International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2016 | Issue 28 | Volume 8 | Number 3 | Pages 42-51

FAILURE RISK ANALYSIS USING DATA FROM A POWER STATION REMOTE MONITORED

N. Bizon [1,2] **M. Oproescu** [1] **G.R. Sisman** [2]

1. Faculty of Electronics, Communications and Computers, University of Pitesti, Pitesti, Romania
nicu.bizon@upit.ro, nicubizon@yahoo.com, mihai.oproescu@upit.ro
2. Doctoral School of Electronics, Communications and Information Technology,
University "Politehnica" of Bucharest, Bucharest, Romania, sisman_george@yahoo.com

Abstract- The purpose of this article is to present methods to failure risk analysis based on data acquired from a power station remote monitored. Besides the classical methods as Fishbone and Pareto methods based on mathematical modeling and statistical probability, a new method for risk prioritization based on fuzzy graphs is proposed and all methods are discussed and compared using some case studies. All analyzes performed help the user to prevent a faulty of the electronic equipment based on the Predictive Maintenance Prioritization (PMP) actions evaluated here based on fuzzy graphs. The resemblance relation between the subsystems which may fail due to partial or complete deterioration of one component is obtained using α-cuts in fuzzy graph defined for the whole system. The modeling is briefly shown and the proposed PMP method was demonstrated with a significant case study.

Keywords: Risk Prioritization, Predictive Maintenance, Fuzzy Relation, Risk Affinity, α-Cuts, Fuzzy Graphs, Pareto Analysis, Fishbone Analysis.

I. INTRODUCTION

The maintenance system for electrical and electronic equipment using a predictive maintenance program is an essential key to increase the life cycle of that equipment [1]. The rules of the predictive maintenance are based on evaluation, diagnosis and monitoring of state variables for maintaining the performance capability of the equipment. These are adopted using maintenance policies established so as to be defined clearly the effective steps for rehabilitation of the equipment. The predictive maintenance allows the timely detection, location and identification of the fault or the worn parts, and evaluation of the duration of safe operation for that equipment [2].

The both monitoring and diagnosis components of the predictive maintenance are inseparable. Monitoring stage is designed to collect data using data acquisition systems. These data are used during the diagnosis stage to detect operating anomalies, poor performance, incipient defects, and advanced wear [3].

To achieve an efficient maintenance plan is needed to use classic methods, but also those based on artificial intelligence. From the classical methods the following can be used: Pareto, Fishbone, 5 Why, DEMATEL (Decision making trial and evaluation laboratory), and Markov [4].

The Pareto chart is a tool to investigate a process that provides categorized information in order to count the repetition of a certain type of defect. The defects are ordered and, therefore, the significant problems can be identified and corrected before the total falling of the equipment [5]. In a Fishbone chart, the problem to be solved is noted in the head of the "fish", and then main causes of defect apparition, along the "bones" are categorized. Additional causes may be added to new ramifications [6]. Traditionally, the prioritization is achieved by developing a number related to risk of failure. The Risk Priority Number (RPN) techniques uses linguistic terms to classify the faults based on specific probabilities defined for failure process [7].

The DEMATEL method uses ten linguistic terms to classify the severity of the fault (G_d, the probability of occurrence of the fault (P_d) and the probability of system stop at a detected defect (P_o) on a numerical scale from 1 to 10. The RPN is a mathematical product of these three factors above mentioned, being in range 1 to 1000 [8]. The proposed PMP method will improve the DEMATEL method by reducing the RPN range and setting a failure probability related to components and subsystems of the whole system under test.

Because the technological advances are the base to produce a growing number of engineering systems and complex products, a strong reason appeared for the integration of advanced maintenance programs. This could avoid the worst case: when defects occur is too late to correct the defects. So, using an advanced system for monitoring and diagnostics, the occurrence of defects can be prevented [9].

A decision problem cannot always be formulated in a mathematical classic language [10]. Frequently, the experts use a mix between natural language and artificial language. Thus, the fuzzy set theory brings a certain advantage in this approach allowing some lack of precision in estimation of input variables through proper treatment of linguistic variables [11].

This paper is structured as following: The second section of article presents two classical methods based on two study cases linked with the methods. The third part of the paper presents a fuzzy method to estimate the RPN based on statistical data available and expertise of the experts. The last section concludes the paper.

II. CLASSICAL ANALYSIS OF DATA RECORDED BASED ON FISHBONE AND PARETO METHODS

The classical methods analyze the data recorded by the equipment which monitors the manufacturing processes based on mathematical modeling of statistical data. All analyzes performed prevent to appear a faulty in the electronic equipment.

A. Pareto Analysis

Pareto chart is a tool used when you want to investigate a process and that provides information categorized in order to count the repetition of a certain category of defect. The information is sorted in order and that is why the significant problems is easy to be identified and corrected early.

This technique is used primarily to identify and evaluate discordances, although it can be used to summarize all types of information. Pareto analysis is a statistical technique for classifying the small tasks as a number but with a significant effect. It is based on the Pareto principle (also known as the 80/20 rule), which states that 20% of resources, generates 80% of all employment, or in terms of quality improvement, most of the problems (80%) have several causes key (20%) [12].

From the standpoint of quality, diagram was introduced by Professor J.M. Juran to distinguish between:

- the essential issues, which are few in number, but their results are important;
- secondary problems, which are many, but with few results.

It is likely the most commonly diagram used for the management presentations that would avoid unscheduled appearance defects.

The analysis of the Pareto diagram will show that:

- 80% of all warranty repairs of a product covers 20% of its parts.
- 75% of quality defects resulting in 15% of operations taking place within a process.
- 10% of inventoried products represent 70% of the total cost of inventory [13].

The Pareto chart can be used in:

- to design of predictive maintenance programs for electronic equipment;
- to analysis of the electronic equipment with several unscheduled stops;

A Pareto chart has the following objectives:

- To separate the important issues as far as possible, because the maintenance team to focus on improving their actions.
- To arrange information according to priority or importance equipment.
- To prioritize issues according to importance equipment based on information and not opinions [13].

To create a Pareto analysis must follow the steps below:

• Step 1- Record the raw data. Record all the data we have about equipment, regardless of their class or their importance.

• Step 2- Order information. It creates a table and arrange the data in order of frequency of occurrence of the events.

• Step 3- Find the cumulative counts. Each category's cumulative count for that category added to the counts for all larger categories.

The main advantage of chart Pareto is the fact that it provides more easily indication of the most important mistakes. The main disadvantage is the hierarchical system of faults and non-conformities that often depends on the person who makes it.

The advantages to using the Pareto diagram are the following:

- Fixes a problem effectively by identifying and prioritizing root causes in order of importance.
- Set priority for many practical applications, such as efforts to improve the process, the needs of customers, suppliers, investment opportunities.
- Highlights where we need to focus maintenance actions [12, 13].

B. Case Study I: Pareto Analysis of Data Recorded From a Power Station

Are presents a case of study for a power station.

The power station studied here has the following elements:

- 2 rectifiers;
- 1 controller;
- 1 Ethernet card;
- 2 groups of batteries.

Tracking of functionality of the power station was made between 10.12.2015 - 02.10.2016 and the number of stations monitored was of 9 pieces.

Monitoring equipment was done remotely by using the dedicated equipment. When it reported a defect was performed and a local analysis (hardware) on the equipment.

For recording data was used to excel in a table that had been all defects arising in Table 1. After analyzing the recorded data of Table 1 resulted the Table 2 which represents a summary of the frequency of damage and for easier analysis is made the chart in Figure 1.

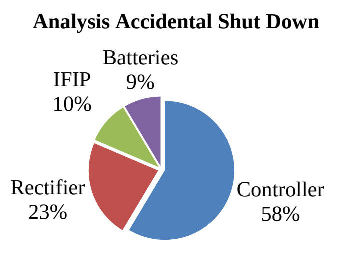


Figure 1. Analysis accidental shut down

Table 1. Data equipment component which caused shutdown

Nr crt	Date	Equipment	Components which caused shutdown
1	10.12.2015	Rectifier	Fan
2	10.12.2015	IFIP	A pin of port to Ethernet card oxidized
3	12.12.2015	Rectifier	Filtering capacitor
5	15.12.2015	Controller	The board monitoring for DC
6	17.12.2015	Controller	Display local
7	19.12.2015	Rectifier	Cable communication between controller and rectifier
8	19.12.2015	Controller	Capacitor on PCB for distance communication
9	24.12.2015	Rectifier	Temperature sensor of rectifier
10	25.12.2015	Batteries	1 battery is discharged from a group under the minimum allowed
11	28.12.2015	Rectifier	Fan
12	31.12.2015	Controller	Capacitor on PCB for distance communication
13	02.01.2016	Controller	Eprom
14	02.01.2016	Rectifier	Filtering capacitor
15	05.01.2016	Batteries	Temperature sensor reading groups linked to batteries
16	10.01.2016	Rectifier	Filtering capacitor
17	13.01.2016	Controller	Internal fan at controller
18	18.01.2016	Controller	Cable communication between controller and rectifier
19	21.01.2016	Controller	Voltage monitor
20	23.01.2016	Rectifier	Fan
21	26.01.2016	Controller	Capacitor on PCB for distance communication
22	30.01.2016	Rectifier	Internal Eprom
23	05.02.2016	Rectifier	Fan
24	07.02.2016	IFIP	A pin of port to Ethernet card is oxidized
25	10.01.2016	Rectifier	Filtering capacitor

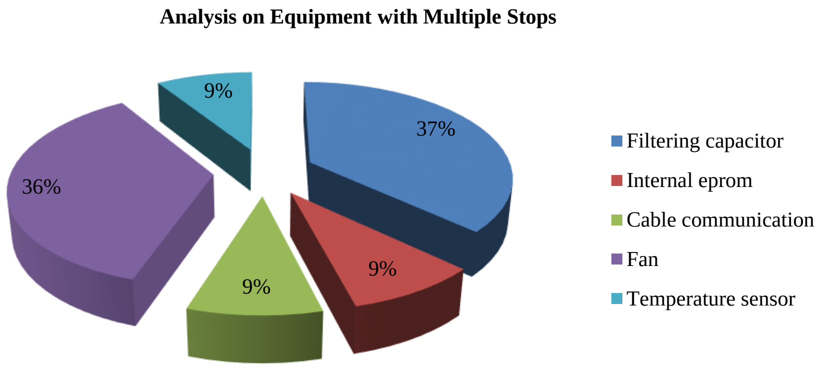


Figure 2. Analysis on equipment with multiple stops

Table 2. Centralization of data according to frequency of occurrence of defects

No	Equipment	Number of accidental shut down
1	Rectifier	11
2	Controller	9
3	IFIP	2
4	Batteries	2

Table 3. Analysis of defective components rectifier

No	Equipment	Components which caused shutdown	Number of stops
1	Rectifier	Filtering capacitor	4
2	Rectifier	Internal Eprom	1
3	Rectifier	Cable communication	1
4	Rectifier	Fan	4
5	Rectifier	Temperature sensor	1

According to data recording in Table 2 following the analysis shows that most accidental shut down equipment is rectifier. This method can identify the components how lead to the failure the equipment how make part of the power station, for analysis it must to extract data from Table 3 with recording data. The chart resulting from Table 3 is shown in Figure 2.

After analyzing the Pareto chart, it can be noted that the vital equipment for power station is the rectifier. This component is the most component with the accidental shut down according to data recorded and studied. After analyzing the causes of defects shows need to make action for preventive maintenance:

- Cleaning fan;
- Lubricate the bearings of the fan;
- Setting the threshold voltages;
- Installing a phase monitor to avoid damaging the filtering capacitors;
- Verification of communication cables and achieving a route through a secure environment without perturbed;
- Periodic recalibration or replacement of temperature sensors of the rectifier.

Finally, it should be noted that it is easier to reduce a high frequency of defects only decreased frequency of defects, the diagram shows that the improvement would be more useful to focus on the first two causes than those secondary (and many minor).

C. Fishbone Analysis

Fishbone diagram is an analysis tool that characterizes a particular process. The diagram is called "Ishikawa" because was developed by Kaoru Ishikawa or fishbone diagram because it looks like a fish skeleton. This diagram illustrates the primary and secondary causes of a particular effect (symptom).

In a typical chart of this type, the problem to be solved is noted in the head of the "fish", then strung causes along bones and categorized. Additional causes may be added to new branches [14]. Fishbone diagram can be used when:

- It wants straightening attention to a specific issue;
- The team turned its attention on the causes and not the symptoms;
- Plot different theories about the causes that could form the basis for problem;
- It shows the links between the various factors that influence a problem;
- To discover important relationships between different variables and possible causes;
- Understand better functioning process [15].

For building a Fishbone diagrams it must follow the next steps.

• Step 1. Identify and define the result to be analyzed. The main problem is formulated and fits in a box in the right-hand side of the chart. Analyzes the effect or problem that can be represented by: set goals, effects, features. This field should be named explained. An effect can be positive (target) or negatively (okay), depending on the topic under discussion.

• Step 2. Use a table, placed at the sight of everyone and draws spine, then the border will note the effect. We draw a horizontal arrow pointing to the right. This is the backbone chart. The right arrow is noted a brief description of the effect or the result.

• Step 3. Identify the main causes that have given rise to effect. These are the names of the main ramifications of the diagram and become categories in front of which there can note many other subcategories. The main causes are established or categories, and in front of these will be listed other possible causes. Names should be used to be relevant in construction of the diagram, which will bind all problems through a diagonal line between them.

• Step 4. It is achieved an analysis of each major causes and identify secondary factors that may have links with effect the issue under examination. In analyzing the subcategories all causes must be identified and related to main branch. Each case must be described in detail, and if a secondary cause can create one new, this may be noted next to each. It is important to identify possible causes and subcategories to note that the right main ramifications.

• Step 5. Using the analysis to identify causes and gradually increasing is placed on subcategories. If the analysis is too high it is recommended to divide diagram into smaller ones to create more subcategories for easier understanding. Any of the main causes can be rewritten as a result.

• Step 6. The final chart helps to identify the causes that require further research. As some cause-effect diagrams help identify possible causes, Pareto analysis can be used to decide the cases to be firstly studied [14, 15].

For efficiency of analysis it is appropriate to examine the balance chart and ascertain details of several common categories. A category with many sub-trees may indicate the need for further analysis. A main category with only a few specific cases may indicate the need to identify other causes [14].

If several main ramifications have few sub-trees, you may need to combine into a single category. Looking for causes is repeated, it may be the root causes.

The advantages of Fishbone diagram are:

- Helps identify the root causes;
- Stimulate group participation;
- It is orderly and easy to decipher and emphasizes the relationships between cause and effect;
- Show what can be changed to improve a system;
- Participants acquire new knowledge related to the process, as more details about the factors that influence this process and the relationships between them;
- Determine the areas that require additional information.

D. Case Study II: Fishbone Analysis Based on Previously Recorded Data

Case study is based on data from previous analysis of power station. In Figure 3 is a diagram Fishbone analysis of damage to a power station. The data have been recorded with dedicated software.

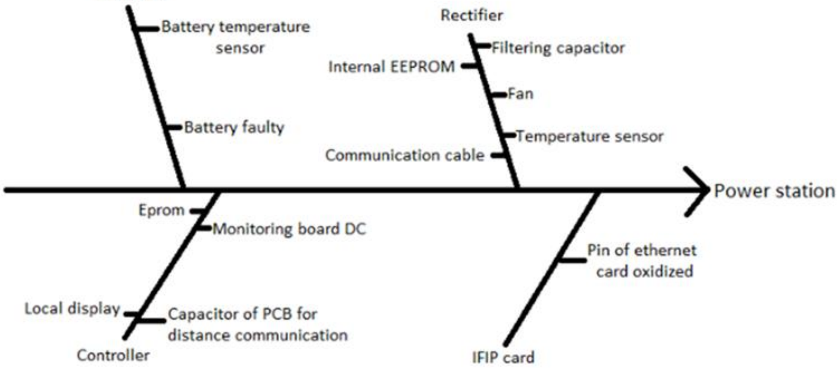


Figure 3. Fishbone diagram for a power station

The main causes that can lead to defects in the equipment can be easily identified using the Fishbone analysis. This shown that the rectifier is the main problem for this electronic equipment (the power station), followed by the controller.

Having all the records of the analysis made available, the vital components in electronic equipment should be treated priority.

III. ANALYSIS OF DATA RECORDED WITH FUZZY GRAPHS

Let be $S = \{S_1, S_2, \ldots, S_m\}$ set of subsystems which may fail due to partial or complete deterioration of one component from set of components $C = \{C_1, C_2, \ldots, C_n\}$.

The experts, $D = \{D_1, D_2, \ldots, D_h\}$ estimate the risk' level to fail the whole system due to partial or complete deterioration of one component considering the following levels of risk $R = \{R_1, R_2, \ldots, R_l\}$.

In the mathematical sense, an *affinity* is a subset of elements with common features [12]. The concept of affinity defined in $S\times C$ set gives the *risk' prioritization* for the whole system [13].

This paper proposes to evaluate the *risk' prioritization* based on Fuzzy Graphs (FG), which have been widely treated in the literature [*fuzzy graphs*]. Fuzzy Graph (FG) on X (a finite set) is defined by the triplet $G(x, \sigma, \mu)$ [14], where: σ: $X\to[0,1]$ is the membership level of each FG node; μ: $X\times X\to[0,1]$ is membership level of each FG arc.

Furthermore, the FG, $G = (x, \sigma, \mu)$, define a Fuzzy Transportation Network (FTN) if and only if [15]:

a) $$(\forall)\, i \in X,\quad \sigma(i) = \sup_{j\in X}\left(\mu_{ij} \wedge \mu_{ji}\right) \tag{1}$$

b) There exist two outstanding nodes, denoted by $q_1, q_2 \in X$, verifying:

b.1) $$\sigma(q_1) = \sigma(q_2) = 1 \tag{2}$$

b.2) $$\mu^{\infty}_{q_1 q_2} = 1,\ \mu_{q_2 q_1} = 1 \tag{3}$$

b.3) $$(\forall)\, i, j \in X \,/\, \mu_{ij} > 0,\quad \mu^{\infty}_{q_1 i} \wedge \mu^{\infty}_{j q_2} \tag{4}$$

Note that $\mu(\cdot,\cdot)$ is a fuzzy relation on X, $\mu^n(\cdot,\cdot)$ is the n-times composition of μ with itself by means of the classical max-min operation and $\mu^{\infty}(\cdot,\cdot)$ define the strength of the stronger path for two nodes in FTN:

$$\mu^{\infty}(i, j) = \sup_{n} \mu^{n}(i, j),\quad (\forall) i, j \in X \tag{5}$$

Thus, using the available data regarding the failure of the system, the experts based on their expertise can define the following fuzzy sets: the set of fuzzy risks in operation ($\tilde{R}_{ij}$) and set of fuzzy risks priori defined ($\tilde{P}$):

$$\tilde{R}_{ij} = \left\{\frac{\eta_{ij}(1)}{C_1}, \ldots \frac{\eta_{ij}(n)}{C_n}\right\} \text{ on } C = \{C_1, \ldots, C_n\} \tag{6}$$

$$\tilde{P} = \left\{\frac{p_1}{R_1}, \ldots \frac{p_n}{R_l}\right\} \text{ on } R = \{R_1, \ldots, R_l\} \tag{7}$$

The set of fuzzy risks in operation ($\tilde{R}_{ij}$) is defined for each subsystem S_i, $i = 1, \ldots, n$, considering the levels of risk defined, R_j, $j = 1, \ldots, l$.

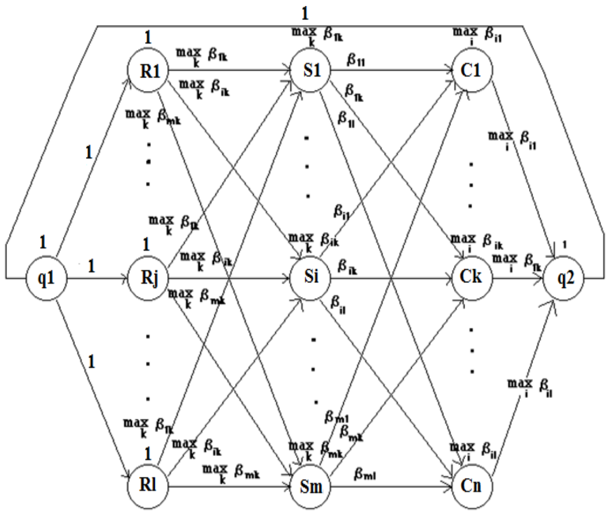


Figure 4. FTN for classifying a problem

The FG for this classifying problem, $G = (x, \sigma, \mu)$, is shown in Figure 4, where:

$$X = \{q_1\} \cup R \cup S \cup C \cup \{q_2\} \tag{8}$$

$$\sigma(x) = \begin{cases} 1, & x \in \{q_1, q_2\} \cup R \\ \max\limits_{i} \beta_{ik}, & x \in C \\ \max\limits_{k} \beta_{ik}, & x \in S \end{cases} \tag{9}$$

$$\mu(x, y) = \begin{cases} 1, & (x, y) \in (\{q_1\}\times R) \cup (\{q_2\}\times\{q_1\}) \\ \beta_{ik}, & (x, y) \in S\times C \\ \max\limits_{k} \beta_{ik}, & (x, y) \in R\times C \\ \max\limits_{i} \beta_{ik}, & (x, y) \in C\times\{q_2\} \end{cases} \tag{10}$$

$$\beta_{ik} = 1 + \eta_i(k) - \max_{i}\max_{k} \eta_i(k) \tag{11}$$

$$\eta_i(k) = \sum_{j=1}^{l} \frac{\eta_{ij}(k)}{l} \tag{12}$$

The last relation is the solution of the fuzzy optimization problem [16]:

$$\min_{\tilde{L}_i} \mathop{S_1}_{i=1}^{m} \mathop{S_1}_{j=1}^{l} \left(\tilde{R}_{ij} \Delta \tilde{R}_i\right)^2 \tag{13}$$

where, $\tilde{R}_i = \left\{\frac{\eta_i(1)}{C_1}, \ldots \frac{\eta_i(n)}{C_n}\right\}$ and S_1 (s-norm bounded sum), Δ (symmetrical difference), $(\cdot)^m$ (mth power) are fuzzy connectives defined in [17].

It is easy to show that G is a FTN [18]. G is entirely define if we specifies the associated capacity for each arc (x, y), $k(\cdot,\cdot)$: $X\times X\to R$

$$k(x, y) = \begin{cases} 1, & (x, y) \in (R\times S) \cup (C\times\{q_2\}) \\ p_j, & (x, y) \in \{q_1\}\times R \\ ct. > 1, & (x, y) \in (S\times C) \cup (\{q_2\}\times\{q_1\}) \end{cases} \tag{14}$$

where, $p_j<1$ is the risk to fail which is priori defined for each component C_j, $j = 1, \ldots, n$, and the constant (ct.>1) is arbitrary defined to not bottleneck this flow inside FTN.

IV. CASE STUDY: PREDICTIVE MAINTENANCE PRIORITIZATION OF A POWER SUPPLY EQUIPMENT USED IN TELECOMMUNICATIONS

The system used in this case study is power supply equipment used in telecommunications. This may be mainly in the following subsystems: S_1 = Rectifier unit; S_2 = Controller unit; S_3 = IFIP card unit; S_4 = Battery unit (Figure 5). Table 4 shows during a year the frequency of occurrence of defects in each subsystem.

Following Pareto analysis, it appears that vital equipment for power supply equipment is the rectifier unit. The frequency of occurrence of defects in rectifier unit is mainly given by the fans and filtering capacitors (Figure 5).

Table 5 shows during a year the frequency of occurrence of defects in rectifier unit due to the following components: C_1=Fans; C_2=PCB Capacitor for communication circuit; C_3=Communication cable; C_4=Filtering capacitors; C_5=EPROM chipset.

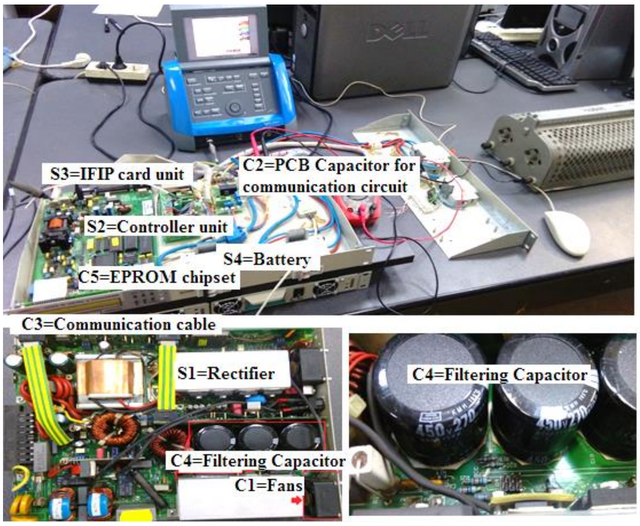


Figure 5. The subsystems of the power supply equipment used in telecommunications

Table 4. The frequency of occurrence of defects in each subsystem

S_i	Subsystems	Frequency of defects occurrence [%]
1	Rectifier unit	46
2	Controller unit	38
3	IFIP card unit	8
4	Battery unit	8

Table 5. The frequency of occurrence of defects in rectifier unit

C_k	Subsystems	The component that caused the shutdown	Frequency of defects occurrence [%]
C_1	Rectifier unit	Fans	36
C_2	Rectifier unit	PCB Capacitor for communication circuit	9
C_3	Rectifier unit	Communication cable	9
C_4	Rectifier unit	Filtering capacitors	37
C_5	Rectifier unit	EPROM chipset	9

The Pareto analysis can be extended to each subsystems based on same components selected as component with risk of high (R_1), moderate (R_2) and low (R_3) level.

As it was mentioned, the DEMATEL method uses a numerical scale from 1 to 10 to classify the severity of the fault (G_d, the probability of occurrence of the fault (P_d) and the probability of system stop at a detected defect (P_o). Although the method uses a large number of degrees linguistic (10), the disadvantage of DEMATEL method is that are used equal weights for any scenario with $RPN = G_d \times P_d \times P_o$. As a result, some ($G_d$, P_d, P_o) scenarios can generate RPN lower than other combinations, although they are potentially dangerous in terms of equipment maintenance. For example, a scenario with G_d = 9 (very high) P_d = 3 (low), P_o = 2 (high) has $RPN_1 = 9\times3\times2 = 54$. The second scenario with G_d = 4 (moderate severity), P_d = 5 (medium), P_o = 6 (low) has $RPN_2 = 4\times5\times6 = 120$.

Note that $RPN_1<RPN_2$, although the first scenario should have a higher priority in developing corrective action. Furthermore, the RPN has values into a wide scale, from 1 to 1000, so the statistical values not evenly cover the entire range.

These disadvantages can be avoided with the PMP method based on FTN. Here, based on their expertise, the experts can define the following fuzzy sets: the set of fuzzy risks in operation ($\tilde{R}_{ij}$) and the set of fuzzy risks priori defined ($\tilde{P}$).

$$\tilde{R}_{11} = \left\{\frac{1}{C_1}, \frac{0.7}{C_2}, \frac{0.4}{C_3}, \frac{0.3}{C_4}, \frac{0.4}{C_5}\right\};$$

$$\tilde{R}_{12} = \left\{\frac{1}{C_1}, \frac{0.5}{C_2}, \frac{0.4}{C_3}, \frac{0.4}{C_4}, \frac{0.7}{C_5}\right\};$$

$$\tilde{R}_{13} = \left\{\frac{1}{C_1}, \frac{0.3}{C_2}, \frac{0.4}{C_3}, \frac{0.5}{C_4}, \frac{1}{C_5}\right\}.$$

$$\tilde{R}_{21} = \left\{\frac{0.7}{C_1}, \frac{0.8}{C_2}, \frac{0.2}{C_3}, \frac{0.4}{C_4}, \frac{0.3}{C_5}\right\};$$

$$\tilde{R}_{22} = \left\{\frac{0.7}{C_1}, \frac{0.9}{C_2}, \frac{0.3}{C_3}, \frac{0.5}{C_4}, \frac{0.25}{C_5}\right\};$$

$$\tilde{R}_{23} = \left\{\frac{0.7}{C_1}, \frac{0.9}{C_2}, \frac{0.4}{C_3}, \frac{0.6}{C_4}, \frac{0.2}{C_5}\right\}.$$

$$\tilde{R}_{31} = \left\{\frac{0.1}{C_1}, \frac{0.5}{C_2}, \frac{0.8}{C_3}, \frac{0.7}{C_4}, \frac{0.2}{C_5}\right\};$$

$$\tilde{R}_{32} = \left\{\frac{0.4}{C_1}, \frac{0.5}{C_2}, \frac{0.8}{C_3}, \frac{0.55}{C_4}, \frac{0.15}{C_5}\right\};$$

$$\tilde{R}_{33} = \left\{\frac{0.7}{C_1}, \frac{0.3}{C_2}, \frac{0.8}{C_3}, \frac{0.4}{C_4}, \frac{0.1}{C_5}\right\}.$$

$$\tilde{R}_{41} = \left\{\frac{0.2}{C_1}, \frac{0.7}{C_2}, \frac{1}{C_3}, \frac{0.7}{C_4}, \frac{0.5}{C_5}\right\};$$

$$\tilde{R}_{42} = \left\{\frac{0.4}{C_1}, \frac{0.5}{C_2}, \frac{0.7}{C_3}, \frac{0.7}{C_4}, \frac{0.45}{C_5}\right\};$$

$$\tilde{R}_{43} = \left\{\frac{0.6}{C_1}, \frac{0.3}{C_2}, \frac{0.4}{C_3}, \frac{0.7}{C_4}, \frac{0.4}{C_5}\right\}.$$

$$\tilde{P} = \left\{ \frac{1}{R_1}, \frac{1}{R_2}, \frac{1}{R_3} \right\} \tag{15}$$

Using

$$\eta_i(k) = \sum_{j=1}^{l} \frac{\eta_{ij}(k)}{l} \tag{16}$$

the following fuzzy sets $\tilde{R}_i$, i = 1,2,3,4, can be computed:

$$\tilde{R}_1 = \left\{ \frac{1}{C_1}, \frac{0.5}{C_2}, \frac{0.4}{C_3}, \frac{0.4}{C_4}, \frac{0.7}{C_5} \right\};$$

$$\tilde{R}_2 = \left\{ \frac{0.7}{C_1}, \frac{0.9}{C_2}, \frac{0.3}{C_3}, \frac{0.5}{C_4}, \frac{0.25}{C_5} \right\};$$

$$\tilde{R}_3 = \left\{ \frac{0.4}{C_1}, \frac{0.4}{C_2}, \frac{0.8}{C_3}, \frac{0.55}{C_4}, \frac{0.15}{C_5} \right\};$$

$$\tilde{R}_4 = \left\{ \frac{0.4}{C_1}, \frac{0.5}{C_2}, \frac{0.7}{C_3}, \frac{0.7}{C_4}, \frac{0.45}{C_5} \right\}.$$

The FTN is presented in Figure 6. The α-cuts in this FTN are shown in Figure 7 for $\alpha \in \{0.7, 0.8, 0.9, 1\}$. The affinity in $S \times C$ set can be found analyzing these α-cuts. Table 1 gives some affinities in $S \times C$ set.

Table 3. Affinities in $S \times C$ set

	α=0.7				α=0.8			α=0.9		α=1
S	S_4	S_3	S_2	S_1	S_3	S_2	S_1	S_2	S_1	S_1
C	C_3	C_3	C_1;C_2	C_1;C_5	C_3	C_2	C_1	C_2	C_1	C_1

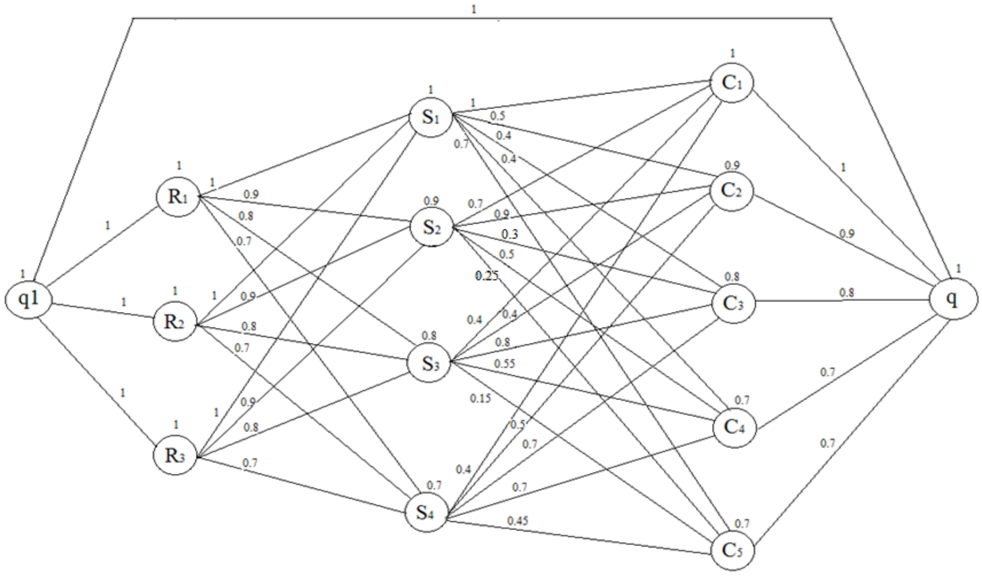


Figure 6. The FTN for the case study

The affinity relation in full, $\tilde{\Re}_{S \times C}$, is given below.

$$\tilde{\Re}_{S \times C} = \left\{ \frac{1}{(S_1, C_1)}, \frac{0.9}{(S_2, C_2)}, \frac{0.8}{(S_3, C_3)}, \frac{0.7}{(S_1, C_5)}, \frac{0.7}{(S_2, C_1)}, \frac{0.7}{(S_4, C_3)}, \frac{0.7}{(S_4, C_5)}, \frac{0.7}{(S_1, C_1)}, \frac{0.55}{(S_3, C_4)}, \frac{0.5}{(S_1, C_2)} \right\} \cup$$

$$\cup \left\{ \frac{0.5}{(S_2, C_4)}, \frac{0.5}{(S_4, C_2)}, \frac{0.45}{(S_4, C_5)}, \frac{0.4}{(S_1, C_3)}, \frac{0.4}{(S_1, C_4)}, \frac{0.4}{(S_3, C_1)}, \frac{0.4}{(S_3, C_2)}, \frac{0.4}{(S_4, C_1)}, \frac{0.3}{(S_2, C_3)}, \frac{0.25}{(S_2, C_5)}, \frac{0.15}{(S_3, C_5)} \right\}$$

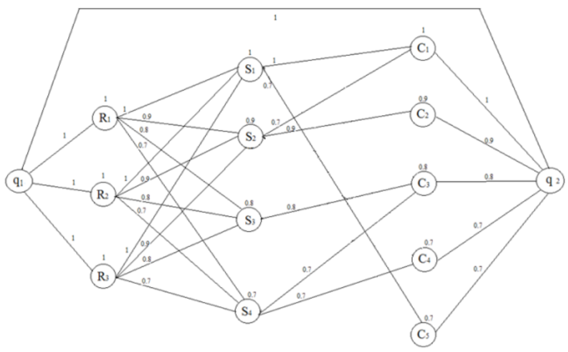
Thus, the maximal affinity relation is:

$$\left\{ \frac{1}{(S_1, C_1)}, \frac{0.9}{(S_2, C_2)}, \frac{0.8}{(S_3, C_3)}, \frac{0.7}{(S_4, C_3)}, \frac{0.7}{(S_4, C_5)}, \frac{0.55}{(S_3, C_4)} \right\}$$

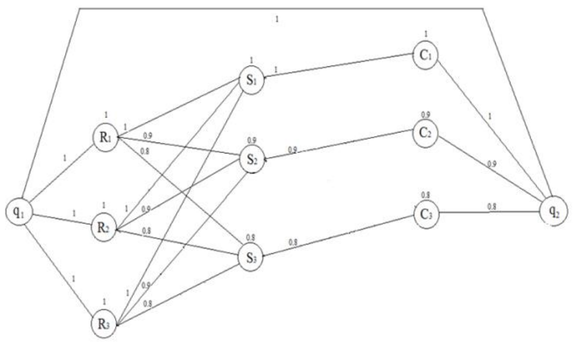
The maximal affinity relation gives important information about the prioritization of the corrective actions as follow:

- 1st corrective action is to change the component C_1 in order to not affect the operation of the subsystem S_1;
- 2nd corrective action is to change the component C_2 in order to not affect the operation of the subsystem S_2;
- 3rd corrective action is to change the component C_3 in order to not affect the operation of subsystems S_3 and S_4;
- 4th corrective action is to change the component C_5 in order to not affect the operation of the subsystem S_4;
- 5th corrective actions is to change the component C_4 in order to not affect the operation of the subsystem S_1;

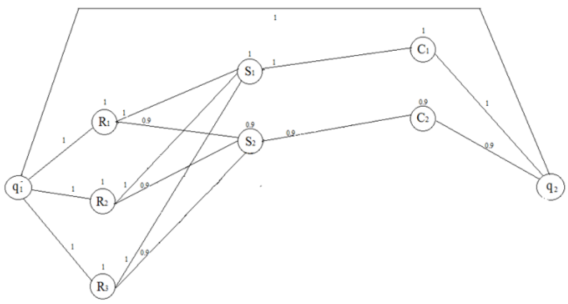
But this method does not offer information about the predicted time to do these corrective actions. Consequently, other methods must be used for this purpose [25, 26, 27, 28].



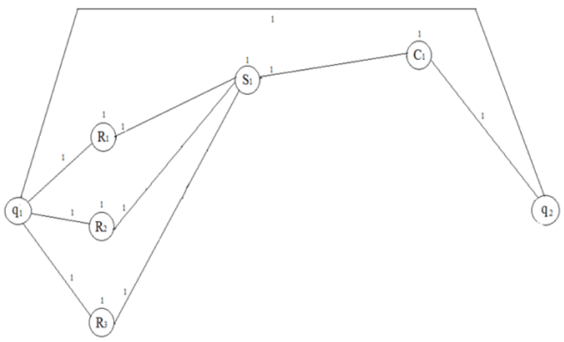
$\alpha = 0.7$



$\alpha = 0.8$



$\alpha = 0.9$



$\alpha = 1.0$

Figure 7. Some α-cuts in the FTN shown in Figure 3

V. CONCLUSIONS

The use of the energy station with management and diagnosis technology included gives the possibility of control and remote monitoring, but the diagnosis and repair as well.

This helps to achieve predictive maintenance actions by rapid diagnosis of defects in-site without expensive trips to remedy the defect at the place of operation. Furthermore, some experiments must be performed in order to validate these rules related to monitoring of voltage and current supplied by the power equipment.

Thus, new ways are identified in this paper to increase the reliability of the power station. For example, the experiments performed shown that the implementation of the circuit to monitor the fan speed can significantly reduce the number of accidental stops.

Other solution to reduce the number accidental stops is to use the protective circuit for filtering capacitors used in the rectifier avoiding overvoltage and overcurrent due to variable load demand.

Using of the Fishbone and the Pareto analysis we can easily identify which are the main causes that can lead to defects in the equipment. In case shown in this paper, the rectifier is the main problem in the electronic equipment (power station), followed by the controller.

Estimation of the RPN based on all the records give information about the vital components in electronic equipment that should be treated priority.

The achievement the predictive maintenance it is the key to keep of the electronic equipment in operating mode at the full capacity. In this paper is proposed the Predictive Maintenance Prioritization (PMP) method based on fuzzy graphs.

The affinity relation between the subsystems and components which may fail is obtained using α- cuts in fuzzy graph defined for the whole system. The experts, estimate the risk' level to fail the whole system due to deterioration of one component considering different levels of risk.

The maximum flow value in Fuzzy Transportation Network (FTN) gives the maximal risk affinity for the system. The α-cuts in the FTN will give the full risk affinity between the subsystems and components. The maximal affinity relation gives important information about the prioritization of the corrective actions. The modeling is briefly shown and the proposed PMP method was demonstrated with a significant case study.

ACKNOWLEDGEMENTS

Work is under Ph.D. stages, contracts SD04/46 and SD04/04. The research that led to the results shown here has received funding from the project "Cost-Efficient Data Collection for Smart Grid and Revenue Assurance (CERA-SG)", ID: 77594, 2016-19, ERA-Net Smart Grids Plus.

REFERENCES

[1] J. Fang, L. Ji, "Life Cycle Cost Prediction for Rolling Stocks in Maintenance Phase Based on VBA Language Program", International Journal of Smart Home, Vol. 9, No. 3, pp. 239-252, 2015.

[2] R. Keith Mobley, "Maintenance Engineering Handbook", Eighth Edition, McGraw-Hill Education, New York, 2014.

[3] G.R. Sisman, M. Oproescu, "Predictive Maintenance of Power Industrial Electronic Equipment", JEEECCS Journal, Vol. 1, No. 2, pp. 21-30, 2015.

[4] N. Kaio, T. Dohi, Sh. Osaki, "Classical Maintenance Models", Springer, 2002.

[5] M. Ahmed, N. Ahmad, "An Application of Pareto Analysis and Cause-and-Effect Diagram (CED) for Minimizing Rejection of Raw Materials in Lamp Production Process", Management Science and Engineering, Vol. 5, No, 3, pp. 87-95, 2011.

[6] J. Phillips, L. Simmonds, "Using Fishbone Analysis to Investigate Problems", Nursing Times, Vol. 109, No. 15, pp. 18-20, 2013.

[7] G.R. Sisman, N. Bizon, M. Oproescu, "On the Remote Diagnostic of the Power Source Used in Telecommunications", 12th International Conference on Technical and Physical Problms of Electrical Engineering (ICTPE-2016), Bilbao, Spain, No. 38, Code 04COM01, pp. 189-193, September 7-9, 2016.
[8] I. Golcuk, A. Baykasoglu, "An Analysis of DEMATEL Approaches for Criteria Interaction Handling within ANP", Expert Systems with Applications, Vol. 46, pp. 346-366, 2016.
[9] A. Kipf, W. Brunette, et al., "A Proposed Integrated Data Collection, Analysis and Sharing Platform for Impact Evaluation", Development Engineering, Vol. 1, pp. 36-44, 2016.
[10] O. Uygun, H. Kacamak, U.A. Kahraman, "An Integrated DEMATEL and Fuzzy ANP Techniques for Evaluation and Selection of Outsourcing Provider for a Telecommunication Company", Computers & Industrial Engineering, Vol. 86, pp. 137-146, 2015.
[11] L.A. Zadeh, "Fuzzy Sets, Fuzzy Logic, and Fuzzy Systems", In: "Advances in Fuzzy Systems - Applications and Theory", Vol. 6, George J. Klir, Bo Yuan (Eds.), Copyright 2016, World Scientific Publishing Co., PTE Ltd, 1996.
[12] R.S. Russell, B.W. Taylor, "Operations Management", Prentice Hall Inc., Upper Saddle River, New Jersey, 2003.
[13] "Pareto Analysis: Selecting the Most Important Changes to Make", Mind Tools, www.mindtools.com/pages/article/newTED_01.htm.
[14] American Society for Quality, Fishbone diagram, www.asq.org/learn-about-quality/cause-analysis-tools/overview/fishbone.html
[15] K. Ishikawa, "Guide to Quality Control", Asian Productivity Organization, Tokyo, Japan, 1986.
[16] A. Kaufmann, J.G. Aluja, "Selection of Affinities by Means of Fuzzy Relations and Galois Lattices", In: "Fuzzy Systems and Artificial Intelligence", H.N. Teodorescu, H.J. Zimmermann, T. Yamakawa, L.A. Zadeh (Eds.), pp. 51-67, 1988.
[17] P. Chemweno, L. Pintelon, A. Van Horenbeek, P. Muchiri, "Development of a Risk Assessment Selection Methodology for Asset Maintenance Decision Making: An Analytic Network Process (ANP) Approach", International Journal of Production Economics, part B, Vol. 170, pp. 663-676, 2015.
[18] H.N. Teodorescu, "Fuzzy Graphs, Fuzzy Logics and New Classes of Fuzzy Neural Networks", In: "Fuzzy Systems and Artificial Intelligence", H.N. Teodorescu, T. Yamakawa, A. Rascanu (Eds.), Iasi University Publishing House, pp. 157-172, 1991.
[19] A. Vitalievich Bozhenyuk, E. Michailovna Gerasimenko, J. Kacprzyk, I. Naymovich Rozenberg, "Flows in Networks under Fuzzy Conditions", Springer, 2017.
[20] H.J. Zimmermann, "Fuzzy Set Theory and its Applications", Second Edition, Kluwer Academic Publishers, Boston, 1991.
[21] C.N. Negoita, D. Ralescu, "Simulation, Knowledge Based, Computing and Fuzzy Statistics", Van Nostrand Reinhold Company, New York, 1987.
[22] N. Bizon, "System Performance Evaluation in Multi-Criterion Conditions", Ph.D. Thesis, University of Bucharest, Romania, 1996 (in Romanian).
[23] N. Bizon, M. Oproescu, G.R. Sisman, "Predictive Maintenance Prioritization using Fuzzy Graphs", 12th International Conference on Technical and Physical Problms of Electrical Engineering (ICTPE-2016), Bilbao, Spain, No. 05, Code 00PLL05, pp. 26-31, September 7-9, 2016.
[24] V. Uraikul, Ch.W. Chan, P. Tontiwachwuthikul, "Artificial Intelligence for Monitoring and Supervisory Control of Process Systems", Engineering Applications of Artificial Intelligence, Vol. 20, pp. 115-131, 2007 .
[25] M.A. Beg, M.K. Khedkar, S.R. Paraskar, G.M. Dhole, "A Novel Clarke Wavelet Transform Method to Classify Power System Disturbances", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 5, Vol. 2, No. 4, pp. 27-31, December 2010.
[26] A.U. Jawadekar, G.M. Dhole, S.R. Paraskar, M.A. Beg, "Novel Wavelet ANN Technique to Classify Bearing Faults in there Phase Induction Motor", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 8, Vol. 3. No. 3, pp. 48-54, September 2011.
[27] H. Erdem, E.O. Tartan, A. Berkol, "Application of Three Intelligent Methods for Harmonic Estimation: Adaline, Adaline-LS, PSO-LS", JEEECCS, Vol. 1, No. 1, pp. 1-6, 2015.
[28] M. Carbureanu, "Automatic Systems for Wastewater pH Control - A Comparative Study", JEEECCS, Vol. 1, No. 1, pp. 34-43, 2015.

BIOGRAPHIES

Nicu Bizon was born in Albesti de Muscel, Arges County, Romania, 1961. He received the B.Sc. degree in Electronic Engineering from the University "Polytechnic" of Bucharest, Bucharest, Romania, in 1986, and the Ph.D. degree in Automatic Systems and Control from the same university, in 1996. From 1996 to 1989, he was in hardware design with the Dacia Renault SA, Romania. He is currently a Professor with the University of Pitesti, Pitesti, Romania, and Dean of the Faculty of Electronics, Communication and Computers from 2012. He is editor of six books and more than 300 papers in related fields to energy, which is his current research interest.

Mihai Oproescu was born in Romania on 2 September 1974. He completed his B.Sc. studies in the University of Pitesti, Pitesti, Romania in 2011 and received the Ph.D. degree in Electrical Engineering Science with particular emphasis in "Modeling and optimizing of power flows on inverter systems powered by fuel cells". He participated in 9 national scientific research projects: 1 project as a manager, in 2 projects as economic responsibility, and the other as a member of the implementation team. Over the last 8 years, he have published over 70 papers most of which focused on renewable energy. His new scientific objectives and appropriate goals of education curriculum are in different levels of higher education in electronics, communications and computers sustained at Faculty of Electronics, Communications and Computer Science, University of Pitesti, Pitesti, Romania. He is a member of the scientific committees of ECAI conferences and ICTPE conference, program chair of ECAI conference and member of scientific board for 4 journals.

George Robert Sisman was born in Calarasi, Romania on 3 February 1989. He graduated from University of Pitesti, Pitesti, Romania with specializing in Telecommunications Network and Software. His master specialization in the same university is Electronic Systems for Managing Industrial Processes. Currently he is working as a telecommunications engineer which was in the past as automation engineer.