PROMETHEE and Fuzzy PROMETHEE Multicriteria Methods for Ranking Equipment Failure Modes

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Abstract — **The objective of this work is to develop and implement a computer program of a methodology for the identification and ranking of failure modes of equipment in operation on electric power substations. It is proposed to rank the problems (failure modes) assuming a multicriteria context in opposition to the empirical methods today adopted. The methodology to support multicriteria decision PROMETHEE is compared with the fuzzy-PROMETHEE method, which is associated with the theory of fuzzy sets. In the fuzzy-PROMETHEE the input data are treated as fuzzy numbers, with the purpose of considering the uncertainty contained in the data. Using the fuzzy-PROMETHEE ranking one gets a more realistic failure mode ranking, considering the lack of data. The severity of the effects associated with the occurrence of each failure mode was used as a criterion for evaluating the methodology developed. It is known that functional failures affect businesses in different ways and may compromise the reliability of the system, operating costs, or even the safety or the environment. Therefore, different degrees of severity in terms of economical, operational, environmental, and safety impacts were attributed. A fuzzy inference system to obtain the overall severity of each crash mode, where the entries are the specific severities above, was built. With the overall severity of each failure mode it is possible to evaluate the risks associated with each one of them. Having a list with the prioritization of failure modes, a methodology for prioritization of actions most appropriate for the reduction or elimination of the consequences of each mode of failure can be applied. The major contribution of this work is to make available a refined model, considering multiple criteria analysis and the interests of different decision makers, for a maintenance plan to be carried out. This plan should aim to increasing operational reliability of equipment and reducing the maintenance overall costs**.

***Keywords*- Multicriteria decision making; PROMETHEE; Fuzzy numbers; RCM**

I. INTRODUCTION

Reliability Centered Maintenance - RCM is a process used in modern maintenance, in which the risk management is considered. RCM differs from the traditional maintenance in the focus given to the functions of the equipment and systems. While in the traditional maintenance the main goal is to preserve the equipment, in RCM, as in [1], the main objective is to preserve the main functions.

The identification of the failure modes, their causes and effects, is a fundamental part in the application of the RCM process. The failure modes with larger risks should be treated with priority, and to them an effective maintenance plan should be made. This plan must establish tasks that are economic and operationally applicable. Obtaining a bad priority or an erroneous priority for the failure modes can lead to an inefficient maintenance plan, and the critical points of the system will not be reached [2].

The priority of the failure modes should serve as a tool for planning the maintenance of substations' equipments, in order to take effective actions that minimize the associated risks to such equipment.

The outlet of a maintenance decision based on risk assessment should be influenced by the probability occurrence of a failure, the severity of its consequences and the detection probability of failure; in other words, it is a multicriteria decision problem, where several criteria may influence in the final decision.

II. THE PROMETHEE METHOD

The PROMETHEE method (Preference Ranking Organization METHod for Enrichment Evaluations) [3], is a multicriteria analysis method that uses concepts introduced by B. Roy, one of the authors of the Electre method, pioneer in the utilization of this kind of procedure.

According to [3], this method is useful to solve multicriteria problems of the kind:

$$Max\{f_1(a), f_2(a), ..., f_k(a) \mid a \in A\}$$

Where:

A – Is a finite set of n alternatives;

$f_j(.)$, for j varying from 1 to k criteria - are the evaluations of the criteria about A.

These evaluations should be real numbers. Each criterion can have its own units and the general case considers the existence of criteria to be minimized and criteria to be maximized, in the sense understood as criteria optimization. For each criterion a preferably function or generalized criterion should be specified, which takes values between 0 and 1, in order to represent the decision maker preference in face of the relative differences to each evaluation criterion, as well as to eliminate the scales effects associated to the units in which the criteria are expressed.

The preferably function or generalized criterion represents the behavior or attitude of the decision maker regarding the differences between options for a given j criterion. The decision maker has degrees of freedom with regard to the kind of criterion he will use and to the indifference limits and strict preferences, as can be seen in [3].

A preferably weighted index π should be defined, as in equation (1), for all the pairs of alternatives, and will indicate the preferably percentile of option $\underline{a}$ regarding the alternative $\underline{b}$, carrying in consideration the attributed weights to each criterion.

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$$\pi(a,b)=\frac{\sum_{j=1}^{k} w_j P_j(a,b)}{\sum_{j=1}^{k} w_j} \quad (1)$$

The coefficients w_j are called weights, and are measures of the importance of each used criterion. The weights should be determined by the decision maker; if all criteria have the same importance, then the weights may be equal. The method defines three outranking flows: leaving flow (ϕ^{+}), entering flow (ϕ^{-}) and net flow (ϕ)

$$\phi^{+}(a)=\frac{\sum_{\substack{b=1\\ b\neq a}}^{n}\pi(a,b)}{n-1} \quad (2) \qquad \phi^{-}(a)=\frac{\sum_{\substack{b=1\\ b\neq a}}^{n}\pi(b,a)}{n-1} \quad (3)$$

$$\phi(a)=\phi^{+}(a)-\phi^{-}(a) \quad (4)$$

The higher the leaving flow and the lower the entering flow, the better the alternative.

The PROMETHEE II uses the net flow for a complete preorder:

$$\begin{cases} aPb & if \quad \phi(a)>\phi(b) \\ aIb & if \quad \phi(a)=\phi(b) \end{cases}$$

Where P and I represent better and indifferent, respectively.

Thus, through PROMETHEE II, one can have a complete preorder preventing the occurrence of incomparable alternatives.

III. FUZZY PROMETHEE

Reference [4] proposed an adaptation of the PROMETHEE method using operations with fuzzy numbers. The weights of the criteria are treated as linguistic variables, represented as trapezoidal fuzzy numbers.

In the context of equipment ranking of failure modes, in which this work is included, the performance of alternatives (failure modes) in each of the criteria can be obtained only at rough. Thus, the use of fuzzy numbers in the evaluation of each failure mode is very adequate and important, since its usage allows a closer look at the reality of the problem, obtaining a more realistic ranking.

Adaptations of the PROMETHEE method to use fuzzy numbers in the evaluations of alternatives, as used in this work, are presented below.

1. Assuming the evaluations of alternatives under a given criterion j as triangular fuzzy numbers, the difference *d(a,b)* between the evaluations of two alternatives a and b, will be a triangular fuzzy number (m,α,β), represented as a rating of [5].
2. Knowing that the choice, done by the decision maker, of the function of preference to be used in each criterion depends on the type of problem, one can consider that, in most cases, the type V preference function (with linear zone of indifference) is one of the most adequate [3].
3. The general criterion type V can be expressed as [6]:

$$\tilde{P}(a,b)=\begin{cases} 0 & m-\alpha\leq 0 \\ \dfrac{(m,\alpha,\beta)-q}{p-q} & se \quad q\leq m-\alpha \quad e \quad m+\beta\leq p \\ 1 & m+\beta\geq p \end{cases} \quad (5)$$

4. According to [4], the degree of preference comparison of the alternatives a and *b*, with the criterion *f*, can be defined as:

$$\begin{aligned} &P_j(\tilde{f}(a)-\tilde{f}(b))=P_j(\tilde{d}) \\ &=P_j((m,\alpha,\beta)_{LR}) \\ &=(P_j(m),(P_j(m)-P_j(m-\alpha)),(P_j(m+\beta)-P_j(m))) \end{aligned} \quad (6)$$

5. The multicriteria preference index is expressed as:[1]

$$\tilde{\pi}(a,b)=\frac{\sum_{j=1}^{k} w_j \tilde{P}_j(a,b)}{\sum_{j=1}^{k} w_j} \quad (7)$$

If the weight is considered as a precise value it will be represented as $(w_j, 0, 0)$.

6. The leaving flow and entering flow will be fuzzy numbers according to equations (8) and (9), respectively.

$$\tilde{\Phi}^{+}(a)=\frac{\sum_{\substack{b=1\\ b\neq a}}^{n}\tilde{\pi}(a,b)}{n-1} \quad (8)$$

$$\tilde{\Phi}^{-}(a)=\frac{\sum_{\substack{b=1\\ b\neq a}}^{n}\tilde{\pi}(b,a)}{n-1} \quad (9)$$

7. The net flow is also a fuzzy number obtained through the difference between leaving and entering flows.

$$\tilde{\Phi}(a)=\tilde{\Phi}^{+}(a)-\tilde{\Phi}^{-}(a) \quad (10)$$

Finally, the ranking of alternatives must be done. The results are presented in the form of fuzzy numbers and the main problem in this step is the comparison of fuzzy numbers..

There are several models proposed for ranking fuzzy numbers. We can not say that there is a better one, once their adequacy is application dependent. A proposal is made that the net flow be defuzzified using the centroid method [4] according to equation (11) below.

$$x_{defuz}=\frac{1}{3}(3m-\alpha+\beta) \quad (11)$$

The defuzzification result by the centroid method is the index x_{defuzz}, know as the YAGER [6] index.

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[1] The symbol ~ is used to indicate fuzzy number

IV. MULTICRITERIA DECISION MODEL

Figure 1 represents the complete model proposed in this work. Steps 1 and 2 of the decision model presented in Figure 1 are based on the methodology suggested by [7][8].

In step 1, the evidences of possible defects to be detected in the equipment are identified. Such evidences are obtained through different analysis methods, which use, as inputs, variables stored in a relational database.

As shown by [7], each analysis method is specialized in the identification of a defect in one specific equipment, and the analysis will return the "degree of fault" G and "confidence in the degree of fault" C with values between 0 and 1.

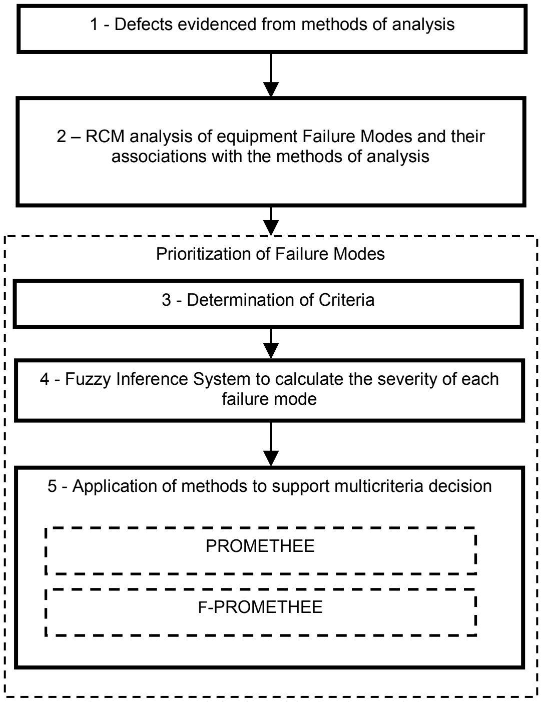


Figure 1 – Model of Multicriteria Decision

The values G and C obtained for different types of defects that may be occurring simultaneously in the equipment will be used as inputs in step 2 of the model. In step 2, through the RCM process, the possible causes (failure functional + component + failure modes) are related to the defects highlighted by the analysis methods used in step 1.

Once the possible causes are highlighted, the methodology developed in this work is applied to prioritize the failure modes and to assist decision-making in the maintenance management.

It is assumed, as basic assumptions for this work, that the RCM process has been applied and the failure modes have been previously identified. Steps 1 and 2 of Figure 1 are, therefore, out of the scope of this work.

After the identification of alternatives (failure modes) from the evidences of abnormality (defects), it is necessary to determine the relevant criteria to the further solution of the problem. This is represented in step 3 of the model shown in Figure 1. This step is described in the next section of this work.

A. Criteria Determination

In step 3 the model determines the criteria to be used for decision, which will evaluate the failure modes that later will be prioritized in step 5 by using the PROMETHEE and F-PROMETHEE multicriteria methods.

The seven criteria used in this study were:

1. Degree of occurrence of the cause (GO);
2. Confirmation of the cause degree (CI);
3. Severity of economic impacts (SE);
4. Severity of operational impacts (SO);
5. Severity of safety in human life impacts (SS);
6. Severity of environmental impacts (SA);
7. Risk degree (GR).

Each of these criteria requires that an expert attach answers to specific questions with degree from 0 to 1, as in [9].

For step 4 of the model depicted in Figure 1, a fuzzy inference system, to obtain the overall severity of each mode of failure, was implemented. This system has as entries the severities SE, SO, SS and SA and the entries are used as evaluation criteria for the ranking of failure modes. The global resulting severity of the fuzzy inference system is used for the risk of failure modes evaluation. The calculation of the degree of risk (GR) of each failure mode will be done according equation (12).

$$GR = GO \times S \qquad (12)$$

The last step of the model, Step 5, is the application of the multicriteria decision methods PROMETHEE and F-PROMETHEE for ranking of the possible failure modes.

V. FUZZY INFERENCE SYSTEM

The fuzzy inference system in Step 4 has, as main objective, to obtain the overall severity S for each failure mode. This system was created using the Matlab® *Fuzzy Logic Toolbox*. The input variables are the severities analyzed from different aspects and these severities are used as evaluation criteria in the problem of failure modes prioritization. The resulting overall severity is used to calculate the risk associated to each failure mode. The input variables are shown in Table 1.

Table 1 - Modeling of input variables

Input Variables	**Universe of Discourse**	**Linguistic Values**
Severity of economic impact (SE)	0-5	Low, Medium, High
Severity of operational impact (SO)	0-5	Low, Medium, High
Severity of safety in human life impact (SS)	0-5	Low, Medium, High
Severity of environmental impact (SA)	0-5	Low, Medium, High

As already mentioned, the output variable of the fuzzy inference system S, is the overall severity of each failure mode. This variable assumes a degree value from 0 to 1, which reflects the intensity for the company of the different impacts of the occurrence of the failure modes. The modeling of this variable is presented in Table 2.

Table 2 – Output Variable Modeling

Output Variables	**Universe of Discourse**	**Linguistic Values**
Overall Severity (SG)	0-1	Insignificant, Minimal, Marginal, Critical, Catastrophic

A set of 81 linguistic fuzzy rules was obtained from experts' knowledge.

VI. DECISION SUPPORT METHODS APPLICATION

A computational system, using the C ++ Builder, with the multicriteria methods PROMETHEE F-PROMETHEE was implemented.

This system has two modules. One module is the implementation of the PROMETHEE method, which provides as output the priority of the failure modes according this method. The other module is the implementation of the F-PROMETHEE. The results provided by the two methods can be viewed simultaneously, facilitating the comparison and evaluation of results. After each of the criterions has been set by the decision maker, the program displays the prioritization of the failure modes. At the F-PROMETHEE method for the evaluation of alternatives under each criterion, triangular fuzzy numbers are used.

The evaluation of the failure modes under the degree of occurrence GO criterion was represented as a fuzzy triangular number triangular $(m, \alpha, \beta)_{LR}$ where:

m = evaluation of the failure mode under the criterion GO. This index is normalized between 0 and 1.

$$\alpha = \begin{cases} error & if \quad error \leq m \\ m & if \quad error > m \end{cases} \qquad \beta = \begin{cases} error & if \quad error \leq 1-m \\ 1-m & if \quad error > 1-m \end{cases}$$

The error represents the uncertainty in the value of this evaluation and can be measured by the expression: error = 1-CI.

For example, you can define, for a particular failure mode, the value of its assessment under the criterion GO to be equal to 0.85 and the value of its assessment under the criterion CI to be equal to 0.75. The representation of this evaluation through a fuzzy number $(m, \alpha, \beta)_{LR}$ will be:

m= 0.85; error = 1-CI = 1-0.75=0.25

Then, $\alpha = 0.25$; $\beta = 0.15$.

A graphical representation of fuzzy number $(0.85, 0.25, 0.15)_{LR}$, can be seen in Figure 2.

Then, the index matrix of weighted preference for each pair of alternatives is calculated according to equation (7). From these indexes, the leaving flow, entering flow and net flow, for each alternative, are then calculated, as shown in equations (8), (9) and (10). These flows are also triangular fuzzy numbers.

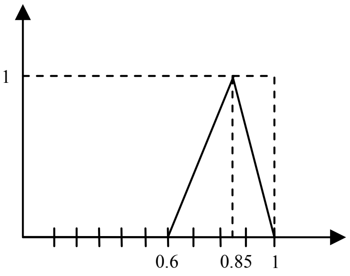
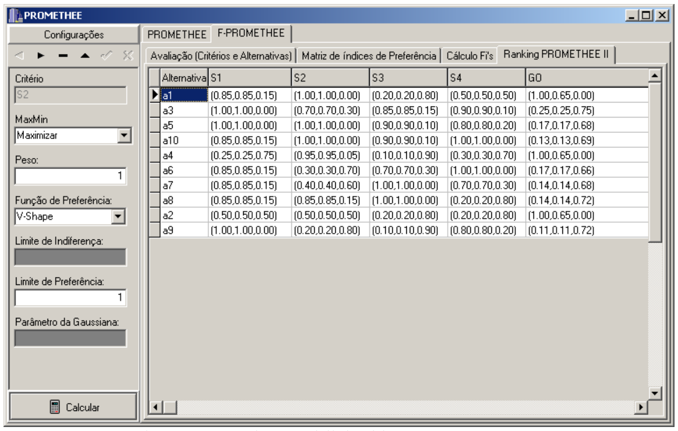


Figure 2 – Representation of fuzzy number $(0.85, 0.25, 0.15)_{LR}$

The alternatives ordering through the net flow, in this case, must be made by a method that allows the ranking of fuzzy numbers. The method used is the ordering by the YAGER index, equation (11).

Figure 3 shows a screen of the program developed in C ++ Builder and an example of ordering established by F-PROMETHEE. The net flow and the Yager index of each alternative are also shown.



Critério: S2

MaxMin: Maximizar

Peso: 1

Função de Preferência: V-Shape

Limite de Indiferença:

Limite de Preferência: 1

Parâmetro da Gaussiana:

Alternativa	S1	S2	S3	S4	GO
a1	(0.85,0.85,0.15)	(1.00,1.00,0.00)	(0.20,0.20,0.80)	(0.50,0.50,0.50)	(1.00,0.65,0.00)
a3	(1.00,1.00,0.00)	(0.70,0.70,0.30)	(0.85,0.85,0.15)	(0.90,0.90,0.10)	(0.25,0.25,0.75)
a5	(1.00,1.00,0.00)	(1.00,1.00,0.00)	(0.90,0.90,0.10)	(0.80,0.80,0.20)	(0.17,0.17,0.68)
a10	(0.85,0.85,0.15)	(1.00,1.00,0.00)	(0.90,0.90,0.10)	(1.00,1.00,0.00)	(0.13,0.13,0.69)
a4	(0.25,0.25,0.75)	(0.95,0.95,0.05)	(0.10,0.10,0.90)	(0.30,0.30,0.70)	(1.00,0.65,0.00)
a6	(0.85,0.85,0.15)	(0.30,0.30,0.70)	(0.70,0.70,0.30)	(1.00,1.00,0.00)	(0.17,0.17,0.66)
a7	(0.85,0.85,0.15)	(0.40,0.40,0.60)	(1.00,1.00,0.00)	(0.70,0.70,0.30)	(0.14,0.14,0.68)
a8	(0.85,0.85,0.15)	(0.85,0.85,0.15)	(1.00,1.00,0.00)	(0.20,0.20,0.80)	(0.14,0.14,0.72)
a2	(0.50,0.50,0.50)	(0.50,0.50,0.50)	(0.20,0.20,0.80)	(0.20,0.20,0.80)	(1.00,0.65,0.00)
a9	(1.00,1.00,0.00)	(0.20,0.20,0.80)	(0.10,0.10,0.90)	(0.80,0.80,0.20)	(0.11,0.11,0.72)

Figure 3 – Order established by F-PROMETHEE

VII. STUDY OF CASES

Aiming to illustrate the application of the developed model, an RCM process was developed to the active part subsystem of power transformers. The active part of power transformers can be considered the most critical part in those equipments, since most of the failure modes that can generate equipment unavailability or explosion occur in this subsystem.

The transformer used for the case study presented below belongs to the Brazilian company Eletronorte and is installed in the Tucuruí (UHE Tucuruí) power plant [10]. The DianE System was used as reference for the list of possible causes to be prioritized by the methods PROMETHEE and F-PROMETHEE.

A. *Case Study: Transformer 58599*

For a diagnosis of the active part of the 58599 transformer, the test results of gas chromatography were added in the DianE System. The DianE System showed as output a sign of overheating in the transformer conductors (SC). The degree of defect was 0.70, with confidence level equal to 0.76 (in a scale of 0-1). No problems were indicated directly associated with electric arc (EA) and partial discharge (PD). The results for de (SC) degree and its confidence resulted from the integration of four analysis methods: ABNT, Dornemburg, Rogers and IEC60599.

From this defect evidence, the DianE System uses the RCM process to provide the diagnosis of this equipment and provide a ranked list of possible causes associated with the shown defect evidence. This list of causes should be prioritized, to help the maintenance managers in the decision making. The system displays the list of prioritized causes considering the greatest GO x S (risk) first as performed by the DianE System. In case of equal risk values, the system prioritizes respectively by the largest CI, S and GO.

The need for a methodology that considers the ordering of evaluations on all criteria simultaneously, led to the model proposed in this work. The methods PROMETHEE and F-PROMETHEE are used to achieve this goal.

The list of possible causes identified and prioritized by the DianE System for the (SC) defect under study is presented in Table 3. Only those ranked in the top positions are shown. The full list can be seen in [9].

Table 3 - Prioritized causes by the DianE System

	Cause		
	Functional Failure	**Component**	**Failure Mode**
1	Elevation of temperature in the oil tank and windings	Connector bushings / active part	Poor electrical contact
2	Elevation of temperature in the oil tank and windings	Taps	Poor fixation
3	Accelerated thermal degradation of insulating paper occurred with currents below those specified	Winding / coil	Channels blocked oil
4	Elevation of temperature in the oil tank and windings	Winding	Poor initial design
5	Elevation of temperature in the oil tank and windings	Winding / coil	Poor initial design
6	High surface overheating (because of dispersion magnetic flux)	Nucleus	Disabilities in the insulation of the screws for fixing
7	Poor electrical connection or poor mechanical contact	Connector bushings / active part	Problem mounting
8	Reduction of insulation located in an active	Connector bushings / active part	Poor attachment to the winding
9	Reduction of insulation located in an active	Sound insulation (paper+oil)	Rupture of the insulating paper
10	Do not allow any movement of electric current	Key derivation of unstrained	Total disruption of the connection

It should be noted that only the values of GO*S, CI, S and GO are currently used by the DianE System. The value of S corresponds to an overall estimate given by the specialist. To improve this estimate, the criterion S was dismembered on several criteria, SE, SO, SS, SA, estimated by individual experts in accordance with the interpretations set out in Tables 4 to 6. Through assessments of each cause by the criterion SE, SO, SS and SA, the fuzzy inference system is then used to obtain the overall severity, SG.

Given the array of failure modes, the next step in the case study was to make a sensitivity analysis by applying the methods PROMETHEE and F-PROMETHEE to sort the list of causes.

B. *Sensitivity Analysis*

Using the computer program developed in this work, a sensitivity analysis using the methods with different combinations of criteria was made. The program allows the easy configuration of different criteria combinations. All criteria were considered with equal weights and the used function of preference was the Type III, according to Brans et al (1986), with p = 1. Tables 4 to 6 show the different combinations of criteria used in each method for the sensitivity analysis.

Table 4 - Models 1 and 2

Model 1	**Model 2**
Method: DianE	*Method: DianE*
GO	GO
CI	CI
S	SG
Risk = GO x S	Risk = GO x SG

Table 5 - Models 3 and 4

Model 3	**Model 4**
Method: PROMETHEE	*Method: PROMETHEE*
GO	GO
CI	CI
Risk = GO x S	Risk = GO x SG

Table 6 - Models 5 and 6

Model 5	**Model 6**
Method: PROMETHEE	*Method: F-PROMETHEE*
GO	$\tilde{GO}$
CI	-
Economic Risk = GO x SE	Economic Risk = GO x SE
Operational Risk = GO x SO	Operational Risk = GO x SO
Security Risk = GO x SS	Security Risk = GO x SS
Environmental Risk = GO x SA	Environmental Risk = GO x SA

Table 7 shows the ranking obtained using the methods described in Tables 4 to 6; Model 1 (DianE System) is used as reference for the ordering of the alternatives.

A full evaluation of the results of Table 7, with advantages and disadvantages of each model can be seen in [9].

Table 7 – Obtained Causes Ordering - Models 1, 2, 3, 4, 5 and 6

Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
1	1	1	1	1	9
2	2	2	2	2	13
3	5	14	14	9	1
4	4	3	4	10	10
5	3	4	5	13	2
6	6	5	3	8	8
7	10	6	10	11	11
8	8	7	8	12	12
9	9	8	9	4	17
10	11	9	11	5	18

C. *Results Analysis*

The photos presented in Figure 4 (a,b) resulted from the studied transformer when opened for maintenance, as in [10].

It can be seen from Table 3, that the cause listed as 1 can be confirmed the failure mode identified in Figure 4a. Moreover, the cause listed as 2 indicates the failure mode shown in Figure 4b. These causes appear as maintenance priorities in models 1, 2, 3, 4 and 5.

Figure 4 (a,b) - Detail of coking, corrosion and fusion in the interconnection links with AT terminals

The same causes appear at model 6 in the third and fifth place in the list, respectively. This happens because model 6 considers the imprecision of the data, so that data with high uncertainty are more prioritized in relation to others with less uncertainty.

Figure 4 shows that the list of causes identified will lead maintenance managers to the correct identification of the problem causes. In fact, until the moment of opening the equipment by performing a detailed inspection, what is available to the maintainer is a ranked list of possibilities that should be used as guidance to facilitate the final identification of the problem and to the definition of the most appropriate corrective action.

Therefore, the proposed model is a good diagnostic system that is able to put the actual failure modes reaching the equipment in a subset of alternatives closer to the top of the list shown in Table 7.

VIII. CONCLUSIONS

This work aimed to propose the use of a multicriteria decision support for the prioritization of failure modes, identified by the application of the RCM process, during the diagnostic of electric power equipment.

Two models were presented based on the employment of methodologies PROMETHEE and F-PROMETHEE. Besides the employment of these methodologies, a fuzzy inference system, to calculate the severity of each failure mode, was also developed. This procedure enabled comparisons and evaluations of sensitivity among the proposed models and some possible variants of them, applied to the model currently used in the System DianE, taken as the available reference.

The PROMETHEE method approach, combined with a model of inference to calculate the severity SG (Model 4), proved to be a tool that could be used for the prioritization of failure modes evaluated under multiple criteria. A study performed on an in-operation transformer showed that the use of this model was quite satisfactory. The flexibility of PROMETHEE that allows the user to easily assign different weights to the criteria of this methodology makes this method very interesting as a tool to assist diagnosis of equipments. Using the proposed model, different decision makers can obtain various rankings appropriate to their main interests. This is the case of diagnoses being made in companies with different profiles of risk acceptance. The F-PROMETHEE methodology proved to be the most sensitive on the issue of appropriate treatment of uncertainty, giving a list of the nearest that could be a reality if the data have many uncertainties.

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