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Conditions for increasing the recognition of degradation in thermal-flow diagnostics, taking into account environmental legal aspects

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Abstract The ever-increasing demand for electricity and the need for conventional sources to cooperate with renewable ones generates the need to increase the efficiency and safety of the generation sources. Therefore, it is necessary to find a way to operate existing facilities more efficiently with full detection of emerging faults. These are the requirements of Polish, European and International law, which demands that energy facilities operate with the highest efficiency and meet a number of restrictive requirements. In order to improve the operation of steam power plants of electric generating stations, thermal-fluid diagnostics have been traditionally used, and in this paper a three-hull steam turbine, having a high-pressure, a medium-pressure and a low-pressure part, has been selected for analysis. The turbine class is of the order of 200 MW electric. Genetic algorithms (GA) were used in the process of creating the diagnostic model. So far, they have been used for diagnostic purposes in gas turbines, and no work has been found in the literature using GA for the diagnostic process of such complex objects as steam turbines located in professional manufacturing facilities. The use of genetic algorithms allowed rapid acquisition of global extremes, that is efficiency and power of the unit. The result of the work undertaken is the possibility to carry out a full diagnostic process, meaning detection, localization and identification of single and double degradations. In this way 100 % of the main faults are found, but there are sometimes additional ones, and these are not perfectly identified especially for single time detection. Thus, the results showed that with a very high success rate the simulated damage to the geometrical elements of the steam turbine under study is found.

Keyword: Steam turbine, genetic algorithms, diagnostics, coal-fired power plant, efficiency analysis

Introduction

Socio-economic development causes a constantly increasing demand for electricity produced from various sources and raw materials. [1,2]. Nowadays Polish energy sector uses most of all black coal and to a lesser extent brown coal [3,4]. In the current political situation, it is important for Poland to have its own energy resources located in coal basins [5]. The use of solid fuel in the form of hard coal allows Poland to achieve relative energy security. Currently, new technologies can be found to reduce the production of CO2, NOx, SOx [6] and other substances generated during the combustion of coal [7]. The use of these technologies is important due to the environmental requirements set by the European Union [6]. In order to apply clean energy technologies, power plants incur high financial outlays. Currently, for technical reasons, the biggest problem in the case of CO2 is to be seen in the storage and disposal system for extracting coal from lower and lower resources, and a large number of jobs for people working in the extraction and transport of coal to power plants. The disadvantage of solid fossil fuels is the constant reduction of their deposits [8]. The future of fossil fuels may be to connect electricity generation systems with systems powered by nuclear energy or renewable energy sources [9,10].

Polish energy, as mentioned, is based on coal, but due to the limitations related to environmental protection, such energy generation process is to be available only until 2050. Currently, in Poland we do not have alternative energy sources that would make it possible to give up coal, so the use of coal-fired power plants will probably continue after this time, so it is important to keep the process of their use as efficient as possible [11]. It is therefore necessary to introduce thermal-flow diagnostics of steam turbines.

Obligation to reduce greenhouse gas emissions due to International, European and domestic law

Poland as a member of UE, likewise 194 other countries [12], is a signatory of "The Paris Agreement"(TPA) [13]. The text of the law was adopted during the 21 UNFCCC Conference in Paris on 12 December 2015[14]. That agreement reviews the strategy for climate change and it is a legally binding international treaty, ratified by the EU on 5th October 2016[14], entered into force on 4th November 2016[13]. Objective treaty replaced Kyoto Protocol (focused on climate changes) enrolled on 11 December 1997, which covered years 2008-2012 and 2013-2020 of the strategy for climate change [15].

Due to the Paris Agreement Poland, likewise other signatories, is obligated to reduce emission of CO2. The most significant goal of that treaty is to prevent overdose of global warming. Nowadays global temperature increased about 2˚C above pre-industrial levels, the aim of the agreement is to reduce that amount to 1,5 ˚C above pre-industrial levels [16] and also to reduce the risks and impacts of climate change [13]. Moreover, the treaty obligates signatories to "increase the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production" and to make easier cash flow dedicated to climate change prevention as presented in The Parris Agreement in article 2 points 1 b and 1 c.

The European Union aim is to achieve climate neutrality by 2050[17]. Evidently there is no possibility to accomplish such a significant goal immediately. The whole program is divided into shorter 5-year selections (cycles). The only exception is the first cycle, which ends this year (2023), so there is 2020-2023 cycle [13].

The Paris Agreement imposes on parties the obligation to "undertake and communicate ambitious effort" [13] (article 3 TPA) enumerated in particular articles of that treaty, which shall be increased over time. According to article 4 of The Paris Agreement the countries shall reach the highest global level (peaking) of greenhouse gas emissions immediately, then reduce it to the greatest degree in accordance with science.

Each signatory of that treaty is obligated to "prepare, communicate and maintain successive nationally determined contributions that it intends to achieve"[13] (article 4 point 2 TPA). Therefore, countries undertake efforts on domestic level to mitigate climate change and its after-effects.

The parties should communicate their targets and plans, which they expect to achieve in a particular cycle. During the cycle signatories could increase their target to be more efficient and to reach earlier the main aim of common climate policy. Each 5-year cycle needs to pledge by a signatory greater target to attain the final aims of the Agreement. Domestic targets are recorded in a public registry maintained by a secretariat, therefore they are easily controlled and enforced. Parties are committed to settle account of their target achievements [13].

To achieve the Paris Agreement's aims European Union has its own intracommunitary law - Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law') [18], which is an answer to treaty's appeal.

The European Union endorsed in 2014 the law to reduce greenhouse gas emissions by 40% in comparison to 1990. The European goals for 2030 national strategy [19] result from article 4 of the Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013[20].

According to article 4 of the above-mentioned regulation: "Each Member State shall, in 2030, limit its greenhouse gas emissions at least by the percentage set for that Member State in Annex I in relation to its greenhouse gas emissions in 2005, determined pursuant to paragraph 3 of this Article.". Polish target is to reach 7% reduction (-7%). Polish Ministry of Climate and Environment has prepared the National Energy and Climate Plan for years 2021 – 2030[21,22], in which there are described main domains of the Polish energy policy.

However ambitious the EU targets were, The European Commission announced that the European Union is ready to increase them up to 55% for 2030[23]. For the moment (30th of March 2023) the legislative process on amendments' adoption is still not finished. The First amendment, as the most significant, recognized by the European Parliament [24] concerns the reduction of CO2 emissions by new cars and 50% of vans compared to 2021 levels. Countries cannot reach a compromise to enact the legislation and to fix the date of 55% reduction target. The full text of the regulation enacted by the Council is not available until its full publication in the EU Official Journal. There are only press releases published on the European Council website [25].

Although there is still no vital 55% reduction of greenhouse gas emissions target in European internal law, nonetheless the European Union has increased their aim on 17 December 2020 by updating the nationally determined contribution to 55% [26].

The European Union countries are not obligated by European law to achieve 55% reduction aim, they commit to reach that point by updating NDI statement of European Union [27].

Poland, to perform duties imposed by the Paris Agreement and EU law, implemented domestic law and regulations. The most important one has been adopted by Council of Ministers and it is called "the Energy policy of Poland until 2040", which sets the directions how Poland should behave to reduce climate change.

Diagnostics of energy objects

To ensure all the restrictive requirements imposed on us in the legal field, it is necessary, apart from administration activities, to improve operating conditions to maintain the highest possible efficiency of energy facilities, and to introduce thermal and flow diagnostics. This is especially important in the era of the Polish energy transformation that is currently underway.

Each technical object undergoes a process of technical diagnostics, which is to determine the non-disassembly technical suitability of the object for the operation, by providing information about its condition, and then transforming it for use in operating procedures [28]. Technical viability is the condition in which the technical object, in this case, a steam turbine, is able to maintain and produce a functional condition necessary for its operation, which allows for the safe use of a given object [29,30]. While the turbine is operating, its operating parameters change, even a small change in parameters or geometry may reduce its efficiency [31], but despite this, for economic reasons, such a facility is still operated.

Technical diagnostics in the power industry can be found in systems ensuring the safety of objects located in a power plant [32,33] or a combined heat and power plant [34], and to be more precise, in objects with rotor machines [35], this diagnostic begins with vibration analysis systems [36,37].

The use of diagnostics aims at the conduct of the diagnostic process with the appropriate accuracy. This process is carried out in three stages:

- fault detection: detection or observation of a fault occurring in the object and determination of the detection time
- fault isolation: isolation, determination of type, size and time of the fault's occurrence
- fault identification: determination of the size and character of the fault's variability in time [30].

Technical diagnostics includes thermal - flow diagnostics tasked with maintaining the operation of the steam turbine in such a way that the efficiency of the facility is as high as possible and fluctuates at the same level [38]. Efficiency is diminished by occurring sudden or time-increasing degradations in geometric dimensions [39]. The diagnostics deals with both the examination of the object and the assessment of energy changes occurring in it. To carry out the process of assessing energy changes, it is necessary to know the diagnostic measure [30], the simplest of them are the symptoms. The symptom (proper name) is understood as the value of the deviation measured from the reference value, i.e., it is the reference value (1) [40].

$$symptom = \frac{parameter_{mesured} - parameter_{nominal}}{parameter_{mesured}} \qquad (1)$$

The reference value is established for the tested object in the time when there are no degradations in it, i.e., for new technical objects, systems or it is made after renovation. The selected research object, i.e., the steam turbine, consists of a large number of elements [41] which cause the occurrence of a very large number of symptoms, which are grouped into syndromes to speed up the calculation process (2). The values of symptoms or syndromes in the further process appear as input data for the determination of diagnostic relationships.

$$syndrome = [symptom_1, symptom_2, symptom_3 \dots sympt \qquad 2$$

n syndrome value.

The literature could be found in scientific papers on the diagnostic process of gas turbine systems or combined systems [42]. To the best of the authors' knowledge of this work, there are no scientific articles on thermal-flow diagnostics using genetic algorithms for steam turbines, other than the authors' works. A literature review was carried out on the basis of which it was found that the largest number of articles are those with the use of artificial neural networks for diagnostic purposes [43]. Genetic algorithms were used, among others, by Chang [44], who used them in connection with neural networks to present a method of managing energy demand. In the next science articles, they were used to assess steam injection [45], or to optimize multiple interconnected steam turbine systems and municipal networks [46]. The presented works show that genetic algorithms are used in various aspects of research related to energy [47], but they have not been applied to thermal-flow diagnostics of steam turbines. Therefore, the aim of this work is to show the possibility of using the model and elements of genetic algorithms for the processes of thermal-flow diagnostics of steam turbines. The result of the work is the recognition of the causes of single and double degradation with high accuracy.

Research object

The object of research in this work is a 200 MW steam turbine located in a Polish power plant (**Error! Reference source not found.**).

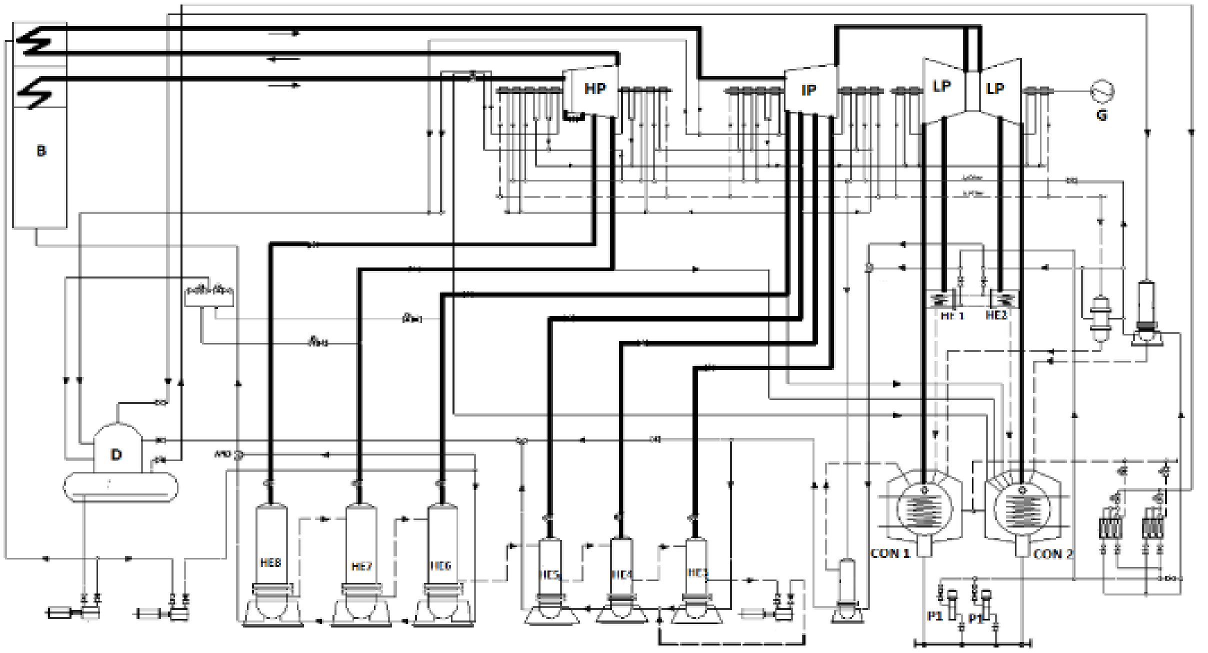


Figure 1 Cycle diagram with steam turbine. HP – high pressure steam turbine, IP – intermediate pressure steam turbine, LP – low pressure steam turbine, B – coal fired boiler, CON – steam condenser, D – deaerator, G– electric generator, P1 – condensate pump, HE – regenerative heat exchanger.

This turbine consists of high, medium and low-pressure parts and seven regenerative exchangers are used here, which correspond to the same number of steam bleeds. The steam system also includes interstage superheat. The steam turbine installed on the steam block is accurately metered, sensors (pressure, temperature, mass flow) are located on the steam or water pipelines. The results of the measurements are parameters such as: pressures, temperatures, mass flows, currents and voltages supplying the motors installed on the power unit and electric power. Due to further calculations, the steam cycle should be presented in numerical form, in order to do so, a special program Projdiag should be used.

The process of obtaining single and double degradation

In order to perform the diagnostic process for off-line diagnostics and, as a result, obtain the identification of the damage, genetic algorithms and the numerical program DIAGAR were used. This program was used to calculate the flow of thermal cycles. Due to the complexity of the steam turbine, the focus was only on its selected elements, first the focus was only on the high-pressure (HP) and intermediate-pressure parts (IP), then the following parameters were selected:

- clearance in the seal of the control valve nozzle box for HP parts
- clearances in the seals of the IP parts nozzle boxes
- clearance in the outer seal of the HP part
- clearance in the external sealing of the IP part
- 12 values associated with the geometry of six groups of HP and IP stages, and consisting, for each of these degree groups, of: seals of inner turbine stages and damage to the trailing edge.

The choice of parameters was made so that their change did not affect the failure rate, which would ultimately lead to the shutdown of the block. Each of the selected parameters had established limits of variability that cannot be exceeded. These variations are presented in **Error! Reference source not found.**.

Table 1 Selected degrading parameters.

Name of the geometric parameter to be degraded	Possible allowed change
Clearance in the seal of the control valve nozzle box for HP parts	increase from 2.15 to 8.15 mm
Clearance in the outer seal of the HP part	increase from 0.8 to 4.8 mm
Clearances in the seals for each stage group of HP and IP parts	increase from 0 to 5 mm
Trailing edges thickness for each stage group of HP and IP parts	increase from 0 to 5%
Clearance in the sealing of the IP control valve nozzle box	increase from 6.70 to 12.70 mm
Clearance in the external sealing of the IP part	increase from od 0.8 to 4.8 mm

Table 1 shows actual values used to determine the simulation of degraded data that served as input data to the DIAGAR program. This process allowed for the designation of the reference syndrome, i.e., one where no simulation changes were made and the degradation syndrome for the changed values. Each individual syndrome was characterized by measured or determined 16 parameters (**Error! Reference source not found.**) located at a selected location of the steam turbine.

Table 2 Elements included in the symptoms.

Symptom number	Parameter name	Parameter unit	Values of symptoms for reference syndrome
1	power deviation	MW	217
2	deviation of specific heat consumption	kJ/kg	8536
3	steam pressure deviation at the I extraction	MPa	41
4	steam temperature deviation at the I extraction	˚C	397
5	steam pressure deviation at the II extraction	MPa	26
6	steam temperature deviation at the II extraction	˚C	326
7	steam pressure deviation at the III extraction	MPa	12
8	steam temperature deviation at the III extraction	˚C	456
9	steam pressure deviation at the IV extraction	MPa	5
10	steam temperature deviation at the IV extraction	˚C	423
11	steam pressure deviation at the V extraction	MPa	2

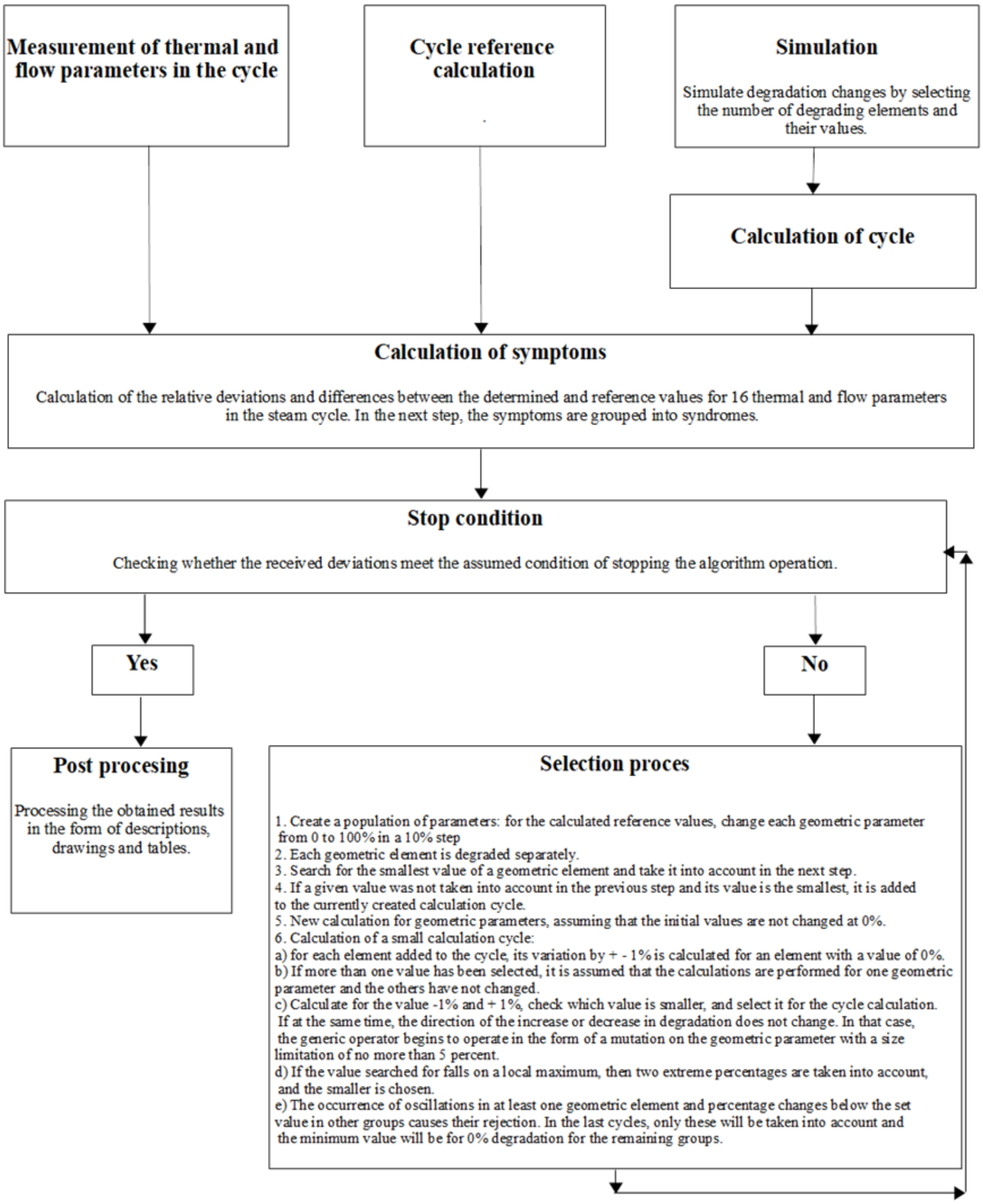
12	steam temperature deviation at the V extraction	˚C	274
13	steam pressure deviation at the VI extraction	MPa	1
14	steam temperature deviation at the VI extraction	˚C	264
15	steam pressure deviation at the VII extraction	MPa	0.1
16	steam temperature deviation at the VII extraction	˚C	57

The first genetic algorithm was created by Holland in 1975, and it was changed by Goldberg in the following years. Genetic algorithms are included in evolutionary algorithms [48,49] and are used to optimize complex systems [48]. In the relevant study, power units are systems like these. Typically, the process of optimization takes place in fields where a high number of variables are found, e.g., system design, economics, transport. The advantage of these algorithms is the quick finding of global extremes for a given function in its time domain.

Description on the diagnostic procedure

In order to obtain single and double degradation, a new proprietary computational model (**Error! Reference source not found.**) was created to search for single and multiple degradations occurring in the steam turbine. This model was made using the genetic algorithm and using elements of this algorithm. This model has been divided into 8 stages, the first four of which are: 1) measurement of parameters, 2) reference cycle calculations, 3) simulations on the basis of which the cycle calculations in the DIAGAR program and 4) the initiation of the algorithm's operation were made, which allowed for the creation of input data for the calculation of 16 symptoms included in the reference syndrome or simulated damage characteristic for a given type. Then, the stopping process should be carried out, i.e., check whether the obtained result agrees with what we are looking for, i.e., the convergence between the looking for degradation syndrome and the degradation syndrome is at an acceptable level, i.e., less than 4%. If there is a stop condition, the obtained results should be processed, if not, the selection process should be carried out. Selection is a complicated process and consists of 6 main steps, and the last step consists of the next 5 sub-steps. After the selection, the stop condition had to be checked once again.

The presented model allowed to obtain single and double degradations. The time needed to run the simulation depended on degradations complexity. During the development of the results, it turned out that there are some correlations in the appearance of an additional geometric parameter, which was caused, among others, by the location of the given components of the steam turbine in close proximity to each other or steam leaks.



Simulate degradation changes by selecting the number of degrading elements and their values.

Calculation of the relative deviations and differences between the determined and reference values for 16 thermal and flow parameters in the steam cycle. In the next step, the symptoms are grouped into syndromes.

Checking whether the received deviations meet the assumed condition of stopping the algorithm operation.

Processing the obtained results in the form of descriptions, drawings and tables.

1. Create a population of parameters: for the calculated reference values, change each geometric parameter from 0 to 100% in a 10% step
2. Each geometric element is degraded separately.
3. Search for the smallest value of a geometric element and take it into account in the next step.
4. If a given value was not taken into account in the previous step and its value is the smallest, it is added to the currently created calculation cycle.
5. New calculation for geometric parameters, assuming that the initial values are not changed at 0%.
6. Calculation of a small calculation cycle:
a) for each element added to the cycle, its variation by + - 1% is calculated for an element with a value of 0%.
b) If more than one value has been selected, it is assumed that the calculations are performed for one geometric parameter and the others have not changed.
c) Calculate for the value -1% and + 1%, check which value is smaller, and select it for the cycle calculation. If at the same time, the direction of the increase or decrease in degradation does not change. In that case, the generic operator begins to operate in the form of a mutation on the geometric parameter with a size limitation of no more than 5 percent.
d) If the value searched for falls on a local maximum, then two extreme percentages are taken into account, and the smaller is chosen.
e) The occurrence of oscillations in at least one geometric element and percentage changes below the set value in other groups causes their rejection. In the last cycles, only these will be taken into account and the minimum value will be for 0% degradation for the remaining groups.

Figure 2 Diagram showing how to perform the diagnostic procedure.

Result for single degradations

The diagnostic process for single degradation is the easiest due to the search for only one value. This value had to be close to the one occurring in the degradation being sought, which resulted in a shorter time of searching for the result than in the case of double degradation. The calculations were made on a typical personal computer.

The first example was calculated for the trailing edges of the profiles of the second group of HP parts, where the value of the change (degradation) was simulated at 8%. As a result of the calculations, it was possible to recognize this damage and the result was 8%. On the basis of the obtained values, the characteristics were created (**Error! Reference source not found.**) presenting the deviations of the simulation and the search for degradation. The comparison of these characteristics showed that both syndromes are the same, which corresponds to the obtained result in the form of a simulation of 8% damage and obtaining the same value for searching for degradation.

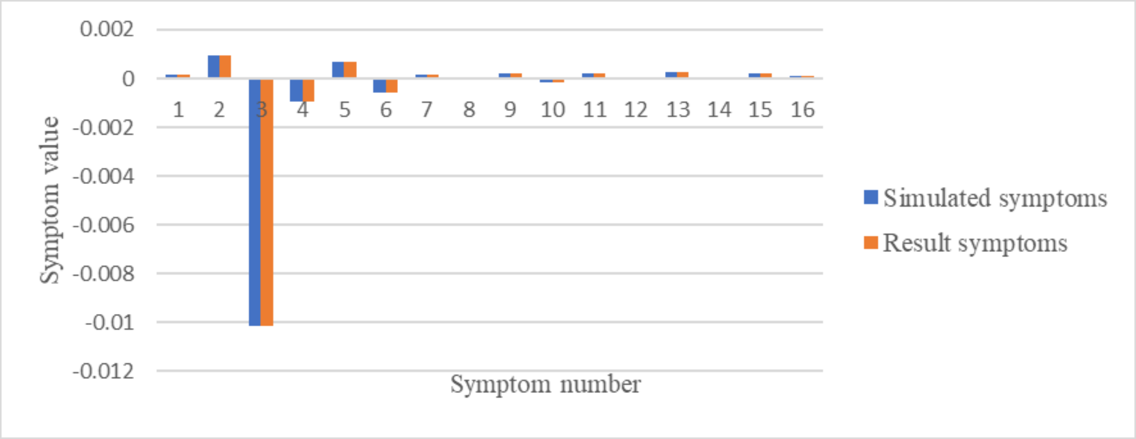


Figure 3 Comparison of the obtained characteristics of simulated degradation and the search for it for the trailing edges of the profiles of the second group of HP parts.

Another example was calculated for the clearance occurring in the seals of the first group of HP parts. The simulation was performed at the level of 10% damage, and the obtained result indicated 9% degradation on the simulated element, but also 8% degradation of the trailing edge of the first group of HP parts. The obtained characteristics are presented in **Error! Reference source not found.** and they show that the greatest differences in the deviation values occur for the fourth symptom, which is caused by the appearance of an additional damage value. The obtained result is satisfactory because it was possible to identify small damage values in the turbine.

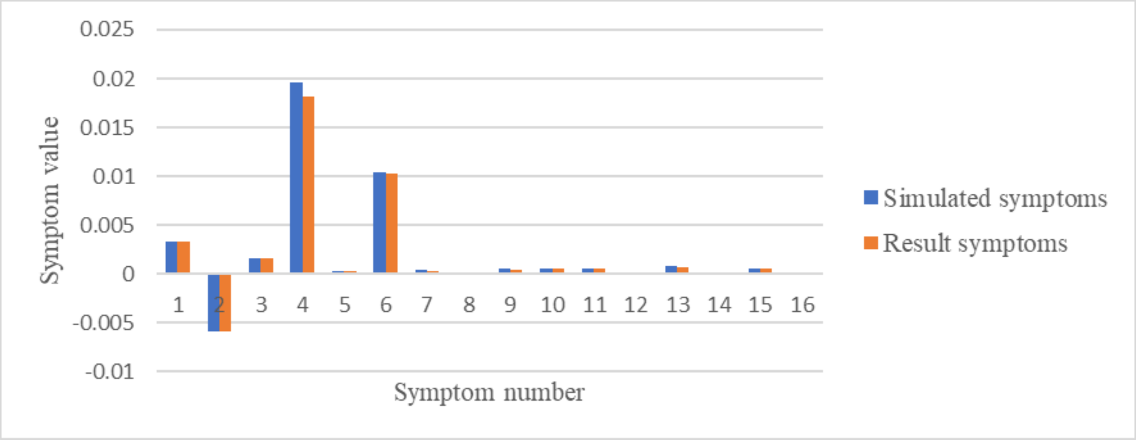


Figure 4 Comparison of the obtained degradation characteristics and searching for it for the clearance in the seals of the first group of HP parts.

Result for double degradations

Double degradations belong to multiple degrades and among them, they are the easiest to obtain and require less computational time.

The first simulated double degradation consisted of the clearance in the seals of the second group of HP stages and the clearance in the seals of the third group of IP stages. The value of degradation for the clearance in part of HP is 23% and for part of IP it is 18% and the syndrome describing it is presented in **Error! Reference source not found.**. We managed to get almost perfect results for searching for this degradation, the value of 18% was achieved, but for part of HP it was higher by 1%, i.e., 24% of the damage value was obtained.

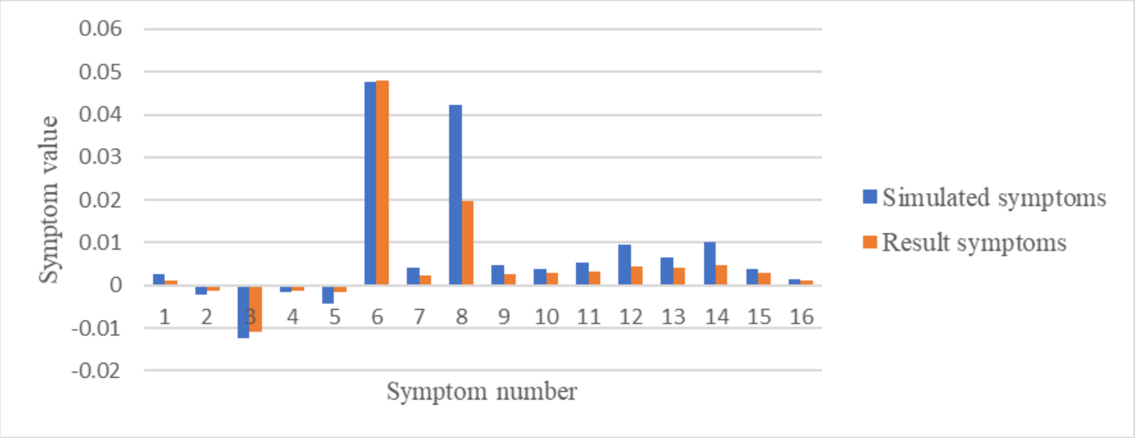


Figure 5 Comparison of the obtained degradation characteristics and searching for it for the clearance in the seals of the second group of HP parts and the clearance in the seals of the third group of IP parts.

Another example of double degradation concerns the trailing edges of the profiles of the HP stage group 1 and the clearance in the sealings of the HP stage group 2 and were changed by 14% and 66%, respectively (**Error! Reference source not found.**). The result of the algorithm's operation in search of degradation was the detection of three possible degrading parts of the steam turbine, two of them were simulated for the trailing edges of profiles of the 1st group of HP stages, the obtained value was 14%, i.e., as set, and the set value of 66% was also obtained for the clearance in the seals. In addition to the set geometric parameters, there were additional trailing edges of the profiles occurring in the 2nd group of HP stages and their value was 28%.

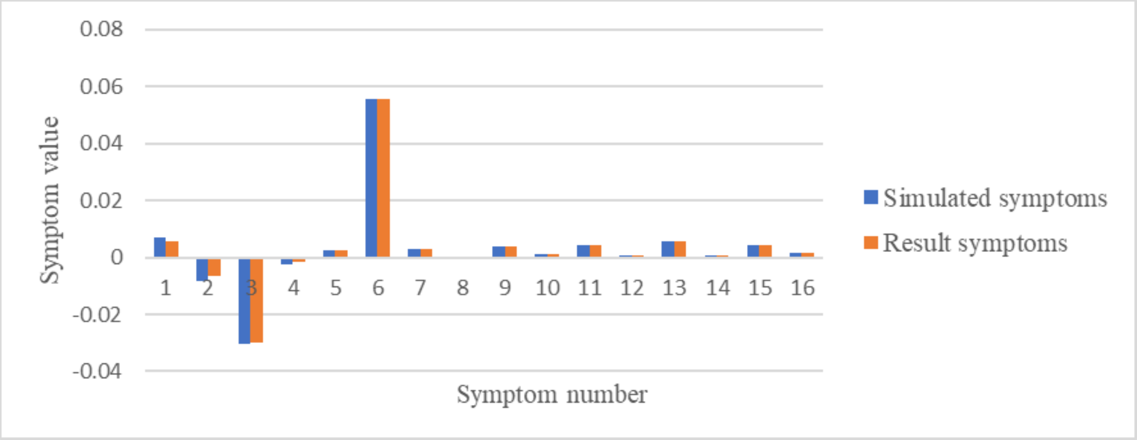


Figure 6 Comparison of the obtained degradation characteristics and the search for the value of 14% of the trailing edges of the profiles of the first group of HP parts and 66% for the clearance in the seals of the second group of HP parts.

Result analysis

The paper presents a statistical analysis of the results obtained for single and double degradation. This simulation was performed only for a certain number of simulated failures. Double degrades have also arisen for different combinations of degrades. The evaluation procedure of obtained diagnostic results uses statistical methods because in that case the results are random.

In the case of single degradation, all 15 geometry parameters analyzed in the available group were degraded, where the damage size was random. Among the simulation results, it was checked whether it was possible to find precisely simulated damage locations, and then whether the degradation size was detected sufficiently. In this statistically small group, it was found that finding only a damaged turbine element was faultless. Whereas discoveries of percentage degradation were for some cases faultless and for some others they show some small errors. At the same time, it can be concluded that 65% of the size of the degradation was discovered flawlessly, while the rest of 35% was characterized by an error, although its value was small. The results are presented in **Error! Reference source not found.**.

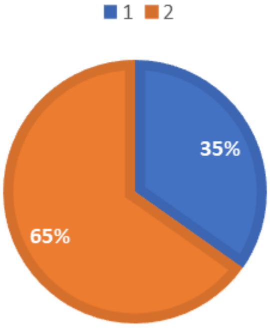


Figure 7 Percentage value of finding a damage in a single degradation, where: 1 - syndrome consisting of more than one geometric element; 2 - finding the searched element, where it had the same percentage value.

The analysis for the double degradation showed that for the set of 12 analyzed different examples, it was possible to find damaged elements immediately and the percentage value was 16.67%. With 83.33% efficiency, only the two sought degradations were not found at once. The resulting syndrome had additional degradations as shown in **Error! Reference source not found.**. Among the results that had additional damage component, 80% had simulated damage and 20% did not, is shown in **Error! Reference source not found.**.

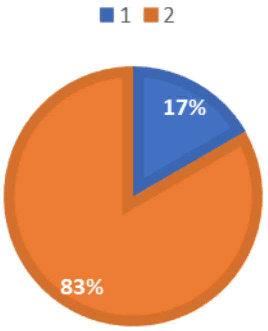


Figure 8 Percentage characteristics of the diagnosis for double degradation, where: 1 – detection of more than two degradation locations; 2 - finding exactly two locations of investigated degradation.

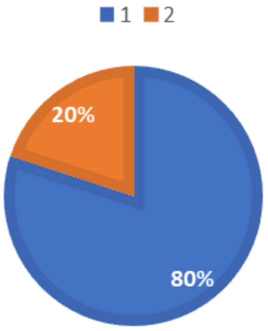


Figure 9 Percentage characteristics of the diagnosis indicating more than two degraded elements, where 1 contains simulated degradation and 2, contains no simulated degradation.

Summary

The innovative diagnostic method for steam turbines discussed in this paper indicates that it can be used in fossil-fuel fired steam units, but only after the necessary modifications. It can also be used in other industrial systems where there are thermal turbines [9] e.g., ORC systems. The presented method allows for single and double degradation. The procedure turned out to be so effective that during the tests it was possible to identify all simulated damages found in the steam turbines. The advantage of the presented method is the possibility of faster localization of damage than in the case of previously used artificial neural networks. The developed diagnostic procedure allowed for the correct diagnosis, location and identification of degradation in the analyzed case. Attention should be paid to the correct localization of the degradation. This result is particularly important for the operators of power units. It shows that the indicated degraded geometric element of the turbine requires its repair to be planned and, if possible, to return to the design value during the next service or repair action. With this planning, precise knowledge of the degradation value, although it is important, is of less importance.

The innovative application of the presented method using genetic algorithms in building modern diagnostic relations in thermal-flow diagnostics influences the development of technical disciplines related to the operation of energy facilities. Besides the use of GA for day-to-day diagnostics concerning power units cooperating with RES, it is possible to use GA for the detailed analysis of super-structured units in order to increase efficiency or improve carbon performance. This superstructure may concern the addition of systems with carbon capture or the co-firing of traditional fuels with hydrogen. In addition, steam blocks can be supercharged with a gas turbine cycle to increase their efficiency and reduce the carbon footprint of the block through higher operating temperatures and the nature of the fuels employed.

The proposed procedure has been correlated with the latest legal requirements in environmental protection imposed in the world, including the Paris Agreement, but also with aspects relating only to Poland.

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