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Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100^{th} Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 263-282

J. KUBIAK[a*], F. SIERRA[a], A. GARCÍA-GUTIÉRREZ[b], G. URQUIZA[c] and G. GONZÁLEZ[a]

Algorithms and expert system for the diagnosis of faults for steam, gas turbines and compressors

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Abstract

The main objective of this paper is to present the algorithms and expert systems for identification of faults which reduce the efficiency of the steam and gas turbines and compressors. The output capacity of power plants is reduced in many cases, and sometimes forced to outages, when its main components are affected by faults. i.e. normally, the overall reduction of the efficiency, and sometimes the component efficiencies, are monitored but it still is difficult to identify the primary causes of the fault of the specific equipment that causes the reduction of plant efficiency [1]. Therefore, to reduce the time of faulty operation, a precise diagnostic tool is needed. One such tool can be an algorithm of the fault identification which can be easily coded into an expert system approach, which is presented in this work. The faults which reduce the plant efficiency in many cases also increase the vibrations of the rotor- bearing system. Based on experience and knowledge, the various algorithms have been constructed and their corresponding expert systems developed for steam turbines, gas turbines and compressors. Knowledge levels and the separate data bases are also built into the system. Several procedures of losses quantification are given and two examples of application are presented.

Keywords: Expert system; Diagnosis; Turbines; Compressors, Efficiency; Wearing out of seals & blades; Rubbing

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Nomenclature

A	–	area
C_p	–	specific heat at constant pressure
g	–	gravity
h	–	enthalpy
H	–	heat rate
HRSG	–	heat Recovery Steam Generator
k	–	isentropic exponent
M	–	mass flow rate
p	–	pressure
P	–	output capacity (power)
Q	–	heat
T	–	temperature
W_d	–	gas heat value

Greek Symbols

Δ	–	increment
η	–	efficiency
η_{cycle}	–	cycle efficiency
γ	–	fluid specific gravity

Subscripts

1	–	inlet
C	–	compressor
CC	–	combustion chamber
IP	–	intermediate pressure turbine
HP	–	high pressure turbine
LP	–	low pressure turbine
$Mech$	–	mechanical
P	–	pump
o	–	isentropic point
RC	–	hot reheat
t	–	turbine
T	–	temperature
TG	–	gas turbine
$valve$	–	valve
$x-o$	–	cross-over pipe
1	–	before the compressor
2	–	after the compressor
3	–	before the gas turbine
4	–	after the gas turbine
1_{st}	–	first stage
2_{nd}	–	second stage

1 Introduction

In the next decade, the number of combined cycle plants, for electricity generation will considerably increase, because of it's attractive efficiency, reaching 60%. Of course, this will depend on availability of the gas and its cost as well. On the other hand, there is no tendency to construct power plants based on large steam turbines. On the contrary, gas turbine capacities are greater than those of steam turbines, reaching 500 MW per unit. It is known that about 65% (2/3) of the gas turbine capacity is used for driving the compressor. Also, the efficiency of the gas turbine cycle is very sensitive to any reductions in efficiency of its components, especially the gas turbine and compressor.

If two thirds of the gas turbine output capacity is used to drive the compressor, then a 1% decrease in gas turbine efficiency causes a drop of 3% in the efficiency of the gas turbine cycle. On the contrary, a drop of 1% in the compressor efficiency affects the cycle efficiency by 2%. Furthermore, the cycle efficiency depends on the temperature ratio between the turbine and compressor, the pressure ratio and the combustion chamber efficiency. The faults, which affect the steam turbine, are solid particle erosion of the nozzle, Fig. 1, seal wearing out, deposits and blade surface roughness. The most common faults which affect the turbo compressor [1,2] are: fouling of the compressor, Fig. 2; deposits on the turbine blading systems, wearing out of blade tips and wearing out of the seals, among others. All these faults affect considerably the efficiency of components and thus, affect the cycle efficiency. Moreover, only the faults that cause their decrement should be identified, possibly by using only the parameters measured with standard instrumentation. Having measured the pressure, temperature, mass flow rate and analyzing the vibration of the rotating equipment, it is possible to indicate any fault that decreases the efficiency of each piece of turbines and compressors, and to estimate its numerical values.

The main objective of this paper is to present the development of the algorithms and expert system for identification of the faults which affect turbine and compressors in power plants.

2 Turbines and compressors efficiency and losses quantification formulas

First of all, the efficiency of the whole plant and its various components must be defined, and the data to be measured must be specified before proceeding with the analysis.

In the case of the combined cycle plant the following parameters should be measured:

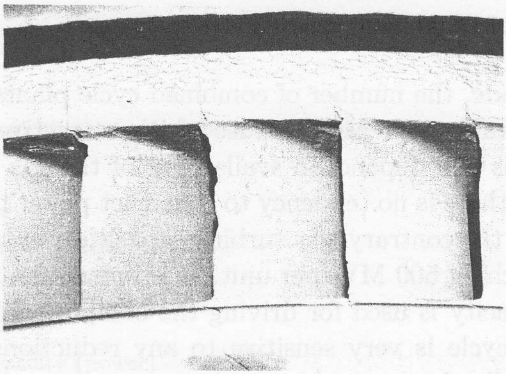

Figure 1. Solid-particle erosion of the first stage nozzles.

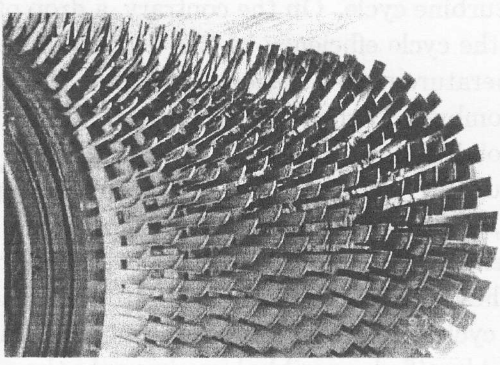

Figure 2. Fouling on the compressor blading system.

- mass flow rate of air, gas, and steam,
- flow of cooling water,
- pressure and temperature of air before and after the compressor,
- temperature of combustion gases from the turbine,
- pressures,
- power output of the generators,
- vibration analysis of the steam and gas turbine,
- temperature of the first row of moving blades of the gas turbine if possible.

Also, the reference data should be stored. The reference data means the same parameters, which were measured during the commissioning test, and moreover simulated data like efficiencies and output capacities with observed losses of the

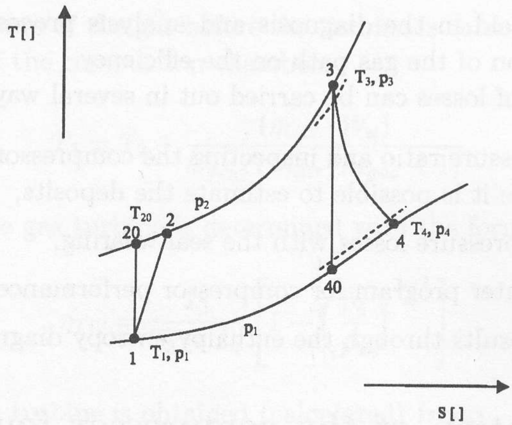

Figure 3. $T - S$ diagram of the TG Cycle.

gas [2] and steam turbine [3] should be measured. In order to perform a reliable diagnosis, a comparison between the actual and reference data should be carried out in the same turbine ambient conditions and with equal temperatures, pressure and mass flow before the turbine. Otherwise, correction factors must be applied.

3 Compressor efficiency

The efficiency of the compressor can be obtained from the isentropic relation, as illustrated in Fig. 3. Having measured the temperatures and pressures T_1, p_1, T_2, p_2 and after obtaining the temperature T_{20} from the $T - S$ diagram (Fig. 3), the efficiency of the compressor can be determined as:

$$\eta_C = \frac{T_1}{T_2 - T_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]. \tag{1}$$

The reference efficiency should be recorded when the blading system and the sealing are new, or after the overhaul. Also, the air flow rate must be measured, sand if possible the compressor characteristic should taken down. Then, the real efficiency is compared with the reference efficiency, always in the same ambient conditions or including a correction factor for barometric pressure and ambient temperature.

The main purposes of the diagnosis are to detect internal causes, which decrease the efficiency, not external causes such as ambient conditions (hot or cold day conditions, etc.), which affect the output capacity. A computer program [4]

can be used as an aid in the diagnosis and analysis processes to simulate the effect of deterioration of the gas path on the efficiency.
The quantification of losses can be carried out in several ways:

- measuring pressure ratio and inspecting the compressor blades through the inspection hole it is possible to estimate the deposits,
- correlate the pressure losses with the seal wearing,
- use the computer program for compressor performance analysis [5],
- combine all results through the enthalpy entropy diagram.

4 Quantification of the compressor fouling and seal wearing out.

Sealing wearing out can be evaluated analyzing the efficiency of the compressor if other fault no occurs otherwise it is necessary to combine the following:

- measurement of the air gas flow,
- analyze the compression ratio,
- simulation results,
- characteristic of the compressor.

5 Observation

Any changes in pressure p_2 and temperature T_2 will indicate either fouling of the compressor blades or deposits occurrence. Also, increased clearances in the seals can be confirmed by occurrence of rubbing, and this, in turn, can be detected by vibration analysis. A decrease in compressor efficiency normally implies a decrease in the output capacity of the gas turbine.

5.1 Gas turbine efficiency

The efficiency of the gas turbine can be determined exactly when the gas temperature before the turbine is known. Otherwise, it is possible to make a fair estimation of the turbine efficiency using the method of the mass balance of the combustion chamber. The algorithm for estimation of combustion chamber efficiency and the gas turbine is presented below. As a first step, the initial efficiency of combustion chamber is assumed according to its design value. For example:

$$\eta_{CC} = 0.99\,. \tag{2}$$

Then, the temperature of the gas before the turbine is calculated using the mass balance equation of the combustion chamber:

$$T_3 = T_2 + \frac{(\eta_{CC} \cdot W_d)}{C_{pCC}\,(M_{air}/M_{gas} + 1)}. \tag{3}$$

The efficiency of the gas turbine is determined with the formula:

$$\eta_{TG} = \frac{T_3}{T_3\ T_4}\left[1 - \left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}}\right]. \tag{4}$$

The capacity of the turbine is obtained (calculated) from:

$$P_{TG} = (M_{gas} + M_{air})\eta_{TG}\ C_{pTG}\ [T_3 - T_{40}]. \tag{5}$$

On the other hand, the output power of the generator, which is measured, and the power for driving the compressor, which is estimated, are combined to give:

$$P_{TG} = P_{el}\ \eta_{mech}\ \eta_{el} + C_{pC}\ M_{air}\ (T_2 - T_1)/\eta_{mech} \tag{6}$$

where P_{el} is the output capacity of the generator, and $[M_{air} C_{pC}(T_2 - T_1)]$ is the power consumed by the compressor. If

$$|P_{TG} - P_{TGI}| \leq 0.01 \tag{7}$$

and the calculations are carried out in the iterative manner till the above condition is satisfied, then, the calculated values of η_{CC} and η_T are the actual values. If not, then the efficiency of the combustion chamber is corrected as follows:

$$\eta'_{CC} = \eta_{CC} - \Delta\eta. \tag{8}$$

In this form, the turbine η_T and the combustion η_{CC} efficiencies can be estimated and compared to the reference data.

It is important to note that any changes in the temperature T_3 indicate a fault of the combustion chamber, while any changes in T_4 indicate rather the faults of the gas turbine.

5.1.1 Quantification of gas turbine losses

Estimation of the effect of deposits in the first stage of gas turbines

For an approximate estimation of the effects of deposits or solid particle erosion of the first stage, or other stage, it is convenient to use the following incompressible form of the flow equation [6], which is commonly used for steam turbines:

$$M_{TG} = A_{1st} p_3 \sqrt{\frac{1}{T_3}} \sqrt{1 - \left(\frac{p_{1st}}{p_3}\right)} \tag{9}$$

and the capacity output:

$$P_{TG} = M_{TG} \cdot \Delta h_{TG} \cdot \eta_{TG} \tag{10}$$

If the area of the first stage decreases due to deposits or damage, the pressure after the first stage and other intermediate stages (except the last) will decrease. If p_{1st} decreases by 1%, then $\sqrt{1 - \frac{p_{1st}}{p_3}}$ increases by 2% and A_{1st} decreases by 2% because p_3 and $\sqrt{\frac{1}{T_3}}$ stay almost constant such that MTG remains constant: Put in another form, this is:

$$M_{TG} = \underset{\downarrow 2\%}{A_{1st}} \underset{-}{P_3} \underset{-}{\sqrt{\frac{1}{T_3}}} \underset{2\% \uparrow}{\sqrt{1 - \left(\frac{P_{1st}}{P_3}\right)}} \tag{11}$$

Therefore, the output of the gas turbine decreases as a result of the efficiency decrease. The amount of these changes can be obtained by simulation using a computer program [4] for each specific design of the gas turbine.

In the same way, the seal losses, and other losses, can be estimated at any point of the turbine if sufficient measurements are available.

5.1.2 Steam turbine efficiency

The efficiency of steam turbine can be estimated for the high and intermediate pressure part (casing) by the enthalpy drop method, while the efficiency of the low-pressure part can be obtained by determining the last point of the expansion curve by one of the following methods:

- using a probe to determine the steam exit velocities (losses) from the last stage [7],
- using an optical probe to determine the steam humidity,
- mass balance of the condenser,
- an approximate estimation method.

The efficiency of the turbine high-pressure part is given by:

$$\eta_{t_{HP}} = \frac{h_{valve} - h_{RC}}{h_{valve} - h_{o,HP}} \tag{12}$$

The efficiency of the intermediate-pressure part is given by:

$$\eta_{t_{IP}} = \frac{h_{RC} - h_{IP}}{h_{RC} - h_{o,IP}} \tag{13}$$

Finally, the efficiency of the low-pressure part can be obtained from:

$$\eta_{t_{LP}} = \frac{h_{IP} - h_{LP}}{h_{IP} - h_{o,LP}} \tag{14}$$

A computer program [8] can be used to estimate the losses in combination with measurements of the real geometry of the turbine steam path during an overhaul of the turbine.

6 Quantification of the steam turbine losses

For evaluation of the flow changes, the following incompressible ideal gas flow equation is used:

$$M = C_p\, A \sqrt{\frac{2gk}{k-1}\frac{p_1}{v_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}\right]} \tag{15}$$

For incompressible flow, this equation becomes:

$$M = C_p\, A \sqrt{2g\frac{p_1}{v_1}\left[1 - \left(\frac{p_2}{p_1}\right)\right]} \tag{16}$$

This equation and its derivatives are used to estimate the flow changes in the turbine due to decreased and increased stage areas in several parts of the turbine. Thus, the following faults can be detected:

- decreased nozzles area in the first stage of the high-pressure (HP) turbine and 1^{st} stage of the intermediate-pressure part by solid particle erosion,
- deposits in the HP, IP and LP parts of the turbine,
- increased flow area due to worn out seals.

7 Estimation of flow changes

Using the incompressible form of the flow equation [6], and measuring the four main pressures p_T, p_{LP}, p_{RC}, and p_{x-0}, the percentage of flow changes can be estimated.

Example 1.
The effect of percentage flow change and area change due to nozzle erosion in the HP turbine stage.
The above incompressible flow equation can be rewritten as:

$$M_T = A_{1st} p_T \sqrt{\frac{1}{T_T}} \sqrt{1 - \left(\frac{p_{1st}}{p_{valve}}\right)} \tag{17}$$

where p_T and p_{valve} are constant and maintained by the boiler control. The increase in the nozzle area required to increase by 1% the throttle flow. Knowing that the throttle pressure and temperature are constant, a 1% increase in flow causes a 1% increase in the first stage pressure which results in a 2% decrease in the $\sqrt{1 - p_{1st}/p_{valve}}$ term. Thus, to balance the equation, the area increase should be 3%.
Resuming

$$M_T = A_{1st} p_T \sqrt{\frac{1}{T_T}} \sqrt{1 - \left(\frac{p_{1st}}{p_{valve}}\right)} \tag{18}$$

$$\uparrow 1\% \qquad \uparrow 3\% \qquad -- \qquad 2\% \downarrow$$

Analyzing, the second HP stage, a simplified version of the above equation can be used:

$$M_{2nd} = A_{2nd} P_{1st} \sqrt{\frac{1}{T_{2nd}}} \tag{19}$$

$$\uparrow 1\% \qquad - \uparrow 1\% -$$

In the case of the IP and LP turbines, a similar equation is used, and in both cases, $M_{RC,LP}$ goes up by 1% because M_T increases also by 1% while $A_{IP,LP}$, $\frac{1}{T_{RC}}$ and $\frac{1}{T_{x-o}}$ stay the same. Thus, to balance the equation, p_{RC} and p_{x-o} must increase by 1%, respectively.

$$M_{RC} = A_{IP}\, p_{RC} \sqrt{\frac{1}{T_{RC}}} \tag{20}$$

$$M_{LP} = A_{LP}\, p_{X-0} \sqrt{\frac{1}{T_{x-o}}} \tag{21}$$

$$\uparrow 1\% \qquad - \uparrow 1\% -$$

This means that the flow through the turbine increases due to solid particle erosion of the first stage nozzle, which also results in an increase in electrical load, but the HP efficiency decreases. The key pressure pattern is that all three pressures increase (heat rate decreases) as illustrated in Fig. 4.

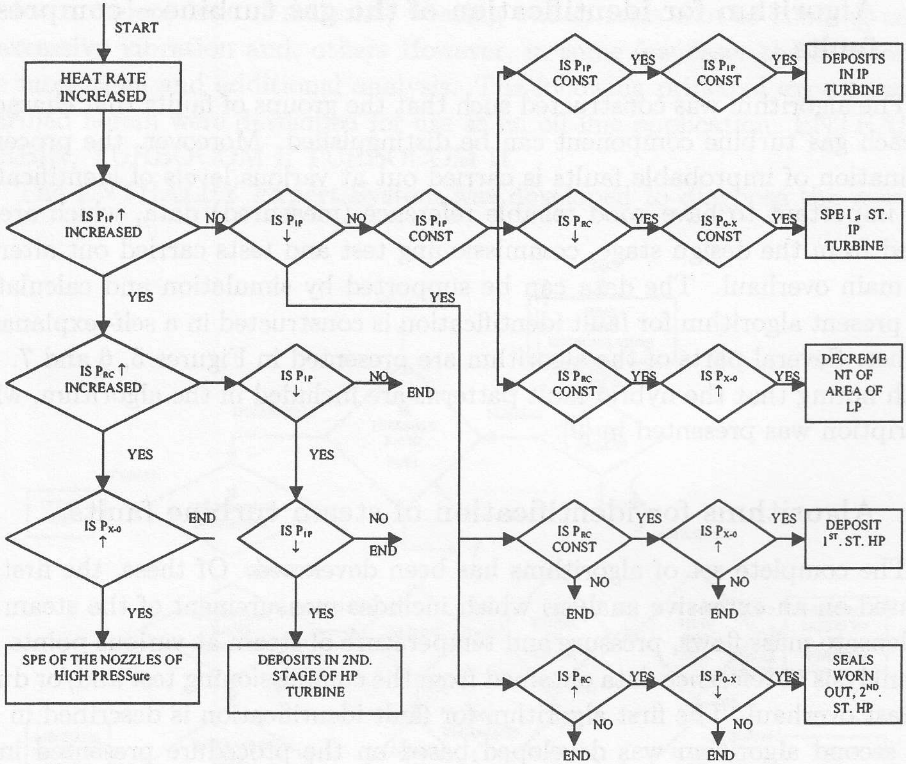

Figure 4. The algorithm for identification of the worn component of steam turbine.

8 Development of the fault identification algorithms for steam, gas turbines and compressors

8.1 General description

The algorithms fault identification in each piece of equipment of a plant were constructed to facilitate the development of the expert system, presented in the next part of the paper. The flow diagrams are represented by a series of questions that require YES or NO responses. The algorithm was constructed to facilitate the process of elimination of improbable faults and to distinguish among the several levels of identification. The data processed are measured data, however, calculated data can be included in the process of faults identification.

8.2 Algorithm for identification of the gas turbine – compressor faults

The algorithm was constructed such that the groups of faults that characterize each gas turbine component can be distinguished. Moreover, the process of elimination of improbable faults is carried out at various levels of identification. It is important to have good reliable reference (measured) data, which are obtained from the design stage, commissioning test and tests carried out after the last main overhaul. The data can be supported by simulation and calculation. The present algorithm for fault identification is constructed in a self- explanatory manner. Several parts of the algorithm are presented in Figures 5, 6 and 7. It is worth noting that the hybrid fault patterns are included in the algorithm, whose description was presented in [9].

8.3 Algorithms for identification of steam turbine faults

The complete set of algorithms has been developed. Of these, the first one is based on an extensive analysis which includes measurement of the steam and condensate mass flows, pressure and temperature of steam at various points, and the analysis of reference data obtained from the commissioning test and/or during the last overhaul. The first algorithm for fault identification is described in [10]. The second algorithm was developed based on the procedure presented in [6]. This algorithm allows identification of the seven main faults caused by wearing out of the turbine blading system, but requires measurement of the three main pressures of a three-casing reheat turbine: the pressure after the control stage, before the intermediate-pressure (IP) casing, and before the low-pressure (LP) casing (Fig. 4). The effect of other six faults can be determined in the same manner.

9 Expert systems

The expert systems are based on the above algorithms. Also, in some cases a vibration analysis is used jointly with thermodynamic analysis to locate precisely a fault, for example in the case of rubbing which damaged the seals of the turbine and/or compressors. The system is used off-line, however it can be installed on-line with a monitoring system. The expert systems identify the faults of the gas turbine, the compressor and the steam turbine (2 versions). Using the expert systems described below the majority of the faults that are characterized by wearing out of the components can be identified and the corrective action taken immediately, saving substantial amounts of time. Among these faults are solid particle erosion of the blades and vanes, deposits, incrustation, loss of material due to corrosion, loss of material, wearing out of seals due to rubbing caused by excessive vibration and, others However, in some few cases the solution can take more time and additional analysis. The following principal expert systems described herein were developed for use as an off-line application: ENTHALPY, TURBIN, TURBOCOM I, TURBOCOM II.

The ENTHALPY Expert System was developed to diagnose the worn out

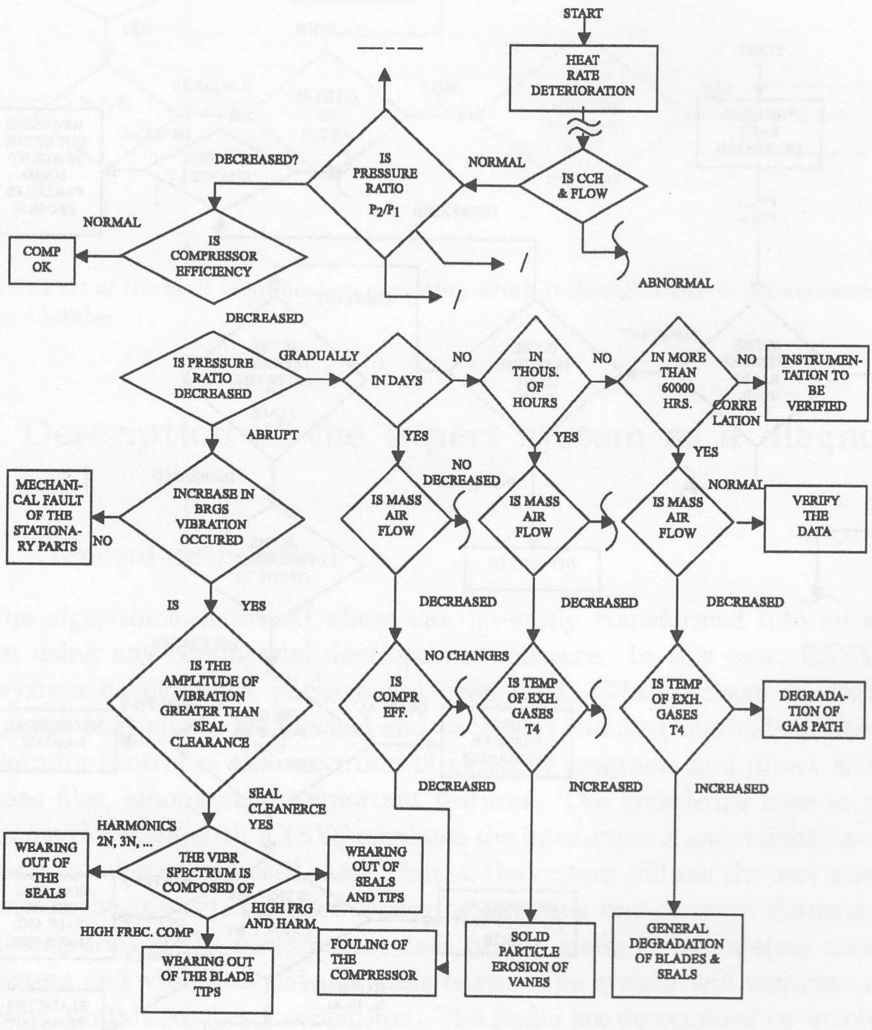

Figure 5. The part of the fault algorithm realized for the compressor.

components of steam turbines utilizing the measured mass flow and the pressure and temperature of steam and condensate steam given by standard installed instrumentation. On the other hand, the TURBIN Expert System of which the algorithm is presented in a sister paper [1], is based on the analysis of the steam pressure to diagnose changes of the turbine stage areas due to either deposits and/or solid particle erosion. In the sister paper, the algorithms of the TURBO-COM II and CONDENSA Expert Systems are also presented. They are based mainly on an analysis of the gas pressure, temperature mass flow and efficiency of the corresponding equipment.

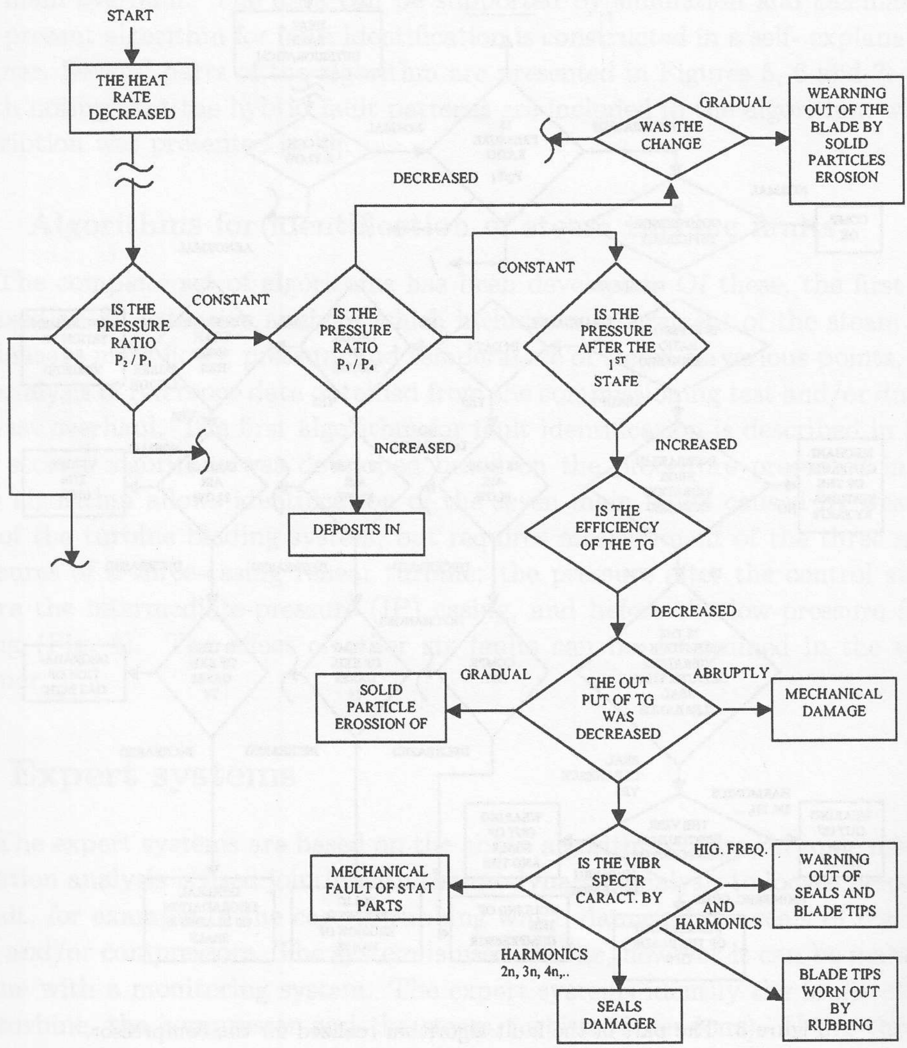

Figure 6. A part of the fault identification algorithm referred to the gas turbine faults.

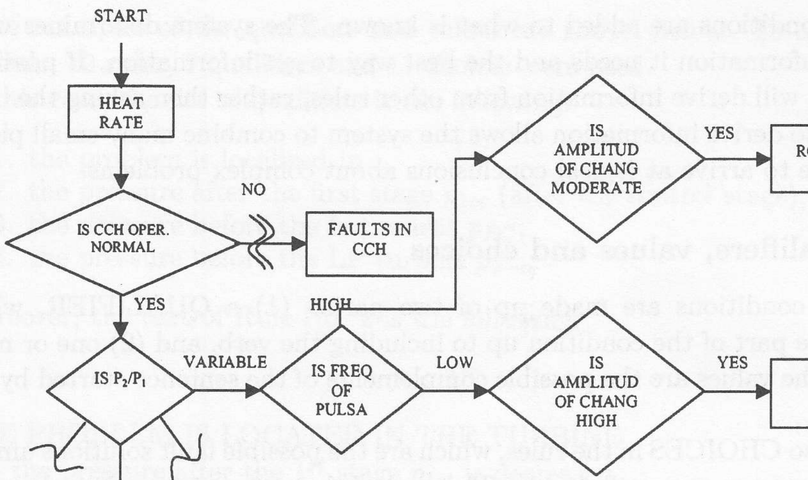

Figure 7. Part of the fault identification algorithm which is characteristic to aerodynamic instabilities.

10 Description of the expert system as a diagnostic tool

10.1 General description

The algorithms described above can be easily transformed into an expert system using any commercial development software. In this case, EXSYS expert system development package has been used. This package is written in C-language that allows for forward and backward chaining methods of the rules, and permits control of the execution of external programs and direct access to database files, among other important features. The knowledge base or expert system development with EXSYS emulates the interaction a user might have with an expert to solve a diagnosed case. That is, the system will ask the user questions relevant to the subject; the user replies by selecting one or more characteristics and descriptions of the performance data from a menu or by entering measured parameters and vibration data in some cases. The system will continue asking questions, until it reaches a conclusion. The faults are determined by involving a selection from a definable group of choices, where the decision is based on logical rules. The rules that the system uses are of the IF-THEN-ELSE type. The rules are made-up of a list of IF conditions and a list of THEN and ELSE statements. If the entire IF conditions in a rule are true, the corresponding THEN statement is added to what it is known to be true. If any of the IF conditions are false, the ELSE conditions are added to what is known. The system determines what additional information it needs and the best way to get information. If possible, the program will derive information from other rules, rather then asking the user. The ability to derive information allows the system to combine many small pieces of knowledge to arrive at logical conclusions about complex problems.

10.2 Qualifiers, values and choices

The IF conditions are made up of two parts: (1) a QUALIFIER, which usually is the part of the condition up to including the verb, and (2) one or more VALUES. The values are the possible complements of the sentence started by the qualifier.

There are also CHOICES in the rules, which are the possible fault solutions among which the expert system will decide. The goal of the system is to select the most likely choice based on the data input. Besides displaying the selection, the system will present the probability value assigned to that choice. In a subsequent part of the paper, some examples of the qualifiers, values and choices for each expert system presented herein will be given. There are two versions of the expert system for identification of the particular faults of the steam turbines. These are called ENTHALPY and TURBIN, followed by two versions of the gas turbine compressor diagnostic TURBOCOM I and TURBOCOM II Expert Systems. In these systems included are also the rules which identify the origin of wearing out of the seals and blade tips which combine the vibration data with temperature, pressure and efficiency analysis. The TURMAYA expert system, which identifies the primary causes of the turbomachinery vibration problem can also be included in the package.

11 Description of some of the expert system modules

Due to a lack of space only three expert system modules are shortly described below with the same examples of the rules, qualifiers and values.

11.1 TURBIN Expert System

The most extensive version of the system for identification of wearing out of steam turbine components is called ENTHALPY and is reported in [10]. The difference between ENTHALPY and TURBIN is that in the former expert system can identify 28 faults whereas TURBIN can identify only 7 faults. Also, in the case of ENTHALPY, the measured data is more extensive. On the other hand, to identify the faults using TURBIN the steam pressure at only 3 points of the turbine are analyzed. The faults and their causes are presented in Fig. 4 and

some examples of the qualifiers and values are shown below. To construct this module, 10 rules, 8 qualifiers and 11 choices were used.
In this case, the list of qualifiers is the following:

1. the problem is localized in...,
2. the pressure after the first stage p_{1st} (after the control stage),
3. the pressure before the hot reheat p_{RC},
4. the pressure before the LP turbine p_{x-o}.

Moreover, the text of Rule No. 2 is the following:

IF

THE PROBLEM IS LOCATED IN THE TURBINE
and the pressure after the 1^{st} stage p_{1st} is decreased
and the pressure before the hot reheat p_{RC} is decreased
and the pressure before the low pressure turbine p_{x-0} decreased

THEN

DEPOSITS IN THE 1_{ST} STAGE OF HP TURBINE
Confidence = 1
WEARING OUT OF THE SUBSEQUENT STAGES OR LOSS OF THE BLADES.
Confidence = 0.2 The choices are the following:

1. SPE of the nozzles of HP turbine ($A_{1st,HP}\uparrow$)
2. Deposits in the 1^{st} stage of HP turbine ($A_{1st,HP}\downarrow$)
3. Wearing out of seals of 2^{nd} HPt stage ($A_{2nd,HP}\uparrow$)
4. Deposits in the IP turbine ($A_{IP}\downarrow$)
5. SPE of the 1^{st} stage of IP turbine ($A_{IP}\uparrow$)
6. Decrease of the LP turbine flow area ($A_{LP}\downarrow$)
7. Deposits in the 2^{nd} stage of HP turbine ($A_{2nd}\downarrow$)

12 Turbocom II Expert System

The TURBOCOM II Expert System deals with 37 qualifiers, 49 choices and 68 rules. The expert system can be continuously modified to include more complicated diagnostic cases. The module is so constructed that the following four faults groups are recognized: fault related to the compressor only, to the gas turbine, to both the compressor and the gas turbine, and to faults characterized by aerodynamic instabilities. The objective of the system is to identify the faults appearing during operation of the turbo-compressor, which increases the heat rate of the unit. The identification is carried out based on the known fault patterns which include the hybrid fault patterns, that were created from the knowledge of the effects of the turbocompressor components wear out due to excessive vibration on the efficiency of the unit.

The TURBOCOM II Expert System deals with 35 qualifiers, 54 choices and 42 rules. Some of the qualifiers, choices and rules are presented below. The most important qualifiers are:

- pressure relation $\frac{p_2}{p_1}$,
- compressor efficiency,
- increased vibrations of the rotor-bearing system,
- mass air flow,
- vibration spectrum,
- amplitude of vibration,
- temperature of the exhaust gases,
- pressure relation $\frac{p_3}{p_4}$,
- gas turbine efficiency,
- if the change occurred,
    - gradually,
    - abruptly,
- and others.

Two examples of the rules are given below. The contents of rule 3 is the following:

<u>IF</u>

THE COMBUSTION CHAMBER IS OK
and pressure ratio $\frac{p_2}{p_1}$ (compressor) is decreased,
and compressor efficiency decreased,
and vibrations increased,
and vibration amplitude is smaller than the seals clearances,
and vibration spectrum shows only the basic component (at the TG rotational frequency)

<u>THEN</u>

SOME PARTS OF THE COMPRESSOR:
<u>BLADING ARE MISSING – confidence $\frac{9}{10}$</u>
OR BLADES ARE BROKEN – confidence $\frac{9}{10}$
<u>**Rule 6.**</u>
IF

COMBUSTION CHAMBER IS OPERATING NORMALLY
and pressure ratio $\frac{p_2}{p_1}$ is decreased
and compressor efficiency decreased
and increase in vibrations occurred
and amplitude of vibration is greater than the seals clearances
and vibration spectrum is characterized by components at high frequency $Fi = n\,fi$

THEN

WEARING OUT OF COMPRESSOR

BLADE TIPS
confidence $= \frac{9}{10}$
and
WEARING OUT OF THE TG BLADE TIPS
Confidence $= \frac{4}{10}$
AND
DEPOSITS IN COMPRESSOR
Conf $= \frac{2}{10}$ (see the air filters).
In Table 2, the most important faults and their causes and symptoms are presented.

13 Conclusions

Simplified methods for the calculation and measurement of the efficiency of turbines and compressors of a power plant for diagnostic purposes are presented. Based on the above, the diagnostic algorithms for the various equipment component of power plants were developed and are shortly described. The algorithms are then applied to construct an expert system for the fault identification of the equipment. Such expert systems are briefly described.

The expert systems developed here identify the principal faults, which affect the efficiency of the power plant equipment. The expert systems can be utilized as an advisory guide for the power plants personnel for rapid identifications of the faults.

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