Chapter 3 Rule based Transformer Fault Diagnosis

In chapter 2, the history of power transformer fault diagnosis has been reviewed and the unsolved problems identified. From this chapter, we will begin studying the artificial intelligence (AI) methods that may be used to solve them. We will discuss in this chapter what we can do to overcome the "no decision" problem that ratio methods usually have.

3.1 Assumptions

The study of this chapter is based on some basic assumptions of the gas-in-oil concentrations, these include:

- The transformer oil is mineral oil. The manufacturer or refinery process of the oil could be different but it must be mineral oil.
- The sampling, storage, extraction, and gas chromatography of the oil samples are under quality control practices [Griffin84, Duval84, Ferrito90, Jalbert94] or the testing results adjusted [Omn821] so that there is no or little error in the resulted concentrations.
- The gases in the transformer oil are distributed homogeneously. In other word, the fault condition has been there for a while such that the gas-in-oil pattern has formed.

The first assumption is very easy to verify. The second assumption is also easy to verify following some precautions and laboratory guidelines. But the third assumption is not always the case because no one knows in advance what is happening in the tank. Some steps may be taken to make it closer to being true. One step is to speed up the oil circulation pump for several days before taking oil samples. The other step is shortening the oil-sampling interval. A combination of these two steps may help obtaining a more representative oil sample.

3.2 Basis of rules – the IEC guidelines

To set up a knowledge-based transformer fault diagnosis system, the first step is gathering rules. Popular guidelines by IEC or IEEE can be very helpful in this step. Precautions must be taken in using these rules because they are guidelines, need proper interpretation, and are revised from time to time.

The IEC standard 599, both the 1978 version and the revision draft, were used in the study. The 1978 version is summarized in Appendix 1 with the following general remarks [IEC599]:

- Significant values quoted for ratios should be regarded as typical only.
- Transformers fitted with in-tank on-load tap changers (OLTC) may indicated faults of type 202/102 depending on the seepage or transmission of arc decomposition in the diverter switch tank into the transformer main tank.
- Combinations of the ratios not included in the Appendix 1 table may occur in practice.

The second and third remarks address the issue of "no decision" problem, which is a major concern of this study.

Based on considerable theoretical and empirical background, the revision draft of IEC 599 was proposed [IEC599r] and is summarized in Appendix 2 and Table 3-1 [Randy97]. It is more like a key gas method instead of a ratio method, presenting a more skillful fault classification philosophy. However, its application is more difficult than the original one in that it needs more judgment.

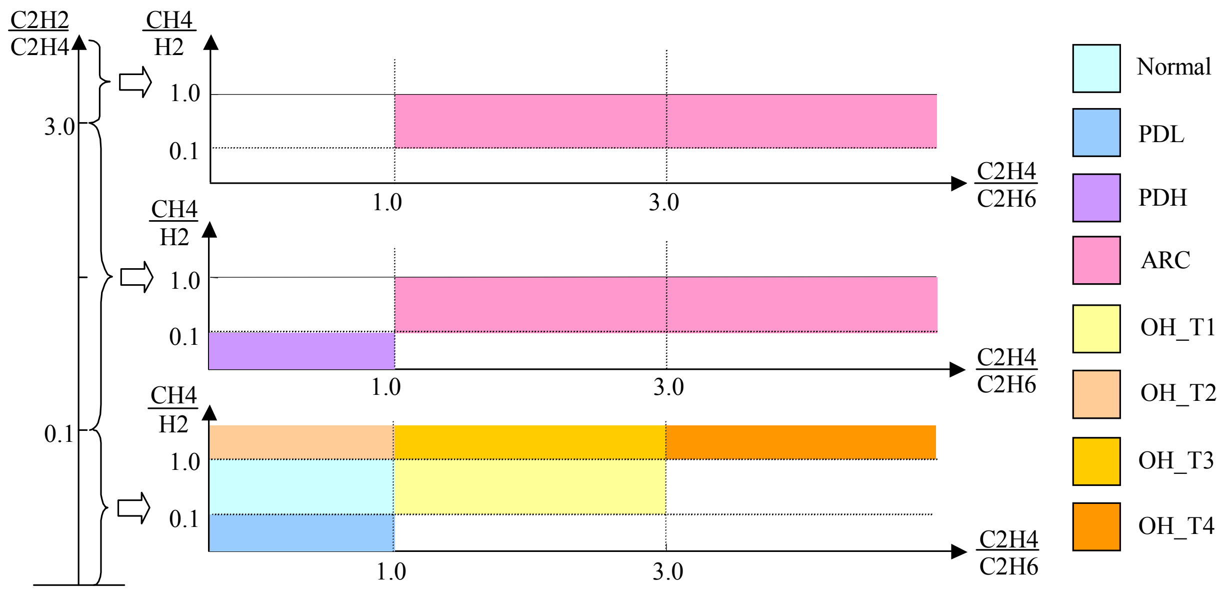
Table 3-1 Draft Revision Table of IEC 599 [Randy97]

Characteristic Fault	C_2H_2/C_2H_4 (R2)	CH_4/H_2 (R1)	C_2H_4/C_2H_6 (R5)
Partial Discharge	Not significant	< 0.2	< 0.2
Discharge of Low Energy	> 1	0.1 – 0.5	> 1
Discharge of High Energy	0.6 – 2.5	0.1 – 1	> 2
Thermal Fault, T < 300°C	< 0.2	Not significant	< 1
Thermal Fault, 300°C < T < 700°C	< 0.1	> 1	1 – 4
Thermal Fault, T > 700°C	< 0.2	> 1	> 4

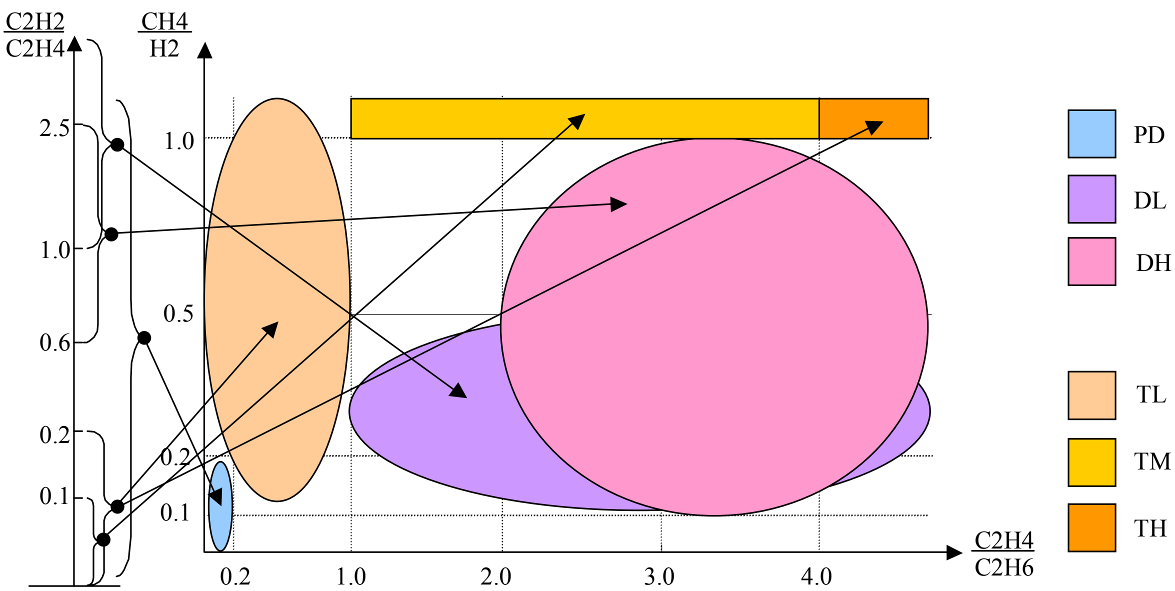
3.3 Interpretation and modification of the guideline rules

To help interpreting the guideline rules, they are represented graphically in Figure 3-1 (a) and (b) where the three-dimension input feature space is transformed into two-dimension planes. Fault types correspond to zones in the planes. Fault type abbreviation meanings are given in Table 3-2.

In Figure 3-1 (a) we see a concise definition of power transformer fault classifications. In Figure 3-1 (b) the overlay of different fault types is obvious. They both have some blank zones where the “no decision” problem occurs.



(a) IEC 599-1978



(b) IEC 599 Revision Draft

Figure 3-1 Fault classification zones based on IEC 599

From Figure 3-1 (b) we realized the limitation of the IEC 599 revision draft includes its uncertainty in some cases, and decided to use Figure 3-1 (a) as the rule basis. Some modifications were applied to these rules by taking into consideration oil/cellulose decomposition principles. The final rule base is shown in Figure 3-2. Fault type abbreviation meanings of Figure 3-2 are given in Table 3-2.

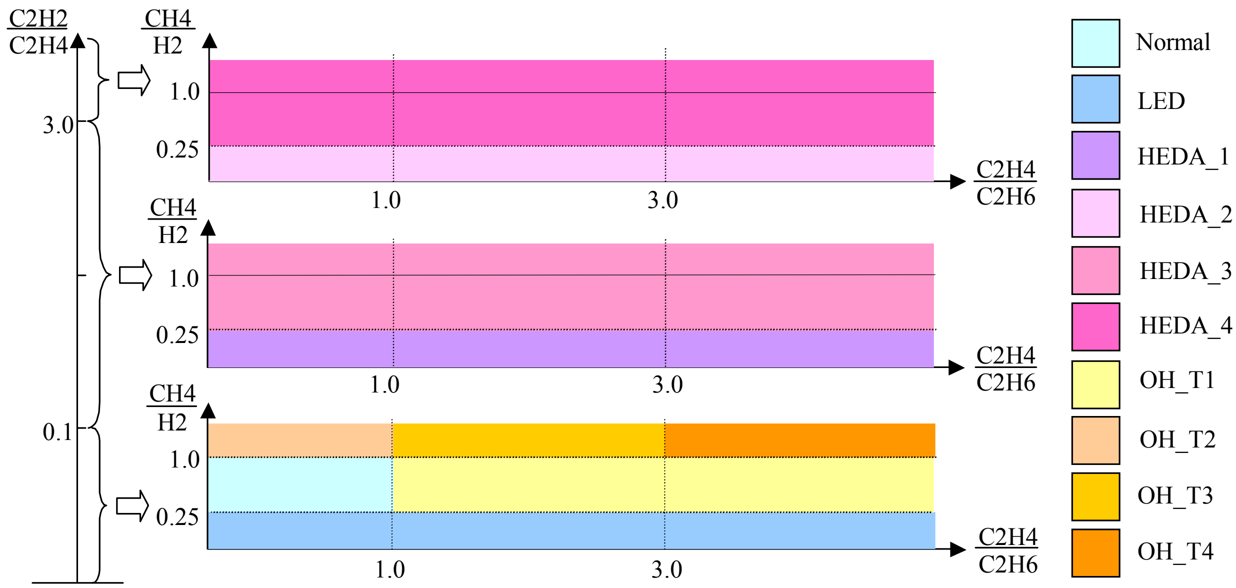


Figure 3-2 Classification zone of the final rule base

There are two major differences between Figure 3-1 (a) and Figure 3-2. One is the position of the lower zone-boundary of CH_4/H_2 (R1). It is 0.1 in Figure 3-1 (a) and 0.25 in Figure 3-2. The value of 0.25 was determined mainly from Figure 3-1 (b), with the consideration that its main purpose is to identify "partial discharge" from "normal" and "low temperature overheating", and distinguish between different level of high energy discharges, which is not a big issue in many cases because the resulted damage is light even if the fault does occur. The other difference is the solution of the "no decision" problem in Figure 3-2 based on the following considerations.

- In the order of partial discharge, overheating, low energy discharge and high energy discharge, the hot spot temperature increases and the major amount of gas-in-oil follows the order of $H_2 \rightarrow CH_4 \rightarrow C_2H_6 \rightarrow C_2H_4 \rightarrow C_2H_2$.
- Ratio C_2H_4/C_2H_6 (R5) is good for overheating temperature classification but not for discharge severity classification, seen from Figure 3-1.
- Ratio CH_4/H_2 (R1) may be good for discharge severity classification, seen also from Figure 3-1, but the classification is not concrete. When used for "partial discharge" diagnosis, the H_2 value needs to be larger than a preset value (150ppm).

- Ratio C_2H_2/C_2H_4 (R2) is critical for discharge diagnosis and is the only factor if C_2H_2 is larger than a preset level (3.9ppm).

Table 3-2 Meanings of fault type abbreviations in Figure 3-1 and 3-2

Figure 3-1 (a)	Figure 3-1 (b)	Figure 3-2	Faults
Normal	-	Normal	Normal aging condition
PDL	PD	LED	Partial discharge
PDH	DL	HEDA_1, HEDA_2	Low energy discharge
ARC	DH	HEDA_3, HEDA_4	High energy discharge and arcing
OH_T1	-	OH_T1	Low temperature overheating, T < 150°C
OH_T2	TL	OH_T2	Thermal fault (overheating), 150°C < T < 300°C
OH_T3	TM	OH_T3	Thermal fault (overheating), 300°C < T < 700°C
OH_T4	TH	OH_T4	High temperature overheating, T > 700°C

Table 3-2 lists eight fault types, where the “low-energy discharge “and “high-energy discharge” faults can be generally called HEDA fault, and the four types of “overheating fault” can be generally called OH fault. NR and LED can be used to represent “normal aging condition” and “partial discharge”, respectively. These terminologies will be used in the subsequent sections and chapters.

3.4 Special fault diagnosis rules

Apart from the fault types in Table 3-2, three other types are necessary to represent whole or sub fault categories. These include “cellulose degradation” fault, “overheating of oil” fault, and “overheating of cellulose” fault. They are abbreviated using CD, OHO and OHC, respectively. OHO and OHC are subcategories of OH fault. OHC is also a subcategory of CD.

Special rules for OH, OHO, OHC, CD and NR diagnosis were deduced from literature and industrial experiences. These experiences are revealed from the 200 data samples that will be introduced in Chapter 4. They were also validated by field experts and confirmed by testing results of those data samples.

3.4.1 OH and OHO diagnosis

Ratio C_2H_6/C_2H_2 (R4) was found to be effective in some cases for OH and OHO diagnosis. The rule reads (R4>5000) OR ((R4>0.2) AND (C_2H_4>250ppm), where 250ppm is the L1 norm for C_2H_4. Besides, whenever there is an OHC, there should be an OH.

3.4.2 Ratio CO/CO_2 based diagnosis

According to many literatures, ratio CO/CO_2 is the major factor in CD diagnosis and ($CO/CO_2>0.3$) OR ($CO/CO_2<0.07$) was used as the only rule. Through this study it was found that the L1 norm of CO also plays an important role, and the ratio also helps OH and OHC diagnosis. The rule reads: if (($CO/CO_2>0.3$) OR ($CO/CO_2<0.1$)) AND (CO>200ppm) then CD, OH and OHC.

3.4.3 Additional CD and OHC diagnosis rule

In LED diagnosis region of Figure 3-2, there is an overlapped sub-region for CD and OHC diagnosis. The rule reads (R1<0.25) AND (R2<0.1) AND (R5>10).

3.4.4 NR diagnosis

Whenever there is a fault condition, the NR condition should be invalid. Therefore in NR region of Figure 3-2, a prerequisite exists which reads NOT (OHO OR OHC).

3.5 The inference engine and fuzzy fault representation

These special rules in Section 3.4 are combined with Figure 3-2 to form the rule database. The representation of this database is combined with an IF-THEN based inference engine. The flow chart of the engine is shown in Figure 3-3, where the confidence of a fault diagnosis is represented by a number between 0 and 1. This is a fuzzy representation and it reflects the uncertainty of diagnosis in some cases. It is also a preparation of the rule and neural network based fault diagnosis combination in Chapter 5.

3.6 Summary and discussions

In this chapter we setup the rule-based power transformer fault diagnosis engine. The rules are obtained from IEC 599 standards but undergo some modifications based on gas generation principles. Special rules are deduced from literatures, industrial experiences and 200 actual data samples. The rules are represented in an inference engine with IF-THEN structure. Fuzzy representations are used in the engine for future compatibility.

Fault types are summarized as NR (normal), OH (overheating), OHO (overheating of oil), OHC (overheating of cellulose), LED (partial discharge or corona), HEDA (high energy discharge and arcing) and CD (cellulose degradation). OH is classified into four temperature ranges, includes

OH_T1, OH_T2, OH_T3 and OH_T4. HEDA is classified into four severity levels, includes HEDA_1, HEDA_2, HEDA_3 and HEDA_4.

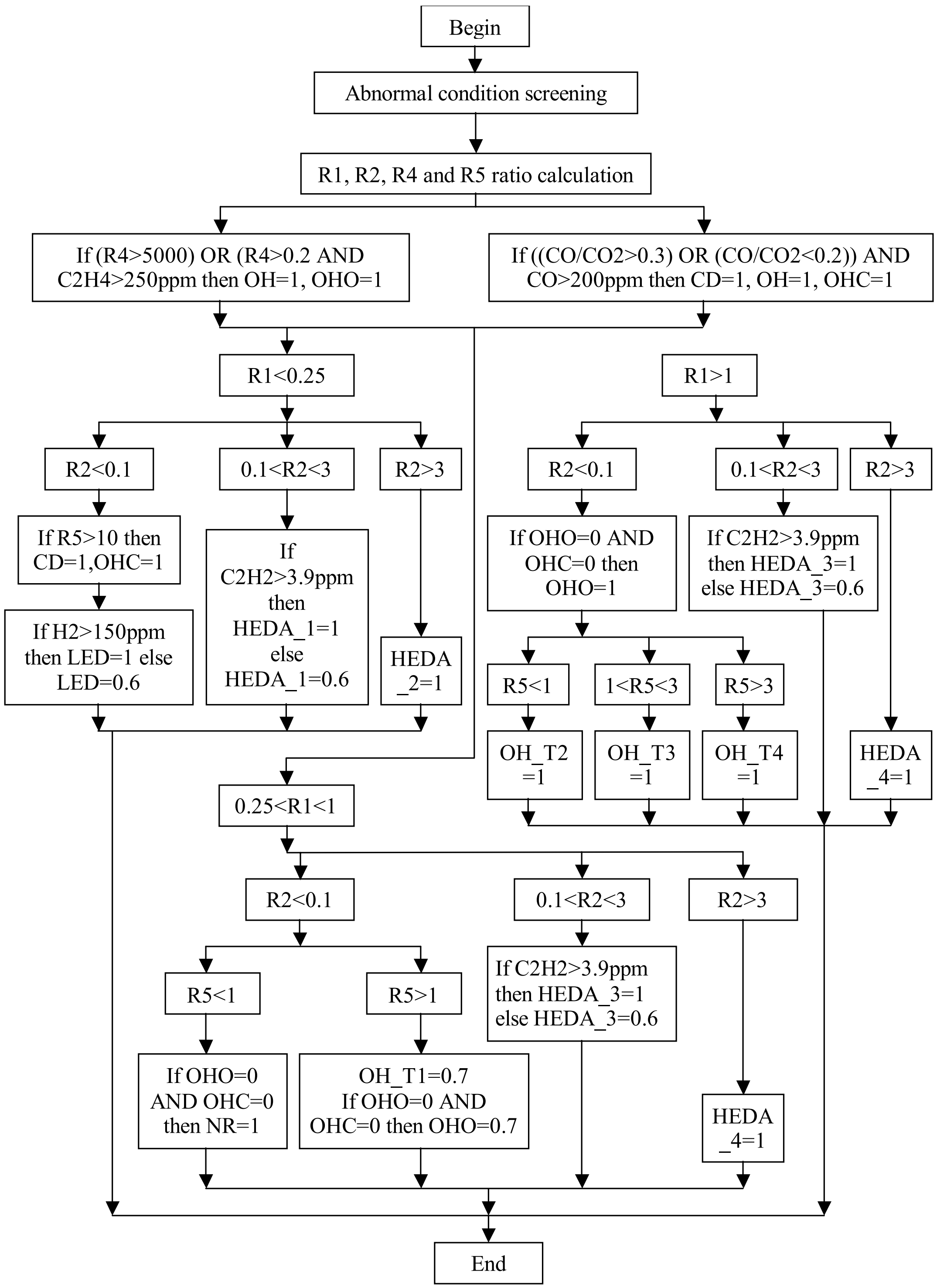


Figure 3-3 Flow chart of the inference engine of rule-based fault diagnosis