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Impact of Load Ramping on Power Transformer Dissolved Gas Analysis

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ABSTRACT Dissolved gas in oil analysis (DGA) is one of the most reliable condition monitoring techniques, which is currently used by the industry to detect incipient faults within the power transformers. While the technique is well matured since the development of various offline and online measurement techniques along with various interpretation methods, no much attention was given so far to the oil sampling time and its correlation with the transformer loading. A power transformer loading is subject to continuous daily and seasonal variations, which is expected to increase with the increased penetration level of renewable energy sources of intermittent characteristics, such as photovoltaic (PV) and wind energy into the current electricity grids. Generating unit transformers also undergoes similar loading variations to follow the demand, particularly in the new electricity market. As such, the insulation system within the power transformers is expected to exhibit operating temperature variations due to the continuous ramping up and down of the generation and load. If the oil is sampled for the DGA measurement during such ramping cycles, results will not be accurate, and a fault may be reported due to a gas evolution resulting from such temporarily loading variation. This paper is aimed at correlating the generation and load ramping with the DGA measurements through extensive experimental analyses. The results reveal a strong correlation between the sampling time and the generation/load ramping. The experimental results show the effect of load variations on the gas generation and demonstrate the vulnerabilities of misinterpretation of transformer faults resulting from temporary gas evolution. To achieve accurate DGA, transformer loading profile during oil sampling for the DGA measurement should be available. Based on the initial investigation in this paper, the more accurate DGA results can be achieved after a ramping down cycle of the load. This sampling time could be defined as an optimum oil sampling time for transformer DGA.

INDEX TERMS Dissolved gas analysis, insulation oil, load ramping, power transformer.

I. INTRODUCTION

Since the Kyoto agreement was ratified by most of the nations, there has been a global common goal for reducing greenhouse gas emissions through adopting more renewable energy sources such as photovoltaic (PV) and wind power generation [1]–[3]. Due to the intermittent characteristics of these sources such as solar irradiations and wind speed fluctuations and impact of diffused solar irradiations resulting from passing clouds, power transformers are expected to exhibit frequent daily generation and load variations [2], [3]. For instance, the daily PV generation profile on a typical distribution feeder in Perth, Western Australia from a range of rooftop PV installations at various locations is shown in Fig. 1. The figure shows a ramped power generation during the day time with a maximum generation at about mid-day that gradually reduces to zero level at sunset. There are however some instantaneous pulsations in the generated power that may be attributed to a passing cloud during the entire generation period.

Dissolved gas analysis (DGA) of transformer oil has been widely accepted as an effective technique to monitor

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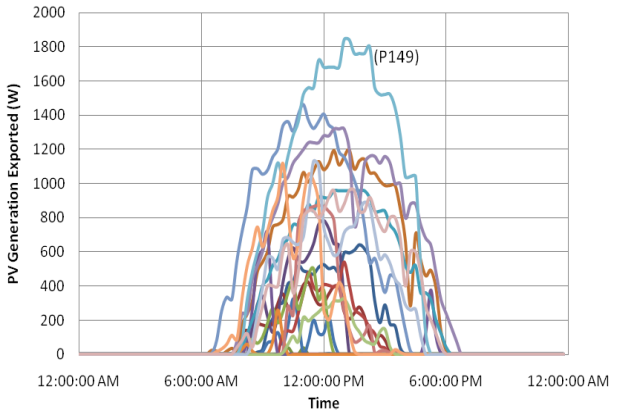

FIGURE 1. Typical daily PV generation at various locations in Western Australian residential sites.

and diagnose the condition of oil-filled power transformers [4]–[6]. Due to the high thermal and electric stresses that the operating transformer insulation system experiences, decomposition of oil and paper takes place and results in chemical by-products that dissolve in the insulation oil and decrease its dielectric strength [7].

These products include gases such as hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6) that are mainly generated due to oil decomposition [8]–[10]. On the other hand, cellulose degradation results in carbon monoxide (CO), carbon dioxide (CO_2) and some furanic compounds [4]. The type and level of each gas can be used to detect various incipient faults within the transformer such as partial discharge, thermal faults and arcing [4].

Partial discharge as a low energy phenomenon generates hydrogen and traceable amounts of methane and ethane [8]. Once high energy discharge has been reached, the phenomenon of arcing emerges in oil, which produces all fault gases especially acetylene [8]. Several guidelines including IEEE C57.104, IEC 60599 and IEC 61464 confirm that combustible gases (except CO_2) dissolved in transformer oil are more representative to indicate the condition of power transformer [11]–[13]. Factors such as metal and deactivators can produce stray gases in transformer oil. However, the tendency of fault gases will not be significantly affected by such stray gassing [14].

DGA measurement can be conducted off line using gas chromatography based on ASTM D3612-02 standards [15] or by using variety of online DGA sensors that are currently available in the market [16]–[18]. Several DGA interpretation methods such as key gas method, Doernenburg, Rogers and IEC ratio methods, and Duval triangle method are currently used by industry practice [19], [20]. While significant research effort has been conducted to improve the accuracy of dissolved gas analysis measurements and interpretation techniques [8], no much attention was given to correlate the oil sampling time with the transformer loading profile. As shown in Fig. 2, instantaneous load ramping leads to an instantaneous variation in the transformer operating temperature [21]–[24]. Practical measurements in Fig. 2 indicate that a 0.4 pu step change in transformer load current during the period 350 min to 550 min results in a temperature change between 50° to 115°. This temperature variation affect the evolution of the characteristic gases dissolved in the transformer oil and hence may result in a false diagnostic of the transformer condition. This will not be due to the inaccuracies of the DGA results but measurements being blinded by momentary variations of gas generation or degeneration.

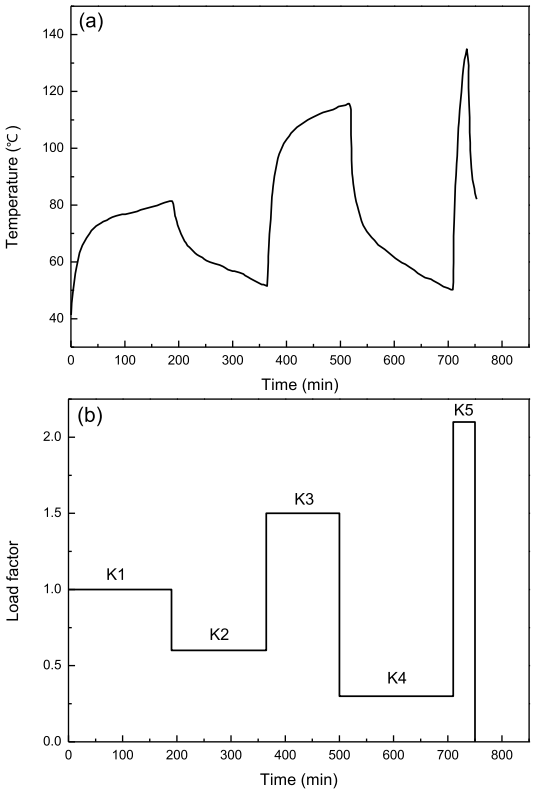

FIGURE 2. Temperature response to step changes in the transformer load current, (a) temperature (b) load current (k is a load factor in pu) [21].

This paper investigates the impact of variable power generation and power market demand on oil filled power transformer gas evolution. In this context, a controllable thermal oil tank embedding paper wrapped-copper conductor samples to emulate an oil-paper transformer insulation system is used to conduct the experiments in this paper. The insulation samples were subjected to temporary linear temperature variation of different slopes to simulate load and generation variations that a real transformer exhibits during its operational life. Three different thermal cycles were used to mimic the nature of PV/wind ramping, cloud coverings and power market fluctuations. In each cycle, three stages are used to extract transformer oil samples for DGA measurement. These stages are: temperature rising that emulates rising PV/wind power or generation increases due to power market demand, constant temperature that emulates stable loading and falling temperature resulting from cloud covering, sudden drop in wind speed or drop in power market demand.

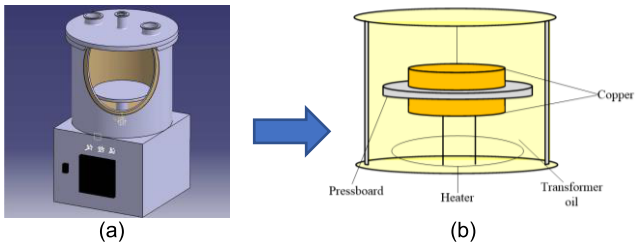

FIGURE 3. (a) Controllable temperature tank and (b) schematic diagram of the experimental setup.

II. EXPERIMENTAL SETUP

Gas chromatography (GC) has been approved by current industry practice to be the most reliable tool to measure dissolved gases in transformer oil. In spite of some disadvantageous such as the complexity of the equipment, the several standards that must be followed in extracting, transporting and storing the oil sample, GC is still a preferred reliable DGA measurement technique for most of worldwide utilities. The experimental measurements in this paper followed the IEEEC57.104-2008 standards to store and transport the transformer oil samples [11]. According to this standard, all oil samples can be stored using calibrated stainless-steel cylinders, flexible metal cans, syringes, or glass bottles that should meet the standards of leak criteria. Amber or clear glass bottles fitted with glass stoppers or screw caps incorporating a pulp board liner face with tin or aluminum foil, can be also used according to ASTM D923-15 standards [25], [26]. Headspace sampler equipped with an injection loop and a line to connect GC was used to measure dissolved gases in oil samples based on ASTM D3612-02 standards, method C [15].

To emulate the insulation system within a power transformer, 25 g circular section of Weidmann T4 insulating paper pressboard with a thickness of 1 mm and diameter of 17 cm is inserted between two identical copper rings of 3 mm thickness and 15 cm diameter each. The oil to pressboard mass ratio is 106:1. The copper-paper set is immersed in 3-liter of transformer insulating mineral oil (Kl50X Karamay or FR3) as shown in the schematic diagram of Fig. 3. Considering gas leakage and security conditions, the 5-liter tank was fully sealed with nitrogen cushion. To remove any residual moisture, the insulating paper pressboard was first placed in a drying oven at a temperature of 105 °C for 48 hours after which the moisture content in the paper was found to be 0.3% based on ASTM D644-09 standards [27]. A brand-new oil was filtered to eliminate any particles using transformer oil filtration system following the IEC 60296-2012 standards [28]. The filtered oil was then filled into a suction flask with a magnetic stirrer of an agitator speed of 400 rpm. In the same time, the oil was heated up to 80° under a pressure of 50 Pa for at least 12 hours after which the moisture in oil was found to be 5 ppm. Moisture in oil sample was measured using Karl Fischer titration method based on ASTM D1533-12 standards [29]. The paper sample was then immersed in the filtered transformer oil at 48 °C for 48 hours under vacuum conditions to fully impregnate the paper pressboard.

The experimental specimen including the oil, paper and copper rings was then placed in a controllable temperature tank as shown in Fig. 3. To emulate load ramping, the temperature of the specimen was raised from 25° to 60° at a rate of 0.0714°/s. During this stage, oil samples were pumped out from the tank at 30°, 40° and 50° for DGA measurements. When the temperature of the oil reached 60°, it was maintained for 2 hours and oil samples were pumped out from the tank three times at 30 min intervals. The thermal controllable tank was turned off after these 2 hours to allow ramping down of the oil temperature and oil samples were pumped out again during this stage when the oil temperature reached 50° and 30°. This heating process is shown schematically in the first cycle of Fig. 4. To investigate the effect of oil temperature and its rate of change on the gas evolution, the temperature

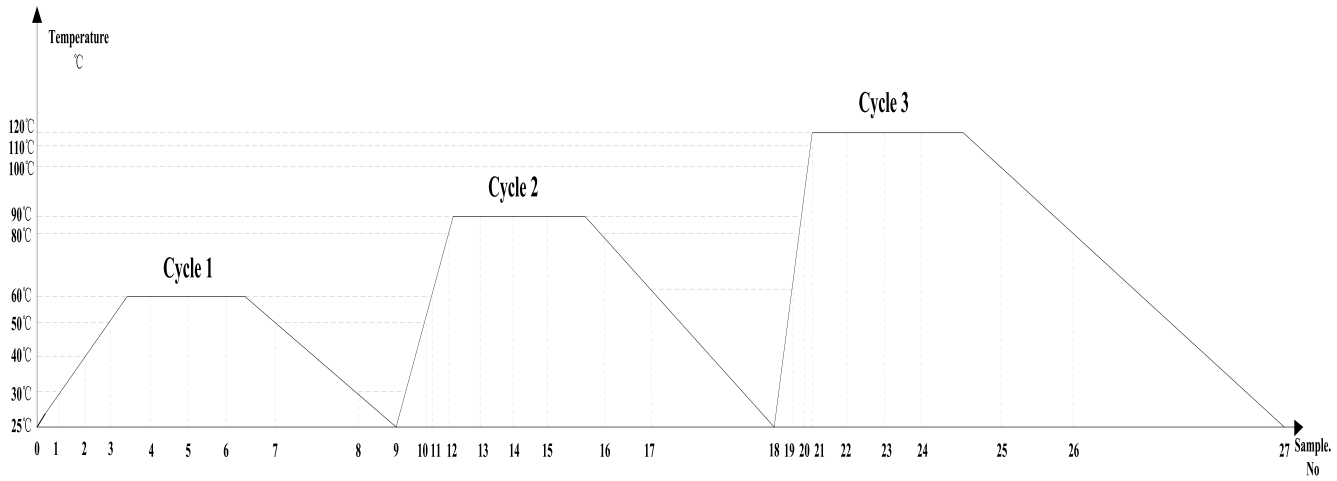

FIGURE 4. Thermal cycles used to emulate power transformer generation and load ramping.

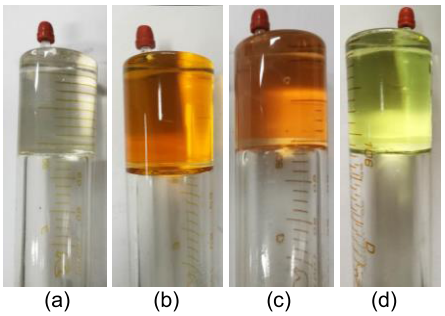

FIGURE 5. Oil samples used in the experiment (a) brand-new mineral oil (b) aged mineral oil #1 (c) aged mineral oil #2 (d) brand-new FR3 fluid.

of the same specimen was raised from 25° to 90° at a rate of 0.208°/s. During the temperature rising stage, oil samples were pumped out at oil temperatures of 50°, 60° and 80° for DGA measurements. When the temperature of the oil reached 90° it was maintained at this level for 2 hours and oil samples were pumped out three times every 30 min. Similar to the previous cycle, after 2 hours, the thermal controllable tank was turned off to allow the cooling down of the investigated oil. During this cooling down stage, oil samples were pumped out when the oil temperature reached 80° and 60°. This process is shown in the second cycle of Fig. 4.

The third heating cycle in Fig. 4 shows oil temperature rise from 25° to 120° at a rate of 0.225°/s after which the oil temperature was maintained at 120° for 2 hours, then the thermal controllable tank was turned off. Similar to the above two cycles DGA was performed on oil samples that were pumped out at 60°, 90° and 110° during thermal ramping up and 3 samples at 30 min intervals when the oil temperature was maintained at 120°.

During the cooling down stage, two oil sample were pumped out at 100° and 80° for DGA measurements. This process was conducted using a brand-new mineral oil and FR3 fluid as well as mineral aged oil as shown in Fig. 5.

III. EXPERIMENTAL RESULTS

Fig. 6 shows the DGA results for the 27 brand-new mineral oil samples that were pumped out during the three heating cycles along with the reference DGA measurements for the new oil. The investigated reference new oil (sample number 0 in Fig. 6) comprises zero ppm of all dissolved key gases. Results show that all characteristic gases are impacted by the momentary thermal change in the entire thermal cycles and hence generation and load ramping in real transformer operation. For instance, CH_4 concentration is increasing from the reference level (0 ppm) to 10 ppm when the temperature increases from 25° to 30° after which it slightly reduces and stabilizes at a level of 6 ppm when the temperature is maintained at 60°. The same pattern is repeated in the second and third cycle as shown in Fig. 6(a). Also, it can be observed that the concentration of CH_4 does not settle down to the original reference value after each heating cycle.

During the entire process the CH_4 average increment is found to be 0.052 ppm/°. As shown in Fig. 6(a), CH_4 is increasing from 0 ppm to 3.4 ppm, at the end of first cycle, 7.46 ppm at the end of the second cycle and to 13.98 ppm at the end of the third heating cycle. Fig. 6(b) shows that C_2H_4 exhibits a continuous increment with a slight drop at the end of each ramping stage. The concentration of C_2H_4 has been increased from 0 ppm at the beginning to more

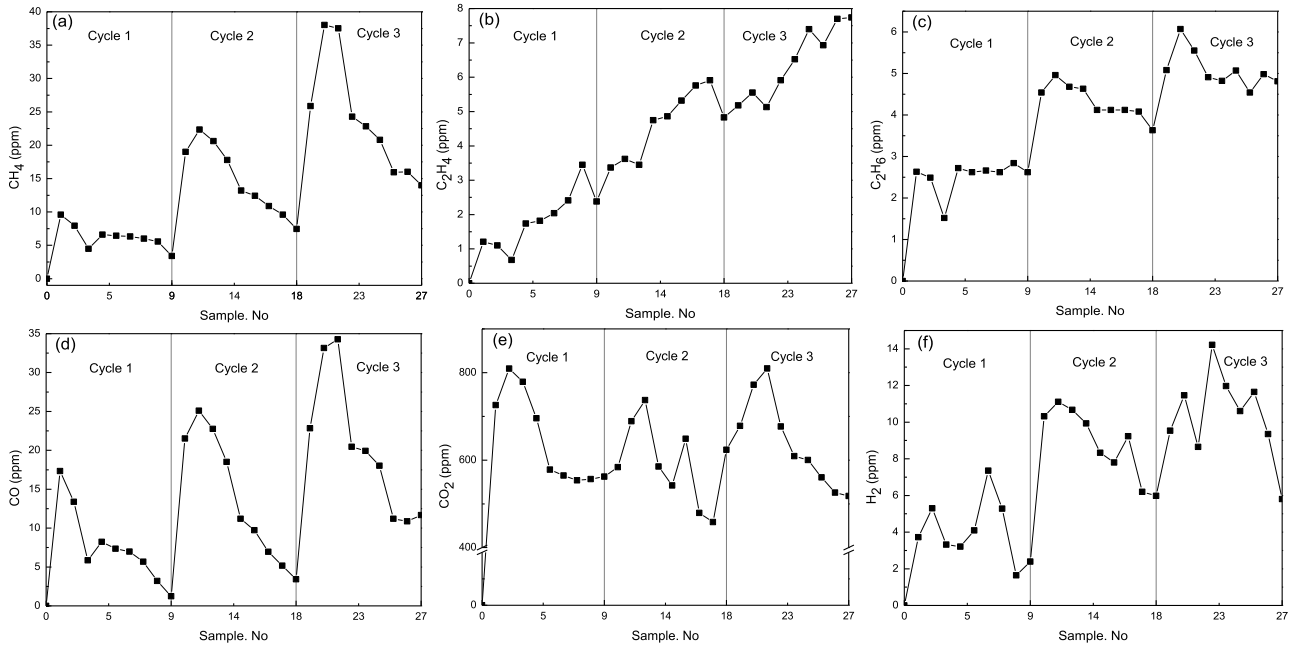

FIGURE 6. Changes in dissolved characteristic gases in mineral oil due to the thermal ramping pattern shown in Figure 4.

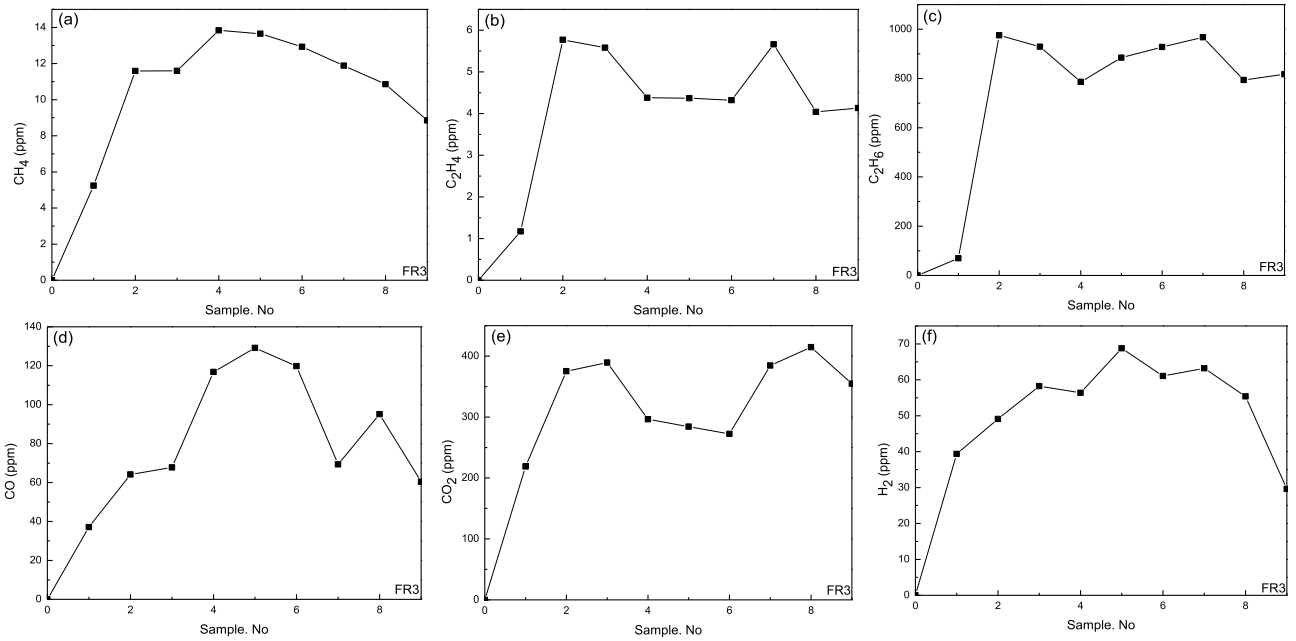

FIGURE 7. Changes in dissolved characteristic gases in FR3 due to the thermal ramping pattern of cycle 3 shown in Figure 4.

than 7.5 ppm at the end of the three thermal cycles. C_2H_6 pattern shown in Fig. 6(c) is almost following the thermal three cycle patterns. This gas exhibits an overall increment of 4.81 ppm over the entire ramping process. Fig. 6(d) shows that CO concentration is reducing with the cooling down stages in the three cycles. However, it does not settle down to the reference value as it records 1.23 ppm at the end of cycle one, 3.41 ppm at the end of cycle two and 11.67 ppm at the end of cycle three. The CO_2 pattern in Fig. 6(e) is similar to the CO pattern. The significant increase in CO_2 may be attributed to some atmospheric leak or oil oxidation during the experimental measurements. Fig. 6(f) shows that H_2 is fluctuating between maximum and minimum levels during the three thermal cycles. Cycle 3 in the thermal pattern shown in Fig. 4 is conducted to investigate the effect of thermal ramping on FR3 fluid. Comparing the results in Fig. 7 by that in Fig. 6 reveals the similar trend of gases changes in FR3 fluid and mineral oil. It can be observed that at the end of the thermal cycle, each gas will settle at a different level than the beginning of the cycle. Also, the evolution of all gases almost follows the thermal pattern of cycle 3 in Fig. 4. Table I shows the increment of each gas concentration for the three stages; ramping up, leveled and ramping down during each thermal cycle. Numerical results in Table I reveal that, any variations in the operating temperature will lead to a variation in the concentration of all characteristic gases. The gas evolution depends on the type of gas, range and rate of temperature change. This can be clearly observed in Table II that shows the rate of generation of each gas for each 1° change in the operating temperature based on the following equation:

$$\text{Gas evolution} = \frac{C_f - C_i}{T_{max} - T_{min}} \tag{1}$$

where C_f and C_i are the final ppm of each gas at the end and beginning of the entire thermal cycle, respectively; T_{max}, T_{min}

TABLE 1. Increment of each gas during the three stages of each thermal cycle.

Gas	Mineral oil (ppm)									FR3 (ppm)		
	Cycle 1 Maximum temperature 60 °C			Cycle 2 Maximum temperature 90 °C			Cycle 3 Maximum temperature 120 °C			Cycle 3 Maximum temperature 120 °C		
	Ramp up	Stay put	Ramp down	Ramp up	Stay put	Ramp down	Ramp up	Stay put	Ramp down	Ramp up	Stay put	Ramp down
CH_4	4.49	-0.28	-2.59	17.22	-5.36	-3.41	30.06	-3.46	-5.56	11.6	-0.91	-3
C_2H_4	0.68	0.3	-0.03	1.07	0.63	-0.93	0.3	1.49	0.81	5.58	-0.06	-1.53
C_2H_6	1.52	-0.06	0	2.06	-0.51	-0.49	1.92	0.16	0.27	929.09	141.52	-150.27
CO	5.85	-1.25	-4.45	21.53	-8.78	-3.54	30.87	-2.43	0.47	67.78	3	-8.99
CO_2	779.1	-130.93	8.98	175.59	63.31	144.07	186.12	-76.7	-42.72	389.28	-24.04	-29.85
H_2	3.32	4.14	-2.89	8.28	-2.13	-3.25	2.67	-3.62	-5.85	58.22	4.67	-33.58

TABLE 2. Rate of gas generation after each entire thermal cycle.

Gas	Mineral oil (ppm/°C)			FR3 (ppm/°C)
	Cycle 1	Cycle 2	Cycle 3	Cycle 3
CH_4	0.097	0.062	0.069	0.086
C_2H_4	0.068	0.038	0.031	0.043
C_2H_6	0.075	0.016	0.012	8.601
CO	0.035	0.034	0.087	0.635
CO_2	16.605	0.942	-1.112	3.839
H_2	0.068	0.055	-0.002	0.312

are the maximum and minimum temperature of the entire thermal cycle, respectively.

Table II shows that the maximum gas evolution in mineral oil due to the emulation of load ramping is observed in carbon dioxide during the first thermal cycle while hydrogen exhibits the least evolution as can be seen in the third thermal cycle. On the other hand, C_2H_6 exhibits the maximum generation rate for FR3 fluid while C_2H_4 shows the lowest generation rate. It is to be noted that C_2H_2 did not exhibit any change for all investigated brand-new oil samples (mineral oil and FR3 fluid). Results in Table II reveals that each gas concentration will exhibit a change due to the increase or decrease in the operating temperature due to load variation. To validate this claim, the investigated specimen with a brand-new FR3 sample was subjected to one heating cycle with a small temperature rise from 25° to 28°. The temperature of the oil was maintained at 28° for an hour after which it was cooled down to 25° again. Oil samples for DGA were pumped out at 25° (reference sample that shows almost zero ppm for all gases) during thermal ramping up and 2 additional samples were extracted at 30 min intervals when the oil temperature was maintained at 28°. During the cooling stage, one more sample was extracted at 25° again to be compared with the reference sample. Results of this case study are shown in Fig. 8 which reveals a variation in all characteristic gases even with such small operating temperature variations. Fig. 9 shows a comparison between the patterns of the characteristic gases generated in brand new mineral oil and two aged mineral oil samples during the third thermal cycle of Fig. 4.

The DGA has been performed on the two aged oil samples similar to the brand-new oil described above. Fig. 9(a) shows that a temperature changes from 25° to 120° results in an increase in CH_4 by 6.52 ppm for the brand-new oil while the increase in the same gas is 41.18 ppm and 25.51 ppm for the two aged oil samples, respectively. The CH_4 patterns for the three oil samples used in the investigation are almost similar with a change in the generation rate and the final concentration. This observation is applied for all other gases including C_2H_2 that was detected in the aged oil samples. As shown in Fig. 9(g), acetylene was not detected in the new oil. The oil-paper sample should undergo a prolonged severely overheating condition to detect a traceable amount of acetylene. It is also to be noted that in the early aging stage of the new oil, dissolved gas generation may not be stable as can be seen in the generation of methane and ethylene in Fig. 9(a) and (b), respectively.

IV. DISCUSSION

It is noted that ethane exhibited a significant increase in FR3 fluid as shown in Fig. 7(c) and 8(c). This is attributed to the fact that ethane can be produced from non-fault condi-

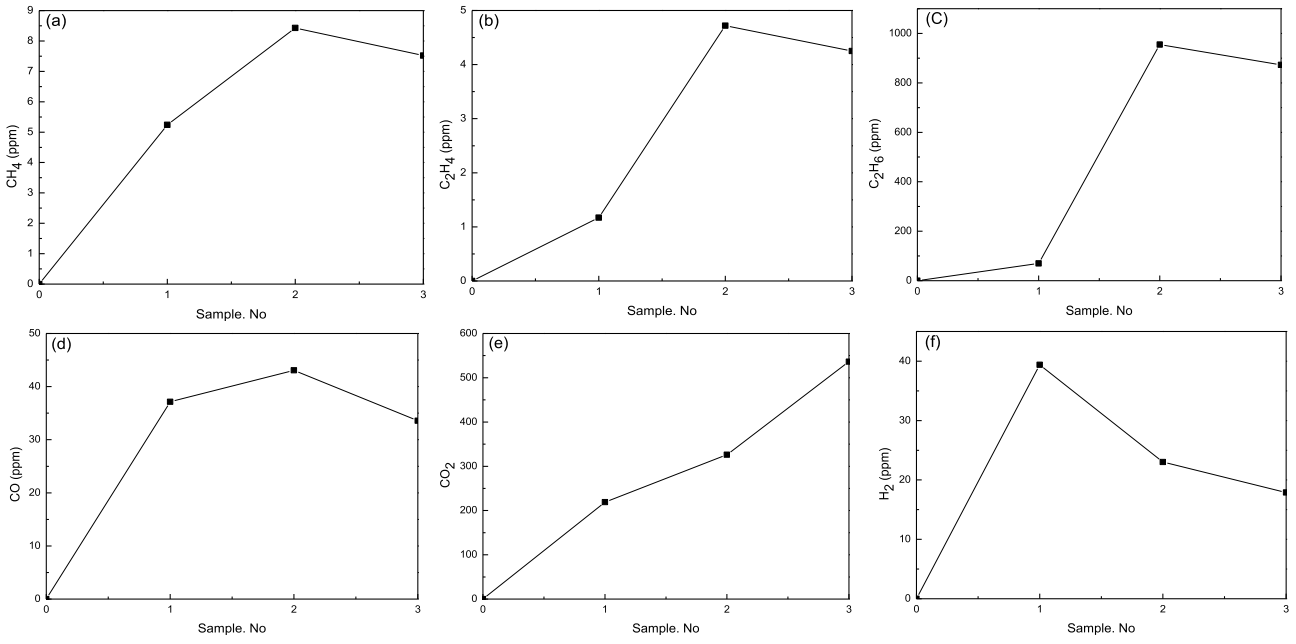

FIGURE 8. Changes in dissolved characteristic gases in FR3 for a temperature change from 25° to 28°.

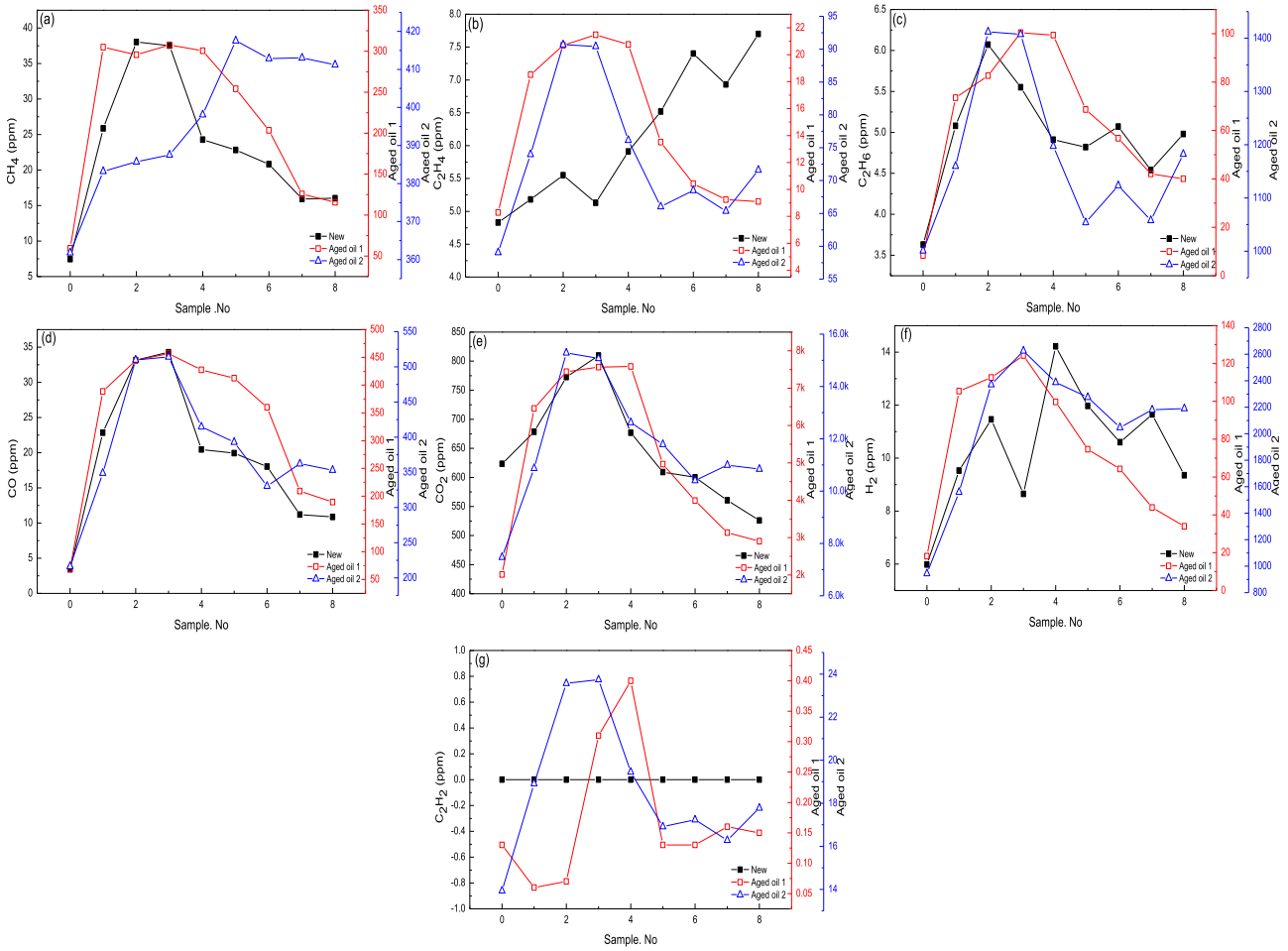

FIGURE 9. **Changes in dissolved characteristic gases in new and 2-aged mineral oil samples due to the thermal ramping pattern of cycle 3 shown in Figure 4.**

tions. For instance, linolenic acid content in ester oil produces ethane as a by-product of oxidation [30], [31].

Karamy mineral oil used in this experiment consists of divergent hydrocarbon molecules that makes the physics of gas formation during thermal aging process hard to explain. Fundamentally, thermal stress can break the C-H and C=C bonds of the oil molecule to form active hydrogen atoms and hydrocarbon fragments. The dissolved gases are then produced by the combination of these free radicals under continuing decomposition process [11], [30]. Although the chemical structure of FR3 fluid is different from mineral oil, the fundamental gas formation process in FR3 fluid is quite similar to mineral oil. The detailed gas formation mechanism in transformer oil has been presented in the literatures [32], [33].

It is to be noted that gas solubility depends on several factors including the type of gas and the solvent it dissolves in as well as on the operating temperature and pressure. Depends on all of these factors, gases solubility may increase or decrease with the temperature change. According to Henry's law, if the temperature goes up, the solubility of gases in transformer oil may increase, decrease or not be affected [34]. At constant temperature, the solubility of the gas is proportional to its partial pressure which may be the cause of gas decrement during constant temperature cycles as seen in the results above. Solubility of each gas during thermal ramping up or down cycles depends on combination effects of temperature, pressure and other chemical byproduct in the oil. In addition, in order to mimic transformer real operation, insulating paper was used in all experiments which will add another effect on gas solubility. According to gas isothermal adsorption [35], under constant temperature condition, the gas partial pressure increases and the adsorption capacity of insulating paper to gases also increases. This means that the distribution ratio of the gas in the oil will decrease. In the conducted experiments, it is assumed that the effect of insulating paper adsorption contributes to the decreasing trend of dissolved gases during stable and cooling down thermal cycles.

In general, the above results confirm the strong correlation between load ramping and the rate of gas generation within transformer oil. As such, measurement of dissolved gases

within transformer oil, in particular using online sensors that continuously detect such gases in real time, must be compensated according to this correlation for accurate diagnosis. Without such compensation, a false diagnosis is most likely to be reported as continuous gas evolution due to load ramping even with a small amount will be interpreted as a fault. Initial investigation in this paper proposes that, appropriate oil sampling time is during a stable load after a cooling down thermal ramping. This implies that oil sampling for DGA must be correlated to the transformer loading profile. For accurate DGA results, oil should be sampled during a stable nominal transformer load. However, further research efforts need to be conducted to quantify this correlation and identify ideal DGA oil sampling time for several in-service transformers of various loading and operating conditions.

V. CONCLUSION

As the transformer load ramping and DGA correlation has not yet been given much attention at the research and industry practice levels, this paper presents an initial investigation to explore such correlation. Experimental results indicate that load and generation ramping lead to a change in the transformer operating temperature. Temperature change even in a small range affects the generation rate of all key gases. The gas evolution depends on the gas type and temperature rate of change. Aged oil samples are more sensitive to load ramping than new oil. Results also show that mineral oil and natural ester (FR3) fluid have almost similar trends when subjected to the same thermal cycles.

To avoid false transformer online/offline DGA-based diagnosis, load variation during oil sampling time must be recorded and compensated. According to the initial experimental results in this paper, it may be more accurate to extract oil samples for DGA during a stable transformer nominal load.

The trend of gas evolution during a stable and cooling down stages along with a quantified correlation between each gas evolution and load ramping for accurate compensation need further investigation in the future research work.

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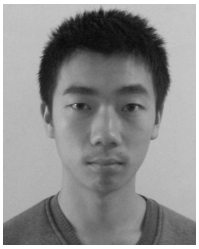

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