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Application of fault tree analysis in the maintenance intervals planning for power unit systems

Fault tree analysis is an advanced method of reliability analysis of complex systems. It makes it possible to estimate the failure probability of the whole system in the function of occurrence probabilities of primary events leading to the system failure. The method can also be applied to assess the risk of complex power engineering facilities. The paper presents the selection procedure of the maintenance intervals for complex systems of power units, taking risk into account. At the stage of risk estimation, the fault tree analysis was used. The calculated risk level was compared to allowable risk. Too high a risk level at present or during further operation necessitates modifications in the schedule of planned maintenance processes. The paper suggests a way to rationally select the scopes and periods of carrying out maintenances of individual system components. An example selection of the maintenance intervals for the turbine set of a power unit was presented.

1 Introduction

The analysis of reliability and risk of complex technological systems requires application of specific methods and techniques which ensure sufficient accuracy of the expected results of research, and has to be understood by the specialists dealing with reliability issues and the technical staff involved in the operation of a given system. One of such methods is the fault tree analysis (FTA) [1–3]. The FTA is a very popular method of reliability analysis of complex technological systems which is based on the theory of probability and Boolean logic. The principles of Boolean logic are used to reduce the fault tree structure resulting from a combination of events which lead to the failure of the system. The theory of probability allows the estimation of the system failure probability as the function

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of time. The probability determined in this way is later used to estimate the level of technical risk related to the operation of a given system. Technical risk R_T understood as the product of the occurrence probability of an adverse event P and its effects K

$$R_T = PK \tag{1}$$

is an important notion which makes it possible to rationalise the operation of various systems, including the machinery and equipment of power units. If monetary units are the measure of the effects and consequences of damage or failure, then the monetary unit in this case is also the unit of technical risk. The management of risk defined in this way is possible only if influence is exerted on the operation of a given system, as well as on the maintenance of its components. In this case, it is especially important to optimise the maintenance intervals for the system components so that they will ensure keeping the risk for the entire system at the allowable level.

In the paper, the FTA method is specified, and a detailed description of the selection procedure of the maintenance intervals is provided. Also, an example of the application of this procedure in the optimisation of the maintenance schedule for the power unit turbine components is also presented.

2 Strategy for the selection of maintenance intervals

2.1 The idea of the fault tree analysis

The fault tree is a graphic, hierarchically structured, representation of events which makes it possible to present various failure combinations of the system components, human errors or external factors leading to the failure of the system. The analysis starts with the identification of the top events (usually the set of most serious system failure events) that could occur. Then, the subsequent causes of the events defined earlier are determined until the so-called primary events are defined. Primary events are events whose occurrence can give rise to the damage process resulting in the failure of the entire system, i.e. in the top event. Individual events are connected with logic gates, the most important of which are OR and AND. Their graphic diagrams are shown in Fig. 1.

The following equations should be used for, accordingly, calculating the occurrence probability of event 3 for the AND gate (according to Fig. 1)

$$P_3 = P_1 P_2 \ , \tag{2}$$

and

$$P_3 = 1 - \left[(1 - P_1)\,(1 - P_2) \right] \ , \tag{3}$$

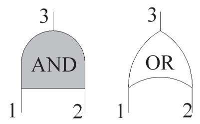

Figure 1. Typical logic gates.

for the OR gate, where P_1 and P_2 are respectively the probabilities of the events 1 and 2. Analogous equations are used if the gates have more than two inputs [4].

Correct construction of the fault tree requires, first of all, precise knowledge of the composition and the structure of the system under analysis, of the technological and structural relationships between the individual system components, and of the principles concerning the system maintenance, repairs, operation etc.

2.2 Procedure for maintenance decision making based on the fault tree analysis results

The procedure is composed of three modules: the risk estimation module, risk assessment module and module of operation-maintenance decision making. In this procedure, the system failure probability is determined by means of the FTA analysis, and the averaged consequences of failure expressed in a monetary unit are the arithmetic average of the consequences of all potential failure scenarios. Basing on the failure probability values and consequence values obtained in this way, the technical risk of the whole system is determined according to Eq. (1). The diagram of the risk estimation module is presented in Fig. 2. The risk assessment module is presented in the diagram in Fig. 3. The first step is to compare the previously estimated risk of a given system with allowable risk. The allowable risk value should take account of the capabilities and the financial situation of the company. If the risk for a given system exceeds the level of allowable risk, the maintenance management for the system has to be modified.

In the last module of the analysis (Fig. 4) the repair operation schedules for the components constituting a system whose risk exceeded the allowable risk level have to be modified. Given the allowable failure probability is determined for a given system on the basis of the allowable risk level. In the next step, the failure probability of primary components has to be modified so that the occurrence probability of the top event will not exceed the allowable value. In the applied model, maintenance is assumed as a perfect one.

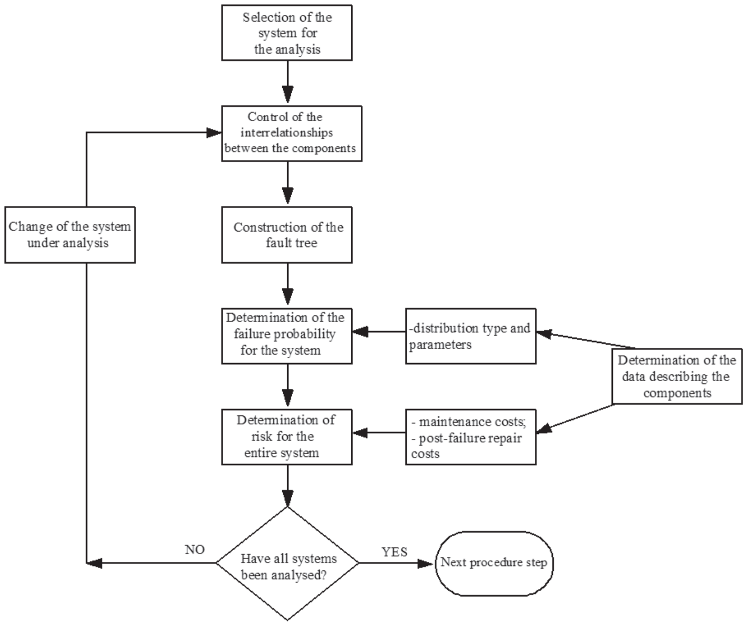

Figure 2. Risk estimation module.

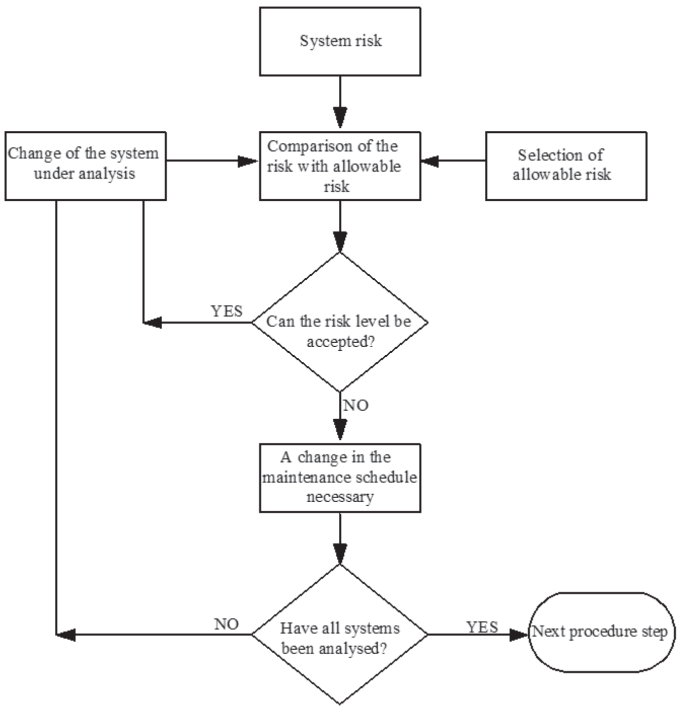

Figure 3. Risk assessment module.

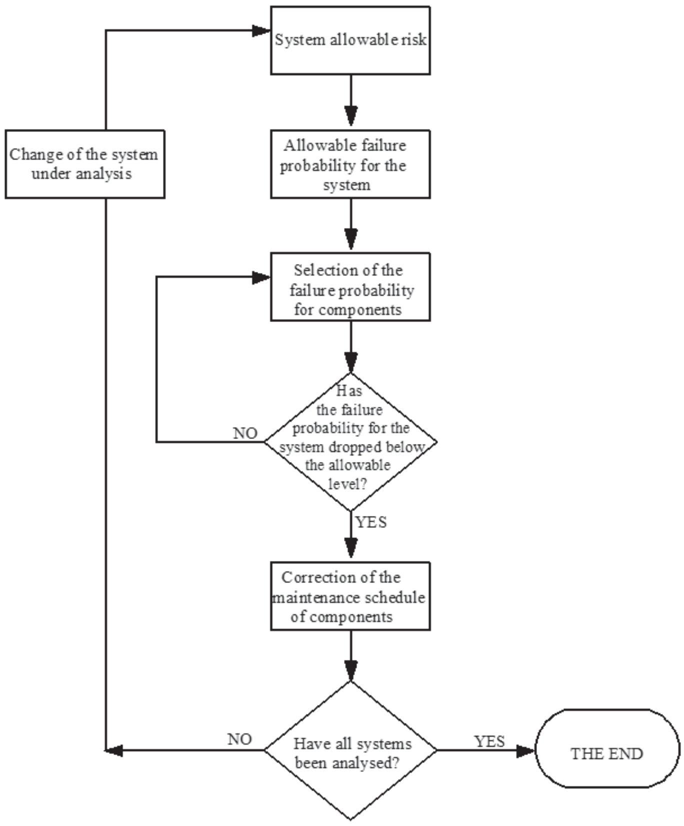

Figure 4. Maintenance schedule modification module.

3 Example of the selection of maintenance intervals for the turbine

A fault tree analysis was carried out for the failure of the turbine set top event. The location of the event on the fault tree of the entire power unit is presented in Fig. 5. The figure also includes the most common causes of the occurrence of event 1 in the form of events 2, 3, 4, 5, which represent the failures of: the turbine, lubrication system, steam supply system, and other failures, respectively. Figure 6 presents primary events A–F leading to the failures of the turbine. These are failures of the casing, flow system, sealing, rotors, bearings and couplings. Lubrication system failure (Fig. 7) is caused by failure of pumps or oil pipelines. Event 6 may occur only if both the main and auxiliary oil pumps fail at the same time.

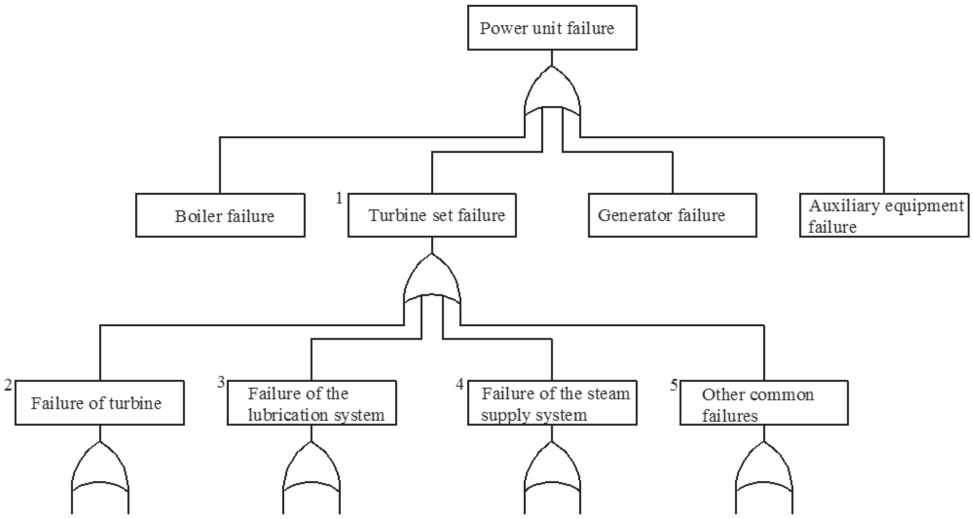

Figure 5. FTA tree for the failure of the power unit event.

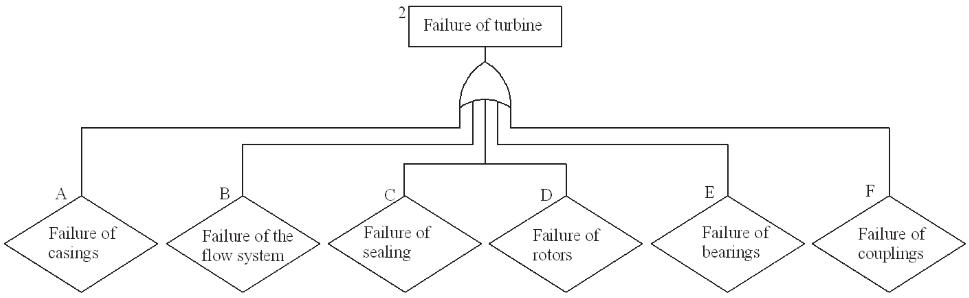

Figure 6. FTA tree for the failure of the turbine event.

The fault tree for the failure of the steam supply system event is presented in Fig. 8, which provides the basis for the identification of the failure cause. The steam supply system fails if the control or cut-off valves are damaged, or if there is a pipeline failure. Event 5 – other common failures – comprises the automatic control failure or faulty operation of technological controls (Fig. 9).

Based on the record of the operation history of this type of machinery and equipment, the type of failure time distribution and its parameters for all the primary events (A–N) were determined. On the basis of the goodness-of-fit tests it was found that the times of components failure could be described with

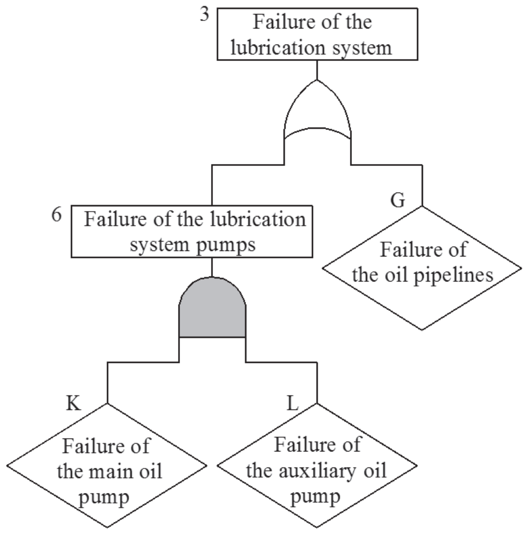

Figure 7. FTA tree for the failure of the lubrication system event.

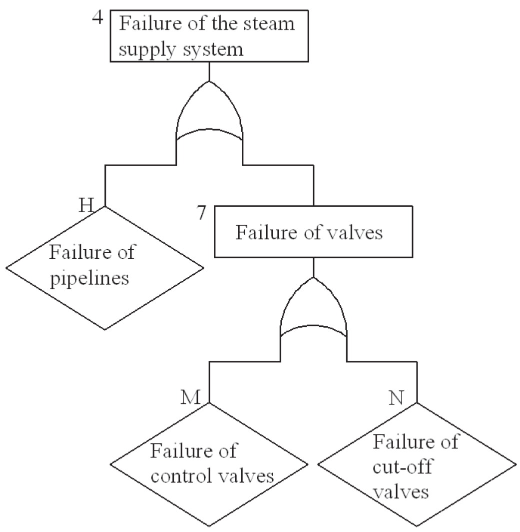

Figure 8. FTA tree for the failure of the steam supply system event.

an exponential distribution or with the Weibull distribution with the following forms of the cumulative distribution function:

- exponential distribution

$$F(t) = 1 - e^{-\lambda t} , \tag{4}$$

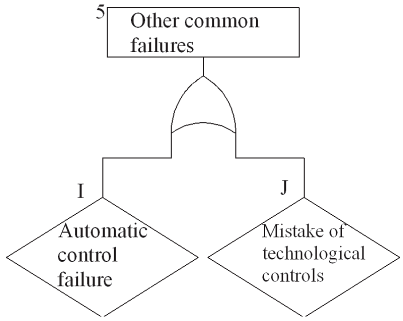

Figure 9. FTA tree for other common failures event.

- Weibull distribution

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \tag{5}$$

where λ is the rate parameter of the exponential distribution, while β and α are respectively the shape and scale parameters of the Weibull distribution.

For each component, the failure costs, K_a, (corrective maintenance), and preventive maintenance costs, K_r, were estimated. All costs were expressed in relative monetary units; the interrelationships between them were kept. The costs of the preventive maintenance of components were assumed at the level of 10% of their failure costs. The input data for the analysis are presented in Tab. 1.

Table 1. Input data.

Component	Distribution	β [–]	α [month]	λ [1/month]	K_a	K_r
A	exponential			0.0006	90	9
B	exponential			0.0003	70	7
C	exponential			0.0006	50	5
D	exponential			0.0014	50	5
E	Weibull	3.4	148		100	10
F	exponential			0.0003	20	2
G	exponential			0.0003	5	0.5
H	Weibull	1.9	180		5	0.5
I	exponential			0.003	10	1
J	exponential			0.006	10	1
K	Weibull	2.2	151		10	1
L	exponential			0.0003	10	1
M	Weibull	2.1	160		30	3
N	Weibull	1.3	201		30	3

On the basis of the distribution parameters, it was possible to determine the probability of the failure of individual components for a given time. The calculations were conducted for 72 months (6 years), due to the usual length of the period between major overhauls of the turbine. For the same period of time, the occurrence probability of top event 1 was determined. The occurrence probabilities of events A–N and 1–7 for 72 months are listed in Tab. 2.

Table 2. Probabilities of occurrence of events A–N and 1–7 for 72 months.

Event	Probability of event	Event	Probability of event
A	0.0423	1	0.8012
B	0.0214	2	0.2715
C	0.0423	3	0.0251
D	0.0959	4	0.4650
E	0.0827	5	0.4769
F	0.0214	6	0.0038
G	0.0214	7	0.3625
H	0.1608		
I	0.1943		
J	0.3508		
K	0.1780		
L	0.0214		
M	0.1705		
N	0.2315		

The averaged failure cost of top event 1 was assumed as the arithmetic average of the failure costs of primary components (K_{ai}), according to

$$K_{a1} = \frac{1}{N} \sum_{i=A}^{N} K_{ai} = 35 \text{ [monetary units]} . \tag{6}$$

The risk related to event 1 is calculated form the following dependence:

$$R_{T1}\,(72 \text{ months}) = P_1\,(72 \text{ months})\, K_{a1} = 28.042 \text{ [monetary units]} \ . \tag{7}$$

As it was mentioned before, the consequences of the failure and the risk are expressed in relative monetary units. The next step in the procedure is to assume the allowable risk level for the entire system, $R_{Tallowable}$, whose value depends, among others, on the financial situation of the company. For the purpose of the analysis it was assumed that $R_{Tallowable} = 12$ units for a given period. The system risk level R_{T1} for data assumed in this way substantially exceeds allowable risk $R_{Tallowable}$. The above means that the maintenance schedules for primary components A–N have to be modified. Using the allowable risk value for Eq. (7), the boundary occurrence probability of the top event was obtained:

$$P_{1allowable} = \frac{R_{Tallowable}}{K_{a1}} = \frac{12}{35} = 0.343 \; . \tag{8}$$

Then, the probabilities of failure of primary components A–N have to be modified so that the newly determined occurrence probability of the top event will not exceed the boundary probability value. The probability level is affected by carrying out maintenance of the component.

The method of the selection of the maintenance intervals that allows the optimisation of the costs of actions related to the maintenance and repairs in a set period of operation is described in [8]. The results of the calculations of the maintenance intervals for components A–N are listed in Tab. 3. In fact,

Table 3. Results of optimization.

Event	Probability of event	Maintenance interval [month]	
		calculated	selected
A	0.0310	52.49	48
B	0.0199	67.15	66
C	0.0282	47.65	42
D	0.0447	32.70	30
E	0.0496	61.64	60
F	0.0114	38.21	36
G	0.0085	28.61	24
H	0.0214	23.96	18
I	0.0389	13.21	12
J	0.0234	3.94	12
K	0.1424	64.45	60
L	0.0171	57.48	54
M	0.0568	41.41	36
N	0.0617	24.17	24

the scheduled repair activities are not carried out at an unspecified time. The works are grouped in periods not shorter than 6 months or their multiplicity. It was also assumed in the analysis that the maintenance of a given component could not take place more frequently than every 12 months. Therefore, the results obtained after the calculations need to be verified. The calculated periods shorter than 12 months are lengthened to one full year, and others are shortened to the nearest multiplicity of 6 months. Then, it is checked once more whether the boundary condition has been met, and – if necessary – the maintenance intervals of components are shortened according to the ranking.

Table 4 allows a comparison of the results of the example solution, in which all elements are repaired every 24 months, with the results of the final optimum solution. On this basis, it can be stated that repairing all components every 24 months ensures a comparable level of the failure probability of the entire system. However, this solution is by 62% more expensive when compared to the final solution. In both cases the boundary condition is met, i.e. the allowable risk level is not exceeded.

Table 4. Comparison of correct solutions.

	Maintenance intervals	
	24-month, for all components	selected [month]
Maintenance cost in the whole period [monetary units]	147	91
Occurrence probability of of event 1	0.3335	0.336

4 Conclusions

The maintenance strategy presented in this paper combines the fault tree analysis with the method of selection of maintenance decisions which take account of risk. This approach can also be applied in the analysis of complex systems. The procedure requires reliability data of the components, as well as the data concerning the corrective and preventive maintenance costs. Based on the example of the analysis carried out for a turbine set, the possibility of an optimisation of the selection of the maintenance intervals for its components with respect to the cost minimisation objective is presented. A substantial reduction in the costs intended for maintenances was obtained when compared to the maintenance schedule based on fixed intervals. At the same time, maintenances conducted in the optimised periods ensure the required level of operational safety.

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Zastosowanie analizy drzewa uszkodzeń w planowaniu okresów międzyremontowych układów bloku energetycznego

S t r e s z c z e n i e

Metoda analizy drzewa uszkodzeń (FTA) jest zaawansowaną metodą analizy niezawodności złożonych systemów. Pozwala ona oszacować prawdopodobieństwo uszkodzenia całego systemu w funkcji prawdopodobieństw zajścia zdarzeń pierwotnych, prowadzących do awarii systemu. Metoda ta może być również stosowana do oceny ryzyka obiektów złożonych. W artykule przedstawiono procedurę doboru okresów międzyremontowych złożonych układów bloków energetycznych z uwzględnieniem ryzyka. W etapie szacowania ryzyka wykorzystano analizę drzewa uszkodzeń. Obliczony poziom ryzyka porównano z ryzykiem dopuszczalnym. Zbyt wysoki poziom ryzyka obecnie lub w dalszej eksploatacji powoduje konieczność modyfikacji harmonogramu planowanych działań remontowych. W artykule zaproponowano sposób racjonalnego doboru zakresów i okresów przeprowadzania remontów poszczególnych elementów układu, oparty o tzw. współczynnik efektywności remontu. Współczynnik ten podaje efektywność remontu rozumianą jako stopień obniżenia ryzyka całego układu, uzyskany jednostką nakładów finansowych na remont danego elementu. Podano przykład doboru okresów remontowych zespołu turbiny bloku energetycznego.