Chapter 2 DGA based Power Transformer Incipient Fault Diagnosis

In this chapter the evolution of DGA based techniques for power transformer incipient fault diagnosis will be summarized. First we will review studies on cellulosic and oil decomposition mechanisms, and the discovery of a thermodynamic equilibrium relationship between the fault temperature and the rate of gas generation. We will then introduce the conventional DGA methods, including ratio and key gas methods, and industrial experiences with DGA-based incipient fault diagnosis. At the end of this chapter we will discuss recent research on artificial intelligence based diagnosis and what are likely the future developments of DGA technology.

2.1 Gassing characteristic study for faulty transformers

The study of gassing mechanism of paper/oil from thermal or electrical stress can be traced back to 1930's [Ber38, Vog51, Bas55, Bag62, She63, Slo67, Ped68]. The break-through work is due to Halstead [Hal73]. Afterwards similar studies continued [Baker82, Baker83, Inoue90, Nick91, Grant92, Omn93, Griffin94], especially on paper degradation.

Before Halstead, it had been realized that under thermal and electrical stresses, the hydrocarbon molecules of mineral oil can decompose and form active hydrogen and hydrocarbon fragments, and that these fragments can combine with each other to form gases like hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), etc. It was also found that the amount of each individual gas is dependent on the temperature in the neighborhood of the stressed point. Halstead proposed a thermodynamic model to describe the relationship between fault temperature and gassing characteristics, which assumes that all hydrocarbons in the oil are decomposed into the same product and each product is in equilibrium with all the others. According to the model [Hal73], the evolution rate of each gas can be calculated at any temperature, so that a relationship between gas generation and temperature can be obtained for each gas. Figure 2-1 shows these relationships [Rogers78, Ger95]. Study of these relationships reveals that gases are generated in the following order with an increase of temperature: $H_2 \rightarrow CH_4 \rightarrow C_2H_6 \rightarrow C_2H_4 \rightarrow C_2H_2$. Hydrogen is generated at low temperature and its amount steadily increases, while acetylene is generated at a very high temperature (close to 1000 ˚C) and also steadily increases its amount.

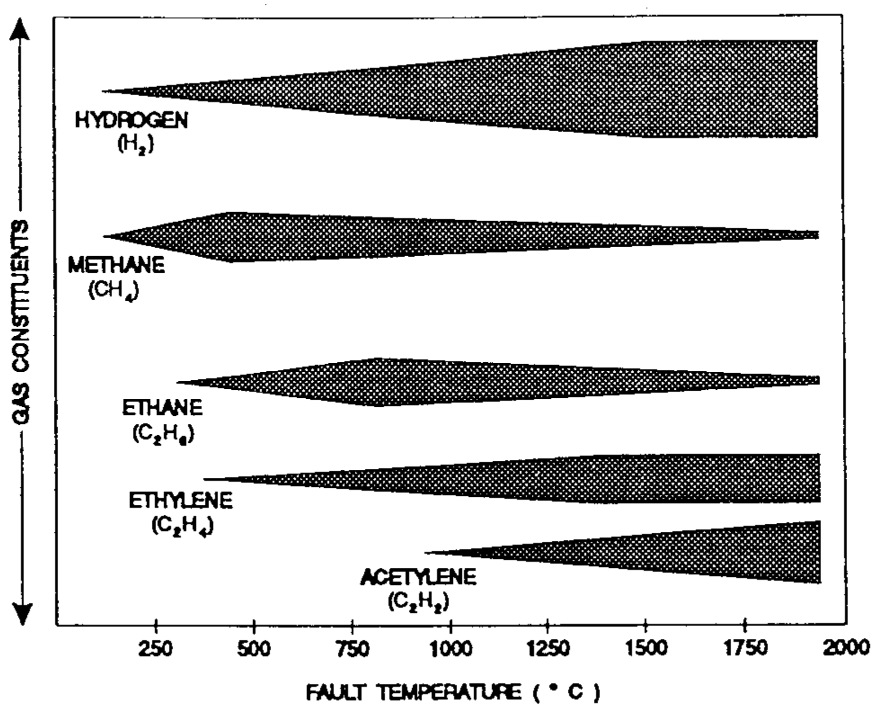

Figure 2-1 Gases Generated During Breakdown of Dielectric Oil [Ger95]

Transformer solid insulation degradation is conventionally diagnosed according to the amount and ratio of dissolved carbon monoxide (CO) and carbon dioxide (CO_2) [IEC599]. Their amount is found to increase dramatically above a threshold temperature of about 140˚C-150˚C [Pugh74, Yosh87]. However, this finding is not sufficient to setup a definitive technique for the diagnosis, because CO and CO_2 can be present in the transformer simply as a result of long-term low-temperature oxidation of oil [Nick91, Anto91]. Researchers have found that CO and CO_2 can be absorbed into the paper insulation after being generated, resulting in a fluctuation of the measured concentrations [Hisao94, Hisao95].

2.2 Transformer incipient faults

Incipient faults of power transformers can be classified into the following major categories [C57.125, C57.104]: electrical arcing, electrical corona, overheating of cellulose, overheating of oil. These faults may due to one or more of the causes shown in Table 2-1. This classification is a standard but not the only one that is being used. For example, Doble Engineering Company used a different classification system [Rick78].

Table 2-1 Correlation between Power Transformer Incipient Faults and Causes

Causes	Faults			
	Arcing	Corona	Overheating of cellulose	Overheating of oil
Winding turn-to-turn short-circuit	X		X	
Winding open circuit	X		X	
Operation of build-in LTC	X			
Winding distortion or displacement		X	X	
Lead distortion or displacement		X	X	
Loose connection to bushing terminals, tap leads, terminal boards	X	X	X	
Free water or excessive moisture in oil	X	X		
Floating metal particles	X	X		
Loose connection to corona shields		X		
Loose collars, spacers, core ground straps, core hold down angle (Braces)		X		
Through fault			X	
Overloading			X	X
Damaged yoke bolt insulation				X
Rust or other damage on core				X
Damaged shunt packs of tank				X
Jammed oil circulating path				X
Cooling system malfunction				X

According to Table 2-1, one fault type may have more than one cause. This makes fault location very difficult. Hence, the current practices often stop at the fault diagnosis and rarely reach the point of fault location using DGA alone. Other tests and even tear down may be necessary to locate the fault area and causes accurately.

Nevertheless, fault diagnosis is good enough to provide information to a maintenance program, and serve as the basis of a preventive maintenance strategy. For this purpose, DGA has been the key tool for power transformer incipient fault diagnosis [C57.125]. It includes many successful approaches under three major categories: ratio methods, key gas method, and artificial intelligence based methods.

2.3 The study and application of ratio methods

Ratio methods use the ratios of dissolved gas concentrations as the basis of fault diagnosis. Historically five ratios (listed in Table 2-2) have been used [Randy97].

Table 2-2 Ratio definition of ratio methods [Randy97]

Ratio	CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_6/C_2H_2	C_2H_4/C_2H_6
Abbreviation	R1	R2	R3	R4	R5

The first attempt was made in late 1960s at the Central Electricity Generating Board (CEGB) [Rogers78]. In 1970 Dornenburg was able to differentiate between thermal and electrical faults using four ratios and six gases [Dorn67, Fallou70, Randy97]. The six gases are H_2, CH_4, CO, C_2H_2, C_2H_4 and C_2H_6. The four ratios and their diagnosis values are shown in Table 2-3. The method has many validation tests before reaching the final decision and it often fails to do so. The most important validation test is the L1 norm test, which sets up a critical level for each gas. In order to apply the method, at least one gas for each of the ratios must exceed the corresponding L1 norm. The revised L1 norms are listed in Table 2-4.

Table 2-3 Dornenburg's ratio method [Randy97]

Fault	R1	R2	R3	R4
Thermal Decomposition	>1.0	<0.75	<0.3	>0.4
Corona (low intensity PD)	<0.1	Not significant	<0.3	>0.4
Arcing (high intensity PD)	>0.1 and <1.0	>0.75	>0.3	<0.4

Table 2-4 Dornenburg's L1 limit [Randy97]

Gas	H_2	CH_4	CO	C_2H_2	C_2H_4	C_2H_6
L1 limit (ppm)	100	120	350	35	50	65

Following Halstead's thermodynamic model, the Rogers ratio method was first proposed in 1973 [Bar73], refined in 1975 [Rogers75], and further refined in 1977 [Rogers77]. Taking into consideration industrial experiences [Man78], laboratory tests, and further theoretical assessment, the method was further modified into an IEC standard [IEC599].

The original Rogers ratio method used Table 2-5 for diagnosis, where a 1 indicates that the actual value is above 1.0, and a 0 indicates that the actual value is below 1.0. The refined Rogers method used two tables: one defined the code, and the other defined the diagnosis rule, as shown in Table 2-6 and Table 2-7. These preliminary methods used four ratios. The ratio ethane/methane (C_2H_6/CH_4) only indicated a limited temperature range of decomposition, but did not assist in further identification of the fault. Therefore, in IEC standard 599, the further development of Rogers ratio method, it was deleted. For a detailed description of IEC 599-1978, see Appendix 1.

Table 2-5 Original diagnosis table of Rogers ratio method [Bar73]

CH_4/H_2	C_2H_6/CH_4	C_2H_4/C_2H_6	C_2H_2/C_2H_4	Diagnosis
0	0	0	0	If CH_4/H_2 is 0.1 or so → partial discharge, otherwise normal deterioration
1	0	0	0	Slight overheating – below 150 ˚C
1	1	0	0	Slight overheating – 150-200 ˚C
0	1	0	0	Slight overheating – 200-300 ˚C
0	0	1	0	General conductor overheating
1	0	1	0	Circulating currents and/or overheating joints
0	0	0	1	Flashover without power follow-through
0	1	0	1	Tap changer selector breaking current
0	0	1	1	Arc with power follow-through – or persistent sparking

A further revision of the IEC 599 was in draft in 1996 [IEC599r]. It should have been finalized at this time. For a summary of the proposed revision, see Chapter 3.

Rogers ratio method and IEC 599 have gained popularity in industrial practices [Kelly80, Sobral86]. However, it may give no conclusion in some cases. This is the "no decision" problem and will be further explained in Chapter 3.

Table 2-6 Code definition of Rogers refined ratio method [Rogers75]

Gas Ratio	Range	Code
CH_4/H_2 (R1)	Not greater than 0.1	5
	Between 0.1 and 1.0	0
	Between 1.0 and 3.0	1
	Not less than 3.0	2
C_2H_6/CH_4 (R4)	Less than 1.0	0
	Not less than 1.0	1
C_2H_4/C_2H_6 (R5)	Less than 1.0	0
	Between 1.0 and 3.0	1
	Not less than 3.0	2
C_2H_2/C_2H_4 (R2)	Less than 0.5	0
	Between 0.5 and 3.0	1
	Not less than 3.0	2

Table 2-7 Diagnosis of Rogers refined ratio method [Rogers75]

R1	R4	R5	R2	Diagnosis
0	0	0	0	Normal deterioration
5	0	0	0	Partial discharge
1 or 2	0	0	0	Slight overheating – below 150 ˚C (?)
1 or 2	1	0	0	Slight overheating – 150-200 ˚C (?)
0	1	0	0	Slight overheating – 200-300 ˚C (?)
0	0	1	0	General conductor overheating
1	0	1	0	Winding circulating currents
1	0	2	0	Core and tank circulating currents, overheated joints
0	0	0	1	Flashover without power follow through
0	0	1 or 2	1 or 2	Arc with power follow through
0	0	2	2	Continuous sparking to floating potential
5	0	0	1 or 2	Partial discharge with tracking (note CO)

2.4 The study and application of key gas method

The study of key gas method started at Doble laboratories and was first summarized in 1973 [Pugh73] and officially proposed in 1974 [Pugh74]. In 1978, a comparison between the key gas method and the Rogers ratio method was presented at the Doble annual conference [Rick78]. It was realized that ratio methods were devised for use on conservator-type transformers, but the key gas method was developed mainly from either sealed or gas blanketed transformer. Griffin gave an extensive review on the key gas method, the ratio methods, and related application issues [Griffin88].

The key gas method identifies the key gas for each type of fault and uses the percent of this gas to diagnose the fault. It interprets DGA results based on a simple set of facts. For example, low intensity PD or corona produces mainly H_2 with trace amounts of some hydrocarbon gases, so the key gas for PD or corona is H_2, and PD or corona can be detected if the percent amount of H_2 is large in an oil sample. Based on the original work of Dr. Pugh and IEEE standard C57.104, Table 2-8 summarizes the diagnostic criteria of the key gas method. The percent amount of gas is based on total dissolved combustible gases (TDCG) and is an approximate number.

Table 2-8 Diagnostic criteria of key gas method

Fault	Key gas	Criteria	Gas percent amount
Arcing	Acetylene (C_2H_2)	Large amount of H_2 and C_2H_2, and minor quantities of CH_4 and C_2H_4. CO and CO_2 may also exist if cellulose is involved.	H_2: 60% C_2H_2: 30%
Corona (PD)	Hydrogen (H_2)	Large amount of H_2, some CH_4, with small quantities of C_2H_6 and C_2H_4. CO and CO_2 may be comparable if cellulose is involved.	H_2: 85% CH_4: 13%
Overheating of oil	Ethylene (C_2H_4)	Large amount of C_2H_4, less amount of C_2H_6, some quantities of CH_4 and H_2. Traces of CO	C_2H_4: 63% C_2H_6: 20%
Overheating of cellulose	Carbon monoxide (CO)	Large amount of CO and CO_2. Hydrocarbon gases may exist.	CO: 92%

2.5 The artificial intelligence based methods

In the past decade, there has been extensive research on the use of artificial intelligence techniques to assist the DGA. These investigations include the expert system approach [Barrett89, Lin93, Joseph94], fuzzy system approach [Duk93, Lin93, Tom93, Huang97, Gao98, Yang981], and the artificial neural network (ANN) approach [Duk93, Sumit93, Ding95, Zhang96, Zhang97, Wang97, Wang98, Yang98, Esp98, Gao98].

An expert system is a decision support system that provides fault diagnosis and maintenance advice. DGA methods form the major part of the system, though other industrial experiences may serve as special diagnostic rules. Information such as transformer type, voltage level, gassing trend, and maintenance history may also be incorporated.

There have been quite a few expert systems developed. Table 2-9 lists three of them as examples, from which we can summarize that at least three functions should be included in a fault diagnostic system for power transformers: first, the “central diagnostic engine” incorporates several DGA methods; second, the “expertise handler” considers special rules; and third, the “maintenance adviser” proposes the date of next analysis and maintenance actions to be taken.

Table 2-9 Expert systems for power transformer fault diagnosis

Reference	DGA methods	Features
[Barrett89]	Rogers ratio IEC 599 Key gas	• Gasket leaking checking and warning • Water content checking and warning • “Norm” based suspicious gas level identification • Maintenance advices based on TDCG
[Lin93]	Dornenburg ratio Rogers ratio IEC 599	• Ratio trend, norm threshold, key gas analysis and other expertise considered • Fuzzy set handles norm thresholds, ratio boundaries and key gas analysis • Heuristic maintenance rules
[Joseph94]	Ratio methods	• “Norm” limits • Historical trend analysis • Heuristic rules of experiences • Database and remote data access enhanced • Maintenance recommendations

The effectiveness of an expert system depends on the precision and completeness of the knowledge base, which is usually very complicated and must be constructed manually. The major problem with an expert system is that it cannot adjust its diagnostic rules automatically, and thus cannot acquire knowledge from new data samples through a self-learning process. Once an expert system is built, it is usually very difficult to upgrade it.

Using fuzzy information theory, a fuzzy set based fault diagnosis system could be built [Tom93]. The major issue is to tune fuzzy membership functions based on existing DGA methods and experiences. Conventionally this is done manually [Tom93, Duk93], and later automatically using sophisticated mathematical methods like evolutionary computation, genetic algorithm, adaptive pruning [Huang97, Yang981]. An advantage of a fuzzy diagnosis system is that it is insensitive to errors in the oil sampling, storage and testing processes. One drawback is that it is bonded with conventional DGA methods, and cannot learn directly from data samples.

Dukarm attempted to use artificial neural networks (ANN) for the diagnosis of transformer faults in the early 1990s without going further, probably due to the lack of high quality data [Duk93]. There are some studies in the late 1990s [Esp98, Yang98, Gao98], but they are separate activities that did not constitute a serious consideration of the problem. Research efforts at Virginia Tech began in the mid of 1990's [Ding95, Zhang96, Zhang97, Wang97, Wang98]. These efforts include not only methodological studies, but also data collection and industrial tests. As a result, a diagnosis system has been developed based on ANN and expert system technologies [Wang98], which is one of the topics of this dissertation.

An important advantage of ANN-based fault diagnosis is that it can learn directly from the training samples, and update its knowledge when necessary. The highly non-linear mapping capability of the neurons provides a comparable and often superior performance over fuzzy system solutions. ANN computational complexity is not too high, especially in the testing (diagnosis) process.

2.6 Other diagnostic methods and industrial expertise

Besides the above DGA methods, there are a large amount of diagnostic knowledge and experiences in the literature. The followings are two examples.

2.6.1 Leakage diagnosis

For transformers with a nitrogen (N_2) gas blanketed oil preservation system, leakage should be repaired because oxygen is one of the key promoters of oil and cellulose oxidation [Barrett89, Griffin88]. The presence of oxygen (O_2), if in quantities is greater than 5% of total gas content, is considered as leaking gasket. Since the amount of O_2 and N_2 is normally much greater than the sum of other gases, sometimes the ratio of N_2/O_2 is used to indicate if a leakage occurs. If N_2/O_2

is much less than 5%, there may be a leakage. The final decision should consider if there is a leak during sampling and testing of the oil [Griffin88]. If that possibility can be eliminated, then the leakage of oil preservation system is sure.

2.6.2 Paper degradation diagnosis

Paper degradation diagnosis is an essential part of transformer insulation condition assessment. Conventionally this is done using the ratio of CO and CO_2. A CO_2/CO ratio of 3.0 to 10.0 is normally consider in the acceptable range [Omn82]. The rule probably came from [IEC599] and [MacD80], where "normal" ranges of $3 < CO_2/CO < 11$ and $0.07 < CO/CO_2 < 0.30$ were proposed, respectively.

For high temperature overheating of cellulose (for instance under arcing conditions), the ratio of CO/CO_2 approaches 1:1 because arcing generates CO very rapidly. For inadequately cooled or overloaded transformers, however, CO_2 increases much more rapidly than CO and therefore the ratio of CO/CO_2 is in the 1:20 to 1:10 range [Griffin91].

In early 1990s, furan based cellulose degradation diagnosis became a great interest of many researchers [Griffin91, Nick91, Anto91, Myers92, Omn93, Domi93, Griffin93, Griffin94]. Furan is the abbreviation of furanic compounds. There are five commonly detected furanic compounds [Griffin95]: 5-hydroxymethyl-2-furfural (HMF), furfuryl alcohol or furfurol (FOL), 2-furfural or 2-furfuraldehyde or 2-furaldehyde (FAL), 5-methyl-2-furfural (MF) and 2-acetyl furan (AF). Large amount of furanic compounds can be generated from cellulosic materials when the temperature is above 120 ˚C. Once generated, they can survive for a long time in the bulk oil of the transformer and thus suitable for incipient fault diagnosis [Griffin95]. 2-furfural is the primary furanic byproduct of cellulose degradation, and has been shown to have greater stability than other furanic compounds [Griffin97]. It is a reliable indicator of paper degradation of power transformers. Some diagnosis criteria have been set for furan detection based diagnosis and will be covered in Chapter 6.

2.7 Future development

Dissolved gas-in-oil analysis is a successful technique for power transformer incipient fault diagnosis, but the knowledge and experiences are usually of experts and some can be found in publications (for example see [Mar77, Oms81, Bak81, Men82, Duval88, Duval89, Gri90, Cro95, Gri96, Gri97, Hau97, Gri98]). It is of the general maintenance engineers' interest that these knowledge and experiences be scientifically organized and represented in intelligent machine language. On the other hand, new fault diagnostic technologies need to be developed into a practical application stage, especially when artificial intelligence (AI) techniques have suggested the possibility of learning directly from raw data.

A completely automated system can be the final goal of AI based techniques. With the popularity of Internet based applications, it could be a server-based abnormal detection and fault diagnosis system without the need of an administrator. The oil sampling, testing, and the AI diagnostic modules can be developed separately but must be reliable. It is a challenge in all aspects if one look into the complexity of the problem.

This dissertation will systematically study artificial intelligence based techniques for power transformer incipient fault diagnosis, and try to reach some useful conclusion as what kind of techniques can be used as reliable fault diagnosis modules. Transformer fault location and on-load tap changer (OLTC) coking diagnosis will also be studied to make the modules complete.

2.8 Summaries

This chapter reviews the history and techniques for power transformer incipient fault diagnosis, and formulates briefly what is expected in the future.

The basis of conventional dissolved gas-in-oil analysis is Halstead's thermodynamic model. Some methods were proposed and used extensively in industry. These include the Rogers ratio method, Dornenburg ratio method, IEC method, and the key gas method.

AI based methods were studied in the past decade but did not gain much popularity. These AI methods include expert system, neural network, and fuzzy system. This dissertation is a systematic study and application of these methods.