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OPTIMIZATION OF POWER MACHINES MAINTENANCE INTERVALS TAKING THE RISK INTO CONSIDERATION

OPTYMALIZACJA OKRESÓW MIĘDZYREMONTOWYCH MASZYN ENERGETYCZNYCH Z UWZGLĘDNIENIEM RYZYKA*

The goal of preventive as well as corrective maintenances is to keep or to restore acceptable level of efficiency and safety of operation of given object. Optimization of maintenance processes allows obtaining these effects at possibly lowest costs. Mathematic model of optimization of maintenance intervals having regard to the risk are presented in the paper. Precise calculations were made for steam turbines that operate in power units.

Keywords: *optimization, maintenance intervals, power machines, risk.*

Celem obsług prewencyjnych jak i korekcyjnych jest zachowanie lub przywrócenie akceptowalnego poziomu efektywności i bezpieczeństwa eksploatacji danego obiektu. Optymalizacja działań remontowych pozwala na uzyskanie tych efektów przy możliwie niskich kosztach. W artykule przedstawiono model matematyczny optymalizacji okresów międzyremontowych z uwzględnieniem ryzyka. Szczegółowe obliczenia przeprowadzono dla turbin pracujących w blokach energetycznych dużej mocy.

Słowa kluczowe: *optymalizacja, okres międzyremontowy, maszyny energetyczne, ryzyko.*

1. Introduction

Maintenance activities, both preventive and corrective ones after a failure occurs, are to keep or restore acceptable level of operation of given object. The goal of these operations is to improve reliability and safety of operation, at as low as possible costs. Development of new techniques and methods of maintenances within the recent years is connected with formal regulations and expectations to improve operation safety of every technical object. These requirements are especially significant for large systems that provide correct functioning of many branches of economy. Power system as well as its basic subsystems of generation and transmission belong, among other, to these systems. Reliability of generation subsystem depends on reliability of power units as well as its main components, i.e. turbines, boilers and generators. The proper and safe operation of these machines and devices provide the safety of electric energy generation in its various forms, i.e. electric energy as well as heat. On the other hand, the market and competition of electric power manufactures at this market requires reducing any possible costs, including maintenance activities that have significant contribution to the final price of energy.

The method to determine the maintenance intervals presented in further sections of the paper is based on operation costs minimization or maximization of profit on operation. Both objective functions forms take into account the risk level. Precise considerations were made for steam turbines components that operate in large power units.

2. Maintenance intervals optimization model

As it was mentioned before, the basic purpose of preventive maintenances is to cancel of negative effects of various wear processes that deteriorate technical condition of objects and to restore it to such a level that object could operate safely until the next renovation not being submitted to a failure within this period. Frequently the industrial usage accomplishes these activities within regular periods of time on the basis of operational experience. More and more frequently, the knowledge gained from diagnostic tests and operation monitoring system of given device is used as well. An approach suggested beneath assumes taking into consideration both the costs of maintenances and operation safety level. Technical risk level connected with operation of given object may be the measure of this safety. Technical risk is understood as the product of probability of an adverse event occurrence as well as it consequences [1, 2, 8, 9, 10]. Denoting the risk as R we note:

$$R = \sum_{i=1}^{n} P_i C_i \tag{1}$$

where: P_i –probability of event "i" occurrence,
C_i – consequences of event "i" occurrence,
n – number of dangerous events that relate to given object.

The risk so defined may constitute the basis to formulate optimization criteria of periods and scopes [3, 11] of preventive

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** maintenance. To do so the concept of admissible risk level is to be used. The basis to perform calculations of probability of disadvantageous events are data on object operation, including, the first of all, data about failures and damage of components. Knowledge on wear processes is indispensable, which, i.e. processes may lead to damage of components. The second of factor, that decides of risk level, i.e. failure and damages consequences are most frequently expressed in terms of monetary units. The appropriate establishing them requires profound knowledge on operation conditions, repairs as well as economy issues of given enterprise.

If consequences shall be expressed in monetary units, so the risk described with relationship (1) has this measure. It becomes an economic category and can be taken into consideration in economic calculation. Using this fact, we may present the planning procedure of maintenance as a procedure of total costs optimization K_c. Risk shall be taken into account in these costs as well. Thus, we obtain:

$$K_c = K_r + R \tag{2}$$

The first term in the above sum K_r denotes total costs incurred to maintenance a given object, i.e.:

$$K_r = \sum_i K_{ri} \tag{3}$$

whereas the second term of the dependence (2) denotes the total risk that given object creates:

$$R = \sum_j R_j \tag{4}$$

Referring the costs in the term (2) to operation time t we obtain a relative cost per unit of time:

$$\overline{K}_c = \frac{K_r + R}{t} = \overline{K}_r + \overline{R} \tag{5}$$

where $\overline{K}_c, \overline{K}_r, \overline{R}$ are the values referred to the time unit. The optimum value of period between overhauls shall be obtained via objective function minimization V, which is – in our case – the total cost $\overline{K}_c$, i.e:

$$V = \overline{K}_c \tag{6}$$

$$V \rightarrow min \quad \Rightarrow \quad t = t_o \tag{7}$$

that is presented on graph in Fig. 1.

If, during optimization process we shall take into consideration the profit Z obtained on object operation, thus objective function could be a difference between profit Z and total costs K_c that take the risk into consideration as well. Thus, we may note:

$$V = \Delta \overline{K} = \overline{Z} - \overline{K}_c = \overline{Z} - (\overline{K}_r + \overline{R}) \tag{8}$$

The goal of optimization for such formulated objective function form is its maximization, i.e.:

$$V \rightarrow max \Rightarrow t = t_o \tag{9}$$

Every value in the above mentioned formulae are related to the unit of time. If we assume that profit is a linear function of operation time thus unit profit as referred to time unit shall be constant and optimum determined from relationship (9) shall be the identity with the optimum obtained from relationship (7).

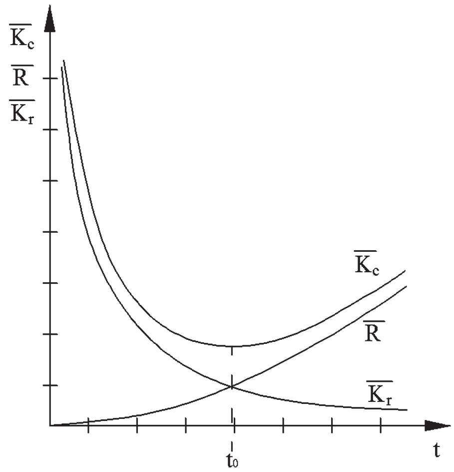

Fig. 1. Concept of selection of optimum maintenance intervals

However, as time elapses, object efficiency drop occurs then the profit in consecutive periods is lesser and lesser that denotes that value $\overline{Z}$ is a decreasing function of time.

In case of machines and power devices, their efficiency η is defined as ratio of energy generated (for instance electric energy) E_w to energy supplied (for instance chemical energy of fuel) E_d:

$$\eta = \frac{E_w}{E_d} \tag{10}$$

Thus, generated energy is a function of efficiency that depends on time:

$$E_w(t) = \eta(t) E_d \tag{11}$$

Assuming that profit Z of operation is proportional to energy volume generated, we may note:

$$Z = pE_w = p\eta(t)E_d \tag{12}$$

where: p is a constant that describes share of profit in total incomes obtained from generated energy E_w.

Thus we may assume that at constant energy volume supplied the profit drop in given period is proportional to devices efficiency drop.

In such a case, optimum obtained from optimization of objective function expressed by relationship (9) may differ from objective function optimum described with equation (7), Fig. 2.

The goal of preventive maintenances is to improve the object operation properties. Taking into consideration the scope of restoration of object output condition, we may distinguish [7]:

- perfect maintenance that restores entirely the initial usable object properties – an object may be considered as a new one,
- minimum maintenance that does not change usable properties of object; its failure intensity does not change,
- imperfect maintenance, as a result of which, object usable properties are improved but not to the level as a new object had.

According to the above classification, minimum and perfect maintenances are boundary state of imperfect maintenance. There are many methods of imperfect maintenance described in

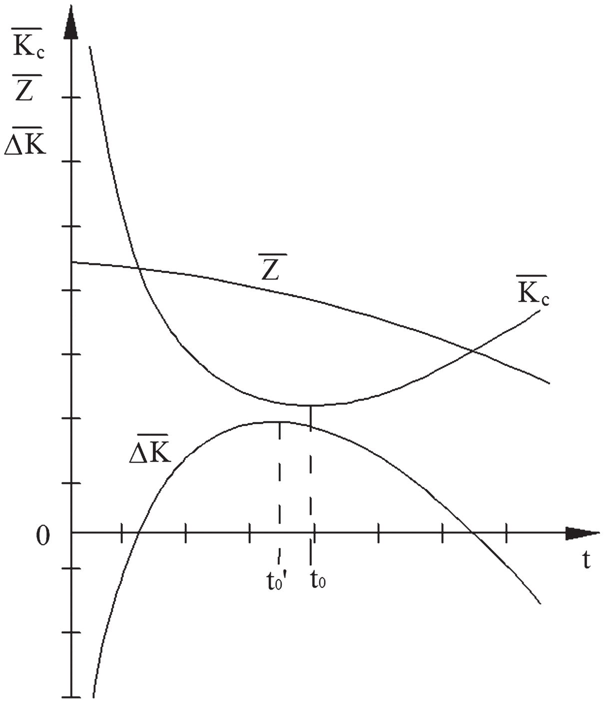

Fig. 2. Concept of selection of optimum maintenance intervals taking the profit into consideration

references [5, 7]. One of them is so called a method of virtual object age [5, 7]. According to this method, if object virtual age after (n-1) of preventive maintenances was (t^*_{n-1}), then, after the next maintenance has the value:

$$t_n^* = t_{n-1}^* + (1 - a)\Delta t \tag{13}$$

where: Δt is a time interval between n-1 and n-th preventive maintenance.
a is so called age reduction coefficient that assumes value from interval <0;1>. Value of this coefficient de pends on scope and results of maintenance.

If maintenance activities cancel significantly negative results of operation and wear processes then value of coefficient *a* assumes values close to one. In an opposite case, when object condition, after maintenance did not change in practice, coefficient *a* assumes the value zero. Undoubtedly, effects of maintenance expressed with coefficient *a* depend on investments paid to execute it.

Further part of the paper describes an example of optimization of preventive maintenance intervals of power machines using the optimization model set forth above.

3. Optimization of preventive maintenance intervals of rotor assemblies of turbines

Turbine rotor assembly that includes, among other, the shaft, rotor blades, discs, bearings, clutches and sealing compose the main turbine component of basic meaning for its reliability and availability. Failure frequency statistics and data on turbine operation indicate that basic failure of rotor assembly are as follows [2, 4, 6, 9]:

- damage of blades caused by vibrations as well as corrosion and erosion processes,
- bearings damage that result from design errors, improper lubrication or turbine operation errors,
- excessive relative elongations of rotor and casing caused, among other, with operation errors of boiler or turbine, design errors,
- leak of oil system caused by cracks of its elements,
- excessive vibrations of turbine shaft, caused by thermal shocks,

Moreover, other failures are also possible, including tear of rotor, but probability of its occurrence is very small at initial stage of operation; it becomes significant after long operation periods.

Finally, four scenarios were assumed for precise analyses of most frequent failures of rotor assembly. These are:

1. Failure of turbine bearings causing secondary damage of flow system,
2. Failure of turbine bearings without damage of other elements,
3. Failure of blade in turbine flow system,
4. Failure of labyrinth sealing of rotor.

The first two scenarios mentioned above relate to turbine bearings; how to distinguish them is advised with the scope and consequences of its damage. If damage of bearings causes damage of flow system of rotor, financial consequences connected with repair as well as necessary standstill of machine and thus losses in energy generation are many times greater. Damage areas described with the above scenarios are marked on turbine diagram in Fig. 3.

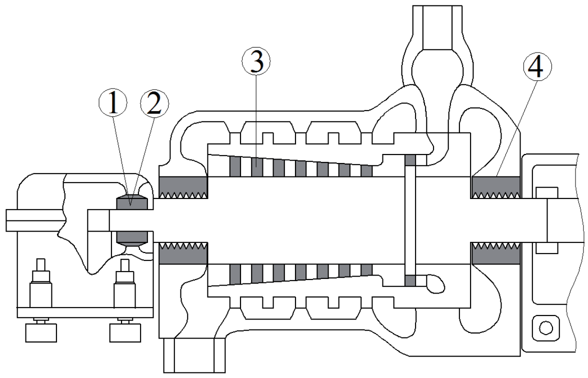

Fig.3. Turbine diagram

On the basis of operation data it was found that operation time up to a failure according to all contemplated scenarios could be described with Weibull cumulative distribution functions:

$$F(t) = 1 - exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{14}$$

where, α, β are Weibull distribution parameters. Values of these parameters for separate events are shown in Table 1.

Table 1

Scenario No	Weibull distribution parameters		Relative failure costs
	α	β	
1	296	2,9	1,00
2	148	3,4	0,33
3	444	2,7	0,33
4	80	2,9	0,04

On the basis of cost analysis connected with occurrence of the above mentioned failures, relative values were established that were referred to the costs of most serious failure described with scenario No 1. These costs, indicated also in Table 1, cover direct repair costs, replacement parts, losses caused by lost production as well as other additional costs incurred in connection with occurrence of failure. Assessment of occurrence probability of a given sort of failure as well as its costs makes possible to calculate the risk. Time functions of risks connected with four scenarios mentioned as well as total risk of rotor assembly were shown in Fig. 4. Risk value is expressed in terms of monetary relative units according to Table 1.

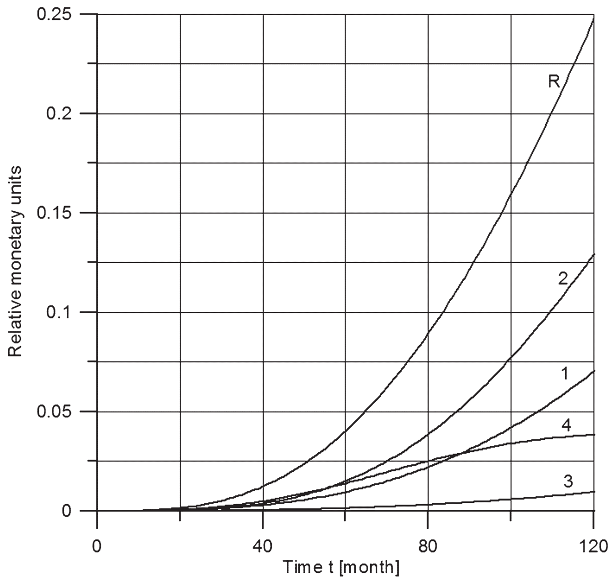

Fig. 4. Risks connected with operation of rotor assembly

Knowledge on investment outlay connected with repairs related to rotor assembly, whose purpose is to avoid the above mentioned damages allows – according to relationship (7) – determining the optimum time to execute maintenance. In calculations, the relative cost of preventive maintenances was assumed

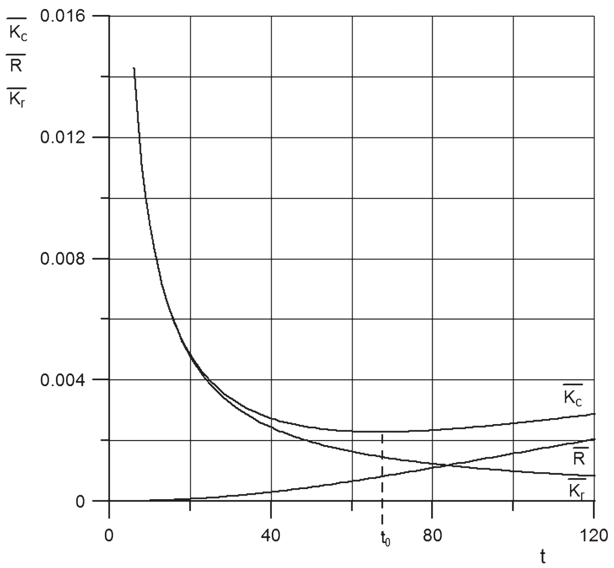

Fig. 5. Optimum maintenance time of the turbine rotor assembly according to criterion (7)

equal 0,1 of failure cost described with scenario No 1. Result of such optimization is given in Fig. 5. For data assumed, the optimum time to execute maintenance is 67 months.

Optimisation results according to criterion (9) are shown in Fig. 6. Maximum profit per time unit was assumed equal to 0.01 of failure cost according to scenario 1. Power unit efficiency within 60 months varies from 34% up to 32%. Optimum time to execute maintenance $t_o' = 52$ months.

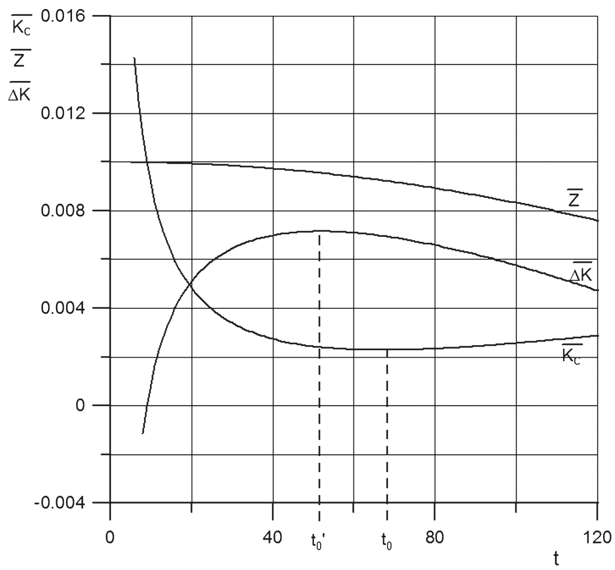

Fig. 6. Comparison of optimum maintenance times of turbine rotor assembly according to criterion (7) and (9)

Assuming that repair actions performed restore the initial condition of rotor assembly component and operation conditions do not change, consecutive maintenances should take place within the same period of time. However it is known in practice that it is not possible to restore entirely the initial condition of elements and renovation process itself should be considered as an imperfect maintenance. Accepting such assumption and assuming that renovation effect could be described by so called virtual object age in accordance with relationship (13), then consecutive periods between maintenances shall depend on value of coefficient of age reduction *a*. Examples of periods optimization between maintenances for two different coefficients *a* are shown in Fig. 7 and 8. Fig. 7 specifies optimum maintenance periods under assumption that reduction coefficient value is 0.95, whereas Fig. 8 gives optimum solution for coefficient $a = 0.85$. In both cases, optimization was accomplished for objective function described with relationship (9).

It results from specific relationships, that consecutive time between maintenances subject to slight reduction. For assumed data the recent times between maintenances are shorter by 2 up to 3 months than the initial ones.

4. Summary

The mathematical model of selection of time between maintenances set forth in the paper takes into account both economy effects and risk level connected with operation of given object. This model has been used to estimate the time between overhauls of steam turbines that constitute one of main component of power unit. On the basis of real data on failure frequency of turbines of domestic power units the probability was calculated

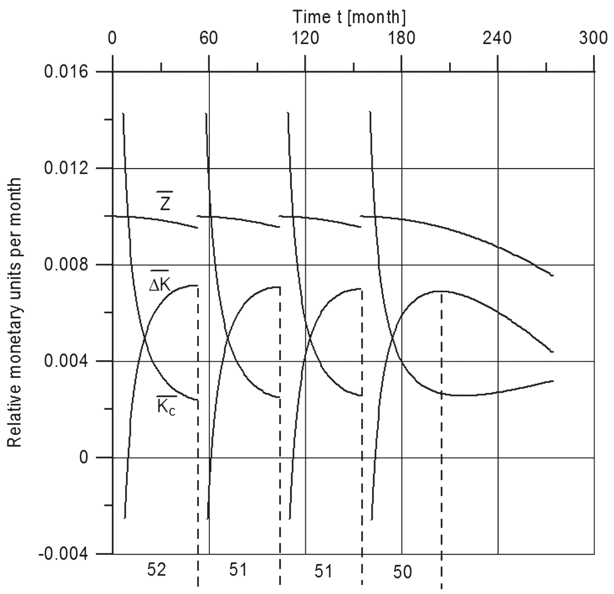

Fig. 7. Optimum times of preventive maintenances for a = 0.95

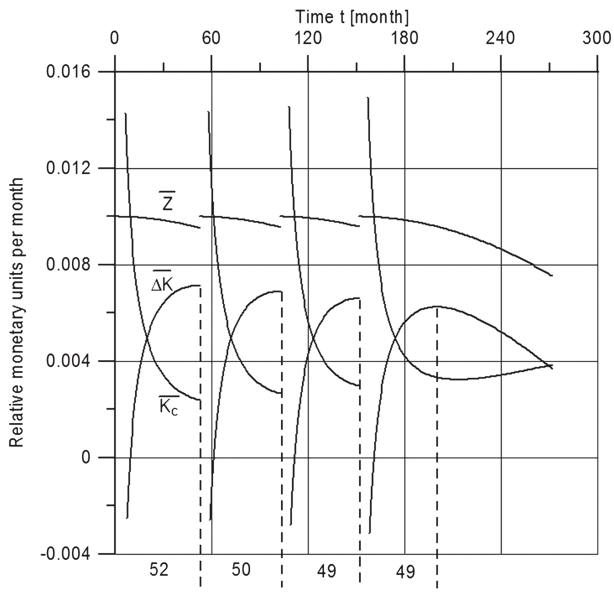

Fig. 8. Optimum times of preventive maintenances for a = 0.85

of occurrence of four main failure scenarios. Relative values of consequences of these events were estimated as well as risk level. As a result of solutions of optimization tasks for various formulation of objective function the optimum periods to execute the first and consecutive maintenances of turbine were obtained. Duration of these times between maintenances depends on quality of performed overhaul.

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