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MULTI-CRITERIA ANALYSIS OF FUZZY SYMPTOMS OF ELECTRICAL FAULTS IN POWER SYSTEMS

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ABSTRACT

The paper considers a possible method of technical diagnostics of electrical equipment of power supply systems and electrical substations based on the fuzzy sets and fuzzy logic. It is shown that, based on the matrix of fuzzy relationships, one can make a plausible enough prediction about possible malfunctions and causes of failures. The prerequisites for this analysis are the current condition (state) of the electrical equipment and expert assessments of diagnostic signs. The paper shows the comparison made using the features scale of Saaty, in accordance with nine degrees of preference.

At the core of fuzzy expert assessments is an attempt to formalize linguistic information, namely linguistic variables whose meanings can be words or phrases. The paper presents a complete range of preconditioned defects consisting of m factors and their corresponding space conclusions as to the causes of these malfunctions (defects) of n symptoms. Fuzzy causal relations in the space of underlying factors are established between the assumptions and conclusions of the experts. The resulting system of equations is solved by the method based on the composition of fuzzy conclusions. Possible failures are ranked according to the experts' preference, which reveals the most significant symptoms of malfunctioning and allows arriving at the conclusion as to the future operation of the facility. The validity of the provisions of the method presented is confirmed by appropriate calculations, which demonstrates the correct behavior of the model concerning the transformer equipment.

It is shown that in case of the fuzzy symptoms occurrence and evaluation of these features by a scale of preferences, it is possible to conclude about the further operation of electrical equipment or its withdrawal for repair. Thus, the mathematical model based on the fuzzy relations of symptoms selected using the experts' estimations contains elements of predicting the possible failures of power systems electrical equipment.

Keywords: electrical equipment, expert evaluation, fuzzy logic, technical diagnostics, transformers

1 INTRODUCTION

Transportation (transmission) of electricity from the source to the consumer involves several stages, including: changing the voltage of electrical energy delivered by power station buses; transmitting electric power by power system grids (networks) to the centers of consumption; converting the voltage up to the rated voltage level at the power consumer end. Changing the voltage and the angle of vectors is necessary to reduce losses and increase the amount of energy transmitted through networks of electric power systems and power supply systems. Furthermore, in many cases, applying reactive power compensation is required for voltage regulation, improving static and dynamic stability and limiting switching surges. It is known that power transformers can convert voltage and shunt reactors are used as a means of reactive power compensation. The duties power transformers and shunt reactors are designed for are different, but their construction and types of faults related to both transformers and reactors operation allow us to refer to them as "transformer equipment."

The term "transformer equipment" includes power transformers and oil shunt reactors, the design of which is similar, and, in the context, we are interested in diagnosing these devices as having the same defects and symptoms. Along with this, it is necessary to diagnose the

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switching equipment and the related equipment: switches, circuit breakers, short-circuiting switches and others.

2 STATEMENT OF THE PROBLEM (PROBLEM STATING)

2.1 Description of the system

The term “rapid diagnosis” includes the collection of data on the state of the transformer equipment in operation and its analysis aimed at evaluating its technical condition. Such a diagnosis can be made after the inspection of the electrical equipment and detection the signs of its malfunctioning. Symptoms can be numerous, but in practice, only some of them occur frequently: P1 – transformer equipment overheating; P2 – increased vibration and transformer equipment noise; P3 – a high leakage current through the insulation of high-voltage input; P4 – moistening the transformer oil.

The main prerequisites or causes of these faults can be the following: G1 – high ambient temperature; G2 – failure of the cooling system of the transformer equipment; G3 – overcurrent; G4 – the fire of the magnetic steel; G5 – phase load asymmetry; G6 – the damage inside the transformer tank or reactor. It is worth noting that, as a rule, the fault causing profound changes in the transformer or reactor (short circuit, intensive gassing), is cleared by relay protection and is not considered in the paper. But there are developing defects which do not cause any serious deviations (faulty performance) in the short term, and, therefore, provide time for them to be recognized and the appropriate action to be taken.

Symptoms’ comparison is made taking into account one of the causes of the fault. The essence of the method lies in the fact that a man is more accustomed to set variable values as words rather than numbers as well as to receive and reproduce the information that contains the erroneous components. The theory of fuzzy sets allows us to formalize linguistic information for building mathematical models. This is based on the idea that the components of a given set of elements having a common property may possess it in varying degrees and, therefore, belong to this set in varying degrees. A linguistic variable is the one the value of which can be a word or phrase. Every day, we make decisions based on the linguistic information such as “very high temperature”; “an exhausting trip,” etc. [1]. This information is not based on precise definitions, therefore, it is fuzzy.

2.2 Mathematical model of expert evaluations

We will consider the mathematical model of technical diagnostics, used for power and industrial electric equipment. This model is based on the indistinct relations between predicted and real causes of failures. The main advantage of this model is that it does not require the creation of a base of fuzzy rules, but requires only the solution of a system of linear algebraic equations.

We will assume the following model of transformers’ technical diagnostics which is based on a fuzzy relations matrix which, in its turn, requires some expert estimates. These linguistic estimates are represented as some points of the membership function reflecting the expert’s subjective perception of the failure, based on the expert’s experience and knowledge.

Let the description of the total space of X predicted failures (prerequisites) consist of **m** factors, and total space of Y causes (failures) of these failures consist of **n** symptoms.

3 METHOD PROPOSED

To facilitate the search for failure causes and their clearing, the most typical failures in the performance (operation) of oil tank switches and methods checking characteristics are given below.

The problem of failures and faults is to be solved taking into account the following:

- in many cases the detected failure can appear to be the cause or a consequence of a failure of another node; for example, nonconformity (incongruity) of a drive parameter can result in mismatching the switch parameters;
- the quality of the maintenance aimed at clearing faults and eliminating failures, as a rule, has to be confirmed by the switch parameters check-out reports; moving elements (drives) should be certified for speed and time parameters;
- in case of sharp changes in parameters within standard limits, it is necessary to carry out changes' analysis.

We will accept the model similar to that given above, in application to transformers diagnostics. For high-voltage switches, the space of predicted failures and causes will be, of course, different. The experts' assessment will be different too.

Let the failures detected in the high-voltage switch be the following:

y1 – the switch fails to switch on;
y2 – gas escaping;
y3 – air escaping.

The list of failure causes is given below in accordance with the above-mentioned ones:

x1 – a control coil circuit break;
x2 – the lack of contact in a trip-free release device;
x3 – welding defects or case material defects;
x4 – the gas pressure sensor failure;
x5 – the gasket valve damage caused by the entry of alien particles.

There are some unclear causes between $\mathbf{x_i}$ and $\mathbf{y_i}$ $\mathbf{r_{ij} = x_i \rightarrow y_i}$ which are after – effect relations which can be represented as some **R** matrix with the $\mathbf{r_{ij}\ \delta\ [0.1]}$ elements. Predicted failures (prerequisites) and causes (failures) can be considered as indistinct sets, **A** and **B** on space of **X** and **Y**.

The relation (ratio) between these indistinct sets can be written as

$$\mathbf{B = A \bullet R},$$

where "•" is the rule of indistinct causes' composition.

In this case, the decision direction is the opposite to that of the rules development d. In case of diagnostics, R matrix (the knowledge of experts) is used and predicted failures (prerequisites) are defined.

Taking into account the abovementioned, it is possible to make a block diagram of matrixes of the possible failure causes and their consequences, using the theory of fuzzy relations and experts' estimates.

Let us analyze an example when a diagnostics expert's report on a high-voltage switch is given in the form of matrixes of fuzzy relations between the failure causes and their consequences

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0.9 & 0.1 & 0.1 \\ 0.2 & 0.9 & 0.7 \\ 0.4 & 0.8 & 0.2 \\ 0 & 0.6 & 1 \end{bmatrix}$$

The switch having been examined, the state of the switch can be estimated as a correlation function

$$\mathbf{B = 0.7/y1 + 0.4/y2 + 0.1/y3}.$$

It is necessary to define a predicted cause of this state

$$\mathbf{A = a1/x1 + a2/x2 + a3/x3 + a4/x4 + a5/x5.}$$

The ratio of the fuzzy sets included can be transposed and showed as fuzzy vectors – columns

$$\begin{bmatrix} 0.7 \\ 0.4 \\ 0.1 \end{bmatrix} = \begin{bmatrix} 1 & 0.9 & 0.2 & 0.4 & 0 \\ 0 & 0.1 & 0.9 & 0.8 & 0.6 \\ 0 & 0.1 & 0.7 & 0.2 & 1 \end{bmatrix} \bullet \begin{bmatrix} a1 \\ a2 \\ a3 \\ a4 \\ a5 \end{bmatrix}$$

When using a composition "max – min" (taking maximum from minimum), the latest ratio will be transformed to

$$0.7 = (1\wedge a1)\vee(0.9\wedge a2)\vee(0.2\wedge a3)\vee(0.4\wedge a4)\ )\vee(0\wedge a5)$$
$$0.4 = (0\wedge a1)\vee(0.1\wedge a2)\vee(0.9\wedge a3)\vee(0.8\wedge a4))\vee(0.6\wedge a5)$$
$$0.1 = (0\wedge a1)\vee(0.1\wedge a2)\vee(0.7\wedge a3)\vee(0.2\wedge a4)\ )\vee(1\wedge a5)$$

From the first equation the following is received:

$$0.7 \geq 1.0\wedge a1,\ a1 \leq 0.7$$

From the second equation the following is received:

$$0.4 \geq 0.9\wedge a3,\ a3 \leq 0.4$$

From the third equation the following is received:

$$0.1 \geq 1.0\wedge a5,\ a5 \leq 0.1$$

Thus, this system of the equations shows that the following causes of failures are the most predictable:

- a control coil open circuit = 0.7;
- welding defects or case material defects = 0.4;
- the gasket valve damage caused by the entry of alien particles = 0.1.

3.1 The mathematical model based on the degree of preference

We have assumed that there are all four symptoms. Let's compare these symptoms, using the fundamental scale of Saaty [2] which has nine degrees of preferences:

1 degree – equal preference; 2 degree – a weak degree of preference; 3 degree – an average degree of preference; 4 degree – higher than average preference; 5 degree – moderately strong preference; 6 degree – strong preference; 7 degree – very strong (obvious) preference; 8 degree – very, very strong preference; 9 degree – the absolute priority. If the symptom of A has a moderately strong degree of preference over the symptom B, the latter has the opposite degree of preference over A.

The following matrices present the degree of preference of one over another symptom of the trouble given of the presence of one of the six prerequisites.

$$\mathrm{A}(\mathrm{G}_1) = \begin{bmatrix} 1 & 1 & 5 & 3 \\ 1 & 1 & 5 & 3 \\ 0.2 & 0.2 & 1 & 0.333 \\ 0.333 & 0.333 & 3 & 1 \end{bmatrix} \qquad \mathrm{A}(\mathrm{G}_2) = \begin{bmatrix} 1 & 5 & 9 & 5 \\ 0.2 & 1 & 7 & 5 \\ 0.111 & 0.142 & 1 & 0.142 \\ 0.2 & 0.142 & 7 & 1 \end{bmatrix}$$

$$\mathrm{A}(\mathrm{G}_3) = \begin{bmatrix} 1 & 1 & 3 & 5 \\ 1 & 1 & 5 & 5 \\ 0.333 & 0.2 & 1 & 1 \\ 0.2 & 0.2 & 1 & 1 \end{bmatrix} \qquad \mathrm{A}(\mathrm{G}_4) = \begin{bmatrix} 1 & 1 & 7 & 3 \\ 1 & 1 & 5 & 3 \\ 0.142 & 0.2 & 1 & 0.333 \\ 0.333 & 0.333 & 3 & 1 \end{bmatrix}$$

$$\mathrm{A}(\mathrm{G}_5) = \begin{bmatrix} 1 & 1 & 7 & 5 \\ 1 & 1 & 5 & 3 \\ 0.142 & 0.2 & 1 & 0.2 \\ 0.2 & 0.333 & 5 & 1 \end{bmatrix} \qquad \mathrm{A}(\mathrm{G}_6) = \begin{bmatrix} 1 & 1 & 7 & 5 \\ 1 & 1 & 7 & 7 \\ 0.142 & 0.142 & 1 & 1 \\ 0.2 & 0.142 & 1 & 1 \end{bmatrix}$$

$$\lambda_{\max G_1} = 4.042;\ I.\mathrm{C}._{G_1} = 0.014. \qquad \lambda_{\max G_2} = 4.559;\ I.\mathrm{C}._{G2} = 0.18.$$

$$\lambda_{\max G_3} = 4.029;\ I.\mathrm{C}._{G_3} = 0.009. \qquad \lambda_{\max G_4} = 4.037;\ I.\mathrm{C}._{G_4} = 0.012.$$

$$\lambda_{\max G_5} = 4.203;\ I.\mathrm{C}._{G_5} = 0.068. \qquad \lambda_{\max G_6} = 4.005;\ I.\mathrm{C}._{G_6} = 0.001.$$

Calculation of the relative importance indices of the criteria has been carried out by the paired comparisons method of the fundamental scale of Saaty. The following linguistic pairwise importance comparisons criteria G1-G6 are considered to be well known:

$$\mathrm{A} = \begin{bmatrix} 1 & 0.333 & 0.333 & 0.333 & 0.333 & 0.2 \\ 3 & 1 & 3 & 1 & 3 & 0.2 \\ 3 & 0.333 & 1 & 0.333 & 1 & 0.2 \\ 3 & 0.333 & 3 & 1 & 3 & 0.333 \\ 3 & 0.333 & 1 & 0.333 & 1 & 0.2 \\ 5 & 5 & 5 & 3 & 5 & 1 \end{bmatrix}$$

We find the relative importance coefficients of the symptoms G1, G2, G3, G4, G5, G6. After the necessary calculations, we obtain: $\alpha_1 = 0.049$; $\alpha_2 = 0.17$; $\alpha_3 = 0.082$; $\alpha_4 = 0.161$; $\alpha_5 = 0.082$; $\alpha_6 = 0.456$, it means that the most important prerequisites are G2 and G6. The maximal eigenvalue of the vector is $\lambda_{\max} = 6.254$, the index of judgment consistency is IC = 0.05.

After that we have calculated the fuzzy sets from the following expression

$$\mu_D(\mathrm{P_j}) = \min(\mu_{G_i}(\mathrm{P_j}))\alpha_i$$

From (1), the fuzzy sets are obtained:

$$\tilde{G}_1^{\alpha_1} = \left\{\frac{0.955}{P_1}, \frac{0.955}{P_2}, \frac{0.877}{P_3}, \frac{0.912}{P_4}\right\};\ \tilde{G}_2^{\alpha_2} = \left\{\frac{0.917}{P_1}, \frac{0.793}{P_2}, \frac{0.563}{P_3}, \frac{0.687}{P_4}\right\};$$

$$\tilde{G}_3^{\alpha_3} = \left\{\frac{0.924}{P_1}, \frac{0.933}{P_2}, \frac{0.827}{P_3}, \frac{0.818}{P_4}\right\};\ \tilde{G}_4^{\alpha_4} = \left\{\frac{0.867}{P_1}, \frac{0.856}{P_2}, \frac{0.637}{P_3}, \frac{0.734}{P_4}\right\};$$

$$\tilde{G}_5^{\alpha_5} = \left\{\frac{0.936}{P_1}, \frac{0.919}{P_2}, \frac{0.783}{P_3}, \frac{0.854}{P_4}\right\};\ \tilde{G}_6^{\alpha_6} = \left\{\frac{0.567}{P_1}, \frac{0.695}{P_2}, \frac{0.286}{P_3}, \frac{0.297}{P_4}\right\}.$$

The intersection of these fuzzy sets gives the following degrees of the fuzzy decision $\tilde{D}$:

$$\mu_D(\mathrm{P_1}) = \min(0.955;0.917;0.924;0.867;0.936;0.67) = 0.67$$
$$\mu_D(\mathrm{P_2}) = \min(0.955;0.793;0.933;0.856;0.919;0.695) = 0.695$$
$$\mu_D(\mathrm{P_3}) = \min(0.877;0.563;0.827;0.637;0.783;0.286) = 0.286$$
$$\mu_D(\mathrm{P_4}) = \min(0.912;0.687;0.818;0.734;0.854;0.297) = 0.297$$

As a result the fuzzy set is obtained.

$$\tilde{D} = \left\{\frac{0.67}{P_1}, \frac{0.695}{P_2}, \frac{0.286}{P_3}, \frac{0.297}{P_4}\right\}$$

It testifies that the combination of the increased vibration and the noise of the transformer equipment dominates all other symptoms.

It is shown that the presence of symptoms and evaluation of these symptoms by the scale of preferences from fuzzy information on the possible causes, taking into account the expert judgment, it is possible to conclude. In this case, the increased vibration and noise can be caused by malfunctioning of the cooling system or damage to the inside of the transformer tank or reactor. In the process, the most likely cause of the noise or vibration assessment of 0.456 is the damage inside the tank, and the failure of the cooling system can cause the increased vibration and noise of the transformer or reactor with a probability degree of 0.17.

4 CONCLUSION

The study proposes equation system based on fuzzy relationships and pairwise comparison of the signs of faults in transformer or switching equipment. This approach does not require the development of a fuzzy rule base. It simplifies the notation of fuzzy cause-effect relations. The study does not consider the generating equipment of a power system, but only the electrical equipment of substations.

The proposed method of technical diagnosis based on fuzzy information allows us choosing the most reliable sign of damage in the presence of several alternatives and criteria. The decision-making process based on the results of technical diagnostics can be based on the symbiosis of fuzzy sets theory and the fundamental scale of paired comparisons using the Saati hierarchy method.

Usage of artificial intelligence methods gets the possibility of final decision-making for two important cases:

- further operation of the equipment with the more frequent parameters control (improper operation);
- immediate removal of the equipment for repairing (marginal state).

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