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An Opportunistic Maintenance Optimization Model for Shaft Seals in Feed-Water Pump Systems in Nuclear Power Plants

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***Abstract*—Nuclear power is one of the main electricity production sources in Sweden today. Maintenance management is one tool for reducing the costs for operation of a power plant. Driving forces for cost-efficiency has pushed the development of new methods for maintenance planning and optimization forward. Reliability Centered Asset Management (RCAM) is one of these new approaches, and maintenance optimization is one way to perform quantitative analysis which is a feature of RCAM. This paper proposes a model for opportunistic maintenance optimization where replacement schedules for shaft seals in feed-water pump systems in nuclear power plants are constructed. The feed-water pump system is important for the availability of the entire nuclear power plant. Results show that the optimization model is dependent on e.g. the discount interest and a limit for when the optimal solution goes from non-opportunistic to opportunistic is calculated. The circumstances for which opportunistic maintenance could be used have been investigated given different values of discount rates and remaining life at start of the planning period.**

***Index Terms*—Maintenance management, nuclear power, opportunistic maintenance, optimization, reliability.**

I. INTRODUCTION

A sustainable energy system must involve several electrical production sources. Local conditions are decisive for determining the electrical production system that should be dominating. About 90% of the electricity production in Sweden is today from nuclear power and hydro power, however there are large increase in renewable energy production from e.g. wind.

One benefit with nuclear power is that the operation is almost free from climate-affecting pollution. A major disadvantage is the waste and its final storage. Nuclear power is associated with several risks. Risk is defined as the probability of failure multiplied by the consequences of failure. The probability of failure is a reliability measure. The performance of operation and maintenance must always be safe and structured. Reliability-centered maintenance (RCM) is a structured approach that focuses on reliability when planning maintenance [1].

The deregulation of the electric power system and the introduction of the electricity market have generally led to lower investments in maintenance. As a result, new approaches
for maintenance management have been developed, such as Reliability Centered Asset Management (RCAM) [2]. RCAM is a development of RCM into a quantitative approach with the aim to relate preventive maintenance to total maintenance cost and system reliability.

This paper focuses on RCAM using a maintenance optimization approach for nuclear power plants. Moreover, an opportunistic approach is used. A general optimization model, applied for example to the replacement of components in aircraft engines [3], is used to gain a maintenance schedule for replacements of subcomponents. The system observed is the feed-water pump system, which is a system in the nuclear power plant critical for the availability of the plant. This system is necessary for maintaining a stable level of water in the reactor, and it must therefore keep a steady flow in the tank. Minimizing costs for replacing shaft seals and costs for production loss would gain an optimal maintenance schedule. As a case study, the Boiling Water Reactors (BWR) at Forsmark nuclear power plant are studied.

II. THEORY

A. Availability

Availability is an important measure of reliability, and has several different definitions. One definition is found in [4]:

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the probability that the component or system is capable of functioning at a time *t*.

B. Maintenance

The purpose of maintenance is to enable a desired system or component performance by maintaining or returning the components' ability to function correctly [5]. The maintenance concept does not provide only one correct operational solution. In this paper it is divided into preventive maintenance (PM) and corrective maintenance (CM) [6]. PM is maintenance carried out before failures occur, and CM is maintenance carried out after failures occur.

Opportunistic maintenance refers to the situation in which preventive maintenance is carried out at opportunities [3]. A typical example is when one component is out for maintenance and it is decided to take out another component for maintenance ahead of the maintenance plan, since it is considered to be rational. Opportunistic maintenance is typically maintenance carried out in a way that is cost-saving as at least two maintenance activities are performed at the same time. For minimizing the total cost for maintenance and production loss, opportunistic maintenance is an interesting approach.

C. Reliability-Centered Maintenance (RCM)

Reliability-centered maintenance, RCM, is a systematic method to balance between preventive and corrective maintenance. This method chooses the right preventive maintenance activities for the right component at the right time to reach the most cost efficient solution. RCM was introduced in nuclear power in 1980 and in hydro power in 1990 [5].

Reliability-centered asset management, RCAM, is a quantitative approach outgoing from RCM [2]. The aim of RCAM is to relate preventive maintenance to total maintenance cost and system reliability. The method is developed from RCM principles, and attempts to more closely relate the maintenance's impact on total system cost and reliability. The aim is to use quantitative methods to see the effect of component-level preventive maintenance on system cost and reliability.

D. Discounting

The Life Cycle Cost (LCC) for a technical system is its total cost during its lifetime. The goal is to minimize the total lifetime cost. The total cost includes all costs associated with planning, purchasing, operation and maintenance, and liquidation of the system. Power plant financial concerns could typically be investment, maintenance, production loss and rest value.

The *Present Value Method* compares all future payments over a certain time to the present time. The present value (PV) means the amount of money that should be deposited into the bank now at a certain interest rate (r) to pay for an outlay (C) after n years. This means that all future payments are re-calculated to the equivalent value at the present time.
The present value of one outlay (C) to be paid after n years is gained by multiplying C by the *present value factor* ($\mathrm{PV}_f(n,d)$) as follows [5]:

$$PV = C \cdot PV_f\left(n,r\right) = C \cdot \left(1+r\right)^{-n} . \quad (1)$$

When discounting with the present value method, real or nominal interest rates could be used. The nominal interest rate takes inflation into account. The discount rate r depends on the real interest r_1, and the inflation r_2, according to:

$$1 + r = (1 + r_1)(1 + r_2)\ . \quad (2)$$

The interest is decided by the company management and indicates the return that is required for making an investment. The choice of interest rate is not obvious or trivial. Examples of interests used are 7 % in the wind power industry [7], while it is usually assumed to be slightly lower in the nuclear power industry. The choice of interest value depends on, for example, the length of the investment. A long investment can include larger risks as the future is unknown. Investments where a higher risk is taken require a higher interest.

III. OVERVIEW OF THE APPROACH

In this paper, an analysis of an opportunistic maintenance optimization model is made. The approach is as follows:

1. The total cost of maintenance is calculated.
2. This cost is minimized according to some constraints and discounted to model the value of money in time.
3. A sensitivity analysis is made where the different parameters are varied in relation to the discount rate.

The opportunistic maintenance optimization model is a deterministic application of a general optimization model [3].

IV. APPLICATION

A. System Description

The system observed is the feed-water system at Forsmark 1. Forsmark 1 is a Boiling Water Reactor (BWR), and its function is explained here to provide an understanding of the importance of the feed-water system and its function. In the reactor tank there is fuel from Uranium that, when nuclear atoms are split, generates large amounts of heating energy [8]. Nuclear fission is started by pulled out control rods from the core. Heat that is generated at nuclear fission is transferred to the water, which is boiled into steam. The steam produced in the reactor is led in large steam pipes to a turbine facility. The difference in pressure between the reactor and the condenser gives the steam force on its way to the turbine, where the steam's heat energy is transformed into kinetic energy. A generator is connected to the shaft of the turbines. The generator's rotor is rotating at the same speed as the turbines.

In the generator, kinetic energy is transformed into electrical energy. The electrical energy leaves the plant from a switchyard that divide the electrical power into different lines that connect to the Swedish national grid.

The steam still has a large energy when it leaves the low-pressure turbines. This energy is cooled off by large amounts of cooling water. The water is brought into the cooling water channel and is pumped into a condenser, which is a large heat exchanger placed under the low pressure turbines. The cooling water is led into water chambers and passes through the condenser through a large number of pipes, where it gathers the heat of the steam. From the outlet chambers, the cooling water is led in a tunnel. The steam that has turned into water again is collected at the bottom of the condenser. The water collected at the bottom of the condenser is called condensate. It is to be returned to the reactor and is therefore passed through a heat- and pressure-increasing process. After a condensate cleaning process, there are feed-water pumps that can give the water the pressure necessary for it to pass into the reactor. The condensate is at this moment changing name to feed water, which will be heated even more in high pressure pre-heaters. These gain steam from the high pressure turbine to warm up the feed water.

The feed water is pumped into the reactor again and the primary circle is closed. The feed water will replace the amount of water that has boiled to steam and left the reactor. The flow is adjusted continuously in relation to the steam output so that the water level in the reactor is preserved. In all situations there must be total control of the neutron flux in the core and the pressure and the water level in the reactor tank. These parameters affect each other mutually, and the feed-water pump system is important for keeping the process stationary.

B. *System modeling*

The feed-water pump system works with a special type of redundancy so that two out of three pumps always must be in operation and one is redundant. Reactor 1 and 2 at Forsmark nuclear power plant are constructed so that they have two turbines with three feed-water pumps on each turbine. If two pumps out of three on one turbine where to go down for some reason, there would be a loss in power of 25 % on the actual reactor. If three pumps where to go down the loss in power would be 50 %. As a first step, production loss is not considered, since one pump at a time is observed. To gain a model that can consider production loss, the entire system with three pumps must be observed. This is planned to be done in future work.

The mechanical failures that dominate in feed-water pumps are failures on shaft seals in the pump. They are today replaced when they fail as they are expensive components, i.e. no PM is carried out. Indications of failures are that hot water is leaking from the shaft. When this phenomenon appears, or when temperature sensors show that the temperature is over a certain limit, inspections are made. Then a decision on whether the shaft seal should be replaced or not is made.[1] Each pump has two shaft seals, and an interesting question is if it is beneficial to replace both of them when one is failing. In this first modeling stage, one pump with two shaft seals is observed.

V. MODEL

A. *Total Cost Model*

In [5] a total cost model for distribution systems is constructed. Costs included are costs of failure, or cost of CM, cost for PM and cost of interruption. For production systems, the interruption cost is the cost for production loss (PL). This gives the following model:

$$TC = C_{PL} + C_{CM} + C_{PM}\,. \qquad (3)$$

The cost for PL can be modeled as a cost per energy unit times Energy Not Supplied (ENS) which, with the typical type of redundancy, would be fourths of the total production loss, depending on how many pumps are down. When observing one pump only, the PL cost is not included in the total cost. The pump is always running and no cost for PL appears. When observing three pumps and when two pumps must be running the cost for PL is taken care of by always running two pumps.

The cost for CM is the cost for maintenance that is done after the failure is observed, that is the cost of failure. At Forsmark today, only CM of shaft seals is performed. Shaft seals used in the pump in the feed-water pump system are expensive components, and no trials have been made yet to do PM-replacements of the shaft seals.

The cost for PM is the cost for maintenance done before the failure has been observed, and opportunistic maintenance is one type of PM. In this paper an attempt is made to see if it is beneficial to make replacements of two shaft seals at one time, that is, to perform opportunistic replacements.

B. *Opportunistic Deterministic Optimization Model*

There are two shaft seals on the pump, which are replaced either one or two at a time. The deterministic model to be given below decides that the replacement of one or two shaft seals should be carried out when, or before, the life length of the shaft seal ends. This decision depends on the constant cost for performing the maintenance, and the spare part cost for the shaft seal. The total cost for maintenance is summed over time and minimized subject to some constraints. Two binary variables indicate if maintenance is performed at all at a certain time, and if a certain shaft seal is replaced at a certain time. The first constraint says that if a replacement is carried out, then maintenance is performed. The first binary variable that indicates maintenance is forced to be one if the other binary variable, which indicates replacement, is 1. The next

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[1] Interview with F.Masman, Forsmark Nuclear Power plant, March 2008.

constraint says that the shaft seal must be replaced within the interval of the life length and the final constraint says that the first replacement must be performed before the initialized life length, which is given by the age of the shaft seal at the beginning of the time period.

1) *Planning period*

The time period used in this approach is six years. Replacements of shafts are carried out after 11000 hours on average. This is the assumed life length of the shaft seals in the model. The system is an ageing system, but is treated with a deterministic approach. The life lengths for shaft seals that were observed were all exceeding 11 000 hours and therefore the choice was made to use a life limit of 11 000 hours. The initialized life length, which is the life length of the shaft seal at the beginning of the time period, needs to be set at the beginning. The remaining life at the beginning is 1 time step for shaft seal 1 and 10 time steps for shaft seal 2, in the basic case.

2) *Time steps*

The six years are divided into hours and the time step has then been chosen to 1000 hours. This gives the contract time 55 time steps and the life length 11 time steps in the basic case.

3) *Input data*

Working orders from Forsmark 1 have been studied and an average time for exchanging one or two shaft seals has been calculated. An average time for the life length of the shaft seals has also been calculated, with data extracted from working orders. The time for exchanging shaft seals times the working cost, is not the only cost included in the constant cost. Other costs should be included to get a more realistic model. This is however difficult to estimate for a single isolated component.

4) *Costs for maintenance*

The cost associated with performing maintenance is a constant cost *d*. The cost associated with the replacement, a cost per shaft seal called *c*, is the spare part cost. An estimation of data that depends on whether both shaft seals are replaced at the same time, or if only one is replaced, were made. The average times for exchanging one or two shaft seals are different. This together with the spare part cost for *k* shaft seals (*k* = 1,2) gives the total cost for replacing *k* shaft seals:

$$n_P \cdot t_{RWT}(k) \cdot c_{WT} + k \cdot c_{SP} \qquad (4)$$

- where *k* is the number of shaft seals being replaced, (one or two),
- n_P is the number of people required to perform the maintenance,
- $t_{RWT}(k)$ is the total working time for the maintenance in hours for *k* shaft seals,
- c_{WT} is the labour cost in SEK for the working time per hour and
- c_{SP} is the cost per spare shaft seal in SEK.

The data is extracted from working orders at Forsmark nuclear power plant. The data given yields the spare part cost $c = 8626$ EUR, and the constant cost $d = 482$ EUR used in the optimization model.

5) *Mathematical model description*

Sets and Indices

$i \in I = \{1, 2\}$	Number of shaft seals.
$t \in T = \{1, \ldots, 55\}$	Time steps.
T_L	Life length of shaft seal, (T_L = 11).
τ_i	Remaining life at the beginning of the planning period for shaft seal *i*.

Decision Variables

$$x_{it} = \begin{cases} 1 & \text{if shaft seal } i \text{ is replaced at time } t,\ i \in I, t \in T \\ 0 & \text{otherwise.} \end{cases}$$

$$z_t = \begin{cases} 1 & \text{if maintenance is carried out at time } t, \\ 0 & \text{otherwise.} \end{cases}$$

Objective function

$$\min \sum_{t=1}^{T} \left(dz_t + c \sum_{i=1}^{2} x_{it} \right)$$

Constraints

A shaft seal can be replaced only when maintenance is performed:

$$x_{it} \le z_t \ ,\ i = 1, 2,\ \ t \in T .$$

Each shaft seal must be replaced within its life T_L:

$$\sum_{t=l}^{l+T_L-1} x_{it} \ge 1,\ i = 1, 2,\ \ l = 1, .., T - T_L + 1 .$$

The first replacement must be carried out before the remaining life τ_i has expired:

$$\sum_{t=1}^{1+\tau_i} x_{it} \ge 1\ ,\ i = 1, 2 .$$

Finally the variables must take binary values:

$$x_{it}, z_t \in \{0,1\}.$$

Cost discount
The total cost is discounted, that is, re-calculated into a present value using a so called discount factor: $disc(t) = \frac{1}{(1+r)^t}$.

Using $d_t = disc(t) \cdot d$ and $c_t = disc(t) \cdot c$ for $t = \{1,...,55\}$ yields the adjusted objective function:

$$\min \sum_{t=1}^{T} \left(d_t z_t + c_t \sum_{i}^{2} x_{it} \right).$$

The nominal discount rate r_n depends on the real interest r_1, and the inflation r_2, according to:

$$1 + r_n = (1 + r_1)(1 + r_2).$$

The mathematical model can then be summarized as:

$$\min \sum_{t=1}^{T} \left(d_t z_t + c_t \sum_{i}^{2} x_{it} \right) \tag{5}$$

subject to

$$x_{it} \le z_t, \; i = 1,2, \; t = 1,..,T \tag{6}$$

$$\sum_{t=l}^{l+T_L-1} x_{it} \ge 1, \; i = 1,2, \; l = 1,..,T - T_L + 1 \tag{7}$$

$$\sum_{t=1}^{1+\tau_i} x_{it} \ge 1, \; i = 1,2 \tag{8}$$

$$x_{it}, z_t \in \{0,1\}, \; i = 1,2, \; t \in T \tag{9}$$

VI. ANALYSIS

The opportunistic deterministic optimization model has been implemented in AMPL and GAMS, and MATLAB has been used to analyze and describe the results graphically. All programs used for the analyses are commercially available tools. A sensitivity analysis where the different parameters were varied has been made.

The first conclusion of the sensitivity analysis was that the result depends on the discount rate. Varying the other parameters (T, τ_i, T_L, c and d) shows that they also are important for the decision of maintenance. It is necessary to study which of these parameters affect the schedule of maintenance the most. Patterns could be found for when opportunistic maintenance is the best solution and when it is not the best solution. Conclusions that can be drawn from the varying of the different parameters are presented in the text below.

Critical nominal discount interest, r_n^*, is defined as the highest nominal discount interest where the opportunistic solution is optimal. Over this interest the optimal solution is to replace shaft seals when they fail. That is, the nominal discount interest, r_n, gives the optimal solution as follows:

$$r_n = \begin{cases} \le r_n^* & \text{opportunistic} \\ > r_n^* & \text{non-opportunistic.} \end{cases} \tag{10}$$

The other parameters have been varied and solutions observed in relation to this discount interest. Observing r_n^* for different choices of remaining life, τ_i, shows that larger difference between τ_1 and τ_2 gives a lower interest r_n^*.

Varying T_L indicates that if the shaft seals' life lengths are one time step longer than in the basic case, the optimal solution, when one shaft seals' remaining life length is zero, is to replace the first one at once.

If the constant cost d is large enough in relation to the spare part cost c, opportunistic replacements would be optimal.
The constant cost d is increased until the opportunistic solution is reached. When the solution is the non-opportunistic and d is increased until the opportunistic solution is reached, d does not have to be increased much until this happens.

VII. RESULTS

The results show that the discount rate has a large effect on how maintenance should be performed on shaft seals in the pump in the feed-water pump system. The optimal solution for the basic case is such that opportunistic replacements are used if the nominal discount rate is lower than 5.3%. Then, the optimal solution is to replace both seals as soon as the first one breaks. The next replacement takes place when the life has ended for the shaft seals, see Fig 1. When the nominal discount interest is higher than 5.3%, the optimal replacement schedule is corrective, that is the shaft seals should be replaced when they fail only, see Fig 2. A nominal discount interest of 5.3% corresponds to, for example, a real interest of 2.6% and an inflation of 2.6%. These are low figures of real interest and inflation and a reasonable result is therefore that the result with nominal interest higher than 5.3% should be the most interesting. This finding had not been possible if opportunistic maintenance had been ignored in the problem formulation.

However, in the basic case, the remaining life at start of the components differs a lot, ($\tau = (1,10)$), which gives a low critical nominal discount interest. A more realistic case would be that τ_i does not differ this much, as the shaft seals often are put in at the same time from start. Less difference between remaining life at start for the components gives a higher critical nominal discount interest and thereby it is more likely that the optimal solution is the opportunistic in most cases.

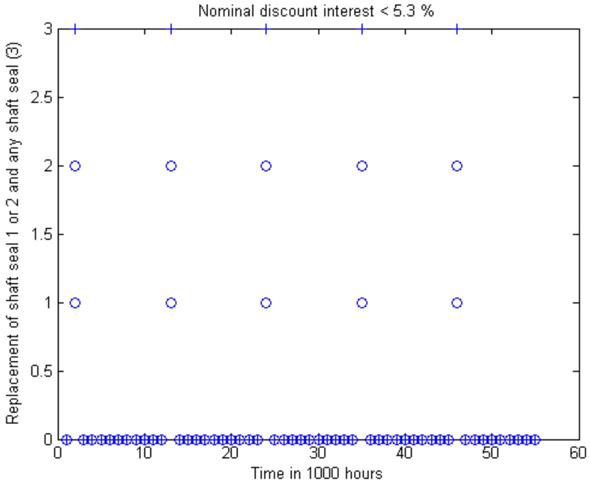

Fig. 1: Results of the deterministic optimization model with nominal discount interest < 5.3 %. The optimal solution is to replace opportunistic as soon as the first shaft seal breaks.

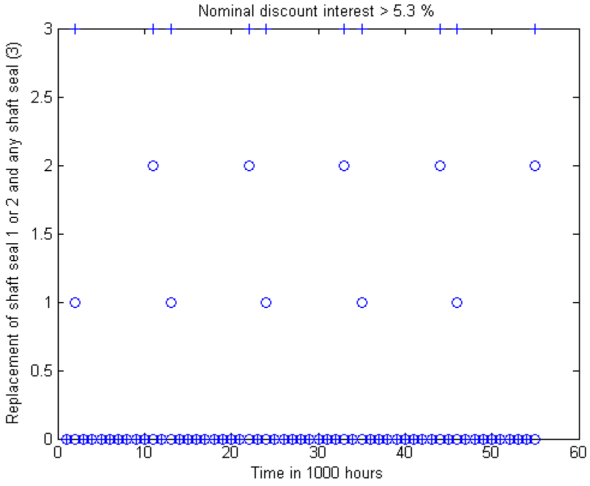

Fig. 2: Results of the deterministic optimization model with nominal discount interest > 5.3 %. The optimal solution is to use only corrective replacements, with no opportunistic approach, as the shaft seals fail.

Tab 1 show r_n^* for some points of remaining life at start for shaft seal 1 and 2. At the same remaining life at start for both components, the optimal solution is to replace both shaft seals at the same time, and this is independent of the interest rate.

For example, the point τ = (4 8) in Tab 1 shows the critical nominal interest r_n^* = 11.5% when the remaining life at start is 4 time units for shaft seal 1 and 8 time units for shaft seal 2. This means that if the nominal interest r_n = 12%, the shaft seals should be replaced when they fail. The total maintenance cost over 6 years is about 63 200 EUR at these discount rates. Discounting by 12%, instead of 11.5%, gives a cost that is about 1 000 EUR less.

TABLE I

REMAINING LIFE AT START AND CRITICAL NOMINAL DISCOUNT INTEREST

τ_1	τ_2	r_n^*	τ_1	τ_2	r_n^*	τ_1	τ_2	r_n^*
0	0	-	2	0	24.0%	4	0	11.5%
0	2	24.0%	2	2	-	4	2	24.0%
0	4	11.5%	2	4	24.0%	4	4	-
0	6	7.5%	2	6	11.5%	4	6	24.0%
0	8	5.5%	2	8	7.5%	4	8	11.5%
0	10	4.5%	2	10	5.5%	4	10	7.5%
τ_1	τ_2	r_n^*	τ_1	τ_2	r_n^*	τ_1	τ_2	r_n^*
6	0	7.5%	8	0	5.5%	10	0	4.5%
6	2	11.5%	8	2	7.5%	10	2	5.5%
6	4	24.0%	8	4	11.5%	10	4	7.5%
6	6	-	8	6	24.0%	10	6	11.5%
6	8	24.0%	8	8	-	10	8	24.0%
6	10	11.5%	8	10	24.0%	10	10	-

VIII. APPLICATION OF MODEL

The proposed maintenance model is generic and could be used for any production system, such as a subsystem in the nuclear power plant or a system of wind turbines. Different input data, with small corrections of the model, should give a maintenance schedule for the required time period and time step. Maintenance of the shaft seals used in the feed-water pumps connected to reactor 1 and 2 at Forsmark nuclear power plant, is today only corrective. A question is if maintenance of the shaft seals can be more efficient with a preventive maintenance program? The opportunistic maintenance optimization model shown here is a general model that first has been applied for the aircraft industry, and now with some corrections used for nuclear power. Input data differs for the different applications; even different systems within nuclear power could differ when it comes to input data.

IX. CLOSURE

A. Conclusion

This paper has proposed an opportunistic maintenance optimization approach for a nuclear power application for the feed-water pump system and especially replacement of shaft seals. Results show that the optimization model is dependent on for example the discount interest and that with reasonable input data for remaining life at start this interest could be relatively high. A high critical nominal discount interest gives more space for opportunistic replacements.

B. Future Work

A limitation in this model is that the cost for production loss is not included. One pump is observed and it is in operation all the time. The cost for production loss thereby never appears. When three pumps are observed, two pumps must always be in operation, and the model could be constructed so that this is a fact. In reality, the case that two pumps out of three are out of operation at the same time is something that has not happened yet. The risk that this could happen is however there, and future models could take this into account.

Applications of the model for other nuclear power plants with different structures of the system and different types of shaft seals are interesting to study in the future. When it comes to feed-water pump systems and shaft seals, different shaft seals are used in different nuclear power plants. The shaft seals at the feed-water pump system in Ringhals nuclear power plant are different from those at Forsmark. Maintenance of these shaft seals takes longer, but the maintenance intervals are also longer. Preventive maintenance is carried out, unlike on the shaft seals at Forsmark 1 and 2, in combination with condition control, that is, corrective maintenance. A future study of these shaft seals and some corrections of the model could in the future show that the general model could be applied for several systems like electrical production systems.

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