Reliability Characteristics of Power Plants

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DOI: 10.15598/aeee.v15i1.2043

Abstract. *This paper describes the phenomenon of reliability of power plants. It gives an explanation of the terms connected with this topic as their proper understanding is important for understanding the relations and equations which model the possible real situations. The reliability phenomenon is analysed using both the exponential distribution and the Weibull distribution. The results of our analysis are specific equations giving information about the characteristics of the power plants, the mean time of operations and the probability of failure-free operation. Equations solved for the Weibull distribution respect the failures as well as the actual operating hours. Thanks to our results, we are able to create a model of dynamic reliability for prediction of future states. It can be useful for improving the current situation of the unit as well as for creating the optimal plan of maintenance and thus have an impact on the overall economics of the operation of these power plants.*

Keywords

Modelling of dynamic behaviour, power plant unit, reliability, Weibull distribution.

1. Introduction

The phenomenon of reliability is a very important aspect of technical research at present and will certainly remain so in the future. We are able to achieve permanent sustainability thanks to the determination of the reliability of the whole system. This reliability has also a significant impact on electric power engineering, because all the components in power engineering systems have certain parameters of reliability, such as probability of failure-free operation and the mean time of operation. If these parameters are determined correctly, we can obtain relatively exact models and also achieve optimization of the key components of these systems. This paper describes the most important parameters of reliability in power plants. These parameters are derived for two types of distribution – the exponential and the Weibull. Parameters for the Weibull distribution are more realistic because this distribution respects the dynamics of the cycle. The exponential distribution does not respect these dynamic features and is used only for verification of the hypothesis. Equations obtained for the reliability parameters can be used as optimizing tools. The optimization process reduces the maintaining costs as well as the additional costs connected with blackouts of the redundant key components. This procedure is also very important for maximizing the efficiency of the whole electric power engineering system.

2. Overview of Current State of Reliability

The reliability may be explained as ability of a unit to successfully operate in required time of operation. Another explanation of the reliability can be this statement: Reliability is equal to probability that a unit will be operating without failures in certain time of operation [1].

Reliability function $p(t)$ describes probability, that the unit works without failures in the time (t) which is longer than the time of operation (T). In the time of operation (T) there is certain reliability guaranteed by the producer:

$$p(t) = P\{T < t\}. \quad (1)$$

Failure probability function $q(t)$ describes probability, that the unit has one or more failures in the

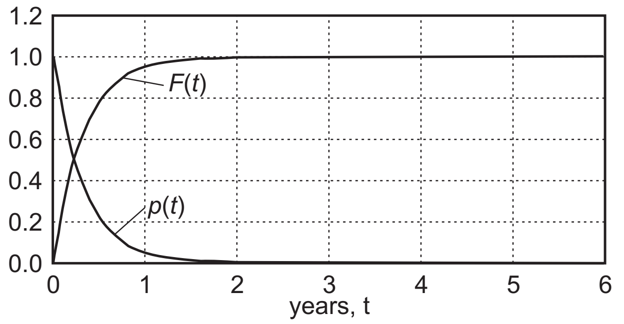

Fig. 1: Reliability function $p(t)$ and distribution function $F(t)$ of a power unit $\lambda = 3$ [1].

time (t):

$$q(t) = 1 - p(t). \tag{2}$$

Distribution function of time without failure:

$$F(t) = P\{T < t\} = q(t). \tag{3}$$

Density function of time without failures:

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}(t)}. \tag{4}$$

If we can consider intensity of failures as a constant, the exponential distribution can be used:

$$p(t) = e^{-\lambda t}, \tag{5}$$

and

$$f(t) = \lambda e^{-\lambda t}. \tag{6}$$

On the basis of density function it is possible to determine the expression for the mean time of operation [1]:

$$m_s = \int_0^\infty t \cdot f(t)\mathrm{d}t. \tag{7}$$

3. Materials and Methods

3.1. Reliability Characteristics of a Power Plant Units

This part describes equations derived for determining the important reliability parameters of a given power plant. The probability of failure-free operation is further referred to as the first parameter and the mean time of operation as the second parameter of the reliability characteristics of the unit. These characteristics are solved below using the exponential distribution for the unrepairable unit and the Weibull distribution for the repairable unit. The Weibull distribution can describe the realistic operation better than the exponential distribution because it includes failures of all the components during the operation as well as the realistic situations which may occur.

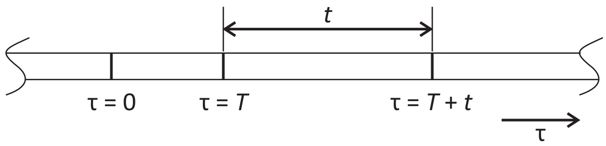

Fig. 2: Situation of the realistic unit shown on time axis [3].

3.2. Characteristics of Time of Failure-Free Operations Using the Exponential Distribution

Firstly, it is necessary to obtain solutions for the unrepairable unit by using the exponential distribution, because this situation is much easier to explain than the situation for the repairable unit. Therefore, it is very important to explain first the situation of the unrepairable unit. For this situation, it is crucial to determine the intensity of repair (μ) and mean-time to repair (r) as follows:

$$\mu = 0 \rightarrow r = \infty. \tag{8}$$

This statement is given by unrepairability of the unit. During operation of the unrepairable unit the intensity of failures (λ) is given as a constant value when using the exponential distribution. It means that the probability of failure-free operation does not depend on the time of operation (T) of the unit [3].

Explanation (Fig. 2):

- Interval from 0 to $\tau = 0$ represents repair.
- Interval from $\tau = 0$ to $\tau = T$ represents real-time operation.
- Interval from $\tau = T$ to $\tau = T + t$ represents prediction of the future state.

Verification can be performed by equation given for conditional probability:

$$P_{B(A)} = \frac{P_{(B\cap A)}}{P_{(B)}}. \tag{9}$$

This equation determines the probability of phenomenon A in the case of success of phenomenon B, [4].

Explanation (Fig. 2):

- Phenomenon A represents the unit in which failure occurs in the interval between T and $T + t$.
- Phenomenon B represents the unit in which failure does not occur in the interval between 0 and T.
- Intersection of these phenomena $A \cap B$ represents both these phenomena simultaneously.

The probability of failure-free operation between time 0 and T is determined as follows:

$$P_{(B)} = P_{1(t)} = e^{-\lambda \cdot T}, \tag{10}$$

and the probability of intersection of phenomena $A \cap B$ is determined as follows:

$$P_{(B \cap A)} = \int_{T}^{T+t} f_t \mathrm{d}t = \int_{T}^{T+t} \lambda * e^{-\lambda t} \mathrm{d}t. \tag{11}$$

Using the equation for conditional probability the following equation is obtained:

$$P_{B(A)} = \frac{e^{-\lambda \cdot T} - e^{-\lambda \cdot T} * e^{-\lambda \cdot T}}{e^{-\lambda \cdot T}} = 1 - e^{-\lambda \cdot T}. \tag{12}$$

Independence of conditional probability $P_{B(A)}$ on the time of operation of unit T is a feature of the exponential distribution [2].

3.3. Characteristics of Time of Failure-Free Operations Using Weibull Distribution

Secondly, we need to find solutions for the unit of the power plant considered repairable. This state is described using the Weibull distribution below. Again, it is necessary to determine the value of $P_{B(A)}$ for the Weibull distribution. The definition of $P_{B(A)}$ is the same for both distributions. However, contrary to the exponential distribution, this state depends on the time of operation T of the unit [3].

Again, it is necessary to determine the probability of failure-free operation between time 0 and T for the Weibull distribution:

$$\begin{aligned} P_{(B)} = P_{0(t)} = 1 - \int_{0}^{T} f(t)\mathrm{d}t = \cdots \\ = 1 - \int_{0}^{T} k \cdot t^m e^{-\left(\frac{k}{m+1} * t^{m+1}\right)}. \end{aligned} \tag{13}$$

As before, we can obtain the equation for $P_{B(A)}$ by using the equation for conditional probability:

$$P_{B(A)} = \frac{\int_{T}^{T+t} f(t)\mathrm{d}t}{1 - \int_{0}^{T} f(t)\mathrm{d}t}. \tag{14}$$

Equation (14) is solved by the method of progressive integration in the following steps [3].

3.4. Solution of Conditional Probability

In the Weibull distribution there are two possible expressions of $\int f(t)\mathrm{d}t$:

$$f(t) = k \cdot t^m e^{-\left(\frac{k}{m+1} t^{m+1}\right)}, \tag{15}$$

$$f(t) = \frac{b}{d} * \left(\frac{t}{d}\right)^{b-1} e^{-\left(\frac{t}{d}\right)^b}. \tag{16}$$

This paper focuses on both expressions of the equation. Equation (15) is solved first and Eq. (16) is solved next [3].

1) Calculation for Eq. (15)

The first step is addition of the following integral to Eg. (8):

$$\int f(t)\mathrm{d}t = \int k \cdot t^m e^{-\left(\frac{k}{m+1} t^{m+1}\right)} \mathrm{d}t. \tag{17}$$

The second step is substitution for t^{m+1}:

$$t^{m+1} = z, (m+1)t^m \mathrm{d}t = \mathrm{d}z, t^m \mathrm{d}t = \frac{\mathrm{d}z}{m+1}. \tag{18}$$

The third step is insertion of the substitution into Eq. (10):

$$\begin{aligned} \int f(t)\mathrm{d}t = \int \frac{k}{m+1} e^{-\left(\frac{k}{m+1} z\right)} \mathrm{d}z = \\ = -e^{-\left(\frac{k}{m+1} t^{m+1}\right)}. \end{aligned} \tag{19}$$

2) Calculation for Eq. (16)

Same procedure:

$$\int f(t)\mathrm{d}t = \int \frac{b}{a} * \left(\frac{t}{d}\right)^{b-1} e^{-\left(\frac{t}{d}\right)^b} \mathrm{d}t. \tag{20}$$

Substitution for $\frac{t}{d}$:

$$\frac{t}{d} = x \rightarrow \frac{\mathrm{d}t}{d} = \mathrm{d}x \tag{21}$$

And next substitution for x^b:

$$x^b = y \rightarrow b x^{b-1} \mathrm{d}x = \mathrm{d}y \tag{22}$$

Equation 19 can be expressed as:

$$\int e^{-y} \mathrm{d}y = -e^{-y} = -e^{-x^b} = -e^{-\left(\frac{t}{d}\right)^b}. \tag{23}$$

3) Determination of Probability of Failure-Free Operation $P_{B(A)}$ for Eq. (15) and Eq. (16)

If we insert Eq. (15) into Eq. (14), we get the following result of $P_{B(A}$:

$$\begin{aligned} P_{B(A)} &= \frac{\left[-e^{-\left(\frac{k}{m+1}t^{m+1}\right)}\right]_T^{T+1}}{1-\left[-e^{-\left(\frac{k}{m+1}t^{m+1}\right)}\right]_0^T} = \\ &= \frac{e^{-\left(\frac{k}{m+1}T^{m+1}\right)}-e^{-\left(\frac{k}{m+1}(T+t)^{m+1}\right)}}{1-\left[1-e^{-\left(\frac{k}{m+1}T^{m+1}\right)}\right]} = \\ &= \frac{e^{-\left(\frac{k}{m+1}T^{m+1}\right)}-e^{-\left(\frac{k}{m+1}(T+t)^{m+1}\right)}}{e^{-\left(\frac{k}{m+1}T^{m+1}\right)}}. \end{aligned} \tag{24}$$

After next simplifications we obtain the following result of $P_{B(A}$:

$$P_{B(A)} = 1 - e^{\left[\frac{k}{m+1}T^{m+1}-\frac{k}{m+1}(T+t)^{m+1}\right]}. \tag{25}$$

The next step is insertion of Eq. (16) into into Eq. (14) which looks as follows:

$$P_{B(A)} = \frac{\left[e^{-\left(\frac{t}{d}\right)^b}\right]_T^{T+t}}{1-\left[e^{-\left(\frac{t}{d}\right)^b}\right]_0^T} = 1 - e^{\left[\left(\frac{T}{d}\right)^b-\left(\frac{T+t}{d}\right)^b\right]}. \tag{26}$$

To verify our results, we consider the value of parameter m from Eq. (15), $m = 0$. This situation is typical of the exponential distribution. The resulting expression is obtained independently of parameter T:

$$P_{B(A)} = 1 - e^{[-k(T+t-T)]} = 1 - e^{-kt}. \tag{27}$$

We perform similar verification also for Eq. (26), $b = 1$:

$$P_{B(A)} = 1 - e^{-\left(\frac{T+t-T}{d}\right)} = 1 - e^{-\left(\frac{t}{d}\right)}. \tag{28}$$

Correctness of those results Eq. (15) and Eq. (16) can also be verified by insertion of the parameter $T = 0$.

We obtain the resultant expression for the probability of failure of the unit until time t; however, we have to know that the unit was in operation until time T, which is for Eq. (15) as follows:

$$P_{B(A)} = P_{1(t)} = 1 - e^{\left[\frac{k}{m+1}T^{m+1}-\frac{k}{m+1}(T+t)^{m+1}\right]}. \tag{29}$$

If we determine the probability of failure of the unit by insertion of Eq. (16), we obtain the following equation:

$$P_{B(A)} = P_{1(t)} = 1 - e^{\left[\left(\frac{T}{d}\right)^b-\left(\frac{T+t}{d}\right)^b\right]}. \tag{30}$$

3.5. Derivation of the Mean Time of Operation without the Time of Operation

Calculation of the mean time of operation m_s for the exponential distribution of time of failure-free operations is as follows [2]:

$$m_s = \int_0^\infty t \cdot f(t)\mathrm{d}t = \int_0^\infty t \cdot \lambda^{-\lambda \cdot t}\mathrm{d}t = \frac{1}{\lambda}. \tag{31}$$

For the Weibull distribution of time of failure-free operations it is as follows:

$$m_s = \int_0^\infty t \cdot k \cdot t^m e^{-\left(\frac{k}{m+1}t^{m+1}\right)}\mathrm{d}t. \tag{32}$$

Calculation of the mean time of operation requires more difficult operations for the Weibull distribution as described below. Firstly, substitution is necessary for kt^{m+1}:

$$\begin{aligned} t^{m+1} &= x \to t = \sqrt[m+1]{x}, \\ (m+1)t^m\mathrm{d}t &= \mathrm{d}x \to t^m\mathrm{d}t = \frac{\mathrm{d}x}{(m+1)}. \end{aligned} \tag{33}$$

Secondly, the boundaries have to be recapitulated:

$$\begin{aligned} t &\to 0, \infty, \\ x &\to 0, \infty. \end{aligned} \tag{34}$$

The third step is the calculation for Eq. (15):

$$\begin{aligned} m_s &= k\int_0^\infty t^{m+1}e^{-\left(\frac{k}{m+1}t^{m+1}\right)}\mathrm{d}t = \\ &= k\int_0^\infty \sqrt[m+1]{x} \cdot e^{-\left(\frac{k \cdot x}{m+1}\right)}\frac{\mathrm{d}x}{(m+1)} = \\ &= \frac{k}{(m+1)}\int_0^\infty \sqrt[m+1]{x} \cdot e^{-\left(\frac{k \cdot x}{m+1}\right)}\mathrm{d}x. \end{aligned} \tag{35}$$

Similar calculation is performed for Eq. (16):

$$\begin{aligned} x = t^b &\to t = \sqrt[b]{x}, \\ b \cdot t^{b-1}\mathrm{d}t &= \mathrm{d}x, \\ t &\to 0, \infty, \\ x &\to 0, \infty. \end{aligned} \tag{36}$$

$$\begin{aligned} m_s &= k\int_0^\infty t\left(\frac{b}{d}\right)\left(\frac{t}{d}\right)^{b-1}e^{-\left(\frac{t}{d}\right)^b}\mathrm{d}t = \\ &= \frac{1}{d^b}\int_0^\infty \sqrt[b]{x} \cdot e^{-\left(\frac{x}{d}\right)}\mathrm{d}x. \end{aligned} \tag{37}$$

For verification of the resulting expressions, expression for the exponential distribution can be obtained by determination of parameters $m = 0$ and $b = 1$. For

Eq. (25) we obtain, by insertion of parameter $m = 0$, this expression:

$$m_s = k\int_0^\infty xe^{-x}\mathrm{d}x = \int_0^\infty k\cdot t\cdot e^{-k\cdot t}\mathrm{d}t = \frac{1}{k}, \quad (38)$$

and the same result must be obtained if we use Eq. (26) with constant parameter $b = 1$:

$$m_s = k\int_0^\infty x\cdot e^{-\frac{x}{d}}\mathrm{d}x = \int_0^\infty \frac{t}{d}e^{-\frac{t}{d}}\mathrm{d}t = d. \quad (39)$$

After verification we know that our equations connected with the two types of expressions of the Weibull distribution for the mean time of operation are both correct. In the next step it is necessary to perform numerical calculation of these integrals, because the given integrals are unsolvable by standard exact methods [3].

3.6. Derivation for the Unit which was in Operation for T Hours

For exponential distribution, independence on time T was shown by Eq. (12). The probability of failure of the unit in time t working during time T is given by Eq. (25) for the Weibull distribution and for the second expression by Eq. (30). Density of failure $f(t)$ is given by differentiating these equations [3].

3.7. Calculation of the Mean Time of Operation of the Unit which was in Operation for T Hours

The first important parameter for the calculation is the probability of failure. The probability of failure in time t is given by Eq. (29) and Eq. (30). The next step is determining the density of failure of these equations, which is given by their differentiating [3]. The density of failure for Eq. (29) is given by the following expression:

$$f(t) = -k(T+t)^m e^{\left[\frac{k}{m+1}T^{m+1} - \frac{k}{m+1}(T+t)^{m+1}\right]} \quad (40)$$

and the mean time of operation for Eq. (29) is determined by the following expression:

$$\begin{gathered} m_s = \int\limits_0^\infty t\cdot f(t)\mathrm{d}t = \\ = \int\limits_0^\infty -k\cdot t(T+t)^m e^{\left[\frac{k}{m+1}T^{m+1} - \frac{k}{m+1}(T+t)^{m+1}\right]}. \end{gathered} \quad (41)$$

Firstly, substitution for $k(T+t)^{m+1}$ is necessary:

$$\begin{gathered} k(T+t)^{m+1} = z \rightarrow t = \sqrt[m+1]{\tfrac{z}{k}} - T \\ k(m+1)(T-t)^m\mathrm{d}t = \mathrm{d}z \rightarrow k(T+t)^m\mathrm{d}t = \tfrac{\mathrm{d}z}{m+1}. \end{gathered} \quad (42)$$

Secondly, boundaries have to be recalculated:

$$\begin{gathered} t \rightarrow 0, \infty \\ z \rightarrow k(T)^{m+1}, \infty. \end{gathered} \quad (43)$$

The third step is insertion of substitution into Eq. (20):

$$\begin{gathered} m_s = \\ = \frac{1}{(m+1)^{m+1}\sqrt{k}} \int\limits_{kT^{m+1}}^{\infty} \sqrt[m+1]{z} e^{\left[\frac{k\cdot T^{m+1} - z}{m+1}\right]}\mathrm{d}z - \\ - \frac{T}{(m+1)} \int\limits_{k\cdot T^{m+1}}^{\infty} e^{\left[\frac{k\cdot T^{m+1} - z}{m+1}\right]}\mathrm{d}z. \end{gathered} \quad (44)$$

We also need to create substitution for $\dfrac{-kT^{m+1}+z}{m+1}$:

$$\begin{gathered} \frac{-k\cdot T^{m+1}+z}{m+1} = x \rightarrow z = k\cdot T^{m+1}x, \\ \frac{\mathrm{d}z}{m+1} = \mathrm{d}x \rightarrow \mathrm{d}z = (m+1)\mathrm{d}x. \end{gathered} \quad (45)$$

Recalculation of boundaries:

$$z \rightarrow k(T)^{m+1}, \infty \;\; x \rightarrow 0, \infty. \quad (46)$$

Insertion of substitution into Eq. (29):

$$\begin{gathered} m_s = \frac{1}{(m+1)\sqrt[m+1]{k}}\cdot \\ \cdot \int\limits_0^\infty \sqrt[m+1]{kT^{m+1} + (m+1)x}\cdot e^{-x}(m+ \\ +1)\mathrm{d}x - \frac{T}{(m+1)}\int\limits_0^\infty e^{-x}(m+1)\mathrm{d}x = \\ = \frac{1}{\sqrt[m+1]{k}}\int\limits_0^\infty e^{-x}\mathrm{d}x - T. \end{gathered} \quad (47)$$

To verify this Eq. (47), $m = 0$ is inserted into it. Again we transform the equation for the Weibull distribution into the equation for the exponential distribution:

$$\begin{gathered} m_s = \int\limits_0^\infty \frac{(k\cdot T + x)}{k}e^{-x}\mathrm{d}x - T = \\ = \frac{1}{k}\int\limits_0^\infty x\cdot e^{-x}\mathrm{d}x + \frac{1}{k}\int\limits_0^\infty k\cdot T\cdot e^{-x}\mathrm{d}x - T = \\ = \frac{1}{k}\int\limits_0^\infty x\cdot e^{-x}\mathrm{d}x = \frac{1}{k}. \end{gathered} \quad (48)$$

For the second expression of the Weibull distribution the mean time of operation is calculated as follows. Firstly, we need to perform conversion for the specific constants:

$$m+1 = b \rightarrow \frac{m+1}{k} = d^b. \quad (49)$$

Secondly, we insert these converted constants into Eq. (41):

$$m_s = d\int_0^{\infty} \sqrt[b]{\frac{T^b}{d^b} + x} \cdot e^{-x}\mathrm{d}x - T. \tag{50}$$

Finally, for verification we choose the constant $b = 1$ and transform it into the exponential distribution. Due to this operation, we obtain the following expression:

$$\begin{aligned} m_s &= d\int_0^{\infty} \left(x + \frac{T}{d}\right) e^{-x}\mathrm{d}x - T = \\ &= d\int_0^{\infty} (x)e^{-x}\mathrm{d}x + T\int_0^{\infty} e^{-x}\mathrm{d}x - T = d. \end{aligned} \tag{51}$$

The resulting Eq. (48) and Eq. (50) for the mean time of operation are correctly determined.

4. Achieved Results

This part is focused on the main results and their explanation. Firstly, the probability of failure-free operation for the exponential distribution was determined by the following equation [2]:

$$P_{B(A)} = 1 - e^{-\lambda t}. \tag{52}$$

After that it was derived from the same expression of probability also for the Weibull distribution. We obtained these two expressions:

$$P_{B(A)} = P_{1(t)} = 1 - e^{\left[\frac{k}{m+1}T^{m+1} - \frac{k}{m+1}(T+t)^{m+1}\right]}, \tag{53}$$

$$P_{B(A)} = P_{1(t)} = 1 - e^{\left[\left(\frac{T}{d}^{b}\right) - \left(\frac{T+t}{d}\right)^{b}\right]}. \tag{54}$$

Secondly, it was necessary to determine the expression of the mean time of operation for the exponential distribution. In this case the time of operation T was not respected:

$$\begin{gathered} t^{m+1} = x \\ m_s = \frac{k}{(m+1)}\int_0^{\infty} \sqrt[m+1]{x}e^{-\frac{kx}{m+1}}\mathrm{d}x, \end{gathered} \tag{55}$$

$$\begin{gathered} t^{b} = x \\ m_s = \frac{1}{d^b}\int_0^{\infty} \sqrt[b]{x}e^{-\frac{x}{d}}\mathrm{d}x. \end{gathered} \tag{56}$$

Finally, calculation of the mean time of operation was performed with respect to the time of operation. Here two expressions representing the most realistic mean time of operation were obtained.

For analytical solution, the substitutions and recalculation of boundaries must be performed twice:

$$k(T+t)^{m+1} = z, \quad \frac{-k \cdot T^{m+1} + z}{m+1} = x, \tag{57}$$

$$z \to k(T)^{m+1}, \infty \quad x \to 0, \infty, \tag{58}$$

$$m_s = \frac{1}{\sqrt[m+1]{k}} \sqrt[m+1]{\frac{k \cdot T^{m+1}}{m+1} + x} \cdot e^{-x}\mathrm{d}x - T. \tag{59}$$

For the second expression, the solution looks like this:

$$m + 1 = b \to \frac{m+1}{k} = d^b, \tag{60}$$

$$m_s = d\int_0^{\infty} \sqrt[b]{\frac{T^b}{d^b} + x} \cdot e^{-x}\mathrm{d}x - T. \tag{61}$$

Integration of Eq. (35) and Eq. (38) is impossible by exact methods. This is the reason for using an approximate numerical method, such as Simpson's rule or Quadrature rule.

4.1. Practical Application of the Final Equations for a Real System

We used real parameters of a feed pump from the Czech nuclear power plant Dukovany. The nuclear power plant Dukovany has four units. Each unit of Dukovany contains the same components, i.e. a turbine with the performance of 250 MWe, condenser, steam generator and feed pump. In this case we have focused only on feed pumps [5].

Parameters used in the following script have been determined from a database of operation values in the software Access by statistical methods. The times of operation have been chosen on the basis of the data of the feed pump used in the power plant. Characteristics of wear $b = 0.65$ and complex characteristics of lifetime $d = 3150$ were also determined by these statistical methods. The script for calculation characteristics of reliability by the Quadrature rule is created and it is shown below:

```
T1=0;
T2=72;
T3=120;
T4=168;
T5=300;
T6=500;
T7=1000;
T8=2000;
T9=3500;
T10=5000;
T11=6000; %Required times
b=0.65; %Characteristics of wear
d=3150; %Characteristics of lifetime
try
sum_old = sum; %Saving previous value
of numerical integral
catch
sum_old = 0;
```

```
end
sum = 0;
h=0.01; %Determination of the step
x_in = 0 :  h :  2e1;
yout = zeros(size(x_in));
s_out = yout;
i = 1;
for i = 1 :  length(x_in) %Calculation
of the numerical integral by the
Quadrature rule
x = x_in(i);
y = d*(((T1./d).^b)+x).^(1./b)*exp(-x)-T1;
if y < 0 %Elimination of negative
values of the integral
break;
end
sum = sum + y * h;
yout(i) = y;
s_out(i) = sum;
end
subplot(2,1,1); %Figure of the function
before integration
plot(x_in,yout);
subplot(2,1,2);
plot(x_in,s_out); %Figure of the
function after integration
```

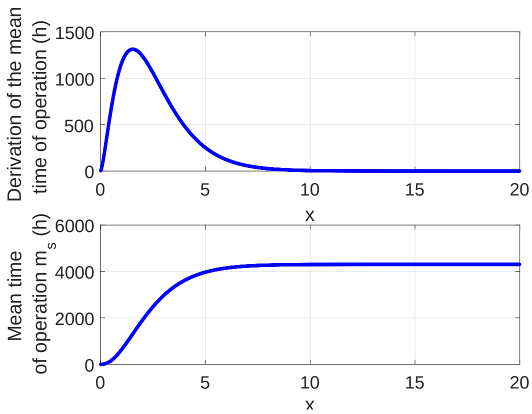

Fig. 3: Graphic expression of calculation before and after integration for $T1$ by the Quadrature rule.

The numerical results in Tab. 1 for Eq. (57) were calculated by the script in Matlab. The graphical expression of Tab. 1 is shown in Fig. 4 below.

In Tab. 1, an example of calculation $m_s = f_{((m,k,T))}$ of a nuclear power plant unit is shown with realistic parameters of reliability using the Weibull distribution. The trend of the mean time of operation is given in Fig. 4. This shows that the mean-time of operation falls with the rising time of operation.

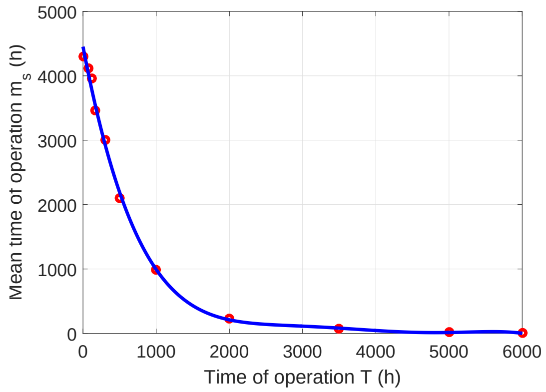

Fig. 4: Graphic expression of interdependence between time of operation and mean-time of operation.

5. Discussion

Dynamic reliability is a very promising field and offers a lot of possibilities for future research. The solution using the Weibull distribution has a significant impact in the field of dynamic reliability because the Weibull distribution is convenient to be used for repairable systems. It is the best tool of dynamic modelling of real systems.

The general procedure described in the experimental section may be used in most types of power plant units. All the necessary steps for calculation of the key parameters of dynamic reliability are described in that section. The final expressions are verified using the exponential distribution.

The results interpreted in the previous section concern the probability of failure-free operation and the mean time of operation. These parameters are representative and give a realistic view of the reliability of our nuclear power unit. Thanks to our results, we are able to create a model of dynamic reliability for prediction of future states. Prediction of future states may be used for optimal planning of maintenance and also for supporting the sustainability of these units. This section is concluded by Tab. 1, which presents the calculated values of the mean time of operation depending on the length of the time of operation, and Fig. 4 which shows a graphic view of the values.

6. Conclusion

In this paper the methodology of reliability characteristics, such as failure-free operation and the mean time of operation, is described. The methodology contains calculations and verifications of unit parameters. The final results were obtained by calculation and verified by the exponential distribution. This methodology is

Tab. 1: Interdependence between mean time of operation (m_s) and time of operation (T).

T (h)	0	72	120	168	300	500	1000	2000	3500	5000	6000
m_s (h)	4304	4113	3964	3821	3465	2999	2102	987	229	17	0.02

applicable to any system. However, this system must be repairable and periodically checked. Of course, we must know the key parameters of the system.

Obtained results of the mean-time of operation for the Weibull distribution is shown in Fig. 2. The results of the mean-time of operation for the Weibull distribution are shown in Fig. 2. The trend in Fig. 2 respects the theoretical assumptions of the theory of reliability. The rising time of operation causes the decreasing hyperbolic trend of the mean time of operation.

These results can be useful for improving the current situation of the unit and also for creating the optimal plan of maintenance.

Acknowledgment

This research was partially supported by the SGS grant from VSB–Technical University of Ostrava (No. SP2016/95) and by the project TUCENET (No. LO1404).

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Appendix A Abbreviations

The following abbreviations are used in this manuscript:

- $P \cdots$ Probability of something
- $\mu \cdots$ Failure probability function
- $q(t) \cdots$ Intensity of repair
- $r \cdots$ Mean time to repair
- $\lambda \cdots$ Intensity of failure
- $b \cdots$ Characteristics of wear
- $d \cdots$ Characteristics of lifetime
- $m \cdots$ Mean time of failure-free operation
- $k \cdots$ Constant inclusive characteristics of d and b
- $T \cdots$ Real time of operation for the unit
- $t \cdots$ Required time for prediction of probability of failure-free operation
- $P_{(B)} \cdots$ Probability of phenomenon B
- $P_{(B\cap A)} \cdots$ Probability of intersection of phenomenon A and phenomenon B simultaneously
- $P_{B(A)} \cdots$ Conditional probability of phenomenon A, if success of phenomenon B
- $P_{1(t)} \cdots$ Probability of failure-free operation
- $f_{(t)} \cdots$ Density of probability of failure-free operation
- $m_{(s)} \cdots$ Mean time of operation