Decision Support System for Diagnosis of Power Transformers

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***Abstract*--Given the complexity of the Brazilian Electric Power System, it is important to ensure that equipments work in satisfactory conditions and with high levels of reliability. Within those equipments, power transformers are one of the most important assets, because they are expensive and functionally complex. Dissolved Gases Analysis (DGA) in mineral oil insulation is widely considered as an appropriate tool for the identification of faults in power transformers. This work proposes a system called SADTRAFOS to support maintenance managers' decisions regarding those faults. The system is composed of a fuzzy inference module for fault diagnosis, and of a decision support module that gives recommendations to maintenance managers. The experiments carried out with a real database attained more than 80% accuracy in the fault diagnosis and correct recommendations for the maintenance team.**

***Index Terms*--Decision support systems, Fuzzy systems, Knowledge based systems, Power transformers.**

I. Introduction

Power transformers are certainly the most expensive and critical equipments within an electric plant. Therefore they are of great concern to the maintenance area, which tries to ensure their operational integrity during their life cycle.

The majority of transformers uses Insulating Mineral Oil with a naphthenic basis [1], due to its dielectric properties regarding insulation and its cooling properties as a heat transfer agent. During operation, transformers are subjected to thermal, electrical and mechanical efforts, which may give origin to dissolved gases in the mineral oil. This directly affects the dielectric properties of the whole insulation. Therefore, to evaluate the operational condition of a power transformer, as well as the possibility of faults, its solid and liquid insulation conditions must be monitored and evaluated.

Dissolved Gases Analysis (DGA) has been one of the most important tools for the diagnosis of faults in power transformers [2]. Many monitoring systems have been developed by major transformers manufacturers to allow real time analysis of relevant information to the diagnosis. Based on the data collected by these monitoring systems, intelligent techniques, such as artificial neural networks [3], are being applied to the identification of faults in a variety of equipments, as power transformers [4].

However, although artificial neural networks provide high accuracy in faults identification, they are unable to provide clear and interpretable information about the relation of monitoring system information and the equipment diagnosis [5].

Additionally, another important issue that still remains is the decision on the possible actions to be taken, preferably in an optimized way, taking into account technical and economic aspects.

This study proposes a complete system, called SADTRAFOS, which consists of a fuzzy inference system to provide the diagnosis, based on interpretable fuzzy rules, and of a decision support system to indicate actions and recommendations for maintenance managers.

This paper is divided into four additional sections. Section II presents the database used to develop the SADTRAFOS system. Section III describes in details the proposed system, which is composed of three basic modules: Pre-processing, Diagnosis and Decision Support. Section IV presents the results obtained in two case studies and, finally, Section V provides the conclusions of this work.

II. Transformers Database

The complete database is composed of 122 transformers and was initially divided into four groups with the following operational conditions identified during inspections:

1. Normal Operating Condition (NCO) – no inspections occurred in this category, since either the DGA or the transformer protections did not indicate any condition of fault or abnormality;
2. Partial Discharges (PD) – inspections have indicated contacts problems and internal connections leading to material losses through little sparks, discharges signals between the high voltage winding and the tank in the core support, lack of insulation in the core, deposit of lees and wax-x as a by-product of the penetration of moisture in paper-oil insulation, as well as grounding problems;
3. Thermal Faults (TF) – this corresponds to cases of hot spots and discoloration of the core, due to fusion, contact problems leading to material losses, problems with the cooling system such as clogging radiators, malfunction of pumps and fans, conductors heating and identification of points, as well carbonization of solid insulation (paper);
4. Electric Arc (EA) – the most severe fault mechanism, due to the high energy necessary for its formation; the related faults are short-circuits between turns in the windings of high

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and low voltage. Some cases are detected through the action of differential protection or over current or even through the action of pressure relief valves and the gas relay. In some more severe cases, the formation of an electric arc preceded explosions in tap changers and bushings.

Results from initial simulations, however, have shown that thermal and partial discharges faults (groups 2 and 3) could not be easily distinguished in the diagnosis phase. This was already expected, since they hardly occur in an isolated way. Despite representing different phenomena, one leads to another within the power transformer [6]. Therefore, Thermal Faults and Partial Discharges were grouped together.

Table I shows the distribution of patterns in each of the final three categories: NOC (normal operating condition), PD&TF (partial discharge or thermal fault) and EA (electric arc).

TABLE I
DISTRIBUTION OF PATTERNS

OPERATING CONDITIONS	DATA STANDARD
NOC	32
PD & TF	60
EA	30
TOTAL	122 TRANSFORMERS

III. SADTRAFOS SYSTEM

The proposed system is basically composed of three modules: Pre-processing, Diagnosis and Decision Support, as shown in Fig. 1.

The data about dissolved gases in the Insulating Mineral Oil are fed into the system and pre-processed, basically for variable normalization purposes. Then the diagnosis module – a Fuzzy Inference System – gives a partial report on the equipment state. The decision support module finally presents the concluding result – recommendations – to the maintenance manager.

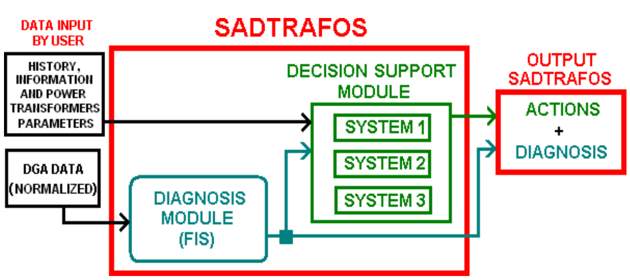

Fig. 1. Architecture of SADTRAFOS

A. Pre-Processing Module

In the DGA, 13 variables are considered: 7 gases and 6 gases ratios, as shown in Table II. Thus, the entire database has 122 rows (transformers) and 13 columns.

TABLE II
VARIABLES CONSIDERED

DATA BASE	
GASES	GASES RATIOS
H_2	CO_2/CO
CH_4	C_2H_2/H_2
CO	CH_4/H_2
CO_2	C_2H_2/C_2H_4
C_2H_4	C_2H_4/C_2H_6
C_2H_6	C_2H_6/CH_4
C_2H_2	_

Pre-processing of data consisted of two steps: normalization and variable selection.

Normalization was done linearly in two ranges of values (two normalization regions with different linear functions), due to the nonuniform distribution of values in the specific range of each variable.

The relevance of variable selection in classification problems is a well known issue and here two traditional methods have been used: Principal Components Analysis (PCA) [7] and Least Squares Estimator (LSE) [8].

The results obtained from both methods, when applied to the 13 variables listed above, are shown in Table III.

In the experiments, in order to obtain a set of interpretable fuzzy rules, only three and four input variables have been considered. In fuzzy inference systems, it is important to assure that the number of rules does not increase to a point where linguistic interpretation becomes unfeasible.

TABLE III
RESULTS FROM VARIABLE SELECTION METHODS

ORDER OF IMPORTANCE	PCA	LSE
1°	C2H6/CH4	CH4
2°	C2H4	C2H4
3°	CO	C2H2/C2H4
4°	CO2	C2H6/CH4
5°	CH4	CO2/CO
6°	C2H6	C2H4/C2H6
7°	CH4/H2	CO
8°	H2	C2H6
9°	C2H4/C2H6	CO2
10°	C2H2/H2	CH4/H2
11°	C2H2	H2
12°	CO2/CO	C2H2/H2
13°	C2H2/C2H4	C2H2

B. Diagnosis Module

The diagnosis module consists of a Mamdani-type fuzzy inference system [9]. Rules are automatically extracted from DGA real data related to transformers removed from operation and diagnosed through inspections. The rule extraction process was performed through the Wang and Mendel method [10],[11]. The basic structure of the fuzzy inference system (FIS) used for diagnosis is shown in Fig. 2.

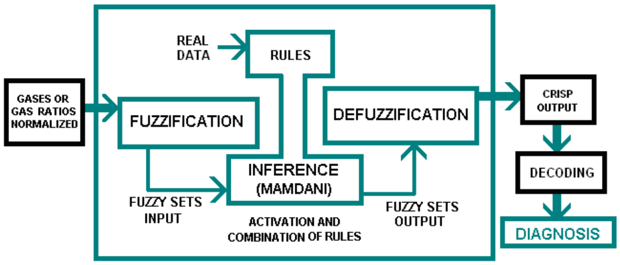

Fig. 2. FIS Structure

Once the fuzzy rules extraction procedure is completed, the FIS does the mapping from DGA input variables (already normalized in the pre-processing module) to the final diagnosis classification. The DGA inputs are *fuzzified* (mapped to fuzzy sets), which can be viewed as the activation value of relevant rules for a given situation. The output fuzzy set computed through the *inference* process is then *defuzzified*, giving as a result a crisp output value. In this specific case, the final class determination (diagnosis) is performed through a decoding process, where a different range of the output variable is associated to each of the three possible output classes (NOC, PD & TF and EA).

C. Decision Support Module

The Decision Support Module of SADTRAFOS is composed of three sub-systems, each specialized in recommending specific actions to the maintenance manager, depending on the type of diagnosis:

- Sub-system 1 – Normal Operating Condition (NOC)
- Sub-system 2 – Partial Discharge or Thermal Fault (PD or TF)
- Sub-system 3 – Electric Arc (EA)

The decision support module receives, in addition to the FIS diagnosis, further information about the transformer under analysis, provided by the user. Fig. 3 presents the structure of the Decision Support Module.

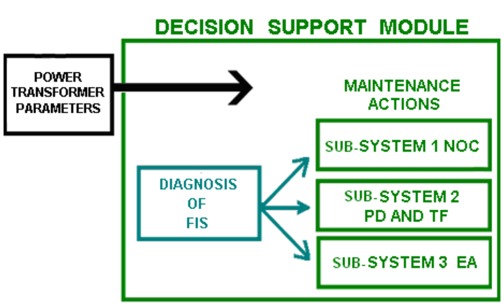

Fig. 3. SADTRAFOS Decision Support Module

The parameters that characterize the transformer under analysis by SADTRAFOS are *structural characteristics of the transformer, operational context, history of events and information from other diagnosis methods*.

Since the Decision Support Module is conditioned to the information provided by the Diagnosis Module, each sub-system is specialized in recommendations and actions realted to one of the three possible diagnoses. Thus, SADTRAFOS provides a complete overview of the transformer under analysis, presenting its operational condition as well as recommendations and actions related to maintenance of the evaluated equipment.

IV. CASE STUDIES

Two case studies have been carried out in this work. The first one considered a database with 122 transformers and was actually used for the development of the Diagnosis Module – modeling of the fuzzy inference system in terms of all its necessary parameters, such as number of fuzzy sets for each variable and defuzzification method, and the variable selection method (PCA or LSE). The second case study was performed with a new group of transformers, used to evaluate the complete SADTRAFOS system. The following section details the results obtained in each case study.

A. Case Study 1

The first case study presents the results obtained from the diagnosis module and the decision support module of the SADTRAFOS with the database acquired from CHESF.

To evaluate the Diagnosis Module, the Wang and Mendel rule extraction method [10],[11] was applied to the available database, with 70% of the patterns used for training and 30% for testing. Two sets of tests were carried out, first with four different diagnoses and then with only three.The average accuracy obtained for four and three output classes are presented in Tables IV and V, respectively.

TABLE IV
AVERAGE ACCURACY OF FIS WITH 4 DIAGNOSES IN THE OUTPUT VARIABLE

AVERAGE ACCURACY 4 DIAGNOSTIC OUTPUT					
NUMBER OF INPUTS VARIABLES	NUMBER OF SIMULATION	NUMBER OF FUZZY SETS/ INPUT VARIABLE			NUMBER OF RULES
		7	5	3	
4	1	40,6%	_	_	65
	2	62,5%	_	_	37
	3	_	56,25%	_	16
	4	_	_	53,12%	47
	5			46,87%	8
	6	_	59,37%		23
	7	_	68,75%	_	24
	8	_		65,62%	10
	9	_	56,25%	_	23
3	10		65,62%		23
	11	_	53,12%	_	23

TABLE V
AVERAGE ACCURACY OF FIS WITH 3 DIAGNOSES IN THE OUTPUT VARIABLE

AVERAGE ACCURACY 3 DIAGNOSTIC OUTPUT					
NUMBER OF INPUTS VARIABLES	NUMBER OF SIMULATION	NUMBER OF FUZZY SETS/ INPUT VARIABLE			NUMBER OF RULES
		7	5	3	
4	12		83,33%		23
	13	79,16%	_	_	30
	14		_	70,83%	15
	15	_	75,00%	_	17
	16	_	66,66%	_	20
	17	_	83,33%	_	23
	18	_	75,00%	_	16
	19	_	79,16%	_	18
	20		79,16%		22
3	21		83,33%		22
	22		75,00%		18

As can be observed, by grouping Partial Discharge and Thermal Fault diagnoses in a single class, the average accuracy is significantly higher than in the initial 4-class configuration.

The chosen configuration for implementing the Diagnosis Module was the one that provided high accuracy as well as more interpretable fuzzy rules. Therefore, simulation 21 (see Table V) was selected, since it provides 83.33% accuracy, with 22 fuzzy rules and only three input variables. Fig. 4 illustrates the selected FIS for the Diagnosis Module. Fig.s 5a and 5b provide the fuzzy sets configuration for the input and output variables, respectively. Table VI presents the set of 22 fuzzy rules obtained by the selected FIS configuration.

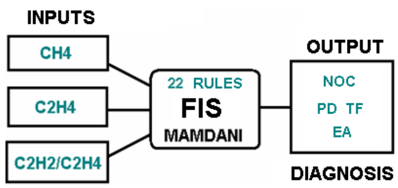

Fig. 4. Selected FIS for SADTRAFOS Diagnosis Module

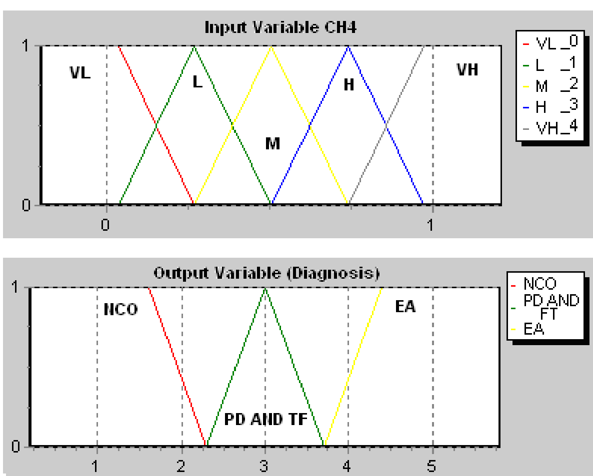

Fig. 5. a) Fuzzy sets of input variables; b) Fuzzy sets of output variable

TABLE VI
EXTRACTED FUZZY RULES

N°	RULES								
1	IF	CH4	VH	C2H4	H	C2H2/C2H4	H	SO	EA
2	IF	CH4	VL	C2H4	VL	C2H2/C2H4	L	SO	EA
3	IF	CH4	VL	C2H4	VL	C2H2/C2H4	VH	SO	EA
4	IF	CH4	M	C2H4	M	C2H2/C2H4	L	SO	EA
5	IF	CH4	L	C2H4	M	C2H2/C2H4	M	SO	EA
6	IF	CH4	L	C2H4	M	C2H2/C2H4	L	SO	EA
7	IF	CH4	L	C2H4	L	C2H2/C2H4	H	SO	EA
8	IF	CH4	L	C2H4	L	C2H2/C2H4	VH	SO	EA
9	IF	CH4	VL	C2H4	L	C2H2/C2H4	L	SO	EA
10	IF	CH4	L	C2H4	L	C2H2/C2H4	L	SO	EA
11	IF	CH4	VH	C2H4	H	C2H2/C2H4	M	SO	EA
12	IF	CH4	L	C2H4	H	C2H2/C2H4	L	SO	EA
13	IF	CH4	VH	C2H4	VH	C2H2/C2H4	VL	SO	EA
14	IF	CH4	M	C2H4	L	C2H2/C2H4	VL	SO	PD AND TF
15	IF	CH4	M	C2H4	M	C2H2/C2H4	VL	SO	PD AND TF
16	IF	CH4	H	C2H4	H	C2H2/C2H4	VL	SO	PD AND TF
17	IF	CH4	VL	C2H4	VL	C2H2/C2H4	VL	SO	NCO
18	IF	CH4	VL	C2H4	L	C2H2/C2H4	VL	SO	PD AND TF
19	IF	CH4	L	C2H4	M	C2H2/C2H4	VL	SO	PD AND TF
20	IF	CH4	M	C2H4	H	C2H2/C2H4	VL	SO	PD AND TF
21	IF	CH4	VH	C2H4	H	C2H2/C2H4	VL	SO	PD AND TF
22	IF	CH4	L	C2H4	L	C2H2/C2H4	VL	SO	PD AND TF

The results from the Diagnosis Module were then applied to the Decision Support Module, in order to provide the final recommendation and actions for maintenance, according to the equipments' specifications registered by the user.

Table VII presents an example of the final recommendation provided by SADTRAFOS for one of the transformers evaluated.

TABLE VII
SADTRAFOS OUTPUT

OUTPUT MODULE OF A DECISION SUPPORT: CASE 1
DIAGNOSIS: ELECTRIC ARC
RECOMENDATIONS OF SADTRAFOS : **SYSTEM 3**
M3: ASSESSING DAMAGE AND IF POSSIBLE REPLACED COMPONENTS, OIL TREATMENT AND RECOVERY SOLID INSULATION

B. Case Study 2

In this case study a new three-phase autotransformer was investigated. This equipment, shown in Fig. 6, was removed from operation by another Brazilian electricity company, due to its DGA in mineral oil insulation.

Fig. 6. Three-Phase Autotransformer used in Case Study 2

This three-phase autotransformer had its operational conditioned monitored by gas chromatography since its energizing, in 1989, due to its high power and importance for the Brazilian electric system. In December 2006, the autotransformer presented 1,3 ppm of acetylene, raising the special attention of maintenance technicians and engineers.

Following this event, further oil samples were analyzed and, in September 2007, the gas chromatography indicated 5 ppm of the same gas, which caused the equipment removal from operation. All DGA information was collected and provided to SADTRAFOS Diagnosis Module. Moreover, additional information about the transformer has also been provided to the Decision Support Module, such as:

- The autotransformer contains a forced cooler system with fans and pumps;
- The tap changer does not operate under load;

- The equipment was inserted in a transmission system and operated since 1989 with a pattern of 0 ppm acetylene;
- Before its inspection, the equipment was submitted to acoustic emission tests and the evaluation confirmed acoustics activities of large magnitude near the tertiary and inside the autotransformer tap changer.

Table VIII presents the output of the Decision Support Module for the autotransformer.

TABLE VIII
OUTPUT OF SADTRAFOS: CASE STUDY 2

OUTPUT MODULE OF A DECISION SUPPORT: CASE 2
DIAGNOSIS: PARTIAL DISCHARGE AND THERMAL FAULTS
RECOMMENDATIONS OF THE SADTRAFOS: **SYSTEM 2**
M 1.4: CHECK THE OBSTRUCTION OF THE RADIATORS AND OPERATION OF FANS AND PUMPS
M 1.8: REDUCE THE FREQUENCY OF ANALYSIS OF MOI. CHECK THE RATES OF EVOLUTION OF H2 OF C2H2 BEYOND EVOLUTION OF CH4. POSSIBILITY OF PD OR CORONA IN OIL, HEATING IN THE CORE WITH WEAR OF MATERIALS AND TAP CHANGER
M 2.2: CHECK THE DEPENDENCE WITH LOAD AND LIMITS REFERENCE OF THE GENERATION OF GASES
M 4: IN CASE OF CONVERGENCE OF THE DIAGNOSIS SCHEDULE INSPECTIONS

To evaluate the performance of the proposed system, an inspection and maintenance report of the equipment was obtained after its removal of operation. Among the problems identified within the autotransformer, the most relevant were:

- Carbonization of the core's metal block;
- Interconnection cables of the tap changer presented heating indication, followed by burning of solid insulation (paper);
- Burning on the outer layer of the insulating paper of the tap changer shielding cables;
- Unlined core plates;
- Fixed contacts of the tap changer with superficial oxidation and mobile contacts with the eroded surface, needing repair.

Figs. 7 and 8 below show photographs of the equipment after inspection.

Fig. 7. Burning of solid insulation (paper)

Fig. 8. Heating indications in the interconnection cable of tap changer

V. CONCLUSIONS

This paper presented the development of a system to provide accurate diagnosis of faults in power transformers and to support maintenance managers' decisions regarding those faults. The results obtained in two case studies demonstrated that the proposed SADTRAFOS system is able to provide good accuracy in fault diagnosis of transformers as well as to indicate correct maintenance actions related to those transformers.

The results obtained with the proposed SADTRAFOS, considering all 25 equipments evaluated in the case studies, were compared with three of the most well-known diagnosis methods based on DGA: IEC 60599 (International Electrotechnical Commission) [12], ROGERS [13] and Duval's Triangle [14]. Table IX presents the performance of all four models. As can be observed, the performance of SADTRAFOS is significantly superior to those of all other methods, with an improvement in accuracy of at least 12%.

TABLE IX
PERFORMANCE OF SADTRAFOS COMPARED WITH TRADITIONAL CRITERIA

ANALYSIS OF PERFORMANCE				
	IEC	ROGERS	DUVAL	SADTRAFOS
CASE 1	19/24 = 79,16%	13/24 = 54,16%	12/24 = 50%	20/24 = 83,33%
CASE 2	0/1 = 0%	0/1 = 0%	1/1 = 100%	1/1 = 100%
TOTAL	76%	52%	52%	84%

Despite the good performance of SADTRAFOS, this can be improved by aggregating other parameters to the available DGA data, obtained from other diagnosis methodologies. Additionally, the system can also be enhanced by standardizing the information provided by the user with respect to transformers' parameters, avoiding subjective information and, therefore, unnecessary maintenance recommendations, resulting in a more reliable system.

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