Comparative Analysis of the Hydrogenerator Technical State Estimation Models in Fuzzy-Information Conditions

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Abstract: - In article developed the number of models for the hydrogenerator technical state complex estimation by using the information about technical state of its local bundles. For the models development are used Mamdani, Sugeno and Zadeh fuzzy methods. Comparison analysis of developed fuzzy models was made. This analysis showed that the most reliable result given the Mamdani model, but its efficiency is decreasing when the number of input values is much. When the number of input values is much, the most effective are Sugeno models. Obtained results are used for the hydrogenerator fault probability estimation and risk-based electric power system management organization.

Key-Words: - hydrogenerator, technical state, fuzzy logic, Mamdani model, Sugeno model, Zadeh method

1 Introduction

Present conditions of Ukrainian Electrical Power System (EPS) exploitation require the complex approach to the equipment technical state (TS) estimation in real-time conditions without the switching off from the grid. The main requirements to the diagnostic parameters are their informative and availability of measurements and observations in on-line regime [1].

One of the most important EPS objects is synchronous hydrogenerator. Estimation of its TS is the complicate problem, because generator is multi-level object, which consists of particular bundles and subsystems [2].

In these conditions it is important to develop the complex approach to the reliability estimation of hydrogenerators and its bundles. This approach must to take into consideration real TS of hydrogenerator, probabilistic character of its faults and possible consequences of faults [2].

For the hydrogenerator reliability estimation it is necessary to have adequate model of TS estimation, which takes in the consideration next impacts:

- very complicate structure of hydrogenerator;
- the great number of different diagnostic parameters and attributes;
- the absence of analytical links between individual diagnostic parameters and attributes of the hydrogenerator complex TS and its local bundles TS.

The listed factors indicate that the problem of hydrogenerator complex TS estimation has the number of uncertainties. Solution of such problems lies in the area of fuzzy models and algorithms that are able to take these uncertainties into consideration.

2 Analysis of scientific literature and the problem statement

In articles [2, 3] for the hydrogenerator local bundles TS estimation is used Mamdani algorithm [4], which given good result in the case of not large number of diagnostic parameters and used ruler base with quality rulers "IF-THEN", which is convenient by experts. Using of this algorithm in the problem of complex TS estimation of hydrogenerator is not effective because the number of input values is large and this given the difficulties for experts in creating the ruler base.

A number of other approaches to the generators TS estimation were analyzed. In [5] for the estimation of magnetic properties was proposed the method of synchronous reactance X_d and X_q controlling with using the finite element method. The advantage of this method it the possibility of the reactance value on-line checking. The disadvantage of this method is the total control of iron core state and the air gap state without separation. The more effective solution of this problem is the generator eccentricity diagnosing method, which proposed in [6]. This method is using the functional relation between the stator winding inductance and air gap eccentricity, which obtained by the comparison analysis of one-type generators. Disadvantage of this method lies in the necessary of the large number of one-type generators.

In [7] was made the stator winding technical state estimation by the results of its electric characteristics measurement. Great advantage of this model is the fuzzy-model using. Simultaneously, in this paper not consider the approach of ruler base creating and the justification of output value. The main disadvantage of this model is rejection of thermal and vibration impact of stator winding.

In [8] authors diagnosed the particular discharges at the large generator stator windings with on-line monitoring using. This method permits to control isolation state without switching off the generator. Disadvantage of this method is the absence of the solutions taking system.

It should be noted, that all proposed models permit to appreciate electrical state of generator. State of mechanical bundles [3] is not considering. So, the problem of generator complex TS estimation is insufficiently reviewed.

3 Fuzzy approach to the hydro-generator TS modeling

Hydrogenerator consists of the great number of bundles, each of them are characterized by a set of heterogeneous diagnostic features. Because of this, it is advisable to represent it as the multi-level object consisting of separate bundles and subsystems. The most damaged bundles of hydrogenerator are next [2]:

- stator core (8% of the total number of faults);
- stator winding (18% of the total number of faults);
- excitation winding (6% of the total number of faults);
- excitation system (11% of the total number of faults);
- control system (9% of the total number of faults);
- bearings (13% of the total number of faults);
- thrust bearing (17% of the total number of faults);
- rotor (5% of the total number of faults);
- cooling system (10% of the total number of faults);
- other (3 % of the total number of faults).

Because the hydrogenerator in this problem is considered as a multi-level object, the fuzzy model describing its TS also has a hierarchical structure. This structure is presented at the Fig.1.

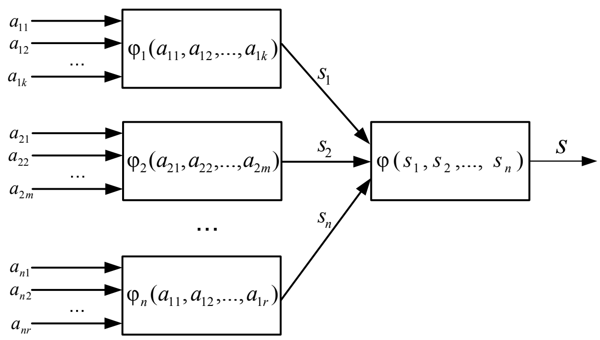

Fig.1 Hierarchical fuzzy model for the hydrogenerator TS estimation

At the Fig.1: a_{ij} - input attribute "*j*" of hydrogenerator bundle "*i*", φ_i - fuzzy function of hydrogenerator bundle "*i*" TS estimation, s_i - TS of hydrogenerator bundle "*i*", φ - fuzzy function of hydrogenerator TS estimation, s - TS of hydrogenerator.

During the synthesis of the model according to this structure, we have the problem of determining fuzzy functions φ_i for the TS estimation of the local bundles of the generator and the fuzzy function of hydrogenerator TS estimation φ . In papers [2, 3] Mamdani algorithm is used for the TS estimation of the local bundles. This algorithm gives satisfactory results for the small number of diagnostic parameters and uses ruler base "IF-THEN" type, which are convenient for the expert formation in the absence of analytical links between diagnostic parameters.

Determining the fuzzy function of the hydrogenerator TS is a more complicate problem because of a significant number of the hydrogenerator bundles on which its complex TS is evaluated.

According to [9] the most effective algorithms of fuzzy output in the case of a large number of diagnostic features are:

- Sugeno algorithm "AND";
- Sugeno algorithm "OR";
- Zadeh algorithm.

Below, the estimation of the hydrogenerator TS is performed by fuzzy models developed by the three above-mentioned algorithms and made the obtained results comparison with the results, given by the Mumdany model.

4 Mamdani Model

The hierarchical fuzzy model of Mamdani type [9, 10] is used for the complex estimation of the hydrogenerator TS (Fig.1). The first level of this model consists of 4 models of its local bundles TS estimation. Input values of the second level of such model will be:

1) S_1=«Stator TS»;
2) S_2=«Thrust bearing TS»;
3) S_3=«Bearing TS»;
4) S_4=«Rotor TS».

Linguistic variables that correspond to the input parameters of the generator TS bundles are described by the following fuzzy terms:

- S_1 : {s_{11}=«Satisfactory», s_{12}= «Unsatisfactory»};
- S_2 : {s_{21}=«Satisfactory», s_{22}= «Unsatisfactory»};
- S_3 : {s_{31}=«Satisfactory», s_{32}= «Unsatisfactory»};
- S_4 : {s_{41}=« Satisfactory», s_{42}= «Unsatisfactory»}.

Membership functions of fuzzy terms values S_i, i=1,…,4 are presented at the Fig.2.

Output value is hydrogenerator complex TS (active resource). Output linguistic variable is described by five fuzzy terms:

S: {s_1= «Very good», s_2= «Good», s_3= «Middle», s_4= «Bad», s_5= «Very bad»}.

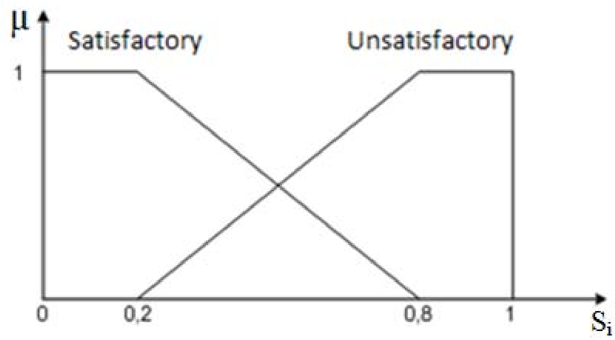

Fig.2 Membership functions of input values fuzzy terms

Membership functions of output linguistic variable are determined at the Harrington scale intervals (Fig.3).

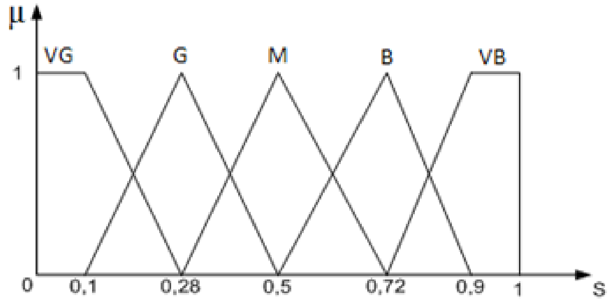

Fig.3 Membership functions of output value fuzzy terms

Ruler base is composed by expert and presented at the Table 1.

Table 1 Ruler base of Mamdani model

S_1 / S_2	S_{11}			S_{12}		
S_{21}	S_3 / S_4	S_{31}	S_{32}	S_3 / S_4	S_{31}	S_{32}
	S_{41}	VG	G	S_{41}	G	M
	S_{42}	G	M	S_{42}	M	B
S_{22}	S_3 / S_4	S_{31}	S_{32}	S_3 / S_4	S_{31}	S_{32}
	S_{41}	G	M	S_{41}	B	VB
	S_{42}	M	B	S_{42}	VB	VB

Defuzzyfication is composed by centroid method for non-recurring ones.

$$s = \frac{\int \mu(s) \cdot s \cdot ds}{\int \mu(s) ds}. \qquad (1)$$

Example. It is necessary to make the hydrogenerator TS estimation by the results of 4 local bundles TS estimation, namely:

1) S_1= 0,68 – stator TS;
2) S_2= 0,45 – thrust bearing TS;
3) S_3= 0,82 – bearing TS;
4) S_4= 0,38 – rotor TS.

By the membership functions is estimated the belonging degree of input values to the fuzzy terms:

- b_1 : {$\mu(s_{11})$=0,21, $\mu(s_{12})$=0,79};
- b_2 : {$\mu(s_{21})$=0,58, $\mu(s_{22})$=0,42};
- b_3 : {$\mu(s_{31})$=0, $\mu(s_{32})$=1};
- b_4 : {$\mu(s_{41})$=0,71, $\mu(s_{42})$=0,29}.

By the ruler base (disjunction procedure using) is performed the fuzzy output:

- ruler 1:

IF *S_{11} AND S_{21} AND S_{31} AND S_{41} THEN S=VG* – ruler is not performed;

- ruler 2:

IF *S_{11} AND S_{21} AND S_{31} AND S_{42} THEN S=G* – ruler is not performed;

- ruler 3:

IF *S_{11} AND S_{21} AND S_{32} AND S_{42} THEN S=G* – $\mu(S)$=0,21;

…

- ruler 15:

IF *S_{12} AND S_{22} AND S_{32} AND S_{41} THEN S=VB* – $\mu(S)$=0,42;

- ruler 16:

IF *S_{12} AND S_{22} AND S_{32} AND S_{42} THEN S=VB* – $\mu(S)$=0,29.

Active rulers according to the conjunction approach is determined the fuzzy output area at the output fuzzy terms membership functions (Fig.4).

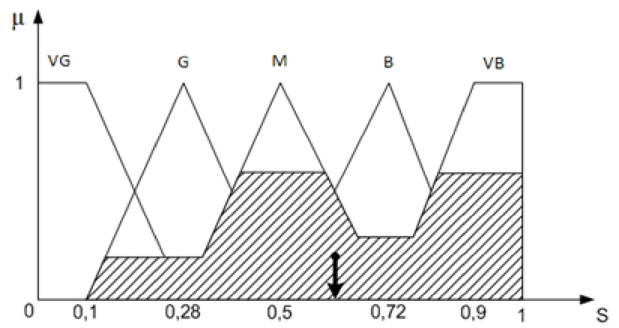

Fig.4 Mamdani fuzzy output

By centroid method is determined technical state of hydrogenerator:

$$s = \frac{\int \mu(s) \cdot s \cdot ds}{\int \mu(s) ds} = 0{,}611 . \qquad (2)$$

5 Sugeno model

Sugeno model fuzzy output is organized by the next algorithm [9,10]:

- formed the ruler base, which includes next rulers: IF «b_1 is s_1», «b_2 is s_2», …, «b_n is s_n» THEN w =$b_1 \cdot w_1 + b_2 \cdot w_2 + \ldots + b_n \cdot w_n$,
  $w_1, w_2, \ldots w_n$ – is the ruler weight;
- fuzzyfication of input values is realized with membership functions using, which performed by expert estimation;
- fuzzy rulers aggregation is performed according to conjunction logic operation, namely that rulers which membership degree is more than zero is considered as active rulers and take the participation in fuzzy output;
- output accumulation by fuzzy rulers is performed with using the real numbers w_i and $\mu(s_i)$;
- defuzzyfication is performed by centroid method for the set of points.

The hierarchical model for the hydrogenerator TS complex estimation, first level of which (Fig.1) consists of four models of local bundles state estimation models is considered. Input values for the second level of such model will be:

1) b_1=«stator TS»;
2) b_2=«bearing TS»;
3) b_3=«rotor TS»;
4) b_4=«thrust bearing TS».

Linguistic variables, which correspond to input values of generator bundles state, described by next terms:

- b_1 : {s_{11}=«Satisfactory», s_{12}= «Unsatisfactory»};
- b_2 : {s_{21}=«Satisfactory», s_{22}= «Unsatisfactory»};
- b_3 : {s_{31}=«Satisfactory», s_{32}= «Unsatisfactory»};
- b_4 : {s_{41}=«Satisfactory», s_{42}= «Unsatisfactory»}.

Membership functions of fuzzy terms b_i, i=1,…,4 are analogical to the Mamdani model membership functions (Fig.2).

Fuzzy output is realized by the next rulers:

- ruler №1:

IF $b_1 = s_{11}$ AND $b_2 = s_{21}$ AND $b_3 = s_{31}$ AND $b_4 = s_{41}$ THEN w =$b_1 \cdot w_{1-1} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-1} + b_4 \cdot w_{4-1}$;

- ruler №2:

IF $b_1 = s_{12}$ AND $b_2 = s_{21}$ AND $b_3 = s_{31}$ AND $b_4 = s_{41}$ THEN w =$b_1 \cdot w_{1-2} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-1} + b_4 \cdot w_{4-1}$;

- ruler №3:

IF $b_1 = s_{13}$ AND $b_2 = s_{21}$ AND $b_3 = s_{33}$ AND $b_4 = s_{41}$ THEN w =$b_1 \cdot w_{1-3} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-1} + b_4 \cdot w_{4-1}$;

…

- ruler №16:

IF $b_1 = s_{22}$ *AND* $b_2 = s_{22}$ *AND* $b_3 = s_{32}$ *AND* $b_4 = s_{42}$ *THEN* $w = b_1 \cdot w_{1-2} + b_2 \cdot w_{2-2} + b_3 \cdot w_{3-2} + b_4 \cdot w_{4-2}$.

From the generated rulers we can see that for the reliable estimation of complex generator TS obtaining is necessary to have the valid vectors of weights $\boldsymbol{w_1}$ and $\boldsymbol{w_2}$:

$$\boldsymbol{w_1} = \{w_{1-1};\ w_{2-1};\ w_{3-1};\ w_{4-1}\}; \quad (3)$$

$$\boldsymbol{w_2} = \{w_{1-2};\ w_{2-2};\ w_{3-2};\ w_{4-2}\}. \quad (4)$$

For the obtaining vectors $\boldsymbol{w_1}$ and $\boldsymbol{w_2}$ method Saaty is used [10]. Method Saaty is used the maximal eigenvalue and expert estimations. According to the expert estimations of the TS of local bundles, which necessary for the generator total state estimation, obtained next relations (Table 2, 3).

Table 2 Expert estimations by the Saaty scale for the determination vector $\boldsymbol{w_1}$

Parameter	b_1	b_2	b_3	b_4
b_1	1	1/2	3	4
b_2	2	1	3	2
b_3	1/3	1/3	1	1/4
b_4	1/4	1/2	4	1

Table 3 Expert estimations by the Saaty scale for the determination vector $\boldsymbol{w_2}$

Parameter	b_1	b_2	b_3	b_4
b_1	1	3	1/2	1/4
b_2	1/3	1	2	3
b_3	2	1/2	1	2
b_4	4	1/3	1/2	1

Determination of vector $\boldsymbol{w_1}$. By the obtained expert estimations is compiled the matrix of paired comparisons:

$$B_1 = \begin{bmatrix} 1 & 0{,}5 & 3 & 4 \\ 2 & 1 & 3 & 2 \\ 0{,}333 & 0{,}333 & 1 & 0{,}25 \\ 0{,}25 & 0{,}5 & 4 & 1 \end{bmatrix}. \quad (5)$$

Determined the maximal eigenvalue of matrix:

$$B_1 - \lambda E = \begin{bmatrix} 1-\lambda & 0{,}5 & 3 & 4 \\ 2 & 1-\lambda & 3 & 2 \\ 0{,}333 & 0{,}333 & 1-\lambda & 0{,}25 \\ 0{,}25 & 0{,}5 & 4 & 1-\lambda \end{bmatrix} = 0. \quad (6)$$

This equation has four roots:

$$\lambda_{1,2} = 0{,}1874 \pm j1{,}1818; \quad \lambda_3 = 3{,}9984; \quad \lambda_4 = -0{,}3733. \quad (7)$$

The maximal eigenvalue of matrix is real positive root $\lambda_3 = 3{,}9984$. After the substitution this root in the input equation and the substitution of last equation by normal equation $\sum_{i=1}^{4} \omega_{i-1} = 1$ is formed equation system for the estimation of optimization criterion weights:

$$\begin{cases} -2{,}9984\omega_{1-1} + 0{,}5\omega_{2-1} + 3\omega_{3-1} + 4\omega_{4-1} = 0; \\ 2\omega_{1-1} - 2{,}9984\omega_{2-1} + 3\omega_{3-1} + 2\omega_{4-1} = 0; \\ 0{,}333\omega_{1-1} + 0{,}333\omega_{2-1} - 2{,}9984\omega_{3-1} + 0{,}25\omega_{4-1} = 0; \\ \omega_{1-1} + \omega_{2-1} + \omega_{3-1} + \omega_{4-1} = 1. \end{cases} \quad (8)$$

The solution of this equation system is weight vector $\boldsymbol{w_1}$:

$$\boldsymbol{w_1} = \{0{,}348;\ 0{,}419;\ 0{,}096;\ 0{,}137\}. \quad (9)$$

Determination of vector $\boldsymbol{w_2}$. According to the expert estimations is compiled the matrix of paired comparisons:

$$B_2 = \begin{bmatrix} 1 & 3 & 0{,}5 & 0{,}25 \\ 0{,}333 & 1 & 2 & 3 \\ 2 & 0{,}5 & 1 & 2 \\ 4 & 0{,}333 & 0{,}5 & 1 \end{bmatrix}. \quad (10)$$

Determined the maximal eigenvalue of matrix:

$$B_2 - \lambda E = \begin{bmatrix} 1-\lambda & 3 & 0{,}5 & 0{,}25 \\ 0{,}333 & 1-\lambda & 2 & 3 \\ 2 & 0{,}5 & 1-\lambda & 2 \\ 4 & 0{,}333 & 0{,}5 & 1-\lambda \end{bmatrix} = 0. \quad (11)$$

This equation has four roots:

$$\lambda_{1,2} = -0{,}6903 \pm j2{,}8125; \quad \lambda_3 = 5{,}5528; \quad \lambda_4 = -0{,}1722. \quad (12)$$

The maximal eigenvalue of matrix is real positive root $\lambda_3 = 5{,}5528$. After the substitution this root in the input equation and the substitution of last equation by normal equation $\sum_{i=1}^{4} \omega_{i-2} = 1$ is formed equation system for the estimation of optimization criterion weights:

$$\begin{cases} -4{,}5528\omega_{1-2} + 3\omega_{2-2} + 0{,}5\omega_{3-2} + 0{,}25\omega_{4-2} = 0; \\ 0{,}333\omega_{1-2} - 4{,}5528\omega_{2-2} + 2\omega_{3-2} + 3\omega_{4-2} = 0; \\ 2\omega_{1-2} + 0{,}5\omega_{2-2} - 4{,}5528\omega_{3-2} + 2\omega_{4-2} = 0; \\ \omega_{1-2} + \omega_{2-2} + \omega_{3-2} + \omega_{4-2} = 1. \end{cases} \quad (13)$$

The solution of this equation system is weight vector $\boldsymbol{w_2}$:

$$\boldsymbol{w_2} = \{0{,}228;\ 0{,}285;\ 0{,}24;\ 0{,}247\}. \quad (14)$$

Determination of complex hydrogenerator TS (defuzzyfication) is performed by centroid method as the superposition of linear laws. For this weighted mean is determined as:

$$s = \frac{\sum_{i=1}^{n} \mu(s_i) \cdot w_i}{\sum_{i=1}^{n} \mu(s_i)}. \quad (15)$$

Example. It is necessary to estimate the hydrogenerator TS by the results of 4 local bundles TS estimation:

1) S_1= 0,68 – stator TS;
2) S_2= 0,45 – thrust bearing TS;
3) S_3= 0,82 – bearing TS;
4) S_4= 0,38– rotor TS.

According to the membership function is obtained:

- b_1 : {μ(s_{11})=0,21, μ(s_{12})=0,79};
- b_2 : {μ(s_{21})=0,58, μ(s_{22})=0,42};
- b_3 : {μ(s_{31})=0, μ(s_{32})=1};
- b_4 : {μ(s_{41})=0,71, μ(s_{42})=0,29}.

Values *w* are obtained according to the Sugeno rulers:

- ruler №1:
IF $b_1 = s_{11}$ *AND* $b_2 = s_{21}$ *AND* $b_3 = s_{31}$ *AND* $b_4 = s_{41}$ *THEN*
$w = b_1 \cdot w_{1-1} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-1} + b_4 \cdot w_{4-1}$ – ruler is not active

- ruler №2:
IF $b_1 = s_{11}$ *AND* $b_2 = s_{21}$ *AND* $b_3 = s_{31}$ *AND* $b_4 = s_{42}$ *THEN*
$w = b_1 \cdot w_{1-1} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-1} + b_4 \cdot w_{4-2}$ – ruler is not active

- ruler №3:
IF $b_1 = s_{11}$ *AND* $b_2 = s_{21}$ *AND* $b_3 = s_{32}$ *AND* $b_4 = s_{41}$ *THEN*
$w = b_1 \cdot w_{1-1} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-2} + b_4 \cdot w_{4-1} =$
=0,21*0,348+0,58*0,419+1*0,24+0,71*0,137=
=0,653

- ruler №4:
IF $b_1 = s_{11}$ *AND* $b_2 = s_{21}$ *AND* $b_3 = s_{32}$ *AND* $b_4 = s_{42}$ *THEN*
$w = b_1 \cdot w_{1-1} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-2} + b_4 \cdot w_{4-2} =$
=0,21*0,348+0,58*0,419+1*0,24+0,29*0,247=
=0,628

- ruler №5:
IF $b_1 = s_{11}$ *AND* $b_2 = s_{22}$ *AND* $b_3 = s_{31}$ *AND* $b_4 = s_{41}$ *THEN*
$w = b_1 \cdot w_{1-1} + b_2 \cdot w_{2-2} + b_3 \cdot w_{3-1} + b_4 \cdot w_{4-1}$ – ruler is not active

…

- ruler №16:
IF $b_1 = s_{12}$ *AND* $b_2 = s_{22}$ *AND* $b_3 = s_{32}$ *AND* $b_4 = s_{42}$ *THEN*
$w = b_1 \cdot w_{1-2} + b_2 \cdot w_{2-1} + b_3 \cdot w_{3-2} + b_4 \cdot w_{4-2} =$
=0,79*0,228+0,42*0,285+1*0,24+0,29*0,247=
=0,611.

TS of hydrogenerator is determined as weighted average (15). If $\mu(s_i)$ is the level of *i*-ruler implementation, which is determined according to the disjunction procedure ("AND"), then technical state of hydrogenerator is equal:

$$s = \frac{\sum_{i=1}^{8} \mu(s_i) \cdot w_i}{\sum_{i=1}^{8} \mu(s_i)} = 0{,}655. \quad (16)$$

If $\mu(s_i)$ is the level of *i*-ruler implementation, which is determined according to the conjunction procedure ("OR"), then TS of hydrogenerator is equal:

$$s = \frac{\sum_{i=1}^{8} \mu(s_i) \cdot w_i}{\sum_{i=1}^{8} \mu(s_i)} = 0{,}632. \quad (17)$$

6 Zadeh method

The set *Y* of generator local bundles TS is existed. Because, the hydrogenerator is the complicate system, the number of subsystems N, from which it consists of, is large. TS of local bundles are:

- y_1 – stator TS;
- y_2 – thrust bearing TS;
- y_3 – bearing TS;
- y_4 – rotor TS;
- y_5 – excitation system TS;
- y_6 – generator controller TS;
- y_7 – cooling system TS;
- …
- y_N – TS of *N* bundle.

Vector of fuzzy relations (standard matrix of states) *R*, which created by experts and determines the influence of *i*-bundle technical state at the total TS of generator:

$$R = \begin{bmatrix} r_1 & r_2 & \dots & r_n \end{bmatrix}^T. \quad (18)$$

Every element of vector *R* is determined as:

$$r_i = \frac{m_i}{M}, \quad (19)$$

m_i - is the number of experts, which decided that the influence of *i*-bundle TS at the total TS of generator is «significant», *M* – the total number of experts.

The set of local bundles technical state is the vector too:

$$Y = \begin{bmatrix} y_1 & y_2 & \dots & y_n \end{bmatrix}. \quad (20)$$

TS of hydrogenerator *S* is determined as composition multiplication of two vectors [4]:

$$S = Y \circ R, \tag{21}$$

$\circ$ - is "max-min" composition.

Example. It is necessary to estimate the hydrogenerator TS by the results of 4 local bundles TS estimation:

1) S_1= 0,68 – stator TS;
2) S_2= 0,45 – thrust bearing TS;
3) S_3= 0,82 – bearing TS;
4) S_4= 0,38– rotor TS.

The number of experts is M=10. They have given next estimation of local bundles influence on the total TS of hydrogenerator:

1) significant influence of stator state at the total TS of hydrogenerator given m_1=9 experts;
2) significant influence of thrust bearing state at the total TS of hydrogenerator given m_2=8 experts;
3) significant influence of bearing state at the total TS of hydrogenerator given m_3=7 experts;
4) significant influence of rotor state at the total TS of hydrogenerator given m_4=9 experts.

According to the expert estimations are calculated the elements of fuzzy relations vector:

$$r_1 = \frac{m_1}{M} = \frac{9}{10} = 0{,}9, \tag{22}$$

$$r_2 = \frac{m_2}{M} = \frac{8}{10} = 0{,}8, \tag{23}$$

$$r_3 = \frac{m_3}{M} = \frac{7}{10} = 0{,}7, \tag{24}$$

$$r_4 = \frac{m_4}{M} = \frac{9}{10} = 0{,}9. \tag{25}$$

Vector R in this case is:

$$R = \begin{bmatrix} 0{,}9 & 0{,}8 & 0{,}7 & 0{,}9 \end{bmatrix}^T. \tag{26}$$

Set of local bundles state Y is:

$$Y = \begin{bmatrix} 0{,}68 & 0{,}45 & 0{,}82 & 0{,}38 \end{bmatrix}. \tag{27}$$

Hydrogenerator total TS S is defined according to the "max-min" approach:

$$S = Y \circ R = \begin{bmatrix} 0{,}68 & 0{,}45 & 0{,}82 & 0{,}38 \end{bmatrix} \circ \begin{bmatrix} 0{,}9 \\ 0{,}8 \\ 0{,}7 \\ 0{,}9 \end{bmatrix} = 0{,}7 \cdot \tag{28}$$

Obtained value of hydrogenerator total TS $S = 0{,}7$ could be used for the definition of fault probability at the time interval, for the comparison analysis of one-type generators at the hydro power plants and for taking the solutions about the necessary of service works providing.

7 Results comparison

In the Table 4 are given the results of hydrogenerator TS estimation by above developed methods.

Table 4 Results comparison of hydrogenerator TS by 4 methods

Mamdani	Sugeno ("OR")	Sugeno ("AND")	Zadeh
0,611	0,632	0,655	0,7

If take the Mamdani model as the most verify (because it needs the minimum information, has quality ruler base and given the good result at the models of local bundles state estimation) comparison analysis of fourth results gives next:

1) the most close result to the verify model given the Sugeno model "Or";
2) close result given the Sugeno model "And";
3) result, obtained by the Zadeh method, has great difference from the result which obtained by Mamdani model, because this method has the most simplified fuzzy output and given the maximal error at the complex estimation of hydrogenerator TS.

8 Conclusions

Developed in article fuzzy models of complex hydrogenerator TS estimation are giving the possibility with high accuracy and validation to estimate the total TS of hydrogenerator. For this purpose is used only available in "on-line" regime parameters of hydrogenerator bundles state and quality expert estimations for identification the relations between diagnostic parameters and local bundles TS.

Among the proposed methods of complex TS hydrogenerator estimation the highest accuracy has Mamdani model, because it used only quality ruler base. The lowest accuracy has the model, which using etalon vector Zadeh, because Zadeh method is used simplify expert estimations. Sufficient accuracy has the Sugeno models. Unlike from Mamdani model, these models are convenient in case of the large number of local bundles state, which inherent to such complicate system as hydrogenerator.

Obtained by developed fuzzy models complex estimation of hydrogenerator TS permit in future to calculate the hydrogenerator fault probability at the time interval with consideration of its individual state characteristics. Obtained values of probabilities is advisable to use for the hydrogenerator reliability estimation, service planning and provide the risk-oriented management in EPS.

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