table I indicates.

TABLE I. Allowable gas Levels [3]

Gases		Combustible Gas	Gas Level Criteria (ppm)
Hydrogen	H_2	Yes	50
Oxygen	O_2	No	-
Nitrogen	N_2	No	-
Methane	CH_4	Yes	50
Carbon monoxide	CO	Yes	1000
Carbon dioxide	CO_2	No	10,000
Ethylene	C_2H_4	Yes	100
Ethane	C_2H_6	Yes	100
Acetylene	C_2H_2	Yes	15
Total combustible gas level			500

If it is found that one or more combustible gas level, or the total combustible gas level has been exceeded, the next step would be to take another oil sample and test it to verify the results. If the results are confirmed to exceed the values in Table I, gas production rates are examined with increased monitoring or the transformer is taken out of service.

The gas quantities found by DGA are analyzed according to IEC 60599 [4], and Roger's Ratio [5]. The IEC 60599 and Roger's Ratio compare gas ratios such as CH_4/H_2, C_2H_2/C_2H_4 and C_2H_4/C_2H_6, and interpret DGA according to the ratio values. According to IEC 60599, there can be six characteristic faults (6 cases) depending on the three gas ratios. These characteristic faults are listed in Table II. The Roger's Ratio gives codes for ranges of gas ratios and the fault diagnosis is according to the three digit code (Table III). For example, if the code is 110 (corresponding to $CH_4/H_2 < 0.1$, $0.1 < C_2H_2/C_2H_4 < 3$, and $C_2H_4/C_2H_6 < 1$), the characteristic fault is partial discharges of high energy density [5]. The Roger's Ratio interprets DGA gas ratios to eight characteristic faults (8 cases), very similar to the ones in Table II. The additional two faults in Roger's Ratio are obtained by replacing PD in Table II with partial discharges of low energy density and partial discharges of high energy density, and having another category for thermal faults: thermal faults below 150 ºC. One drawback in analyzing gas ratios is that a combination of gas ratios might fall outside the range of characteristic faults, which can be either due to a combination of faults or due to a new fault. In such cases diagnosis is difficult; however, IEC 60599 shows a graphical method [4] of obtaining an approximation to the characteristic fault.

TABLE II. Characteristic Faults According to IEC 60599 [4]

Case	Characteristic Fault
PD	Partial discharges
D1	Discharges of low energy density
D2	Discharges of high energy density
T1	Thermal fault, $t < 300$ ºC
T2	Thermal fault, 300 ºC $< t <$ 700 ºC
T3	Thermal fault, $t > 700$ ºC

TABLE III. Codes for Examining Dissolved Gases [4]

Code of range of ratios	Ratios of Characteristic Gases		
	CH_4/H_2	C_2H_2/C_2H_4	C_2H_4/C_2H_6
< 0.1	1	0	0
0.1 - 1	0	1	0
1 - 3	2	1	1
> 3	2	2	2

B. Online Gas Monitors

Transpower has recently installed online gas monitors on some important power transformers and on ones with known issues, and is also specifying them for large power transformers planned for purchase. Online gas monitors can be categorized into two types, based on the number of gases they can monitor [6]: Key gas monitors and multi gas monitors. Key gas monitors (like the Serveron TM3) only monitor few fault gases like methane (CH_4), ethylene (C_2H_4), and acetylene

(C_2H_2), and the diagnosis is according to the Duval's triangle (Figure 2). The Duval's Triangle [7] uses triangular coordinates, and shows various fault conditions based on relative concentrations of methane (CH_4), ethylene (C_2H_4) and acetylene (C_2H_2).

One advantage of using the Duval Triangle is that for any concentrations of the three gases there is a unique point inside the triangle which corresponds to a faulty condition in the transformer. Table IV [7] identifies these different regions within the Duval triangle. Software implementations of the Duval Triangle [8] are available, which simplifies the diagnostics once the gas concentrations are known.

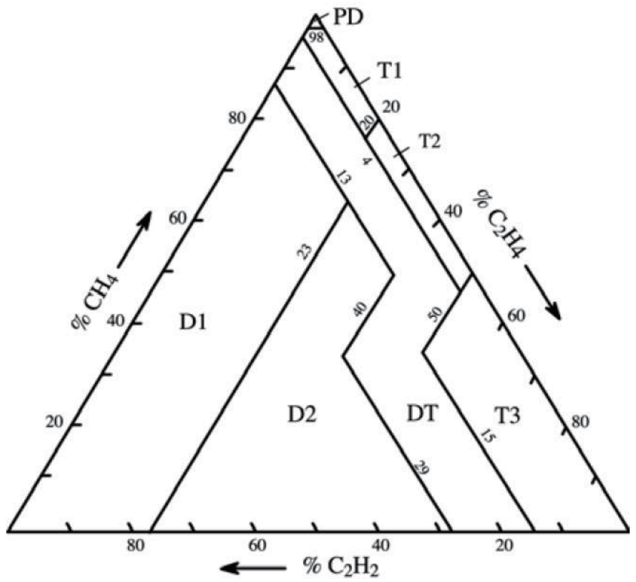

Figure 2. Duval triangle [7]

TABLE IV. EXAMPLES OF FAULTS DETECTABLE BY DGA [7]

Symbol	Fault	Examples
PD	Partial discharges	Discharges of cold plasma (corona) type in gas bubbles or voids, with possible formation of X-wax in paper.
D1	Discharges of low energy	Partial discharges of sparking type, inducing pinholes, carbonized punctures in paper. Low energy arcing inducing carbonized perforation or surface tracking of paper, or the formation of carbon particles in oil.
D2	Discharges of high energy	Discharges in paper or oil, with power follow-through, resulting in extensive damage to paper or large formation of carbon particles in oil, metal fusion, tripping of the equipment and gas alarms.
T1	Thermal fault, $T < 300$ ºC	Evidenced by paper turning brownish (>200 ºC) or carbonized (>300 ºC).
T2	Thermal fault, $300<T<700$ ºC	Carbonization of paper, formation of carbon particles in oil.
T3	Thermal fault, $T>700$ ºC	Extensive formation of carbon particles in oil, metal coloration (800 ºC) or metal fusion (> 1000 ºC).

Multi gas monitors, (like the GE Energy Kelman Transfix) can monitor most gases in Table I, in addition to the moisture. Monitoring more gases other than the three required for analysis based on Duval Triangle (methane, ethylene and acetylene), can give more insight into an incipient fault and further confirm the type of fault [9]. For example, if online monitoring of methane, ethylene and acetylene indicates to a point at the center of the Duval Triangle with simultaneous increase in monitored carbon monoxide (CO) and carbon dioxide (CO_2) concentrations and decrease in the monitored oxygen (O_2) concentration, the analysis based on the Duval triangle says that it is a high energy discharge (region D2 in Duval Triangle). Increased concentrations of CO, CO_2 and decrease in O_2 confirm thermal degradation of cellulose paper [9].

C. Winding Resistance Measurements

Winding resistance measurement is carried out according to IEC 60076: Part 1, every 4 years. The windings' dc resistance on each phase and tap is measured and the results are temperature corrected to 75 ºC. These results are then compared with previous test results or factory test results, and the percentage deviation calculated [11]. The percentage deviation is used as a measure to calculate the remaining life in the transformer. If the deviation is less than 5%, the remaining life is estimated to be greater than 4 years; otherwise, it is less than 4 years [12].

D. Winding Insulation Resistance Measurements

The insulation resistance test results can indicate abnormal conditions in insulation due to moisture, contaminations or damaged windings. Insulation resistance is measured between each winding to other, and to earth using a 2500 V dc or 5000 V dc instrument, if the windings are in oil. If the windings are in air, the voltage used is less than 1000 V, dc [11]. Similar to the winding resistance test, these test results are then compared with previous values and the percentage deviation is calculated. If the deviation is less than 5%, the remaining life of power transformer is estimated to be greater than 4 years; otherwise, it is less than 4 years [12].

III. WHAT TO MONITOR?

A major survey carried out on Australian and New Zealand transformers numbering around 3000 over a period of 10 years (1985 – 1995), has shown that [10], winding and winding accessories account for 25% of all failures; tap changers (excluding motor drives) account for another 25%, and 19% failures account for bushings and terminals. In another survey carried out by Doble Engineering Company between 1993 and 1998, it was found [6] that in 43% of all transformer failures the source was the windings, followed by the bushings (19%) and load tap changers (16%). These data indicate that the primary source of all transformer failures is the windings or the active part, followed by tap changers and bushings. Therefore, in a power transformer, the order of monitoring has to be the windings, tap changers and bushings. These three account for more than two thirds of all failures.

IV. How to Monitor?

A. Windings

Gas in oil monitoring has been the most common type of monitoring used for the most common type of fault (winding fault). This can be performed by periodic DGA or using online gas monitors. Use of online gas monitors *and* periodic DGA would verify the accuracy of the online monitoring system [6]. Electrical diagnostic tests carried out on windings include the winding resistance test and the winding insulation resistance test.

B. On load tap changers

On load tap changers (OLTC) have the second highest failure rate among transformer components. At Transpower, the monitoring of tap changers has been according to the number of operations, as specified by the manufacturer. For convenience, Transpower sets a default service interval for each OLTC [13], based on an average number of operations, which matches with the manufacturers' specifications. The default service interval is 4 years. The condition monitoring is based on visual inspection of diverters, selector switches, and drive mechanisms [13].

Elsewhere, condition monitoring of OLTC is based on vibration analysis, DGA and offline non-intrusive electrical tests. Among these, online vibrations analysis tests are becoming popular [14, 15, 16]. The vibrations from each tap changer at each tap whilst it is operating are a footprint for that particular tap changer. Such data can then be stored and compared with online data using wavelet analysis to detect any malfunction [14, 16].

C. Bushings

At Transpower, the condition assessments of bushings is by visual inspection [12] (every 4 years), and by regular diagnostic testing [13] (every 4 years). For the regular diagnostic testing, bushing insulation resistance, and power factor are measured for all the bushings which operate at 66 kV or above [13].

Other methods of condition monitoring of bushings found elsewhere include capacitance and tanδ measurements, polarization and depolarization current (PDC) measurements, DGA, thermographic examination, depolymerisation analysis, partial discharge measurements and moisture analysis.

V. Conclusion

Power utilities, including Transpower, are moving away from the time based maintenance schemes to condition based maintenance to optimize the use of available resources. This comes at a cost of monitoring equipment with DGA being the single most widely used diagnostic test, it is important to accurately interpret the results. Power transformer windings have the highest rate of failure, followed by the OLTC and the bushings. Therefore, condition monitoring of these three components is highly important.

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