An expert system for diagnostics and estimation of steam turbine components condition

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Abstract. The report describes an expert system of probability type for diagnostics and state estimation of steam turbine technological subsystems components. The expert system is based on Bayes' theorem and permits to troubleshoot the equipment components, using expert experience, when there is a lack of baseline information on the indicators of turbine operation. Within a unified approach the expert system solves the problems of diagnosing the flow steam path of the turbine, bearings, thermal expansion system, regulatory system, condensing unit, the systems of regenerative feed-water and hot water heating. The knowledge base of the expert system for turbine unit rotors and bearings contains a description of 34 defects and of 104 related diagnostic features that cause a change in its vibration state. The knowledge base for the condensing unit contains 12 hypotheses and 15 evidence (indications); the procedures are also designated for 20 state parameters estimation. Similar knowledge base containing the diagnostic features and faults hypotheses are formulated for other technological subsystems of turbine unit. With the necessary initial information available a number of problems can be solved within the expert system for various technological subsystems of steam turbine unit: for steam flow path it is the correlation and regression analysis of multifactor relationship between the vibration parameters variations and the regime parameters; for system of thermal expansions it is the evaluation of force acting on the longitudinal keys depending on the temperature state of the turbine cylinder; for condensing unit it is the evaluation of separate effect of the heat exchange surface contamination and of the presence of air in condenser steam space on condenser thermal efficiency performance, as well as the evaluation of term for condenser cleaning and for tube system replacement and so forth. With a lack of initial information the expert system enables to formulate a diagnosis, calculating the probability of faults hypotheses, given the degree of the expert confidence in estimation of turbine components operation parameters.

Expert systems are very advantageous for steam turbine units (STU) diagnosis. These systems are designed to solve problems that are difficult to formalize. The expert system is based on Bayes' theorem and permits to troubleshoot the equipment components when there is a lack of baseline information on the indicators of turbine unit operation. The system also employs the experience of experts. The inaccuracy and lack of initial information is taken into account by probabilistic methods using Bayes' formula. The value of each evidence is determined by C. Naylor method [1-4].

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An expert system comprises a knowledge base and an information processing algorithm. The knowledge base contains information about STU failures as fault hypotheses and a table of evidence. The a priori probability of fault hypotheses and the evidence value are determined by the experts. The expert system analyzes the evidence. If information is missing, the system receives it from a user or out of a database. The user sets the values of evidence and expert system calculates a posteriori probabilities of hypotheses and forms a conclusion about the cause of failure. The system then makes recommendations to the staff about how to eliminate the malfunction.
According to Bayes' theorem [1], a posteriori probability of the hypothesis is calculated by the formula:

$$P(H/E) = \frac{P(E/H) \cdot P(H)}{P(E)}, \quad (1)$$

here P(E/H) is the probability of evidence E, if the hypotheses H is true;
P(H) stands for a priori probability of the hypotheses H; P(E) stands for the probability of evidence E.
P(E) is determined by the formula of total probability

$$P(E) = P(E/H)\cdot P(H) + P(E/\overline{H})\cdot P(\overline{H}), \quad (2)$$

here $P(E/\overline{H})$ is the probability of evidence E, if the hypotheses H is false;
$P(\overline{H}) = 1 - P(H)$.
From (1) and (2) a posteriori probability of the hypothesis is calculated

$$P(H/E) = \frac{P(E/H)\cdot P(H)}{P(E/H)\cdot P(H) + P(E/\overline{H})\cdot P(\overline{H})}. \quad (3)$$

The expert system comprises the knowledge bases designed for turbine flow part, for turbine bearings, for system of thermal expansions, for automatic regulatory system, for condensing unit, for the systems of regenerative feed-water heating and hot water heating. The knowledge bases of the expert system for turbine rotors, bearings and other components of turbine unit contain a description of 34 defects and 104 diagnostic features. These defects cause a change of vibration state of the turbine unit. All defects are divided into two groups: defects that occur during the turbine operation and defects added during turbine mounting and repair.
The defects of turbine unit mounting and repair are identified in the analysis of start-stop actions. The defects of operation are revealed in the analysis of turbine components vibration, vibration changes or the relationship of vibration to the turbine operation.
A number of connections are used to diagnose the system of steam distribution and turbine regulatory system (see Table 1). On the basis of these relationships the parameters of Table 2 are calculated.

Table 1

Parametric relationships generated in the diagnosis of the turbine automatic regulatory system (TAR)

№	Name
1	Turbine steam flow rate — setting of high pressure part servomotor
2	Turbine steam flow rate — turbine capacity
3	Settings of high (medium) pressure control valves — settings of high (medium) pressure part servomotor
4	Steam pressure beyond the valves of high (medium) pressure part — settings of high (medium) pressure part servomotor
5	Force of high (medium, low) pressure part servomotor — settings of high (medium, low) pressure part servomotor
7	Force of medium (low) pressure part servomotor — steam pressure in a chamber of process or heating steam extraction

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8	Steam pressure in control stage (or 1-st stage) chamber — settings of high pressure part servomotor
9	Steam pressure in control stage (or 1-st stage) chamber — turbine steam flow rate
10	Settings of steam stop valve autoactuators — oil pressure above the autoactuators slide valves
11	Settings of steam stop valve autoactuators — oil pressure below the autoactuators slide valves

When diagnosing turbine regulatory systems the expert system also makes use of the dynamic response of the actuators — servomotors and slide valves.

Table 2

Main features for diagnostics and adjustment of the turbine automatic regulatory system (TAR)

№	Feature name	Electrohydraulic system of regulation and protection characteristic, determined from the recorded dependencies
1	Static characteristic of rotation speed control (RS)	Degree of frequency response variations (FR)
		Degree of frequency regulation insensitivity
		Areas and values of the local non-uniformity of frequency regulation
2	Cam-operated steam distribution device (CSD) and nozzle unit performances	CSD technical condition
		Quality of the control valve setting adjustment
		Nozzle unit condition
		Flow part condition (salt fouling)
3	Force margins of regulatory system servomotors	Identification of unstable operation areas of automatic regulatory system
		Regulation units lock detection
		Turbine regime optimization
4	Performances of steam stop valve autoactuators	Technical condition of steam stop (safety) valves autoactuators
		Insensitivity of steam stop (safety) valves autoactuators

To diagnose steam turbine subsystem parts the expert system employs various approaches, such as:
for turbine flow part — a correlation and regression analysis of the multi-factor relationship between vibration and regime parameters;
for thermal expansion system — the evaluation of forces acting on longitudinal keys under different temperatures of the left and right sides of turbine cylinder;
for condensing unit — the estimation of the effect of cooling surface fouling as well as of air content in condenser steam chamber on condenser efficiency; optimization of condenser cleaning period; justification of periods of condenser tube system replacement, etc.
The algorithms are presented below of the data analysis for defects causing the vibration. The indications of these defects are divided as follows:

boundary group where the defect indications are determined by a measured parameter fall outside the normalized limits;
factorial group where the defect indications are determined by an occurrence of a previously unobserved factor;
correlation group where the defect indications are determined by a connection between the vibration and technologic parameters.
Boundary indications are determined by a measured parameter fall outside the permissible limits that is beyond the zone of partial or full serviceability. As a rule, the boundaries of these zones are designated in the regulations.
Factor indications are characterized by a qualitative change in vibration parameters, for example, by the rise of rotational component of vibration in vertical or transverse direction or vibration components with frequency of 2w, 3w, 4w and so on, by abrupt increase in high frequency harmonics; by the emergence of new frequencies in the turbine unit vibration spectrum: frequencies from 500 to 2000 Hz) point to leakage in regulatory system while frequencies of 1000 — 1050 Hz point to backlash in control valves.
For the correlation indications a change is estimated in the coefficient of correlation between the vibration characteristics and technologic process parameters.
The expert system functioning can be described taking steam turbine condensing unit as an example [5-6].
A knowledge base for the condensing unit contains more than 30 hypotheses and 25 evidence (or indications); estimation procedures for 20 parameters of state are also specified. Tables 3 and 4 show a sample from the knowledge base.
Preliminary list of malfunction hypothesis is set up on the basis of performed investigations, statistical processing of data on equipment damage and literature data. After expert examination the final list of hypotheses is filled in the knowledge base.

Table 3

Hypotheses of condenser unit (CU) equipment malfunction

CU equipment	Malfunction hypotheses
Condenser	Tube plates fouling
	Overpressure in the drain pipe
	Deterioration of siphon rarefaction
	Cooling surface fouling on the steam side
	Cooling surface fouling on the water side
	Elevated quantity of induced air
	Incomplete opening of the drain valve
	Elevated hydraulic resistance in the pressure line
	Condensate flooding on lower tube rows
	Level regulator fault
	Cooling water suction in the steam space
	Air suction between the condenser and condensate removal pump
	Water leakage from water ejector into condenser
	Improper organization of various streams discharge into condenser
Steam jet ejector	Steam grates or working nozzle clogging
	Inadequate flow rate of the full-flow condensate entering the ejector cooler
	Cooler heat transfer surface fouling on the water side
	Cooler heat transfer surface fouling on the steam side

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CU equipment	Malfunction hypotheses
	Steam-air mixture recirculation through one of the ejector stages
	Leaks in the partitions separating the coolers
	Airmeter or the exhaust pipe clogging
	High temperature of the full-flow condensate
	Dead air zones occurence in the drain pipe
	Leakage in ejector cooler
	Reduced heat exchange surface of the ejector cooler
Circulation path (geodesic height)	Changes in the hydraulic regime of water reservoir
	Skid of coarse gratings with aquatic vegetation and debris
	Significant fouling of rotating grates due to late cleaning or to washing device malfunction
	Accumulation of air released by heating water
	Incomplete opening of the drain valve
	Water level lowering in the admission chamber

The evidence list is being set up during the condenser unit operation. We analyze the measurement circuit, the results of the condenser unit tests, operation regimes, maintenance logs.

Table 4

Evidence of CU equipment malfunction

CU equipment	Malfunction evidence
Condenser	High water heating
	High steam pressure at the condenser inlet
	Low flow rate of cooling water
	High cooling water pressure at the condenser inlet
	Increased temperature difference between steam and cooling water outlet
	Oxygen presence in the full-flow condensate
	Condensate overcooling $(t_c - t_s) < 0$
	High pressure in the cooling water drain pipes
	Low cooling water pressure at the condenser inlet
	Low pressure in the pressure line of the circulation pump
	High condensate hardness
	Exhaust steam pressure is above the standard (low vacuum)
	High hydraulic resistance of the condeser
	High condensate level in the condenser
Steam jet ejector	Pressure pulsations of steam-air mixture at the ejector inlet and discharge
	Low pressure in the pipeline upstream of the ejector
	High pressure of the working steam upstream of the ejector
	Increased working steam flow rate
	The sharp increase of the pressure in the suction chamber of the ejector when the exhaust air flow is within the range corresponding to the design part of ejector performance
	A number of ejector cooler tubes are gagged

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CU equipment	Malfunction evidence
	High back pressure beyond the last stage of the ejector
	Water ejection from the exhaust
	Inlet pressure pulsations at the 2-nd and 3-rd ejector stages
	High pressure at the ejector suction
Circulation path	Unsatisfactory performance of the drain water siphon

Then a priori probabilities of the hypotheses and evidence probabilities are entered in the table of probabilities. In addition, evidence probabilities are entered to detect the fault (to confirm the hypothesis) and not to detect the fault (reject the hypothesis). These probabilities are specified for each evidence. In the first case, the evidence probability is denoted by the superscript (+), in the second case — by the superscript (–). Table 5 shows an example of probabilities table for 4 hypotheses and 3 evidence.

Table 5

A sample of the probability table

№	Hypothesis	A priori probabilities	Evidence probability for detection (non-detection) of failure (hypothesis)					
			1^+	1^-	2^+	2^-	3^+	3^-
1	Condenser tube plates fouling	0,5	0,8	0,2	0,005	0,005	0,5	0,005
2	Overpressure in the drain pipe	0,5	0,8	0,2	0,05	0,05	0,5	0,05
3	Deterioration of siphon rarefaction	0,6	0,1	0,05	0,05	0,1	0,05	0,2
4	Elevated quantity of induced air	0,7	0,05	0,05	0,7	0,05	0,7	0,05

Malfunctions evidence listed in Table 5:

1. High water heating;
2. Temperature difference between steam and cooling water outlet exceeds the norm;
3. Condenser pressure exceeds the norm.

For hypotheses there are also evaluated the values of the maximal and minimal probability. This permits to form a justified diagnosis for limiting values of probabilities.

During the expert system function it analyzes the equipment operation parameters and then, if there is a lack of information, it asks the user a series of questions to make the information more precise.

Fig. shows the form for evidence processing. The users click the buttons "Yes" or "No" and so indicate

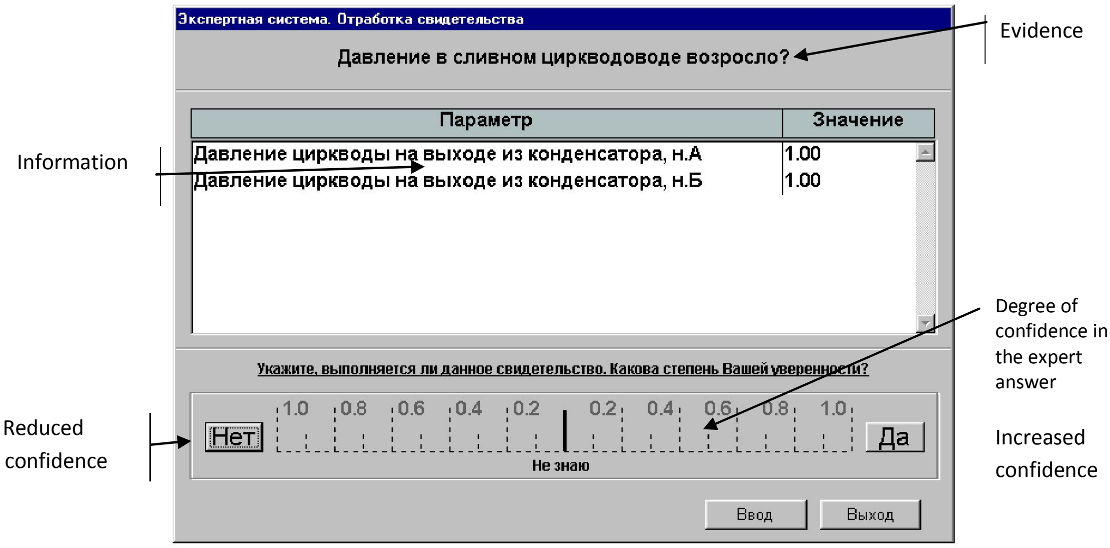

Fig. Evidence processing

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the degree of confidence in their answer to the question. The program corrects the a posteriori probabilities of the hypotheses taking into consideration the degree of confidence in the user answers.
The number of such questions corresponds to the number of evidence in the database of the expert system leaving the evidence already processed out.

Conclusions

The expert system of probability type is presented for diagnostics and state estimation of steam turbine technological subsystems components. The knowledge base is made up for rotors, bearings, turbine automatic control and protection system and for other components of the turbine unit, condensing unit equipment and other technological subsystems.
The expert system permits to diagnose the condition of various subsystems and components of the turbine unit, to troubleshoot the equipment components and to formulate recommendations about the ways and terms of defect elimination and of reduction the risk of their development. To do this the system employs the experience of experts. Information from the expert system can be used to adjust the turbine operation regimes and to optimize the amount and timing of equipment repair.

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