

Chapter 6 Power Transformer Insulation Condition Assessment and Maintenance Recommendation

We have identified and implemented a series of AI techniques for power transformer incipient fault diagnosis, but what measures can a field maintenance engineer use to evaluate the overall transformer insulation condition? What actions should he take when an abnormal condition does occur? We will have AI based answers in this chapter.

6.1 Why these are important

There are potential advantages from overall power transformer insulation condition assessment. Years of research and industry experience have accumulated a large amount of knowledge in individual areas. They are scattered in various publications, national and international standards, etc. For a field maintenance engineer, it is a big burden trying to sort out the facts and sometimes the recommendations may be inconsistent with each other. No matter how good the knowledge could be, its potential benefits may never be realized in the real world. On the other hand, people are still trying to accumulate more and more knowledge, making the application more complex. One way of dealing with this problem is to find a way of incorporating all the related individual power transformer condition assessment knowledge to make an overall decision, so that a field engineer can easily benefit from pioneers' work. Because of the maturity of fuzzy system concepts, the problem could have a solution.

Maintenance recommendations are also important besides the fault diagnosis. Knowing the fault type is not enough for most cases, a field engineer must have an idea of how far away the equipment is from the potential outage. If the estimation can be made very clearly, he can start planning maintenance and system solution in advance. A large amount of money can be saved if he takes proper actions. Like the aforementioned situation, knowledge is not short but needs incorporation. Again, fuzzy concept could be the solution.

6.2 Transformer condition assessment

There are many techniques in literature for transformer insulation condition assessment. They can be classified into two categories, transformer oil assessment and solid insulation assessment. In the following the two categories are treated separately.

6.2.1 Oil condition assessment

Transformer oil degradation comes largely from decomposition, contamination and oxidation. For oil condition assessment, some test items, their limit values and testing methods are listed in Table 6-1. Other tests are also being used in industry but not listed here. The principle of using these tests can be found in various publications.

Table 6-1 Power Transformer Oil Condition Assessment Tests

Test Item	Method	Unit	Limit Value	Reference
Dielectric Breakdown Voltage (minimum) ^a	ASTM D 1816	kV	Voltage: ≤ 69kV 69-288kV >345kV .04" gap: 23 26 26 .08" gap: 34 45 45	[C57.106]
	ASTM D 877	kV	Voltage: ≤ 69kV 69-288kV >345kV 26 26 26	[C57.106]
Interfacial Tension (IFT, minimum) ^b	ASTM D 971	mN/m	Voltage: ≤ 69kV 69-288kV >345kV 24 26 30	[C57.106]
Acid Number (KOH, maximum) ^b	ASTM D 974	mg KOH/g	Voltage: ≤ 69kV 69-288kV >345kV 0.2 0.2 0.1	[C57.106]
Water (H ₂ O, maximum) ^c	ASTM D 1553	ppm	Voltage: ≤ 69kV 69-288kV >345kV 35 25 20	[C57.106]
Power Factor (PF, maximum) ^d	ASTM D 924 PFVO/SFL ^e	%	Voltage: ≤ 69kV 69-230kV >345kV @25°C 0.15 0.1 0.05 @100°C 1.5 1.0 0.3	[C57.106] [Gri87]
Oxidation Stability (SFL, minimum)	ASTM D 2440 PFVO/SFL ^e	Hours	80 ^f	[C57.106] [Gri87]
Electrostatic Charging Tendency (ECT, minimum)	-	μC/m ³	-500 ^g	[Gri90] [Hey98]

- a) Dielectric breakdown voltage indicates the presence of electrically conductive contaminants in oil.
- b) Interfacial tension and acid number (sometimes called neutralization number or acidity) are affected by oxidation and contamination
- c) Water content is temperature dependent. Refer to Section 6.2.1 for more explanations.
- d) Power factor is also temperature dependent. Refer to Section 6.2.1 for more explanations.
- e) PFVO stands for Power Factor Valued Oxidation. SFL stands for Sludge-Free Life. PFVO/SFL is a Doble test unit.
- f) The limit value depends to some extent upon the concentration of inhibitor. The given number is based on a 0.15% inhibitor.
- g) This number was guessed from [Hey98]. According to [Gri87], there is a risk of using ECT as a tool for oil condition assessment because of static electrification in transformers.

In this study, IFT, KOH, H₂O and PF are used to implement an AI based oil condition assessment, because these tests are relatively easier to perform, and their results often correlate closely with each other. Actually, IFT test is an excellent means of detecting oil-soluble polar contaminants and oxidation products, KOH is a measure of the acidic by-products of the oxidation, H₂O is a major contaminant, and PF is an overall indication of the oil deterioration and contamination. Although they may yield an oil condition assessment individually, their proper combination could lead to a more precise conclusion.

A fuzzy model is developed to do the job. This is a fuzzy inference system aims to combine all the aforementioned information.

First, a fuzzy membership function was defined for each test. The input of the function is the outcome of the test, and the output of the function is an index representing the condition of the oil. The indices are a number in the range of 0 to 1, where 1 means good oil. These functions are shown in Figure 6-1 and they are monotonic fuzzy logic transfer functions.

Then, an unconditional fuzzy proposition based on Equation 6-1 was used to combine these indices, yielding an overall oil condition assessment index.

$$Idx_oil_condition = \min(Idx_IFT, Idx_KOH, Idx_H_2O, Idx_PF) \quad (6-1)$$

When *Idx_oil_condition* is 1, the oil is in good condition. When *Idx_oil_condition* is changing towards 0, the quality of oil becomes poor.

It must be emphasized that in Figure 6.1 (c) and (d) the H₂O and PF inputs need be the values at 25°C, otherwise the conclusion could be wrong.

Water has higher solubility in transformer oil at higher temperature [Gri881]. Unless water is saturated in oil and the oil temperature is dropped, there is no danger of free-water forming, which is a major concern because free-water can increase the risk of electrical breakdown significantly. Therefore, high water content at high temperature is allowed as long as it is not saturated.

Measured PF at a temperature other than 25°C must be adjusted using a correction factor before being used, because PF of transformer oil is highly temperature dependent [Gri87]. A sample correction factor vs. temperature curve is given in Figure 6-2.

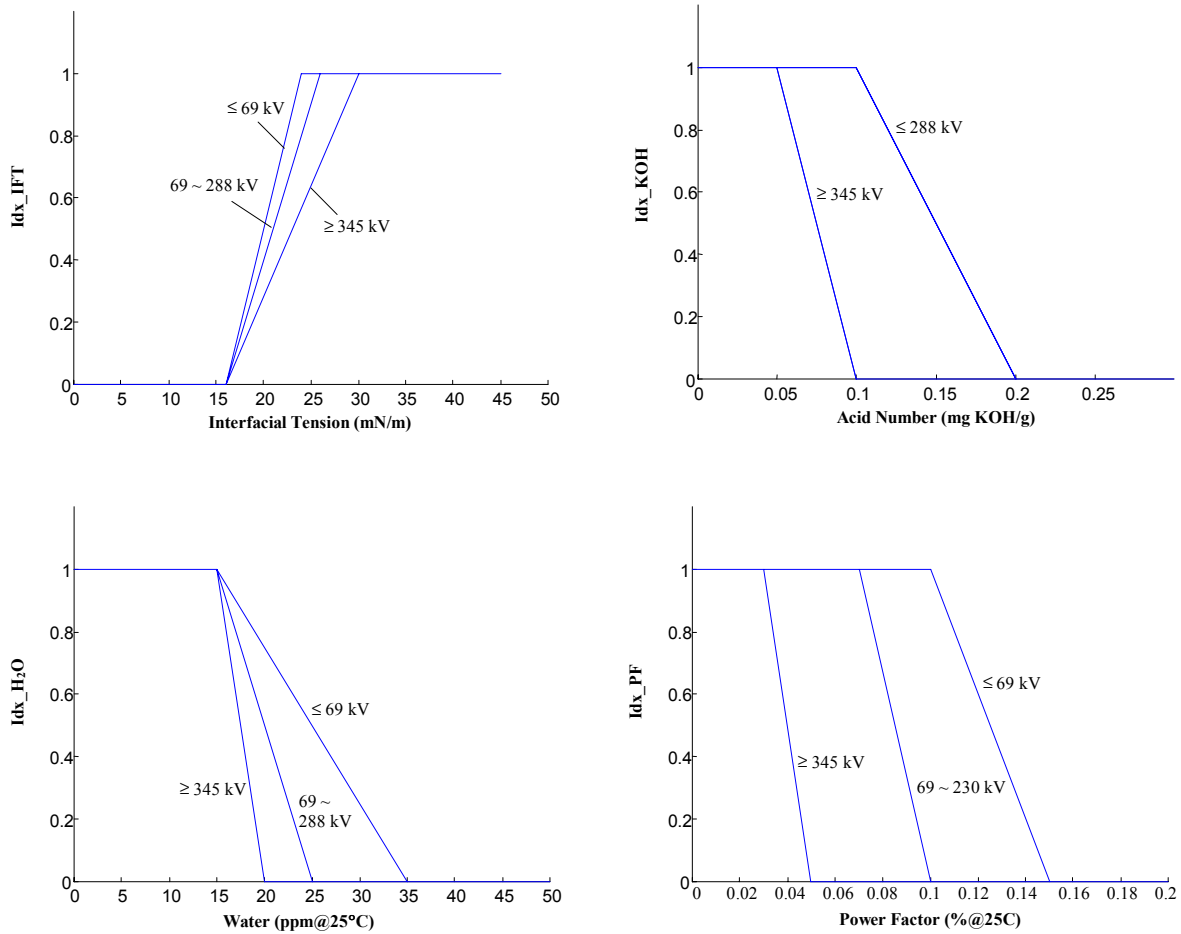


Figure 6-1 Transformer Oil Condition Assessment Indices

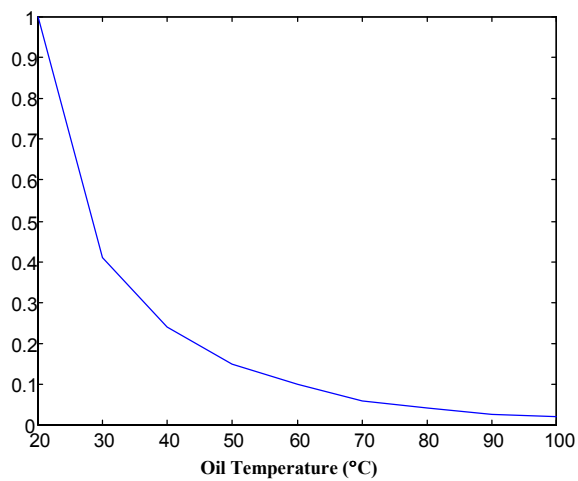


Figure 6-2 Transformer Oil Power Factor Correction Factor [Gri87]

6.2.2 Solid Insulation Condition Assessment

Solid insulation of transformers refers to paper insulation of windings and leads, and pressboard mechanical supporting parts. The requirement for solid insulation is high electrical and mechanical integrity. New transformers usually meet the requirement. Aged transformers may or may not, due to deteriorations such as decomposition, developing of voids/gaps, and being burnt away. Tests to assess the insulation condition are listed in Table 6-2. Principles behind these tests are complex and some of them are still under investigation.

Table 6-2 Tests for Power Transformer Solid Insulation Assessment

Test Item	Method	Unit	Limit Value
Induced Voltage (Maximum)	Partial Discharge (PD)	pC	100 [James86, C57.113]
	Radio Interference Voltage (RIV)	μV	500 [C57.125], 200 [C57.21]
	Acoustic Emissions (AE)	1/s	10000 [C57.125]
Insulation Resistance (IR, minimum)	Megohm Meter	MΩ	1.5V _{winding} /kVA [C57.125]
	Polarization Index (PI)		1.0 [C57.125]
Power Factor (PF, maximum)	[C57.12.90]	%	0.5 @ 20°C [Vaz95, Griffin89]
2-Furfural (FUR, maximum)	High Performance Liquid Chromatography (HPLC)	ppm	10 [Griffin91], 5 [Ali96], 0.25 [Myers92]
Degree of Polymerization (DP, minimum)	ASTM D 1795-90 ASTM D 4243-86		150 [Griffin91, Bas90, Omn93], 200 [Ali96, Griffin92], 150-250 [Domi93, Philip91, Griffin91, Anto91]

Induced voltage tests are live tests, which means that the transformer needs to be energized. Among them, RIV is the most preferred method, while PD and AE can be on-line applications. The problem with on-line PD and AE tests is interferences. Therefore, in this study only the result of RIV test was used.

Insulation resistance tests are basically off-line DC test. Test results are influenced by environmental factors such as temperature and humidity, and also by external leakage paths such as contaminated insulators and bushings. Nevertheless, polarization index was used in the study.

Power factors of solid insulation are often tested to detect inside water buildup [Griffin89]. The 0.5% limit is for new transformers and was considered to be valid for aged transformers as well in this study.

Furfural test of transformer oil and degree of polymerization (DP) test of paper samples drew great attention in the last decade [Griffin91, Griffin92, Griffin93, Griffin94, Griffin95, Griffin97, Ali96, Omn93, Domi93, Myers92, Philip91, Anto91, Bas90]. Their diagnostic abilities have been confirmed, though different researchers used a slightly different threshold value. Furfural test is relatively convenient because the oil sample can be obtained while the transformer is in operation. DP test needs a paper sample obtained directly from the winding insulation, which may damage the integrity of the transformer insulation. It is therefore not preferred in most cases. A correlation curve between the furfural concentration in oil and DP was found by Burton [Burton85] and verified by Corvo [Anto91], which may partly solve this problem. The relationship can be written as:

$$DP = -187.5 \log_{10}(\text{FUR}) + 487.5 \quad (6-2)$$

Where FUR denotes the ppm concentration of 2-furfuraldehyde, or simply 2-furfural, the most common and abundant furan derivative present in oil samples.

Some researchers used the amount of CO + CO₂ in oil to predict the solid insulation life of transformers [Kgoto90, Kawa91], but this is not a definitive technique because these gases can present simply because the oxidation of transformer oil or paper involved discharging activity.

The same as oil condition assessment, a set of indices can be defined for solid insulation condition assessment. These are also fuzzy membership functions, as shown in Figure 6-3. It should be noted that the index function for PI is based on [C57.125], and the index function for 2-furfural is based on all the experiences obtained from the literature. The transition part of the latter is described as:

$$Idx_FUR = \frac{1 - \log_{10}(\text{FUR})}{2} \quad (6-3)$$

The same as oil condition assessment, an unconditional fuzzy proposition based on Equation 6-4 was used to combine the indices, yielding an overall solid insulation condition assessment index.

$$Idx_paper_condition = \min(Idx_RIV, Idx_PI, Idx_DP, Idx_FUR) \quad (6-4)$$

When $Idx_paper_condition = 1$, the solid insulation is healthy. When $Idx_paper_condition$ is close to 0, the solid insulation is weak.

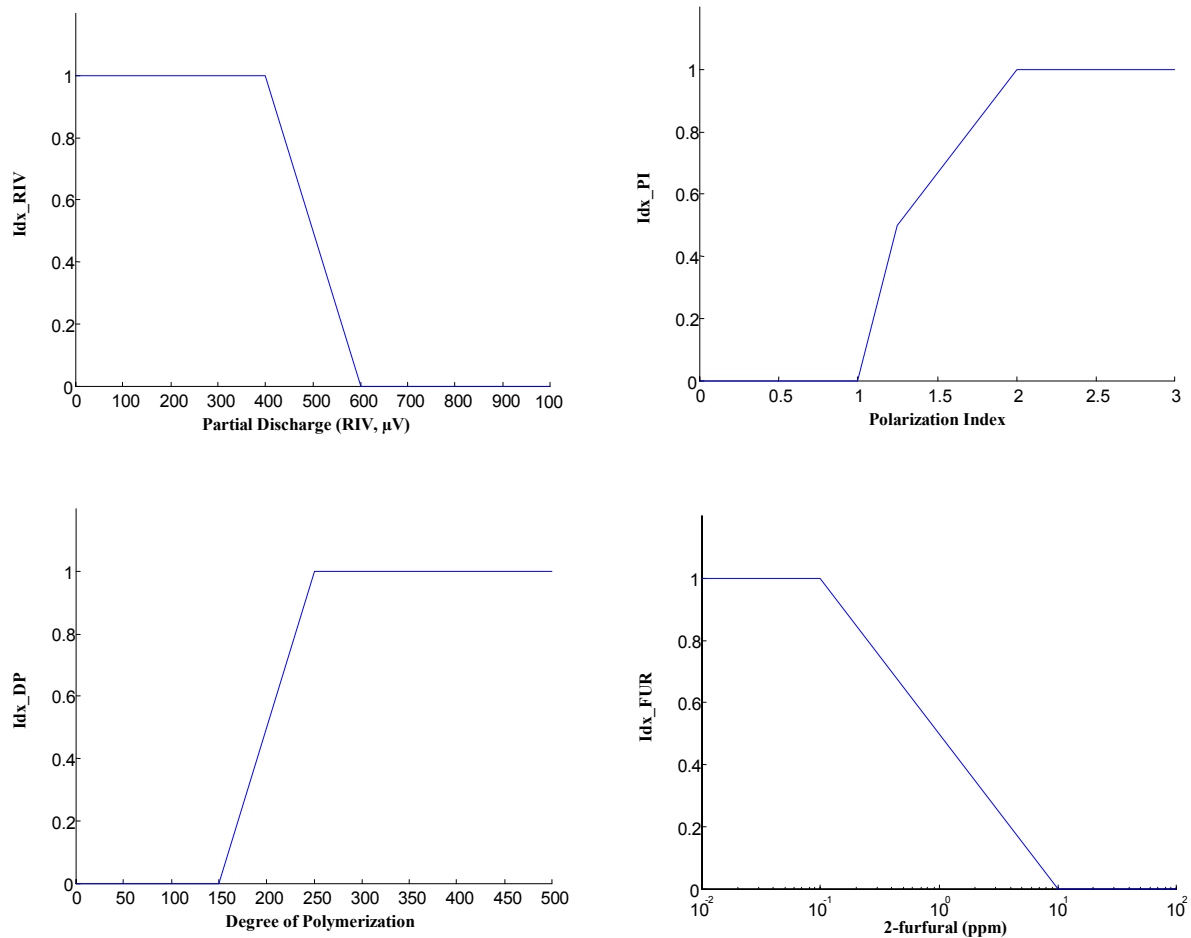


Figure 6-3 Transformer Paper Insulation Condition Assessment Indices

6.3 Index of oil sampling intervals

Transformer oil is normally sampled and tested annually if no concern is raised. Depend on the gas-in-oil concentrations and gassing trend, the recommended sample interval can decrease to half a year, three months, one month, one week or just one day, with increased concerns. An index of oil sampling interval is defined in Table 6-3 and labeled as T_S . It can be estimated using different schemes.

Table 6-3 Index of Transformer Oil Sampling Intervals

Oil Sampling Interval	Annually	Half a year	Three months	One month	One week	One day
T_S	1	2	3	4	5	6

6.3.1 T_s Estimation Scheme 1: Based on Present TDCG concentrations and TDCG Gassing Rate

This scheme recognizes the importance of total dissolved combustible gases (TDCG). T_{S1} is determined using Figure 6-4, where blue numbers and lines come from IEEE standard [C57.104], red numbers and lines are defined in this study. Numbers represent T_{S1} .

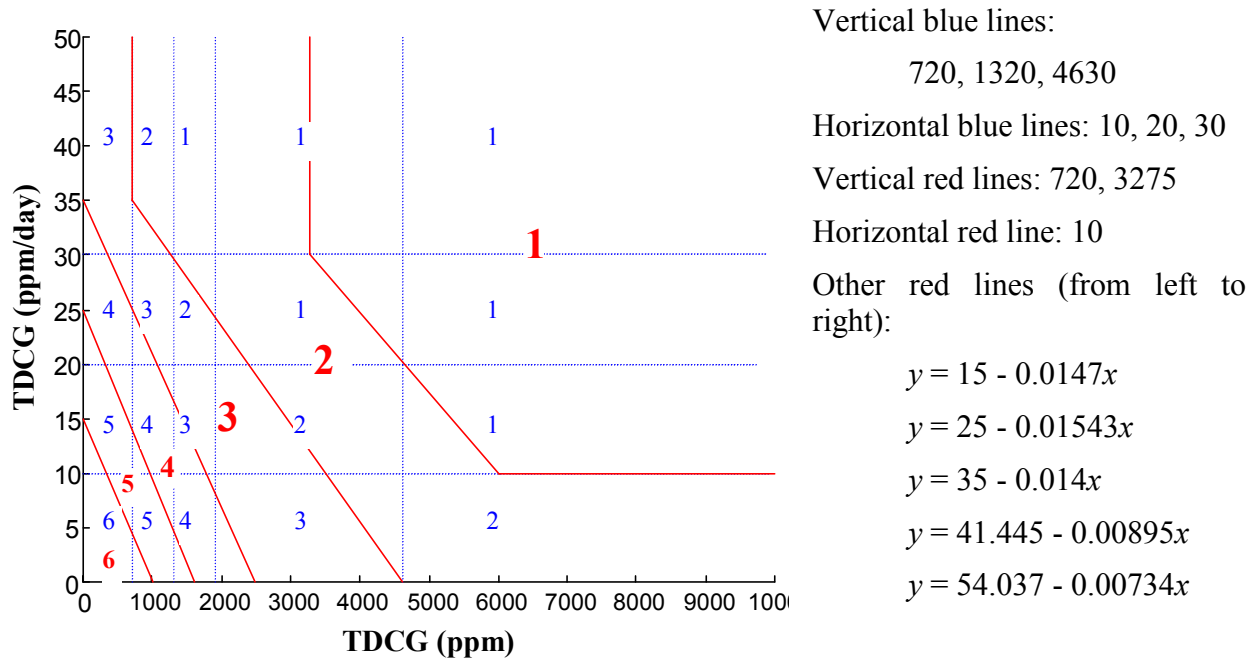


Figure 6-4 Scheme 1 T_{S1} Definition

6.3.2 T_s Estimation Scheme 2: Based on Present TDHG and C_2H_2 concentrations

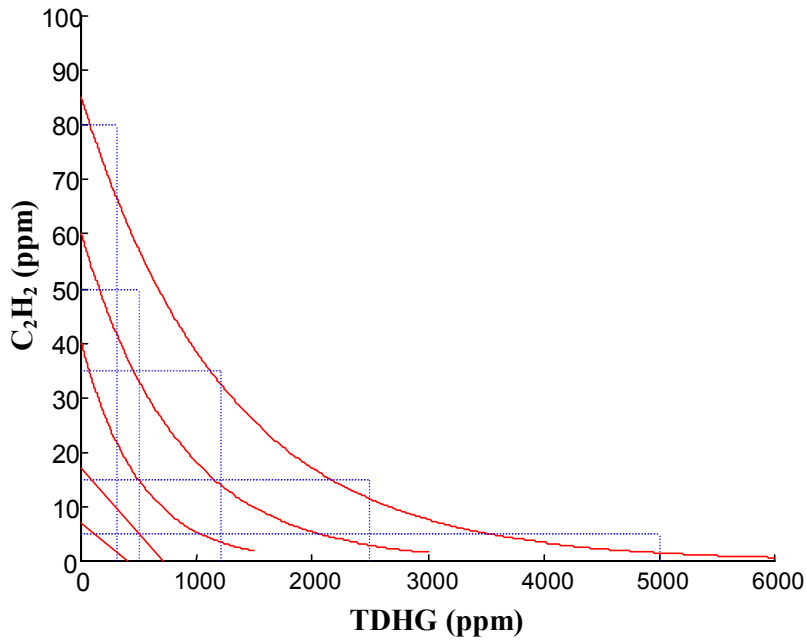
This scheme recognizes the importance of TDHG and C_2H_2 . T_{S2} is determined using Figure 6-5, where blue lines and red lines divide the 1st quadrant into areas similar to Scheme 1.

6.3.3 T_s Estimation Scheme 3: Based on Present TCG percentage and TCG Gassing Rate

This scheme takes Gas Space (TCG) into consideration. T_{S3} is determined using Figure 6-6, where blue lines and red lines divide the 1st quadrant into areas similar to Scheme 1. TCG is defined in Equation 6-5 according to [C57.104].

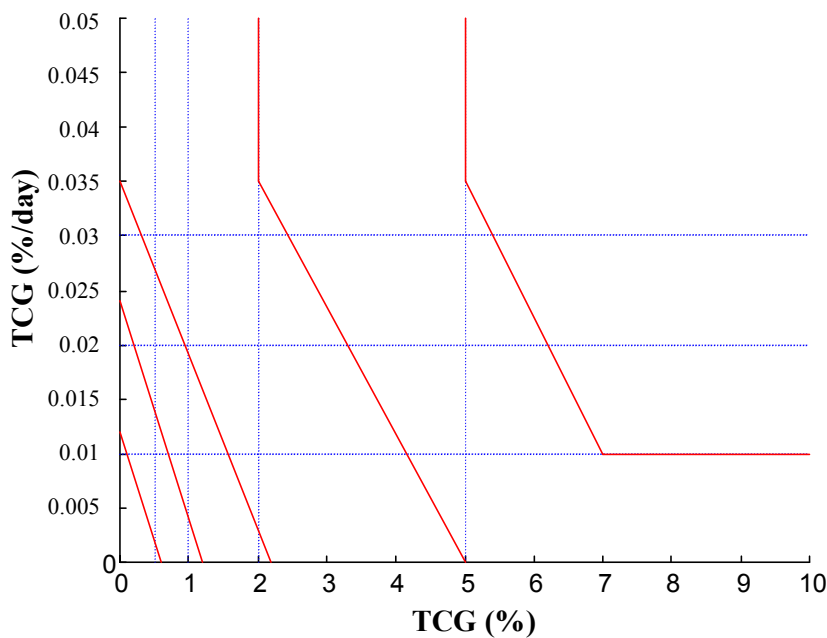
$$TCG = 100 \times \sum_{C_1}^{C_n} \frac{\frac{F_c}{B_c}}{\sum_{g_1}^{g_n} \frac{F_g}{B_g}} \quad (6-5)$$

Where $C_{1...n}$ represents each combustible gas, $g_{1...n}$ represents each gas dissolved in oil, $F_{c,g}$ represents gases-in-oil concentrations (ppm), $B_{c,g}$ represents the Ostwald solubility coefficient of the gas.



Vertical blue lines:
 300, 500, 1200,
 2500, 5000
 Horizontal blue lines:
 5, 15, 35, 50, 80
 Red lines (from left to right):
 $y = 7 - 0.0175x$
 $y = 17 - 0.0243x$

Figure 6-5 Scheme 2 T_{S2} Definition



Vertical blue lines:
 0.5, 1, 5
 Horizontal blue lines:
 0.01, 0.02, 0.03
 Vertical red lines: 2, 5
 Horizontal red line: 0.01
 Red lines (from left to right):
 $y = 0.012 - 0.02x$
 $y = 0.024 - 0.02x$

Figure 6-6 Scheme 3 T_{S3} Definition

6.3.4 T_s Estimation Scheme 4: Based on Gassing Rate of H_2

This scheme recognizes the importance of hydrogen generation as a result of partial discharge. The T_{S4} definition is in Table 6-4, which is based on [Omn98].

Table 6-4 Scheme 4 T_{S4} Definition

H_2 (ppm/day)	> 10	5 – 10	1 – 5	0.5 – 1	0.1 – 0.5	< 0.1
T_{S4}	1	2	3	4	5	6

6.3.5 T_s Estimation Scheme 5: Based on Present Gas-in-oil Concentrations

This scheme considers each individual combustible gas as well as TDCG. Table 6-5 gives the T_{S5} definition. This definition originates from [C57.104].

Table 6-5 Scheme 5 T_{S5} Definition

T_{S5}	Operator	H_2		CH_4		C_2H_2		C_2H_4		C_2H_6		CO		TDCG
1	If	>1800	or	>1000	or	>80	or	>200	or	>150	or	>1400	or	>4630
2	Else if	>700	or	>400	or	>35	or	>100	or	>100	or	>570	or	>1920
3	Else if	>100	or	>120	or	>5	or	>50	or	>65	or	>350	or	>720
4	Else if	>50	or	>60	or	>1	or	>25	or	>30	or	>200	or	>366
5	Else if	>25	or	>30	or	>0.1	or	>10	or	>15	or	>100	or	>180
6	Else													

6.4 Combination of the oil sampling interval indices

Five indices are defined in Section 6.3 and each represents an estimation of the overall oil sampling interval index. The combination of these indices follows several steps.

Step 1: Define a set of fuzzy membership functions for each index. The Outputs are the future overall index and the input is the just estimated index. These functions are shown in Figure 6-7. The different maximum values of the functions represent different weights given to the schemes. For instance, Scheme 3 and 5 are given more weights because they come from IEEE standards.

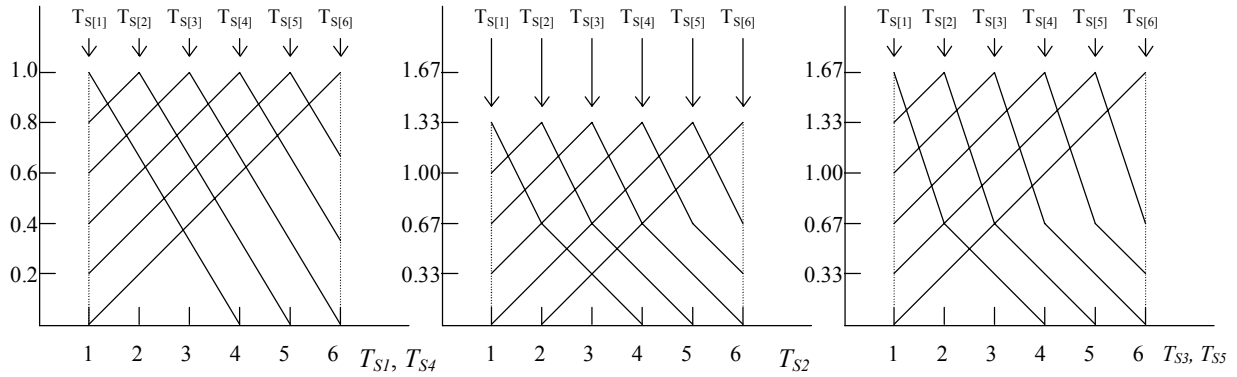


Figure 6-7 Membership Functions of Oil Sampling Interval Indices

These membership functions are not symmetrical because the index estimation needs to deviate to shorter oil sampling intervals.

Step 2: Combine the fuzzy membership function outputs using Equation 6-6.

$$T'_{S[i]} = \frac{1}{6.67} \sum_{j=1}^5 T_{S[i]}(T_{Sj}) \quad i = 1, 2, 3, 4, 5, 6 \quad (6-6)$$

Step 3: Select the overall oil sampling interval index according to the following rule.

$$\text{If } T'_{S[i]} = \max_{j=1}^6 (T'_{S[j]}) \text{ then } T'_S = i$$

6.5 Adjustment of the overall oil sampling interval index

The overall oil sampling interval index obtained in Section 6.4 applies to normal transformer age, capacity, voltage level and load level. If these factors are different from the normal, the index needs adjustment.

Figure 6-8 shows the adjustment function corresponding to each factor. These functions are based on the study of IEEE standard [C57.104] and industrial experiences.

The final overall oil sampling interval index is:

$$T_S = \text{INT} \left(T'_S + \sum_{i=1}^4 \Delta T_{Si} \right) \quad (6-7)$$

Where INT(.) denotes a round-off-to-integer function.

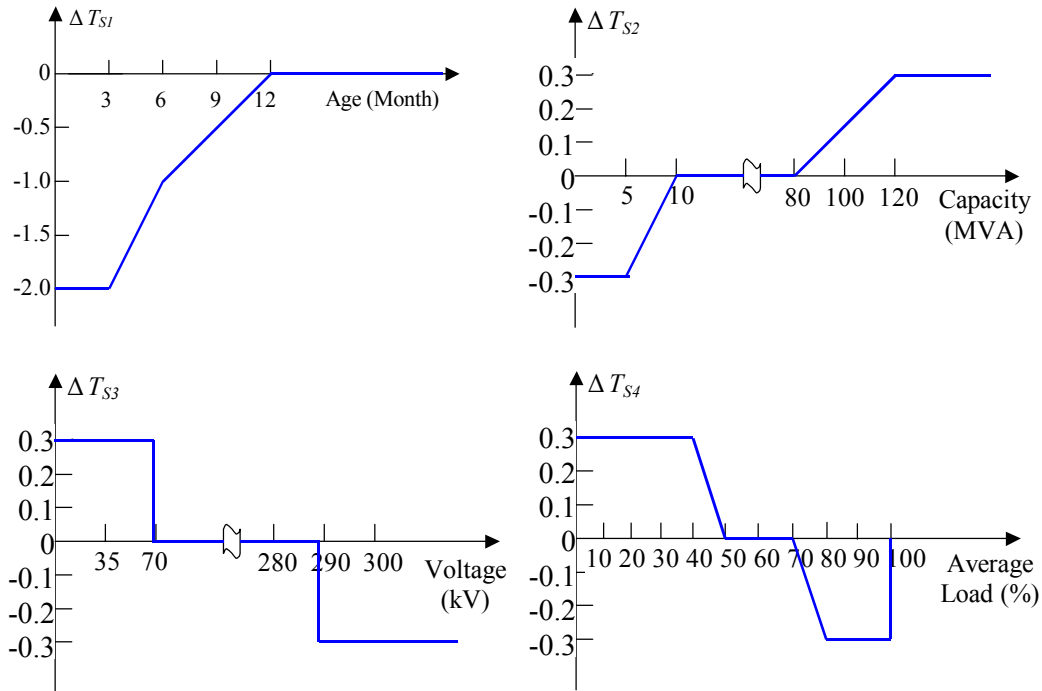


Figure 6-8 Overall Oil Sampling Index Adjustment Functions

6.6 Maintenance recommendations based on overall oil sampling interval index

These are relatively simple. Table 6-6 shows the relationships. They are based on [C57.104].

Table 6-6 Overall Oil Sampling Interval Index and Maintenance Recommendations

T_S	Maintenance Recommendations
≤ 1	Sample oil daily! Consider remove the unit from service. Advise manufacturer.
2	Sample oil in a week! Consider planned outage. Advise manufacturer.
3	Sample oil in a month! Analyze for individual gases. Determine load dependence.
4	Sample oil in three months to monitor the situation.
5	Sample oil in half a year to set up gassing trends.
≥ 6	Sample oil annually and continue normal operation.

6.7 Summary and discussions

In this chapter the techniques of transformer condition assessment, oil sampling interval and maintenance recommendations are developed based on literature study and industrial experience. Fuzzy logic was extensively used besides systematic analysis. These techniques allow the related human knowledge be integrated into machine intelligence.