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New methodology for remanent life assessment of oil-immersed power transformers

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SUMMARY

A new methodology for the estimation of the possible remanent life of a power transformer is presented in this paper, considering several types of uncertainties which are involved in the solution of this problem. The premise is to consider the transformer as individual equipment and not as a part of a group of transformers, so as to get its remanent life considering for this purpose the condition of the insulating paper and the location of the substation in which the transformer is installed regarding the power system network. An interval of remanent possible life is estimated, using intervals of possibility, which are obtained from experts' opinion. The proposed evidences (input variables) to be taken into account in order to obtain these intervals are the following: the risk of short circuits external to the transformer regarding the condition of the paper insulation, the diagnosis obtained from the dissolved gas analysis of the transformer tank oil and another variables that influence the condition of the transformer insulation, the risk due to the load and temperature and the loss of life of the transformer. Each one of these parameters is considered as an influence index taken as condition level evidence in obtaining a possible interval of remanent life.

The external short circuit risk index considers the stochastic nature which is present in external faults, as well as the degree of polymerization of the insulating paper. The external short circuit risk index is obtained by contrasting the insulation paper condition with the probability that the transformer withstands the short-circuit current flowing along the winding during an external fault. In order to assess the risk, this probability and the value of the degree of polymerization of the insulating paper are regarded as inputs of a type-2 fuzzy logic system (T-2 FLS), which computes the fuzzy risk level.

The index related to the diagnosis by means of dissolved gases analysis and another variables, evaluates the condition of the transformer insulation and the result is given using words easy to understand by the maintenance personnel. This tool is a translator that converts the diagnosis from the dissolved gas analysis of the transformer oil in words, obtaining a diagnosis expressed in a simple form which is easy to understand. These two indexes are derived using T-2 FLS which allow to take into account the uncertainty present in the words.

In the same way, in the evaluation of the condition of the transformer insulation the recommended procedures given by the present international standards are used, such as IEC 60599 method and Duval's triangle.

Furthermore, the risk index due to load and temperature is the one proposed for Weihui Fu et al., which is based on the history of load and temperature of the transformer in order to obtain a risk level for the near future. The methodology is tested shown useful results.

KEYWORDS

Diagnostic reasoning, Fuzzy diagnostic, Power transformers life, Power transformer insulation, Remaining life assessment.

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1 INTRODUCTION

Power transformers are generally very reliable, designed to achieve a useful life between 20 and 35 years [1], with a minimum life of 25 years at an operating temperature of 65-95 º C [2]. Although in practice, the life of a transformer can reach as much as 60 years with proper maintenance. The paper impregnated with oil is widely used to insulate the windings of power transformers and the industry employs the premise that *the life of a transformer is the life of paper insulation* [3].
The insulation paper - oil degrades over time and this process depends on the thermal, electrical, water and oxygen content, and other internal conditions in the transformer. Other aspects, such as the transformer external faults also affect the operating condition of the insulating material, so monitor it becomes much more important when the internal isolation transformer is in advanced state of aging.
Thus, this isolation system that is used in the most transformers at the current power systems, it is considered the weakest link of the chain in any transmission system. Therefore, the transmission companies have an obvious incentive to assess the condition of power transformers, with the objective of minimizing the risk of failure and avoiding forced outputs of strategic units installed at power substations of high and medium voltage.
This work presents a methodology that uses field data statistically manipulated, empirical rules used in industry and expert knowledge, to obtain an interval of remaining life of power transformers. The methodology allows the manipulation of the uncertainties associated with data and the lack thereof, to obtain an estimated remaining life of the equipment. Obtaining these estimates will allow the operator of the transformer makes decisions consistent with the equipment's living conditions, thereby avoiding unnecessary interruptions of service.

2 GENERAL MODEL FOR CALCULATING REMAINING LIFE OF THE POWER TRANSFORMER

The strategy followed for the assessment of remaining life of the power transformer seeks a range of equipment life from the evaluation of various indexes that are considered most important in this evaluation, i.e, those that hold influence in the life of power transformer. In this sense, it is consulted at a group of experts who provide the range of life, considering the indexes abovementioned. A brief explanation of these indexes is presented following:

a. Diagnostic index of isolation system.
b. Risk Index for external short circuits to the equipment.
c. Risk Index for load and temperature.

In addition and in order to consider the loss of life at the time of the equipment evaluation, it taking into account the IEEE C57.91-1995 [4], which evaluates the loss of life from equipment according with load and temperature (among other parameters) that the equipment has endured during its operational life.
Also, it is taking into account the chronological age of the equipment. This data is considered necessary in order of assessing the range of remaining life as a failure will not have the same effect on a new equipment than on an older one.
Thus, all this information is provided as indexes and / or data to a fuzzy inference system type-1 (T-1 FLS), so that the various uncertainties are considered in a compact way, thus providing the possibility curves intervals in which is estimated to be the remaining life of the equipment. This possibility curves intervals are the result of the application of α-cuts known as levels of confidence λ_1, .., λm in [5] to the type-1 fuzzy set result of the inference in the T-1 FLS. Fuzzy inference systems provide a robust mathematical framework capable of modeling the uncertainty of natural language and linguistic expression and calculated using numerical values. The λ_1 can be interpreted as the smallest probability that the true value of remmanent life hits the interval of life A_1. Thus, the interval A_i is the smallest one whose probability of being hit is at least λ_i. In practice, only three intervals have been kept: A1 with λ1=0.05, A2 with λ2 =0.5, and A3 with λ3=0.95. Whole the theory about these intervals is showed in reference [5]. In the same way, the whole theory about the fuzzy inference systems type-1 and type-2 is showed in reference [6].

The model considers whether the equipment has been ageing "Normal" or not, according to IEEE Standard C57.104-1991 [7], Table 3 (shown below as table I), where recommended actions to be implemented by the operator are showed, according with the levels and growth rates of the Total Dissolved Combustible Gas in Oil (TDCG). It also uses the fuzzy diagnostic model for analysis by Dissolved Gas in Oil (DGA), as shown in Figure 1, which shows the general model used in assessing the range of equipment life. A more detailed analysis of the model is shown in the following.
Thus, initially the full model tests whether the equipment has an ageing "Normal" or not, for which first analyzes the state of the equipment considering the levels and the growth rate of TDCG.

Table I. Actions to implement standards-based on TDCG levels

	Levels TDGC (ppm)	**Rate TDGC (ppm/yr)**	**Sampling intervals and operative procedures by rates of gases generation**	
			Sampling intervals	**Procedure**
Condition 4	>4630	>30	Daily	Consider renoval from service. Advice manufacturer.
		10-30	Daily	
		<10	Weekly	Extreme caution. Individual gases analysis. Plan outage. Advice manufacturer.
Condition 3	1921-4630	>30	Weekly	Extreme caution. Plan outage. Advice manufacturer.
		10-30	Weekly	
		<10	Monthly	
Condition 2	721-1920	>30	Monthly	Warning. Individual gases analysis. Determine load dependence.
		10-30	Monthly	
		<10	Quarterly	
Condition 1	≤720	>30	Monthly	Warning. Individual gases analysis. Determine load dependence.
		10-30	Quarterly	Continue normal operation.
		<10	Annual	

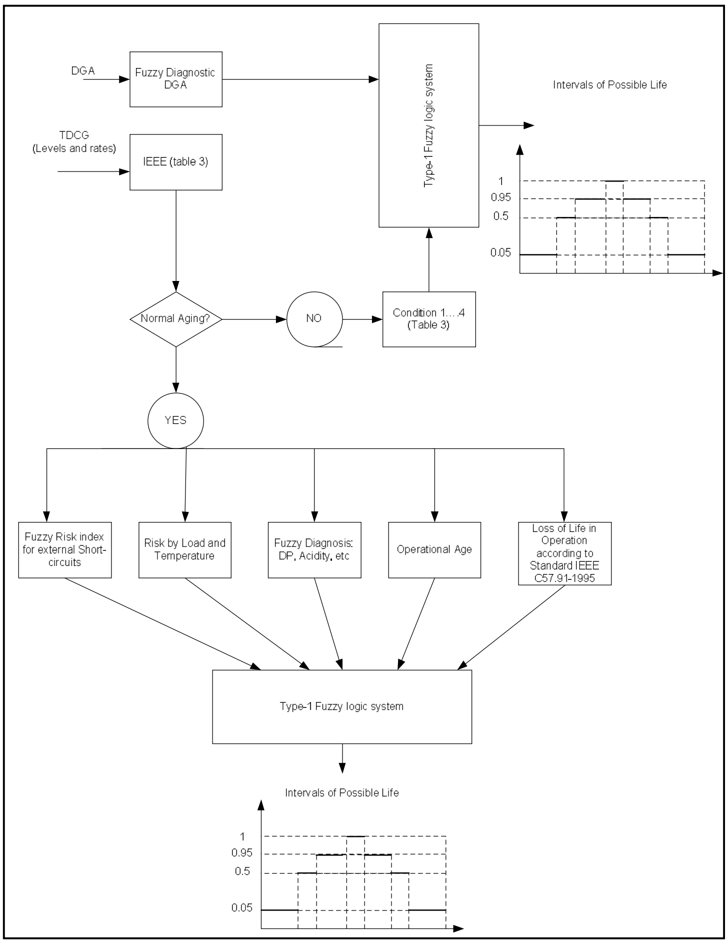

Fig. 1 General model to estimate the possible intervals of power transformer remaining life

If the equipment has an ageing "Abnormal", it is used the condition proposed in Table I, together with the fuzzy diagnosis result for dissolved gases such as inputs to the inference system of remaining life**.** Both inference systems, for abnormal and normal ageing, are type-1 FLS such as the shown in figure

2. In this figure is showed the output of the T-1 FLS (life remaining), which is the output of the inference block without taking into account the block of “output processing” (with dash line, see figure 2), which is usually used in this type of FLS.

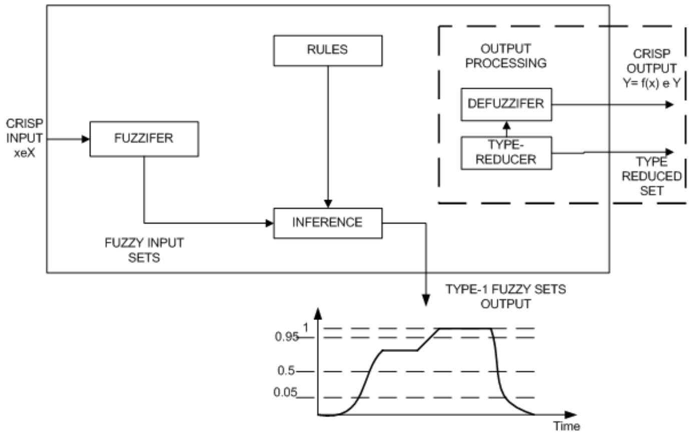

Fig. 2. Type-1 fuzzy inference system to evaluate the equipment remaining life

For the "Abnormal" case is considered that conditions 3 and 4 of table I are necessary and sufficient. Conditions 1 and 2 are considered as "Normal" ageing.
On the other hand, if according to the result obtained with the use of table I, the equipment presents a "Normal" ageing, are used the abovementioned indexes as inputs of another system of inference, which provides a range of remaining life of the equipment analyzed.

3 DIAGNOSTIC OF THE POWER TRANSFORMER PAPER-OIL SYSTEM

Making an efficient and accurate diagnosis in the paper-oil system of a power transformer requires the conjunction of different variables, which are obtained by testing with the equipment on and off-line. Once obtained these variables or input data, their processing is necessary. This processing can be performed using the empirical rules proposed by IEEE [7] and IEC [8] (in the case of gas analysis) among other variables. In this work, this estimation is made in such a way that is easily and readily understood by an expert, so that he/she can use it in assessing the remaining life of the transformer. This is considered advisable, because for the evaluation of the remaining lifespan, it is usual to give an expert opinion using a natural language.
For integrating data from tests conducted at the equipment and to get the diagnosis result of it in words easily understood by the operator of the transformer, it is proposed the use of an inference system that uses fuzzy logic-based type-2.
Given the differing characteristics of the data, it is necessary to divide the diagnosis of paper-oil system in two inference systems: an T-2 FLS to consider only the possible results of diagnostic gases dissolved in the oil and a T-2 FLS which use as input the values of various physical and chemical variables, such as moisture, acidity, etc. Latter also takes into account the outcome of the inference system by DGA, so in this way it is obtained a full picture of the state paper-oil system.
These T-2 FLS can be seen in figures 3 and 4, respectively. A typical output of these T-2 FLS is showed at figure 5. The full methodology to obtain the diagnosis by dissolved gas analysis is showed in reference [9].The T-2 FLS used for the diagnostic by dissolved gases in oil is of singleton type (the inputs are crisp values) and uses a base of rules of 512 rules. Each rule has nine antecedents (PD, D1, D2, T1, T2, T3, DFE, SC, and DC) and one consequent (condition of the equipment). Where, PD: Partial discharges, D1: Discharges of low energy, D2: Discharges of high energy, T1: Thermal faults below 300 ºC, T2: Thermal faults above 300 ºC, T3: Thermal faults above 700 ºC, DFE: Excessive degradation of insulation paper, SC: Cellulose overheating and DC: Continuous degradation of cellulose. The output of the second T-2 FLS is the final result of the diagnosis of paper insulation system of power transformer oil, which is one of the indicators used by the T-1 FLS in the estimation of remaining life of the equipment. This is an inference system for multiple inputs and one output. In this work is assumed that, in general, to know the status of power transformer insulation quickly and

without using lots of data, it is enough to use the monitoring of dissolved gases in oil along with four major additional variables: The degree of polymerization (DP), humidity in the paper by dry weight, the winding power factor (PF) and the acidity of the oil. These four factors are inputs of a second inference system for diagnosis, which is called T-2 FLS for diagnosis by physical-chemical data (see figure 4).

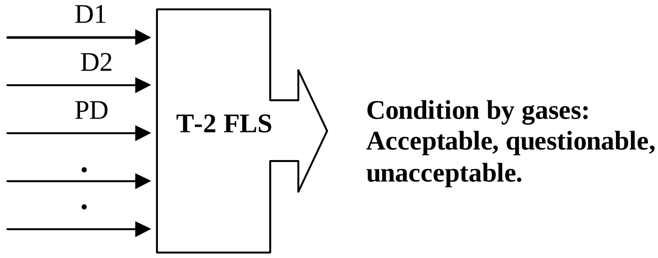

Fig. 3. T-2 FLS for dissolved gases in oil diagnosis

It is assumed that transformers analyzed by this algorithm not have access to the Overload Tap Changer (OLTC), so do not are taken into account the levels of OLTC gases.

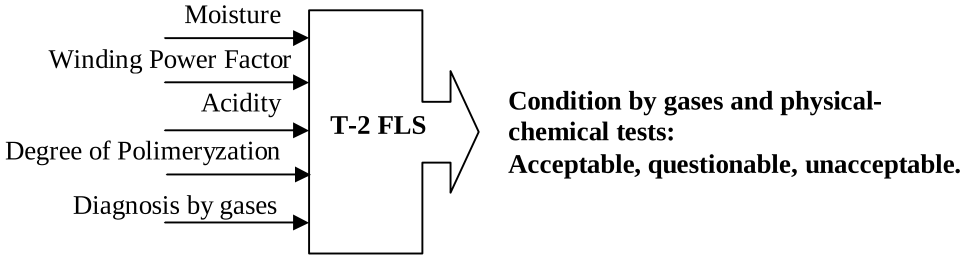

Fig. 4. T-2 FLS for physical-chemical diagnosis

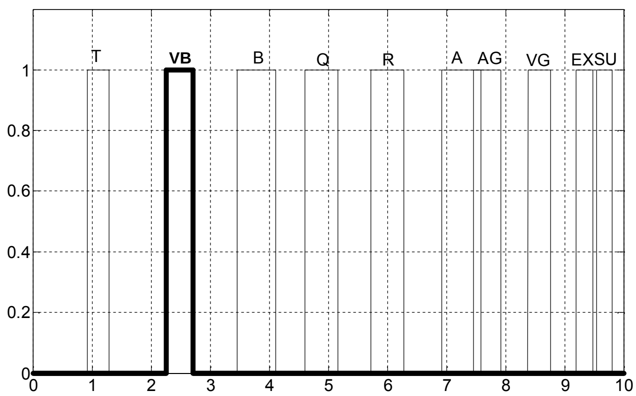

Fig. 5. Typical output of the diagnostic algorithm from DGA and oil test results
(T: terrible, VB: Very Bad, B. Bad, Q: Questionable, R: Regular,
A: Acceptable, AG: Good, VG: Very Good, EX: Excellent, SU: Superb)

Specifically, what is being done with this procedure is a translator, which "translates" the values of each variable (DP, FP, gas, etc.) into linguistic values that provide the operator with the state procurement of equipment, so make the most appropiate decision. Figure 6 shows the algorithm that integrates the two T-2 FLS used in the diagnosis of paper-oil system equipment. An important point is that if all gas concentrations are below 90% of typical values, it is not necessary to calculate gas relations and the equipment is in good condition, so the probability of failure is low [10]. The algorithm was tested with the entire database proposed by Duval in [11] (for power transformers and reactors) and shows a good performance.

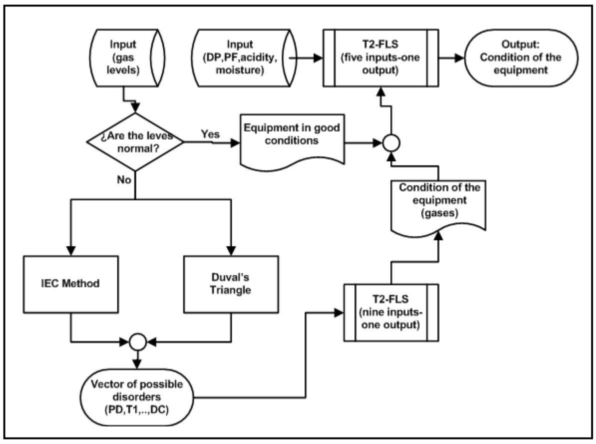

Fig. 6. Algorithm of diagnosis by gas and oil test values.

4 FUZZY RISK INDEX FOR POWER TRANSFORMERS DUE TO EXTERNAL SHORT-CIRCUITS

A T-2 FLS is used to evaluate the fault risk due to short-circuits, since it has suitable characteristics of T-2 FLS for this purpose. This T-2 FLS can be seen in figure 7. A typical output of this T-2 FLS is showed at figures 8 and 9. The first one is the result of all values of DP and the probability (*So*) that the current circulating through the transformer during short-circuits, be greater than the value that the equipment can hold up. The second one is the risk for one specific value of DP and *So*.
One important observation is that from the point of view of short-circuits it is considered that the transformer has reached its end of life when the DP has reached a value lower than or equal to 450 [12]. The complete methodology to calculate this fuzzy risk is shown in reference [13].

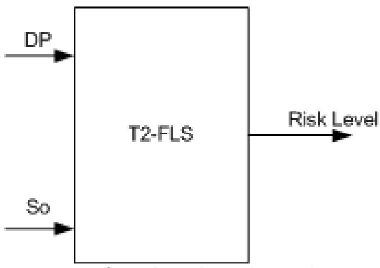

Fig..7. T-2 FLS for risk analysis due to short-circuits

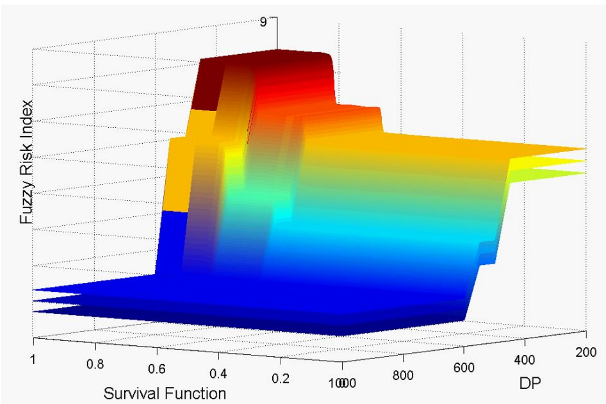

Fig. 8. Typical fuzzy risk index type-2

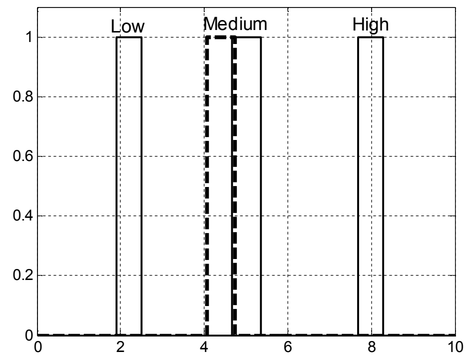

Fig. 9. Fuzzy risk for DP = 460 and a low short-circuit probability

5 RISK INDEX FOR LOAD AND TEMPERATURE

Temperature in its windings is a condition that limits the load capacity of a transformer. This condition is characterized by the hot spot temperature in the winding (θ_H). This value depends on temperature, load profile and the transformer's design characteristics. In this way, it is used the model proposed by

Weihui Fu et al [14] to obtain a risk profile. The load and temperature are considered uncertain, hence it is applied a Monte Carlo technique to calculate the probability distribution of θ_H. Based on the value of θ_H, it is calculated the loss of life and the failure probability of the transformer. The total failure risk of the transformer is obtained by adding the product of probability and consequence on all possible values of θ_H. Because the temperature distribution inside the transformer is not uniform, the loading guides are used for calculation of the loss of life of the power transformer from the estimated value of θ_H. Whole the procedure is shown in [14]. Figures 10 and 11 shows the algorithms to calculate the hot spot temperature in the winding and total risk of the transformer, respectively. Figures 12-15 shows the profiles of load, environment temperature, hot spot temperature and total risk, respectivley, for a case of study.

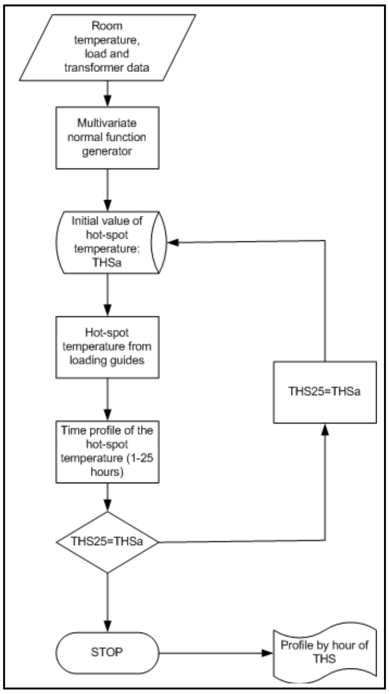

Fig. 10. Algorithm to calculate the hot spot temperature

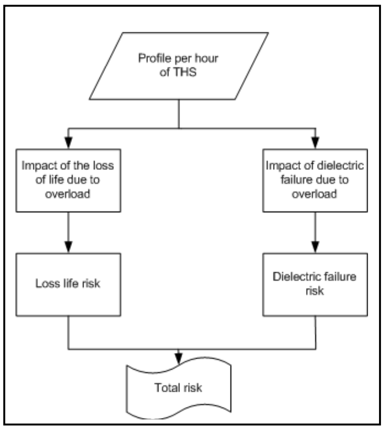

Fig. 11 Algorithm to calculate total risk

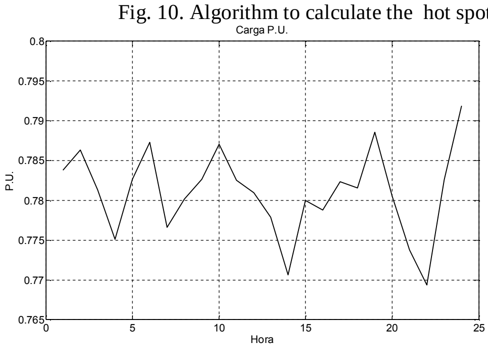

Fig. 12 Load profile

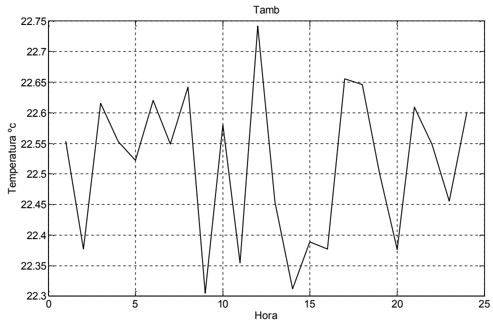

Fig. 13 Room Temperature profile

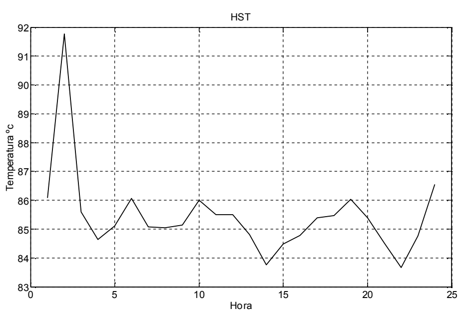

Fig. 14 Hot spot profile

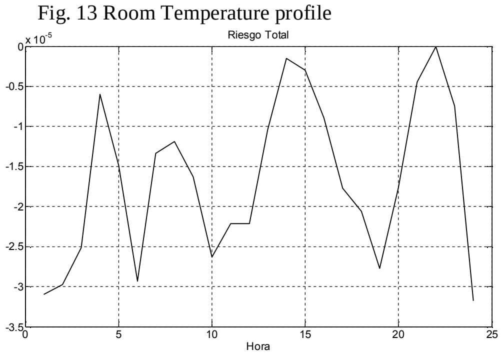

Fig. 15 Total risk profile

6 EXPERIMENTAL VERIFICATION

Due to the reduced space only are showed the results of a power transformer (TP1) of 300/300/100 MVA, 500/138/34.5 kV, located at Buenos Aires, Argentina. However, for the elaboration of this research were analyzed several transformers installed in power substations located at Argentina and Brazil.

The inspection of the equipment, installed in 1998 (10 years in operation), was do it on the period 13-02-2008 and 15-02-2008.

Table II shows the results obtained during the transformer oil inspection. Metane (CH_4) and ethane (C_2H_6) concentrations are over the limit values for a normal condition accord to IEC 60599 [8]. DGA shows the presence of an internal thermal failure. Due to the last years the equipment has been working with the core overexcited over its permitted value, it is assumed the presence of local hot spots in the core. The levels of TDCG are 1.886 ppm with a rate of 2 ppm/day. Considering these two values the equipment present a normal ageing (see table I), then it is neccesary make the calculation of all the indexes abovementioned. On the other hand, the Degree of Polimerization is 500 and based on the explotation reports, the equipment works with a load of 60-80% of maximum load. Table III shows the indexes for the transformer analyzed. This summary shows that the equipment is exposed to a possible failure by short-circuit, with a possible internal failure and the insulation life has been almost totally used regarding to the history of load and temperature.

Table II. Dissolved gases concentration of TP1. Data laboratory of Ezeiza (Ez) and Salto Grande (SG).

Gases concentration, ppm									
Date of sampling/Gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	ΣCxHy	CO	CO_2	TDCG
21.08.03, Ez	80	170	220	11	0,1	401	560	1750	1041
10.08.04, Ez	65	180	280	12	0,1	472	545	1990	1082
22.08.05, Ez	60	190	290	13	0,1	493	530	1950	1083
11.08.06, Ez	77	225	520	13	0,1	758	550	1740	1385
22.08.07, Ez	70	230	630	16	0,1	876	640	2390	1586
14.02.08, SG	43	247	993	25	NA	1265	578	3546	1886

NA – the gas was undected by the cromatrograph;
ΣCxHy – sumatory of CH4, C2H6, C2H4, C2H2.

Table III. Summary of indexes for TP1

Index		Results
No1	DGA	Regular
	DGA + Physical-chemical tests	Questionable
No2	Operative age (10 years)	Low
No3	Load and temperature	Without risk
No4	Risk by external short-circuits	Questionable
No5	Insulation lost life	High

Using these indexes as inputs the T-1 FLS estimate that the intervals remaining life are the showed in figure 16. Thus, the equipment has a high possibility of a useful remaining life of 4 to 15 years if are keeping the actual conditions of evaluation and operation. This result is in the interval of evaluation of the experts that made the sampling of data and analysis of the equipment, whose estimate that the transformer has a remaining life of 4 to 10 years and more.

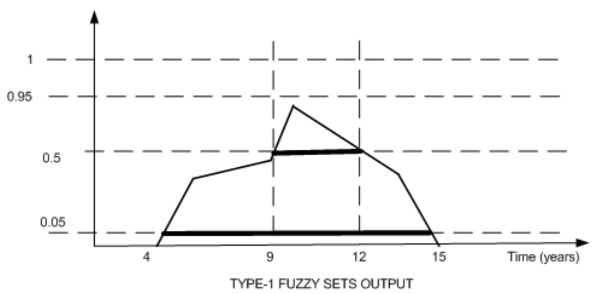

Fig. 16 Interval of remaining life for TP1

7 CONCLUSIONS

It is showed a new methodology to estimate the remaining life of a power transformer, using different tools to manage the uncertainty present in this problem. The methodology is modular because allows to evaluate of individual manner the paper-oil system condition, the risk of failure by external short-circuit and the risk by load and temperature. With these results as inputs, are obtained intervals of possible remanent life of the equipment using a type-1 fuzzy logic system. The methodology is applied to a power transformer obtaining useful results, which are optimus to make decisions about the management of the equipment.

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