The International Journal Of Engineering And Science (IJES)
||Volume||3 ||Issue|| 1||Pages|| 85-95||2014||
ISSN(e): 2319 – 1813 ISSN(p): 2319 – 1805

Fuzzy-Statistical Modeling of Hydrogenerator for Its Reliability Appreciation

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ABSTRACT
In article are reviewed the problems of Risk-Oriented Management of hydro power station generating equipment. Fuzzy-statistical method of hydrogenerator and its bundles fault risk estimation is proposed. This method lies in the using both generators operation statistical data and individual characteristics of concrete generator. For the consideration of generator individual characteristics fuzzy model of stator winding technical stuff appreciation is developed. Obtained method and model are used for the appreciation of the Dnipro-2 HPS generators fault risk at the 1 year time interval.

KEYWORDS*: hydrogenerator, stator winding, risk, fault probability, technical stuff, fuzzy model*

Date of Submission: 08 January 2014 Date of Acceptance: 16 January 2014

I. INTRODUCTION

One of the important problems in Ukrainian Power Engineering is the providing of Electrical Power System (EPS) reliable operation in the conditions when the power station generating equipment worked off its nominal resource. This problem is especially actual for the Ukrainian hydro power stations (HPS). For example: among the 100 hydrogenerators, which installed at the 10 Ukrainian HPS, 93 generators operate more then 25 years. Present conditions of Ukrainian EPS exploitation require the complex approach to the equipment technical stuff (TS) estimation in real-time conditions without the switching off from the grid. The main requirements to the diagnostic parameters and signs are their informative and availability of measurements and observations in on-line regime. One of the most important EPS objects is synchronous generator. Estimation of its TS is a complicated problem, because generator is multi-level object, which consists of particular bundles and subsystems. According to the statistical data, the most damaged bundle of generator is stator winding (near the 37 % from the total number of faults). 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.

II. GENERATOR FAULT RISK ESTIMATION DUE TO THE STATOR WINDING DAMAGE

Modern approaches to the providing of EPS reliable operates show the growing of the risk-management role in taking the credible solutions about the EPS management [1,2]. When the risk-management is used, the main criterion of object reliability is the risk. Risk is the production of undesirable event probability on its consequences [2]. So, hydrogenerator fault risk is determined as:

$$R = p(\Delta t) \cdot 1000 \cdot P_n \cdot T_{rep} \cdot C\,, \qquad (1)$$

where $p(\Delta t)$ – is the generator fault probability at the time interval; P_n – is the nominal active power of generator, MW; T_{rep} – is the generator repair time, hours; C – is the power energy cost for the HPS, €/kW·hour.

The most complicated problem in the risk appreciation, according to the equation (1), is the credible definition of probability $p(\Delta t)$, because hydrogenerator is the multi-level object. In these conditions is appropriately to present the generator as a subsystem, which consist of (in general case) n elements (bundles) such as stator winding, stator core, rotor, field winding, excitation system etc. Let A_i, $i = 1,..., n$ – is the event which means the fault of bundle i, $p(A_i)$ – is the probability of bundle i fault at the time interval Δt. Because events $A_1 \dots A_n$ are compatible, the generator fault probability, as a subsystem which consists of n bundles, at the time interval Δt is determined according to the compatible events probabilities addition formula [3]:

$$p(\Delta t) = \sum_{i=1}^{n} p(A_i) - \sum_{i=1,j=1,i\neq j}^{n} p(A_i)\cdot p(A_j) + \sum_{i=1,j=1,k=1,i\neq j\neq k}^{n} p(A_i)\cdot p(A_j)\cdot p(A_k) + \\ + \dots + (-1)^{n-1}\cdot p(A_1)\cdot p(A_2)\cdot \dots \cdot p(A_n). \quad (2)$$

In particular case, when the appreciation of generator fault risk by the damage of concrete bundle is made (for example: event A_1 – is the generator fault due to stator winding damage), are accepted then $p(\Delta t) = p(A_1)$.

It is important to choose the approach to the generator fault probability and risk estimation. Determined approach is simpler, but does not take into account probabilistic character of object fault, does not take into consideration real TS of concrete unit of equipment and does not fully address fault consequences [4]. So, for the hydrogenerator fault risk estimation is accepted the probabilistically-statistical approach [3], which takes into consideration these uncertainties.

III. HYDROGENERATOR BUNDLES FAULT PROBABILITY ESTIMATION AT THE TIME INTERVAL

For the estimation of hydrogenerator fault probability value it is necessary to know fault probabilities of its bundles at the time interval [4]. For this purpose next events are introduced:

- H_{1i} – event, which lies in that, then bundle i has refused at the time interval Δt;
- H_{2i} – event, which lies in that, then bundle i has not refused at the time interval Δt;
- B_i – event, which lies in that, bundle i has TS S_i at the moment of time t_1.

Assumed, that event B_i took place (bundle i has TS S_i). In this case, conditional probability of bundle i fault at the time interval Δt is defined by Bayes theorem [3]:

$$p(A_i) = p(H_{1i}/B_i) = \frac{p(H_{1i})\cdot p(B_i/H_{1i})}{p(H_{1i})\cdot p(B_i/H_{1i}) + p(H_{2i})\cdot p(B_i/H_{2i})}, \quad (3)$$

where $p(H_{1i})$ – is the priori probability of event H_{1i} to the appearance of event B_i; $p(H_{2i})$ – is the priori probability of event H_{2i} to the appearance of event B_i; $p(B_i/H_{1i})$ – is the conditional probability of event B_i in the appearance of event H_{1i}; $p(B_i/H_{2i})$ – is the conditional probability of event B_i in the appearance of event H_{2i}.

Priori probabilities of refused and non-refused operates of bundle i at the time interval Δt in the case of its reliable condition at the time moment t_1 is determined by the statistical integral function of generators faults distribution:

$$p(H_{1i}) = \frac{F(t_{2i}) - F(t_{1i})}{1 - F(t_{1i})}, \quad (4)$$

$$p(H_{2i}) = 1 - p(H_{1i}). \quad (5)$$

Function of hydrogenerators faults distribution $\omega(t)$ and integral function of hydrogenerators faults distribution $F(t)$ building according to the statistical data about the hydrogenerators faults. In this article these functions are built by the statistical data about the faults of Dnipro HPS Cascade generators (Ukraine). These functions are presented at the fig.1 and fig.2.

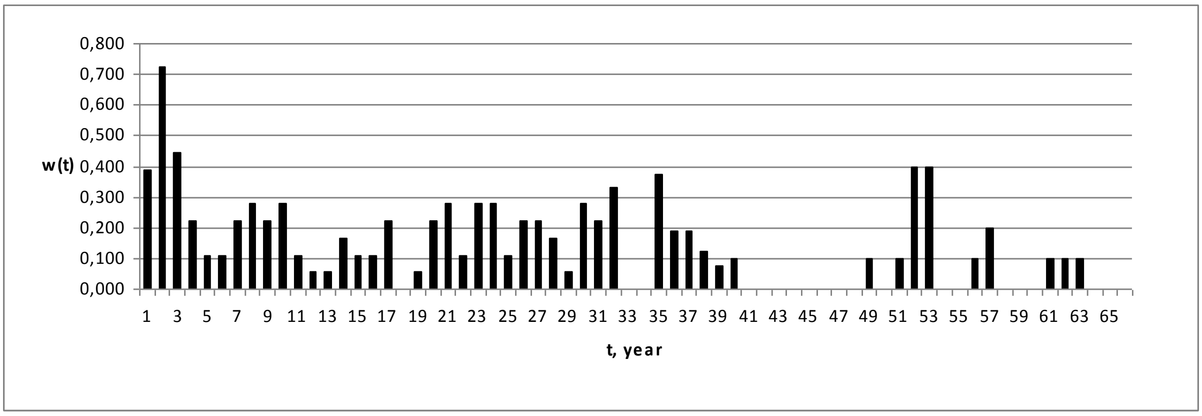

Fig.1. Function of hydrogenerators faults distribution

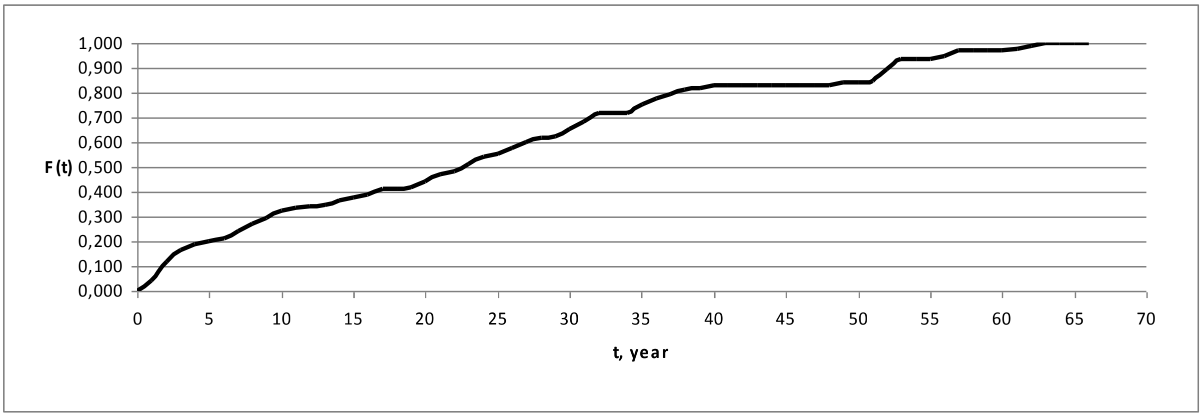

Fig.2. Integral function of hydrogenerators faults distribution

Conditional probabilities $p(B_i / H_{1i})$ and $p(B_i / H_{2i})$ are determined on the basis of expert estimations with using the Saaty method [5] and max-min composition of Zadeh rule [6]. Concrete signs and alternatives in this case are considered as fuzzy sets S_i, P_i and Q_i, which defined on the universal sets X, Y_P та Y_Q. Connection between signs and alternatives are defined by composition Zadeh rule [4]:

$$P_i = R_{Pi} \circ S_i , \tag{6}$$

$$Q_i = R_{Qi} \circ S_i , \tag{7}$$

where R_{Pi}, R_{Qi} – the expert matrices of the causal relationships between signs and alternatives of bundle i condition for the determination of probabilities $p(B_i / H_{1i})$ and $p(B_i / H_{2i})$ respectively.

Values of probabilities $p(B_i / H_{1i})$ and $p(B_i / H_{2i})$ are defined on the Harrington scale intervals by the next equations:

$$p(B_i / H_{1i}) = y_{P\max} - \frac{\sum_{j=1}^{n} p_j \cdot y_j}{\sum_{j=1}^{n} p_j} \cdot (y_{P\max} - y_{P\min}) , \tag{8}$$

$$p(B_i / H_{2i}) = y_{Q\max} - \frac{\sum_{j=1}^{n} q_j \cdot y_j}{\sum_{j=1}^{n} q_j} \cdot (y_{Q\max} - y_{Q\min}) . \tag{9}$$

As a measure of generator bundle i TS is taken the value S_i. This value characterizes the resource of this bundle. Definition of value S_i is a complicate problem, which must to be solved in the next conditions:

- the big number of different generator bundle diagnostic parameters, which have not mathematical dependence among themselves;
- presence a number of generator regime conditions, which characterize total stuff of its bundles.

Going from these conditions, for the appreciation of generator bundles real TS the fuzzy model is used.

IV. FUZZY MODEL FOR THE HYDROGENERATOR STATOR WINDING STUFF APPRECIATION

If to consider the hydrogenerator as the EPS subsystem, then for its TS appreciation is possible to propose two-level fuzzy model, which has the structure, showing at the fig.3.

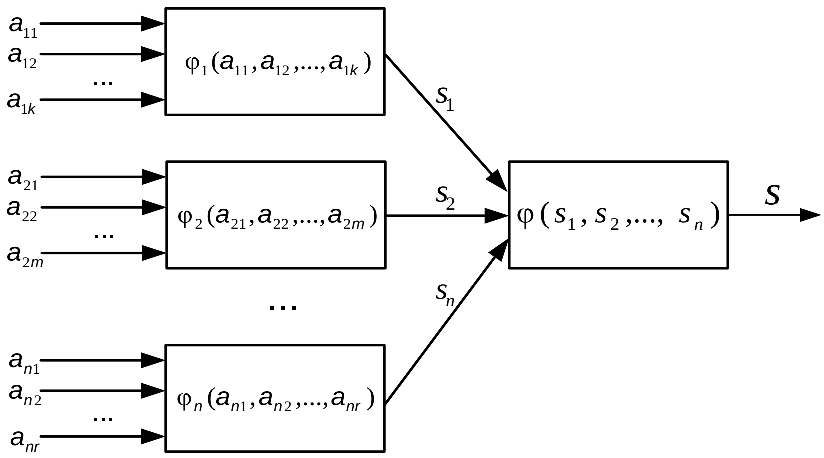

Fig.3. Two-level fuzzy model for the hydrogenerator TS appreciation

At the fig.3: a_{ij} – input sign j of hydrogenerator bundle i; φ_i – fuzzy function of hydrogenerator bundle i TS appreciation; s_i – TS of hydrogenerator bundle i; φ – fuzzy function of hydrogenerator total TS appreciation, s – hydrogenerator total TS.

Such two-level structure could be used by appreciation the TS of particular bundles, for example stator winding. There are next requirements to the fuzzy model of stator winding TS appreciation [7]:

- the inclusion of all its regime stuffs (electrical, temperature, vibration);
- using as the input values such parameters, which could be measured without switching off the generator;
- adaptability of model to the additional input information.

At the first level of model appreciation of hydrogenerator regime stuffs is performed. At the second level – the total TS stator winding appreciation. Essence of such approach lies in that, which output parameters of first level, is the input parameters of second level. This is allowed to obtain complex bundle TS appreciation.

As input parameters of the first level of fuzzy model are taken next values:

- copper temperature (t_C°);
- iron temperature (t_I°);
- cooling air temperature (t_A°);
- vibrovelocity (v);
- vibroacceleration (a);
- stator current (I_S);
- zero sequence voltage ($3U_0$).

Output parameters of the first level and the input parameters of the second level are the next characteristics:

- temperature stuff (S_T);
- vibration stuff (S_V);
- electrical stuff (S_E).

Output parameter of the second level and whole model is the total stuff of stator winding (*S*). Values S_T, S_V, S_E measured in the limits [0;1] and represent the quantity characteristic of total residual resource of stator winding. Structural scheme of this fuzzy model is shown at the fig.4.

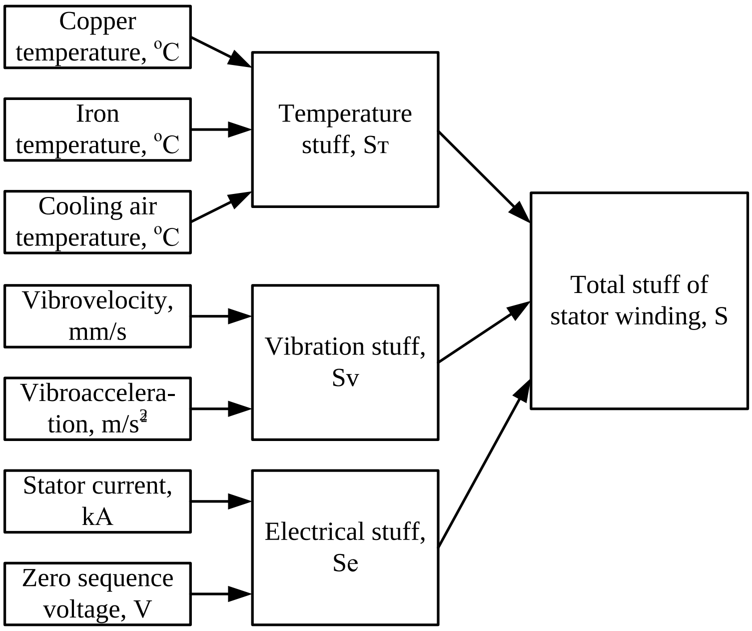

Fig.4. Structural scheme of the fuzzy model for the stator winding TS appreciation

For the realized the fuzzy output in this model is used Mamdani type algorithm [8] for the forming of rule base in the conditions of absence the mathematical dependence among diagnostic parameters and between input and output values. Fuzzy output is the approximation of dependency between input and output parameters by linguistic equations “IF-THEN” type and max-min composition. Definition of the quantities of output values is run by defuzzyfication. Defuzzyfication procedure done by centroid method [8]:

$$s = \frac{\int_{s_1}^{s_2} s \cdot \mu(s) \cdot ds}{\int_{s_1}^{s_2} \mu(s) \cdot ds}. \quad (10)$$

For the using the choosing parameters in the appreciation of stator winding total TS by fuzzy model, next input linguistic variables with corresponding terms are used:

- A = «Copper temperature»: A_1 = «Normal», A_2 = «High»;
- B = «Iron temperature»: B_1 = «Normal», B_2 = «High»;
- C = «Cooling air temperature»: C_1 = «Normal», C_2 = «High»;
- D = «Vibrovelocity»: D_1 = «Satisfactory», D_2 = «Unsatisfactory»;
- E = «Vibroacceleration»: E_1 = «Satisfactory», E_2 = «Unsatisfactory»;
- F = «Stator current»: F_1 = «Valid», F_2 = «Invalid»;
- G = «Zero sequence voltage»: G_1 = «Valid», G_2 = «Invalid».

Output sets of stator winding local stuffs have such names:

- S_T = «Temperature stuff of stator winding»;
- S_V = «Vibration stuff of stator winding»;
- S_E = «Electrical stuff of stator winding».

Each output value includes three fuzzy terms: G = «Good», M = «Middle», B = «Bad».

Output set *S* is described by linguistic variable «Total stuff of stator winding», which consists of five terms: VG = «Very good»; G = «Good»; M = «Middle»; B = «Bad»; VB = «Very bad».

For the building the fuzzy terms membership functions (MF) expert estimations are used. For this aim made the pall of 5 experts from Dnipro-1 HPS. Results of pall are presented in the table 1.

Table 1. Expert estimations

A = «Copper temperature»						
t_c°, ^{0}C	50	60	70	80	90	100
A_1 = «Normal»	5	5	4	2	0	0
A_2 = «High»	0	0	1	3	5	5
B = «Iron temperature»						
t_I°, ^{0}C	50	60	70	80	90	100
B_1= «Normal»	5	4	2	0	0	0
B_2= «High»	0	1	3	5	5	5
C = «Cooling air temperature»						
t_A°, ^{0}C	50	60	70	80	90	100
C_1= «Normal»	4	2	1	0	0	0
C_2= «High»	1	3	4	5	5	5
D = «Vibrovelocity»						
v , mm/s	2,5	5	7,5	10	12,5	15
D_1 = «Satisfactory»	5	3	0	0	0	0
D_2 = «Unsatisfactory»	0	2	5	5	5	5
E = «Vibroacceleration»						
a , m/s^2	1	2	3	4	5	6
E_1 = «Satisfactory»	5	5	4	2	0	0
E_2 = «Unsatisfactory»	0	0	1	3	5	5
F = «Stator current»						
I_s , kA	5,5	5,6	5,7	5,8	5,9	6,0
F_1 = «Valid»	5	5	4	2	0	0
F_2 = «Invalid»	0	0	1	3	5	5
G = «Zero sequence voltage»						
$3U_0$, V	1	2	3	4	5	6
G_1 = «Valid»	5	4	3	1	5	5
G_2 = «Invalid»	0	1	2	4	0	0

MF of input values was built by the Saaty method [5]. Obtained MF of input values are presented at the fig.5 – fig.11.

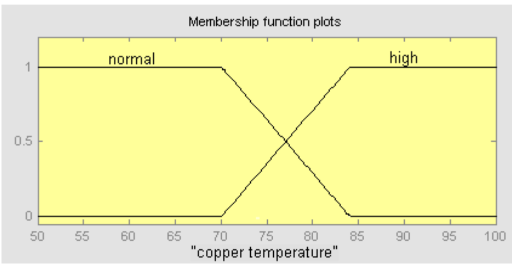

Fig.5. Input MF «Copper temperature»

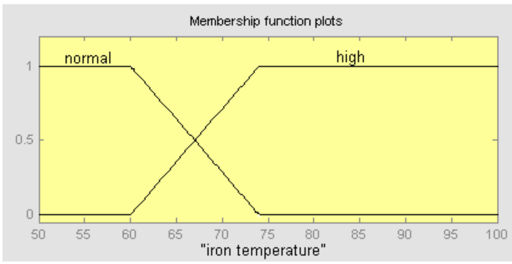

Fig.6. Input MF «Iron temperature»

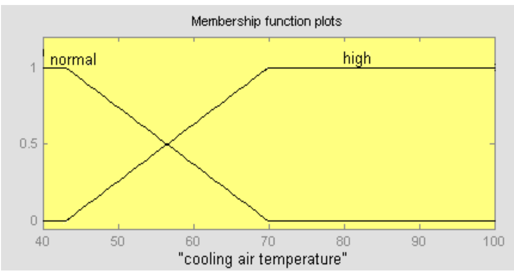

Fig.7. Input MF «Cooling air temperature»

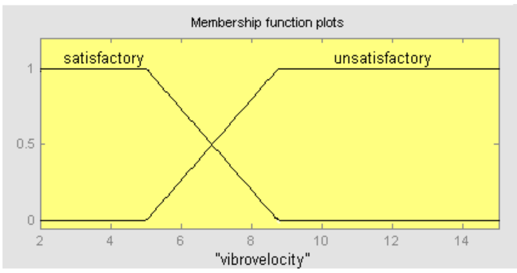

Fig.8. Input MF «Vibrovelocity»

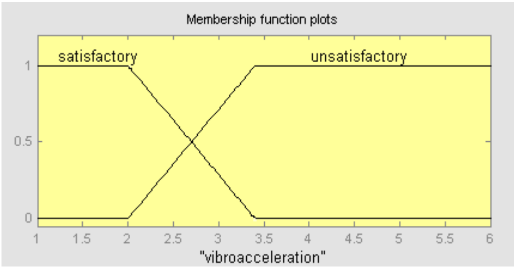

Fig.9. Input MF «Vibroacceleration»

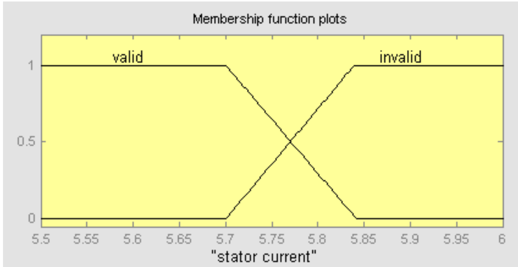

Fig.10. Input MF «Stator current»

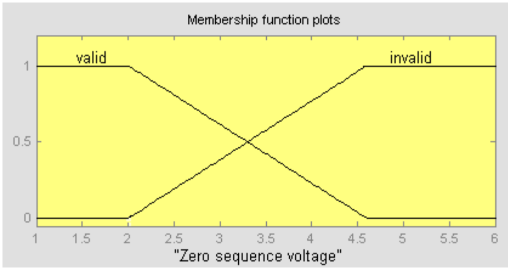

Fig.11. Input MF «Zero sequence voltage»

MF of output values was built at the Harrington scale intervals [4]. Obtained MF of output values are presented at the fig.12, fig.13.

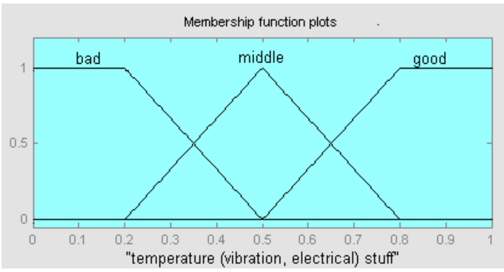

Fig.12. Output MF «Temp. (vibr., electr.) stuff»

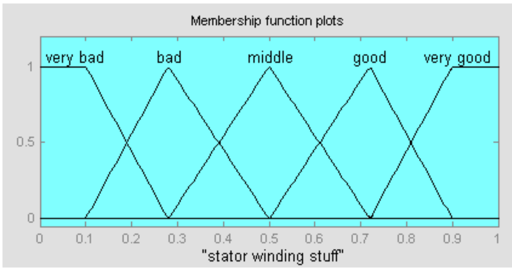

Fig.13. Output MF «Stator winding stuff»

Rule bases of both model levels formed according to the expert knowledge about the characteristics and processes, which take place into the hydrogenerator stator winding. Rule bases of first level are presented at the table 2. Rule base of second level is presented in the table 3.

Table 2. Rule bases of local stuffs

Temperature stuff								Vibration stuff			Electrical stuff		
$C=C_1$	A \ B	A_1	A_2	$C=C_2$	A \ B	A_1	A_2	D \ E	D_1	D_2	F \ G	F_1	F_2
	B_1	G	M		B_1	M	B	E_1	G	M	G_1	G	M
	B_2	M	B		B_2	B	B	E_2	M	B	G_2	M	B

Table 3. Rule base of total stuff

Se = «G»				Se = «M»				Se = «B»			
S_V \ S_T	G	M	B	S_V \ S_T	G	M	B	S_B \ S_T	G	M	B
G	VG	G	B	G	G	M	B	G	M	B	B
M	G	M	B	M	M	M	B	M	B	B	VB
B	B	B	VB	B	B	B	VB	B	B	VB	VB

EXAMPLE

As example, in article was completed the estimation of fault probabilities and risks of Dnipro-2 HPS generators due to its stator windings damages at the time interval $\Delta t = 1$ year. Electrical scheme of Dnipro-2 HPS are shown at the fig.14.

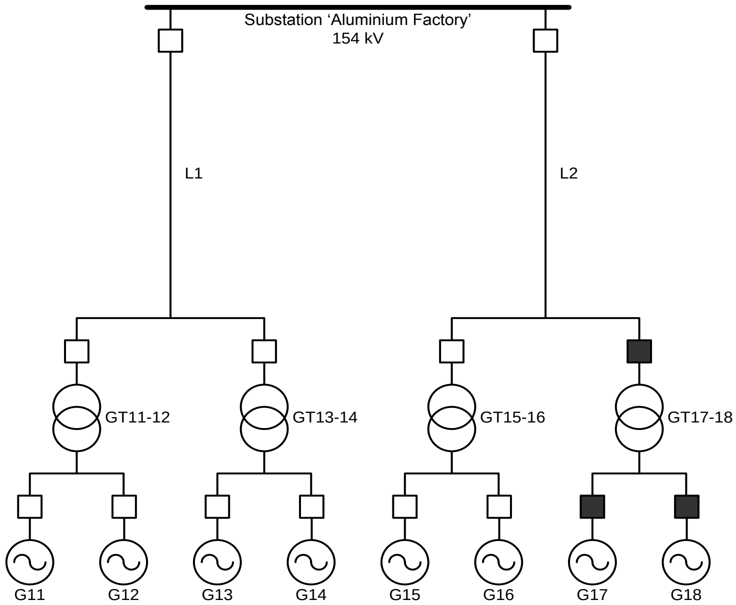

Fig.14. Electrical scheme of Dnipro-2 HPS

By the developed fuzzy model is performed the estimation of generators G11-G16 stator windings TS. Generators G17 and G18 are withdrawn from exploitation due to replacement the transformer GT17-18. For the estimation of G11-G16 stator windings TS were fulfilled the measurements of generator regime parameters and represented in the table 4.

Table 4. Regime parameters of generators

№	t°_{C},	t°_{I},	t°_{A},	v,	a,	I_S, kA	$3U_0$, V B
G11	72	66	47	5,2	2,8	5,707	2,1
G12	80	75	51	6,9	4,1	5,796	2,8
G13	75	71	54	6,1	3,3	5,645	1,6
G14	79	71	52	5,9	3,3	5,852	2,2
G15	81	70	50	5,5	3,1	5,761	2,2
G16	82	68	55	7,2	3,8	5,934	1,9

Results of the generators G11-G16 TS appreciation are represented in the table 5.

Table 5. Local stuffs and total stuff estimation

№	S_T	S_V	S_E	S
G11	0,613	0,771	0,6	0,628
G12	0,293	0,494	0,348	0,333
G13	0,451	0,817	0,433	0,453
G14	0,386	0,479	0,449	0,424
G15	0,363	0,636	0,518	0,429
G16	0,382	0,5	0,322	0,332

The matrixes R_P and R_Q were formed by the Saaty method. According to the obtained total stuffs S, at the Harrington scale intervals were obtained vectors $\overline{S}$ of TS. According to composition Zadeh rule were obtained conditional probabilities $p(B/H_1)$ and $p(B/H_2)$. By the statistical function $F(t)$ were defined values $F(t_1)$ and $F(t_2)$ (for G11-G13 $t_1 = 39$ years, $t_2 = t_1 + \Delta t = 40$ years; for G14-G16 $t_1 = 38$ years, $t_2 = t_1 + \Delta t = 39$ years) and defined apriority probabilities $p(H_1)$ and $p(H_2)$ according to the equations (4), (5). By the Bayes formula (3) were calculated generators G11-G16 fault probabilities due to the stator winding damage at the time interval $\Delta t = 1$ year. Obtained results are represented in the table 6.

Table 6. Generators G11-G16 probabilities of fault

№	S	$p(B/H_1)$	$p(B/H_2)$	$p(H_1)$	$p(H_2)$	$p(H_1/B)$
G11	0,628	0,264	0,734	0,055	0,945	0,021
G12	0,333	0,736	0,26	0,055	0,945	0,139
G13	0,453	0,508	0,482	0,055	0,945	0,058
G14	0,424	0,52	0,473	0,047	0,953	0,051
G15	0,429	0,519	0,473	0,047	0,953	0,051
G16	0,332	0,736	0,26	0,047	0,953	0,124

Below is a total example of calculations for generator G12. Fuzzy modeling of hydrogenerator stator winding was completed in MATLAB Simulink and shown at the fig.15.

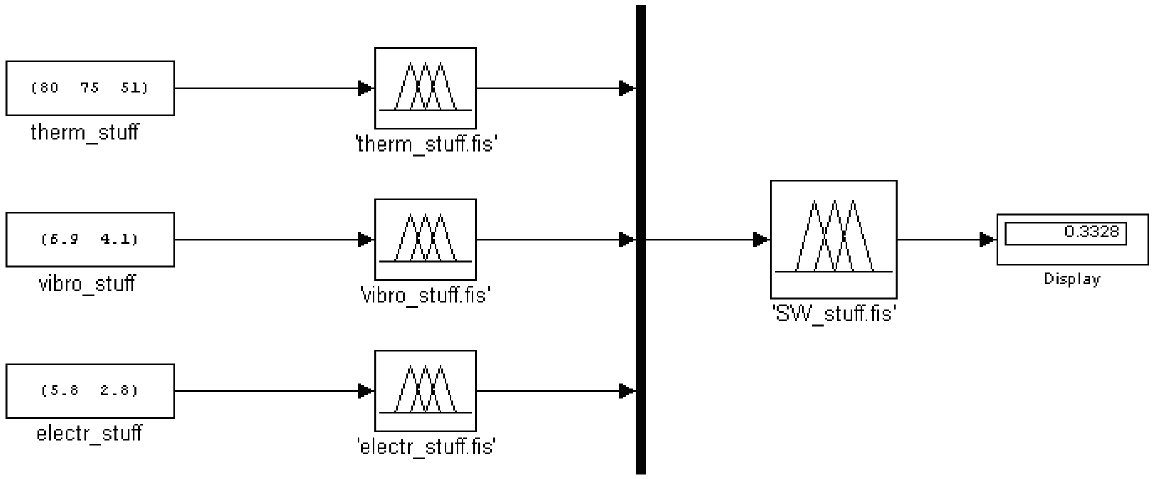

Fig.15. Fuzzy modeling of hydrogenerator stator winding

According to the equations (6), (7) for the generator G12 were obtained the output vectors of alternatives P and Q :

$$P = R_P \circ S = \begin{bmatrix} 0,401 & 0,307 & 0,032 & 0,036 & 0,038 \\ 0,270 & 0,409 & 0,165 & 0,090 & 0,069 \\ 0,202 & 0,187 & 0,437 & 0,203 & 0,165 \\ 0,098 & 0,063 & 0,283 & 0,475 & 0,293 \\ 0,029 & 0,034 & 0,083 & 0,196 & 0,435 \end{bmatrix} \circ \begin{bmatrix} 0 \\ 0,759 \\ 0,241 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0,307 \\ 0,409 \\ 0,241 \\ 0,241 \\ 0,083 \end{bmatrix}, \qquad (11)$$

$$Q = R_Q \circ S = \begin{bmatrix} 0{,}037 & 0{,}031 & 0{,}033 & 0{,}194 & 0{,}471 \\ 0{,}067 & 0{,}080 & 0{,}193 & 0{,}529 & 0{,}265 \\ 0{,}155 & 0{,}236 & 0{,}521 & 0{,}164 & 0{,}148 \\ 0{,}283 & 0{,}357 & 0{,}187 & 0{,}075 & 0{,}076 \\ 0{,}457 & 0{,}296 & 0{,}065 & 0{,}039 & 0{,}040 \end{bmatrix} \circ \begin{bmatrix} 0 \\ 0{,}759 \\ 0{,}241 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0{,}033 \\ 0{,}193 \\ 0{,}236 \\ 0{,}357 \\ 0{,}296 \end{bmatrix}. \quad (12)$$

According to the equations (8), (9) were calculated the conditional probabilities $p(B/H_1)$ and $p(B/H_2)$:

$$p(B/H_1) = y_{P\max} - \frac{\sum_{j=1}^{n} p_j \cdot y_j}{\sum_{j=1}^{n} p_j} \cdot (y_{P\max} - y_{P\min}) = 0{,}8 - 0{,}403 \cdot (0{,}8 - 0{,}64) = 0{,}736, \quad (13)$$

$$p(B/H_2) = y_{Q\max} - \frac{\sum_{j=1}^{n} q_j \cdot y_j}{\sum_{j=1}^{n} q_j} \cdot (y_{Q\max} - y_{Q\min}) = 0{,}36 - 0{,}623 \cdot (0{,}36 - 0{,}2) = 0{,}26. \quad (14)$$

By the equations (4) та (5) were calculated the probabilities $p(H_1)$ and $p(H_2)$:

$$p(H_1) = \frac{F(40) - F(39)}{1 - F(39)} = \frac{0{,}828 - 0{,}818}{1 - 0{,}818} = 0{,}055, \quad (15)$$

$$p(H_2) = 1 - p(H_1) = 1 - 0{,}055 = 0{,}945. \quad (16)$$

By the equation (3) was defined the probability of generator G12 fault at the time interval $\Delta t = 1$ year due to the damage of stator winding:

$$p(H_1/B) = \frac{p(H_1) \cdot p(B/H_1)}{p(H_1) \cdot p(B/H_1) + p(H_2) \cdot p(B/H_2)} = \frac{0{,}055 \cdot 0{,}736}{0{,}055 \cdot 0{,}736 + 0{,}945 \cdot 0{,}26} = 0{,}139. \quad (17)$$

For the risk estimation it is necessary to know the damage cost from generator fault. Damage costs *У* and risks *R* from G11-G16 faults were calculated according to the equation (1). The results are represented in the table 7.

Table 7. Estimation of damage costs and risks of G11-G16 faults

№	P_n, MW	T_{rep}, hours	c, €/kW·hours	*У*, €	$p(H_1/B)$	*R*, €
G11	104,5	50	0,02	104500	0,021	2194,5
G12	104,5	50	0,02	104500	0,139	14525,5
G13	113,1	50	0,02	113100	0,058	6559,8
G14	113,1	50	0,02	113100	0,051	5768,1
G15	113,1	50	0,02	113100	0,051	5768,1
G16	113,1	50	0,02	113100	0,124	14024,4

Total risk of Dnipro-2 HPS generators fault at the time interval $\Delta t = 1$ year due to the damage of stator winding comprises:

$$R = \sum_{i=1}^{6} p_i(H_1/B) \cdot Y_i = \sum_{i=1}^{6} R_i = 48840{,}4 \text{ €}. \quad (18)$$

Obtained value is the input information for the implementation of Risk-Oriented Management of HPS and adoption of effective solutions about the increasing of generating equipment reliability.

V. CONCLUSION

The risk application for the appreciating of HPS generating equipment reliability allows simultaneously considering causes and consequences of equipment faults and gives the possibility of organization the effective Risk-Oriented Management of HPS for the increasing its exploitation and regime reliability. In article is proposed the method of generator fault risk estimation with taking into account its TS. In article are obtained the next results:

1) Fuzzy-statistical model for the generator fault probability appreciation is proposed. This model can be used both for complex appreciation of generator fault probability and for appreciation of local generator bundle fault. This model using the statistical function of hydrogenerators faults distribution $F(t)$, which has been modified at the time interval for each generator due to its TS.
2) Approach to the hydrogenerator and their bundles TS appreciation fuzzy model building is determined. This approach is realized in the fuzzy model for the stator winding TS appreciation. Developed model takes into consideration temperature, vibration and electrical stuff of generator stator winding, that gives the opportunity to obtain verify complex estimation of stator winding TS in the conditions of absence the mathematical dependence among the diagnostic parameters.
3) Future development of this research lies in developing of fuzzy-statistical approach to the estimation of damage costs from generator fault and in creating fuzzy models of other generator bundles. This development gives the possibility of more verify appreciation both probability component and damage cost component, and, as a result, to improve Risk-Oriented Management of HPS generating equipment.

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