International Journal on Electrical Engineering and Informatics - Volume 5, Number 2, June 2013

Comparison between Online and Laboratory Measurements of Fault Gases for Mineral Oil and Natural Ester

Zhongdong Wang[1], Xiao Yi[1], Xin Wang[1], Sitao Li[1], John V. Hinshaw[2], John Noakhes[3]

[1]The University of Manchester, Manchester, UK, [2]BPL Global, Beaverton, Oregon, USA,
[3]TJ|H2b UK Laboratory, Chester, UK
zhongdong.wang@manchester.ac.uk, john.hinshaw@serveron.com, jnoakhes@tjh2b.com

Abstract: Dissolved gas analysis (DGA) is a well-approved technique to diagnose incipient faults in liquid-filled transformers. It is usually performed by periodically sampling liquids from power transformers and analyzing the dissolved gases in laboratories. In the past decade, the emergence of multi-gas online monitors avails a much timelier monitoring for transformers. However, it is still not certain whether the monitor readings are accurate and reliable and whether they agree with laboratory results. This raises additional concerns when applying natural esters in power transformers. This paper comparatively studied the lab and online fault gas measurement results of a mineral oil and a natural ester under various faults, including thermal faults, partial discharge faults and sparking faults. The results show that the online gas measurement results agree with the laboratory analysis generally within an error of 30%. Gas leakage or air ingression might occur during the transport of liquid samples for laboratory analysis. Therefore, liquid samples should be analyzed as soon as sampled for laboratory analysis.

Keywords: Dissolved gas analysis (DGA); Power transformers; Mineral oil; Natural ester

1. Introduction

Transformers are one of the most critical and cost-intensive components in the electrical power system. In order to ensure their safe operations, extend their lives and reduce their maintenance cost, the operational conditions of power transformers should be closely monitored. Dissolved gas analysis (DGA) is a well-known and approved technique to diagnose the incipient faults in liquid-filled transformers [1].

Recently, natural ester fluids (vegetable oils) are increasingly used in distribution transformers to substitute mineral oils. The established DGA interpretation methods for mineral-oil-filled transformers should be revised for the application to natural-ester-filled transformers. Our previous research have identified that under thermal faults, the fault gases generated in the natural ester are similar to those generated in the mineral oil; however, the generation rate of dissolved gases in the natural ester is slightly lower than in the mineral oil, and the natural ester is particularly stable under medium-temperature thermal faults. Ethane is generated in the natural ester if exposed to oxygen under normal operating temperatures (<140°C); under thermal faults up to 600°C, ethane and carbon oxides account for more than 70% of fault gas generation [2]. Under PD faults and under sparking faults, the key gases generated are hydrogen and acetylene, in both the mineral oil and the natural ester. Under PD faults, the total volume of fault gases was more than 50 times higher in the natural ester than in the mineral oil, due to the higher rate of PD occurrence. The total volume of fault gases per unit fault energy is similar for the two liquids [3].

So far, DGA has been performed mostly by periodically sampling liquids from power transformers and analyzing the dissolved gas components in laboratories, using standardized

---

Received: October 24th, 2012. Accepted: March 14th, 2013

methods for the extraction and analysis. However, with a large number of the transformer population soon approaching the end of their designed life [4], more frequent inspections including DGA monitoring should be carried out in order to ensure the timely diagnosis of incipient faults and implement necessary maintenance plans. At some point, laboratory DGA analysis becomes less attractive, concerning the economic importance and safe operations of power transformers. In the past decade, an increasing number of multi-gas online monitors have become commercially available, and some monitors were installed on old transformers to continuously monitor their condition [5]. These on-line monitors allow the continuous detection of abnormal gassing in service in comparison to regular laboratory analysis, and they are also relatively robust with an expected cost effective life span. However, it is still unknown whether the monitor readings agree with the laboratory results for the same transformer fault, or whether the monitor results are accurate and reliable. This is particularly pertinent with regard to the recent wide application of natural esters as dielectric fluids in power transformers, as DGA analysis procedures for natural esters differ to that of mineral oils. For example, the gas solubility coefficients used in the headspace gas extraction methods should be carefully determined for natural esters. This requires a credible comparison to be made between the results of online monitor and laboratory analysis.

This paper comparatively studied the online and laboratory gas measurement results of a mineral oil and a natural ester under various faults. A Serveron® TM8™ transformer DGA monitor, manufactured by BPL Global, with Headspace Gas Extraction and Gas Chromatography (GC) methods was assessed in the tests. Standard laboratory gas analysis was provided by TJH2b analytical laboratory. Since faults in operating power transformers are usually caused by high electrical and/or thermal stresses [6], the faults investigated in this paper include high-temperature thermal faults, partial discharge (PD) faults, and sparking (interrupted breakdown) faults.

2. Test Description

A. Test Liquids

Two types of transformer liquids were investigated, namely a mineral oil (Nytro Gemini X produced by Nynas), and a natural ester (Envirotemp FR3 produced by Cargill). The mineral oil mainly consists of hydrocarbon molecules, such as paraffins, naphthenes and aromatics; whereas FR3 is a type of triglyceride-fatty acid ester and it is refined from soya bean oil.

The fluids used for the study were stored in a cool and ventilated area upon receipt from the manufacturers. Prior to test, the as-received samples were dried and degassed in a vacuum oven at 80° C and less than 5 mbar for 48 hours. An additional 24 hours were given for the samples to cool down to ambient temperature under vacuum condition before the tests.

B. Experimental Setup

B.1. Localized Thermal Faults

The experimental circuit for the thermal tests is identical to the one used in [2]. The setup sketch is shown in Figure 1.

A load transformer supplied a large current through power cables rated at 700 A; a high temperature was obtained when the current flowed through the "W" shaped copper heating element. The variac and clamp current meter were used to control and maintain the target temperatures. During the test, the temperature of the heating element was measured by two K-type thermocouples. The thermocouple tips were inserted into the small holes drilled in the heating element for a better contact between the sensor tip and the heating element. The measured temperatures of the two thermocouples were similar with the differences less than 20 °C during the test.

The cylinder shaped test vessel was made of transparent Perspex, and the inlet and outlet of the test vessel were connected to an on-line TM8 gas monitor, providing a sealed path for the liquid circulation. The overall volume of liquid in circulation was 2.73 L.

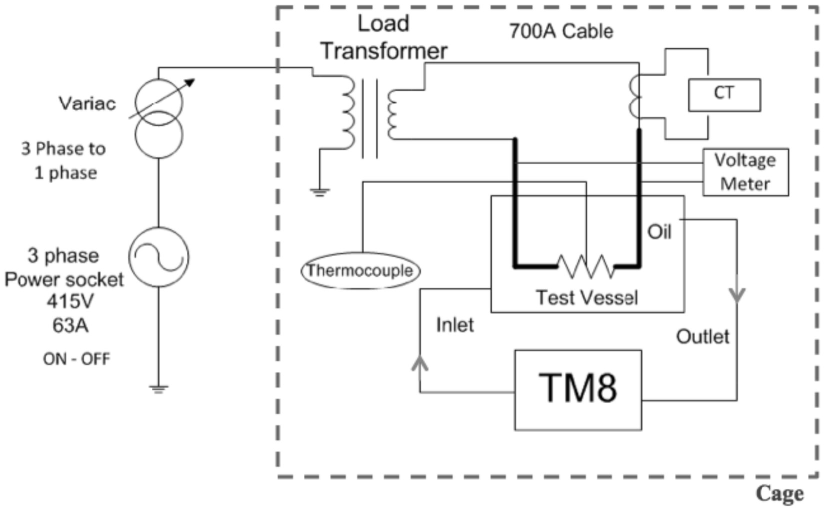


Figure 1. Test setup for thermal test.

B.2. Electrical Faults

The experimental circuit for the electrical test is identical to the one used in [3]. The setup sketch is shown in Figure 2.

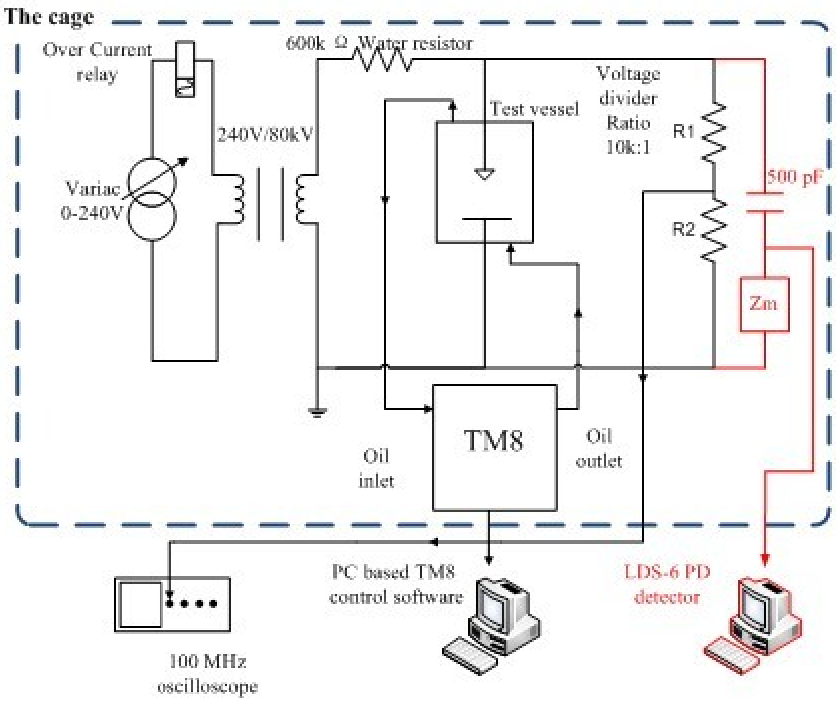


Figure 2. Test setup for electrical test.

In the PD tests, a discharge-free transformer supplied 50 Hz ac voltages up to 80 kV. The applied voltage was measured by a voltage divider connected in parallel with the test vessel. A 600 kΩ water resistor was connected between the high voltage output and the test vessel in order to reduce the current and damage to the liquid samples when a breakdown occurs. An over-current protection relay was set to trip off the power source when the primary side current exceeded 6.5 A. A needle-plate electrode was used to initiate PDs. The needle was made of steel and with a tip curvature of 700 µm, and the ground electrode was a brass plate with a diameter of 2 cm. The gap distance was 50 mm. A 500 pF coupling capacitor and measuring impedance were connected in parallel with the container to measure the PD apparent charge; the apparent charges were recorded by a LDS-6 PD detector. Before the test, the background noise was measured and ensured less than 50 pC up to 70 kV.

In the sparking tests, the circuit branch for apparent charge measurement (marked in red) was disconnected. The gap distance was reduced to 35 mm. The over-current protection relay was set at 5 A for a more sensitive interruption when a breakdown occurred.

The test vessel was connected with the on-line TM8 DGA monitor, forming a sealed liquid circulation system with a volume of 2.57 L.

C. DGA Measurement Methods

The amounts of generated fault gases were measured both by the TM8 online gas monitor and in the analytical laboratory using the standardized methods.

C.1. Online DGA Method

When the fault gases were produced by the simulated faults, the liquid was circulated in the sealed system and passed through a TM8 gas monitor. The TM8 monitor continuously detected the type and amount of faults gases generated every hour. After the experiment, the TM8 was kept running for a further three hours in order for the fault gases to thoroughly dissolve in the liquid or reach equilibrium between the headspace and liquid phases. For each test, the gas amount was reported here as the instantaneous value just before the liquid or free gases were sampled by syringes for laboratory analysis.

The TM8 monitor extracted the dissolved gases through a gas-liquid membrane extractor, using a headspace equilibrium method, so that the amount of dissolved gases in the liquid phase could be identified from the amount of gases in the gas phase when an equilibrium state was reached. After that, the concentrations of fault gases in the gas phase were determined by a built-in gas chromatography (GC). The gases passed through a series of GC columns, in which the different gases were separated with helium carrier gas, in accordance with IEC 60567 [7]. The concentrations of separated gases were detected by a specialized high-sensitivity thermal conductivity detector (TCD) that met or exceeded the sensitivity requirements of IEC 60567. Finally, the gas concentration in the headspace phase was calculated back to the concentration of dissolved gas in the liquid. The influence of temperature and pressure was also considered in the calculation. During the experiments, system calibration was performed weekly.

C.2. Laboratory DGA Method

After obtaining the online DGA results, the liquid samples and free-state fault gases were also sampled in syringes and send to the analytical laboratory for analysis. The analysis procedure strictly followed the IEC 60567 [7]. At first, the dissolved gases in the liquid samples were extracted by Toepler pump with multiple cycles. Then the type and amount of gases were determined by gas chromatography. Although a flame ionization detector (FID) was used for the lab measurement of hydrocarbon gases, the detected gassing levels generally ran at least several times the minimum quantifiable amounts of the on-line monitor's TCD such that the incrementally greater sensitivity of the laboratory FID did not influence the comparative results.

3. Comparison Results

The fault gas generations of both Gemini X and FR3 were studied using both online and laboratory DGA analysis under thermal and electrical faults including both partial discharge and sparking faults. These faults were simulated under laboratory conditions.

A. Comparison under Simulated Thermal Faults

The thermal test simulated the hot-spot areas in power transformers. In this test, Gemini X was used as the sample liquid. The applied current was increased slowly and sustained until the fault temperature reached 400 ºC. Then, the thermal fault was kept at 400 °C for 5 minutes and then the current was cut off. One hour later, another test was conducted again by increasing the current until 400 °C was shown by the thermocouples; however, only after 50 seconds, a significant amount of fault gases were produced and 36 mL of free gases were collected by the syringe connecting with the test vessel.

In the next five hours, TM8 measured the gas concentrations every hour. The measured values reached a maximum level at the third hour after the test, and then leveled off during the next two hours before dropping, indicating the equilibrium of the generated fault gases was reached between the liquid and headspace phases during the third and fifth hours after completion of the test. Then the liquid and free gasses in the test vessel were sampled and immediately sent to the analytical laboratory. Due to the transportation delay, the fault gas concentrations were measured in the laboratory 8 hours later. Table 1 shows the online and lab analysis results for dissolved gases under thermal fault.

Table 1. Online and Lab Results for Dissolved Gases in Gemini X under Thermal Fault Conditions

		Online DGA	**Lab DGA**	**Deviation value/Lab value**
Gases (ppm)	**O_2**	14752	25164.5	41.4%
	CO	187	88	112.5%
	CO_2	1164	995.5	16.9%
	H_2	946	926	2.2%
	CH_4	2967	3823.5	22.4%
	C_2H_6	1061	898.5	18.1%
	C_2H_4	6150	6343.5	3.1%
	C_2H_2	59	61	3.3%

As can be seen in Table 1, the key gases for the thermal faults at and above 400 °C are C_2H_4, CH_4 and H_2 which conforms to a previous study [8]. C_2H_6 also existed in significant amounts.

When comparing the online and lab DGA analyses, it can be seen that the amounts of fault gases are similar, with the deviations for most fault gases within 15 %, except for CO, O_2 and CH_4. The amount of CO from laboratory analysis was only half that obtained by the TM8, which might be caused by gas leakage during transportation due to the low solubility of CO. On the other hand, the amount of O_2 from laboratory analysis was twice that obtained by the TM8, which might indicate air ingression during the transport delay. The deviation of measured values of CH_4 between laboratory and TM8 might be attributed to the different gas extraction methods used; laboratory measurement used a Toepler pump to extract essentially all of the dissolved gases, whereas the TM8 uses headspace extraction which is closely dependant on the Ostwald coefficients used.

Table 2 shows the online and lab results of free gases under thermal fault. It also shows that the gas amounts measured by laboratory analysis and TM8 were reasonably comparable, although the deviations between the two methods were more pronounced for free gas measurement than for dissolved gas measurement as shown in Table.1, because the gases in the free state can leak and escape more easily from the syringe than the gases dissolved in liquids. Similar to the case of dissolved gases, the differences between the two methods were more obvious for CO, O_2 and CH_4 than the other gases, probably due to the same reasons as for dissolved gas measurement: easier gas leakage for less soluble gases CO and CH_4 and O_2 ingression into the syringe.

Table 2. Online and Lab Results of Free Gases for Gemini X under Thermal Fault Conditions

		Online DGA	**Lab DGA**	**Deviation value/Lab value**
Gases (ppm)	**O_2**	125281	175855	28.8%
	CO	1694	784	116.1%
	CO_2	1132	981	15.4%
	H_2	22082	14387	53.5%
	CH_4	11774	8764	34.3%
	C_2H_6	478	389	22.9%
	C_2H_4	4746	4157	14.2%
	C_2H_2	60	69	13.0%

B. Comparison under Simulated PD Faults

In the PD test, Gemini X was taken as the sample liquid. In the preliminary test, it was found that for Gemini X, when the applied voltage was lower than 55 kV, only the PDs occurring in positive half cycles could be detected by the LDS-6 PD detector, and the PD repetition rate was less than 100 per minute, with a PD power less than 0.17 mW. Due to the low PD repetition rate and low PD power, in order to generate sufficient fault gases, the applied voltage was sustained for 23 hours while the maximum PD magnitude remained at 2000 pC and then the voltage was further increased and maintained for 21.5 hours while the PD magnitude remained at 4000 pC. During the experiment, no free gas bubbles were observed during the test. After the PD test, the gas components were measured by both lab analysis and online monitor for comparison. The lab DGA results were obtained 7 days later.

Table 3 shows the online and lab results of dissolved gases in Gemini X under PD faults. The amount of fault gases generated from long-term PD faults was much smaller than that produced under thermal faults. This denotes that in power transformers, usually a PD fault has been active for a long time before it can be detected by DGA diagnosis. The result also shows that both H_2 and C_2H_2 were produced in larger amounts than other hydrocarbon gases and should be the key indicator gases for PD faults. The PDs produced in the test were of low energy type, rather than corona type discharges; because corona type discharges usually correspond to PDs with magnitudes of less than 100 pC, and they are characterized by only H_2 [9 , 10]. The amounts of fault gases are reasonably close between online and lab DGA methods, with a deviation of 30% which was probably introduced by the delay between the sampling and the laboratory analysis.

Table 3. Online and Lab Results of Dissolved Gases in Gemini X under PD Fault Conditions

		Online DGA	**Lab DGA**	**Deviation value/Lab value**
Gases (ppm)	**O_2**	18118	20513	11.7%
	CO	9	10	10.0%
	CO_2	498	928	46.3%
	H_2	46	58	20.7%
	CH_4	23	22	4.5%
	C_2H_6	12	9	33.3%
	C_2H_4	12	15	20.0%
	C_2H_2	41	36	13.9%

C. Comparison under Simulated Sparking Faults

For sparking fault tests, FR3 was used as the sample fluid. Since the over-current relay could operate and trip off the power supply within 50 ms in a breakdown, the energy dissipation during the breakdown event was limited. 15 breakdown tests were conducted so that sufficient fault gases were produced in the liquid. After the test, the lab analysis results were obtained within 16 hours.

Table 4 shows the online and lab analysis results of dissolved gases under sparking faults. As can be seen, for a sparking fault in FR3, C_2H_2 accounts for the most part of the hydrocarbon gases, and H_2 was also produced in a significant amount. It is also shown that the hydrocarbon gases in the lab analysis results are relatively similar to the online results, within a deviation of 20 %. However, the lab results for O_2 were higher, and for CO and CH_4 lower than the online result, which might be attributed to air ingression and loss of volatiles during the transportation and delay between sampling and laboratory analysis.

Table 4. Online and Lab Results of Dissolved Gases in FR3 under Sparking Test Conditions

		Online DGA	**Lab DGA**	**Deviation value/Lab value**
Gases (ppm)	**O_2**	14190	59060	76.0%
	CO	54	34	58.8%
	CO_2	513	592	13.3%
	H_2	80	59	35.6%
	CH_4	12	8	50.0%
	C_2H_6	3	3	0.0%
	C_2H_4	24	19	26.3%
	C_2H_2	197	151	30.5%

After 45 breakdowns, no free gas headspace was observed. However, after the TM8 monitor was kept running for three days, a headspace emerged gradually in the circulatory system, which might be caused by slow but accumulative air ingression. After air got into the circulatory system, it generated a headspace above the liquid, which further helped the dissolved gas to dissipate into the headspace and become free gases. The TM8 measured the gas concentrations in the headspace; the headspace gases were sampled and after four hours, measured in the analytical laboratory.

Table 5 shows the online and lab results for the free gases collected in the headspace. It can also be seen that the amounts of fault gases are similar between the two gas analysis methods, with very small deviation. When compared with Table 2, it can also been deduced that the deviation between the results from the online monitor and laboratory analysis depends upon the sealing efficiency of individual sample syringe, especially when the delay between sampling and laboratory analysis is longer.

Table 5. Online and Lab Results of Free Gases in FR3 under Sparking Fault Conditions

		Online DGA	**Lab DGA**	**Deviation value/Lab value**
Gases (ppm)	**O_2**	106737	147125	27.5%
	CO	601	635	5.4%
	CO_2	417	441	5.4%
	H_2	3037	2922	3.9%
	CH_4	53	58	8.6%
	C_2H_6	1	1	0.0%
	C_2H_4	23	24	4.2%
	C_2H_2	111	114	2.6%

Conclusions

This paper compares online and laboratory gas measurements under simulated thermal faults and electrical faults. Gemini X and FR3 were used in these tests. It is concluded that the measurement results by online gas monitoring are comparable with laboratory analysis results generally within an error of 30% or less; online as well as laboratory analyses yield results that provide meaningful DGA interpretation.

The good comparability between the online and laboratory gas analyses might be due to the fact that both of them use gas chromatography, which is an effective approach to separate individual gas components. Although the different gas extraction methods (headspace versus vacuum) and gas detection methods (TCD versus FID for hydrocarbons) might cast slight differences in the gas analysis, the differences between the online and lab analysis can be effectively minimized by conducting periodic calibration using gas standards.

On the contrary, for laboratory analysis, gas leakage and air ingression might occur during sample transportation and measurement delay, which might be the main reason for the deviations between the online and lab analysis. And the differences between the online and laboratory results for the same fault test are heavily dependent on the sealing efficiency of individual sample syringes. Therefore, it is suggested that liquid samples collected from in-service transformers should be sent for laboratory analysis as soon as possible after sampled. A shorter delay between the sampling of transformer liquids and the laboratory analysis can provide more accurate results.

Acknowledgement

Special thanks are given to the staff from the UK laboratory of TJ|H2b analytical services for the measurement of the samples.

References

[1] J. J. Kelly, "Transformer fault diagnosis by dissolved-gas analysis," *IEEE Trans. Indu. Applicat.*, vol. IA-16, pp. 777-782, 1980.

[2] Z.D. Wang, X. Wang, X. Yi, S.T. Li and J. Hinshaw, "Fault Gas Generations of Natural Ester and Mineral Oil under Electrical Faults", *IEEE Electrical Insulation Magazine*, 2013 (accepted in April, 2013)

[3] Z.D. Wang, X. Yi, J.P. Huang, J. Hinshaw and J. Noakhes, "Fault Gas Generation in Natural Ester Fluid under Localized Thermal Faults", *IEEE Electrical Insulation Magazine*, vol.28, no.6, pp.45-56, 2012

[4] Z.D. Wang, A. Darwin, and R. Martin, "New insulation fluids: use of environmentally friendly fluids in power transformers," *in CIGRE Colloq., Bruges, Belgium*, 2007, pp. PS1-04.

[5] CIGRE Working Group D1.01 (TF 15), “Report on gas monitors for oil-filled electrical equipment”, *CIGRE technical brochure* 409, 2010.

[6] M. Duval, "A review of faults detectable by gas-in-oil analysis in transformers," *IEEE Electr. Insul. Mag.*, vol. 18, pp. 8-17, 2002.

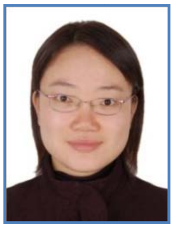
[7] IEC 60567, "Oil-filled electrical equipment-sampling of gases and of oil for analysis of free and dissolved gases-Guidance", 2006.

[8] I. Khan, Z.D. Wang, and I. Cotton, "Dissolved gas analysis of alternative fluids for power transformers," *IEEE Electr. Insul. Mag.*, vol. 23, pp. 5 - 14, September 2007.

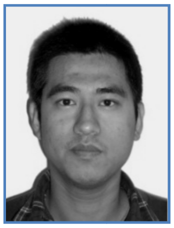
[9] X. Wang, "Partial discharge behaviours and breakdown mechanisms of ester transformer liquids under ac stress", *in School of Electrical and Electronic Engineering, University of Manchester, PhD Thesis, Manchester*, 2011.

[10] M. Duval, "The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers," *IEEE Electr. Insul. Mag.*, vol. 24, pp. 22-29, 2008.

Zhongdong Wang received a B.Eng. and an M.Eng. degree in High Voltage Engineering from Tsinghua University of Beijing in 1991 and 1993 respectively, and a Ph.D. degree in Electrical Engineering & Electronic from UMIST in 1999. Currently she is Professor of High Voltage Engineering in the Electrical Energy and Power Systems Group of the School of Electrical and Electronic Engineering at the University of Manchester. Her current research interests include condition monitoring, transformer modelling, frequency response analysis, power system transient analysis, insulation ageing and alternative insulation materials for transformers. Her email address is: zhongdong.wang@manchester.ac.uk



Xiao Yi received a Ph.D. degree in Electrical Engineering from the University of Manchester, UK in 2012, where she is currently a research associate in the School of Electrical and Electronic Engineering. Her present research interests are the dielectric performance of insulating liquid-pressboard composite insulations, dissolved gas analysis and diagnosis of liquid-filled transformers, and ageing assessment of transformer liquids. Her email address is: xiao.yi@manchester.ac.uk



Xin Wang received a B.Eng. degree in Electrical Engineering and an M.Eng. degree in High Voltage Engineering from Tsinghua University of Beijing in 2004 and 2007 respectively, and a Ph.D. degree in Electrical and Electronics Engineering from the University of Manchester in 2011. He is currently working for Alstom Generation, Switzerland. His research interests include partial discharge behaviour and breakdown mechanisms in transformer liquid insulation. His email address is: xin-a.wang @power.alstom.com

Sitao Li enrolled in the 2+2 collaborative undergraduate teaching programme between the University of Manchester and North China Electrical Power University, and received a BEng degree in Electrical Engineering from both universities in 2010. In 2012 he received an MPhil degree in Electrical Engineering from the University of Manchester. He is now working in Fuzhou Electric Power Bureau, State Grid of China. His email address is: lisitao.p@gmail.com

John V. Hinshaw received a PhD in Analytical Chemistry from Duke University in 1979. He joined BPL Global (Beaverton, Oregon, USA) in 2002, where he is senior scientist. He serves as the chair of ASTM subcommittee E13.19 on chromatography, and is a member of the executive committee of the subdivision of chromatography and separations chemistry of the American Chemical Society (ACS) Division of Analytical Chemistry. His email address is: john.hinshaw@serveron.com

John Noakhes is currently the manager of TJ|H2b UK laboratory which he joined as a senior chemist in 2000. Previously, he worked for UKF Fertilisers (formerly Shellstar) between 1972 and 1979 and EA Technology (formerly ECRC) between 1979 and 2000. His specialties include transformer condition assessment, condition-based transformer maintenance, insulating oil analysis and electrochemistry. His email address is: jnoakhes@tjh2b.com