Assessment of failure probability and operation risks of process plants according to data of condition monitoring systems

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Abstract

In the last few years a common means for reliability control at refineries has become a risk management system which should provide optimization of maintenance and repair costs while increasing the turnaround interval of process plants. However, a large amount of data required for risk calculation, as well as significant problems connected with unevenness of the data, lack of standards for their collection, subjectiveness of manual data input, does not allow to consider the risk management systems to be complete enough for the increase of turnaround interval and providing required minimal risk level. The main parameter for risk assessment is the probability of equipment failure. Considering the possibilities and properties of the modern condition monitoring systems it becomes possible to propose real-time calculation of process plant failure probability and operation risk.

The paper considers a statistical approach to the assessment of equipment failure probability according to the data of permanently installed condition monitoring systems. It gives the results of research on statistical parameters of machinery operation time and failure probabilities.

Usage of condition monitoring systems for calculation and monitoring of machinery operation risk allows improving the efficiency of implementation of condition monitoring means and turnaround interval of process plants.

Keywords: Operation risk, fault probability, condition monitoring.

In the last few years a common means for reliability control at refineries has become a risk management system which should provide optimization of maintenance and repair costs while increasing the turnaround interval of process plants [1,2]. However, a large amount of data required for risk calculation, as well as significant problems connected with unevenness of the data, lack of standards for their collection. Besides, subjectiveness of manual data input, does not allow to consider the risk management systems to be complete enough for the increase of turnaround interval and providing required minimal risk level.

All of the major factors causing high operating costs and losses due to accidents are manifested through the life of machinery, and the total damage depends on the timely detection of faults and the adequacy of the personnel actions taken in case of machinery resource loss due to wear of its components depending on the loss speed. The later the personnel reacted to the deteriorating condition of the equipment, the greater the amount of expenses is necessary for its recovery, and in the case of emergency the costs can exceed the cost of constructing a new processing facility. In
turn, the speed rate of the personnel reaction is determined by two main reasons: the observability of machinery condition and the adequacy of the personnel’s response to the deterioration, which is caused by the corporate discipline and understanding of the criticality of the situation. Therefore, it is necessary to provide real-time monitoring of machinery failure risk omission, i.e. suggest to managers of all levels the current financial assessment of potential costs and losses that may be incurred by the company under the current conditions of machinery operation. Observability of machinery degradation in real-time and high performance discipline of the personnel allows virtually eliminate the risk of accidents (Fig 1) [3].

The main parameter for risk calculation is a fault probability which may be found by the formula:

$$Q = 1 - P$$

where

$Q$ - probability of failure;

$P$ - probability of failure-free operation.

![Figure 1](image)

**Figure 1.** Tools for risk reduction: 1) risk curve when using repair schedule approved by the applicable regulatory documents 2) risk curve increasing from excessive inspection activity from using repair schedule approved by the applicable regulatory documents 3) risk curve when using the schedule on the basis of RBI and RCM 4) risk curve when applying fault and condition monitoring of machinery in real time.

The probability of failure-free operation of the equipment is calculated by the following expression:

$$P = e^{-\lambda t}$$

where

$\lambda$ – failure rate;
Applying in the expression 2 in expression 1 we get the expression for calculation of failure probability:

\[ Q = 1 - e^{-\lambda t} \]  

(3)

Using the expression 3 we can make a failure probability assessment in the current moment of time if we know the current run-to-failure values and failure rates. However, if the facility is equipped with an automatic condition monitoring system, the information on its current state is available every time moment. According to [8], machinery condition is divided into 3 categories: "Acceptable" (ACC) “Actions required” (ARQ), "Unacceptable" (UAC). It is clear that if a machinery condition turned UAC, calculating the fault probability by the expression 3 will lead to a substantial error.

The research is aimed at increase of reliability of a failure probability assessment, as well as an operation risk evaluation using additional data on the machinery condition in real time.

Let us assume that the machine operates in “Acceptable” state. In that case, probability of its faultless operation after some run time \( t_D \) can be calculated by the expression 2:

\[ P_D = e^{-\lambda_D t_D} \]  

(4)

where
\( \lambda_D \) – failure rate in ACC state;
\( t_D \) - operating time of the unit in ACC state.

For units working in ARQ or UAC state the probability of failure-free operation for the moment of time \( t_T \) (\( t_N \)) will be determined by the similar expression:

\[ P_T = e^{-\lambda_T t_T} \quad , \quad P_N = e^{-\lambda_N t_N} \]  

(5)

\( \lambda_T, \lambda_N \) –failure rate in ARQ, UAC states ;
\( t_T, t_N \) - operating time of the unit in ARQ, UAC states.

In reality, a unit may operate in different states, and, in general, at the total operating time moment \( t \), there are all three types of operation: operating time in ACC state (\( t_D \)), operating time in ARQ state (\( t_T \)), operating time in UAC state (\( t_N \)). In this case, since the joint probability is the product of those three probabilities, the probability of failure-free operation may be found by:
Applying in the expression 5 in expression 1 we get the expression for calculation of failure probability $Q$:

$$Q = 1 - e^{-\lambda_D t_D} \cdot e^{-\lambda_T t_T} \cdot e^{-\lambda_N t_N}$$

(7)

Let us consider the following example of the failure probability calculation by the expression 7: the unit operating in ACC state turned ARQ and then UAC. Figure 2 shows trends of the unit running in different states: $t_D$ – running in ACC state; $t_T$ – running in ARQ state; $t_N$ – running in UAC state. Figure 3 shows a trend of unit failure probability, calculated by the expression 7, consisting of 3 segments according to the failure rates in different states ($\lambda_D$, $\lambda_T$, $\lambda_N$).

![Figure 2. Trends of the unit current running time in different states.](image)

![Figure 3 – Trend of unit failure probability in different states.](image)

From the example above one can see that in the moment when the state changes – the failure probability jumps and then changes by more sharp exponent. To compare with, there is a part of the trend which is calculated without using the information on the
unit’s state (by the expression 3 with failure intensity rate $\lambda_D$). The trend shows, that in this case the failure probability equals 0.4, but the unit is operating in UAC state for some time already, and the probability of its failure is almost 1.

The expression 7 reveals, that the algorithm for calculating the failure probability presupposes the calculation of the current operating time in the corresponded states ($t_D, t_T, t_N$) and the failure rate values for the corresponded states ($\lambda_D, \lambda_T, \lambda_N$). Calculation of the current operation time in corresponded states is easy enough, but determination of the failure rate values for the various states requires research work.

For that purpose, the research uses a statistical approach – an analysis of multi-year trends of pump units vibration parameters obtained by means of stationary condition monitoring systems.

The initial data used for studying vibration parameters trends (vibration acceleration - A, vibration velocity - V, vibration displacement - S) on 538 centrifugal pumps of 17 Omsk Refinery plants. All initial trends were divided into 6 groups according to the type of the machine (pump - motor) and its size-power group [7,8,9].

Table 1 lists designations of these groups. Each of the 6 groups was also divided into 3 groups according to the vibration parameter (A, V, S). Thus, 18 trend groups were formed.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Motor (H-center height, mm)</th>
<th>Pumps (P - power in kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H &lt; 132</td>
<td>H &lt; 225</td>
</tr>
<tr>
<td></td>
<td>H &lt; 400</td>
<td>P &lt; 50</td>
</tr>
<tr>
<td></td>
<td>P &lt; 200</td>
<td>P &gt; 200</td>
</tr>
<tr>
<td>Vibration features</td>
<td>A,V,S</td>
<td>A,V,S</td>
</tr>
<tr>
<td>Number of units</td>
<td>20</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td>373</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>226</td>
<td>135</td>
</tr>
</tbody>
</table>

For each unit in each analyzed group the values of failure intensity rate $\lambda$ were calculated by the expressions:

$$\lambda = \frac{1}{Tc}$$

where

$$Tc = \frac{\sum_{i=1}^{N} T_i}{N}$$

$Tc$ – Average operating time.

From the values of the current operating time $T_i$ the average value of operating time $Tc$ was determined by the expression:

$$N – The number of current operating time periods.$$
The value of the current operating time were calculated as an interval between the machinery repairs conducted. To obtain more reliable assessment, the operating time was determined by the longtime vibration parameter trends.

Figure 4 shows a 1,5-year trend of vibration acceleration on the centrifugal pump unit. The figure shows that in time moments 1 and 3 the unit was shut down with high values of the parameters (in ARQ and UAC states, respectively), and then in time moments 2 and 4 the machine was started up in ACC state. Consequently, one can assume with high probability that during the gaps 1 - 2 and 3 - 4 the unit was under repair so its condition was improved. The current operating time values in various states in this case was taken as the time that vibration parameter spent in ACC, ARQ, UAC states in the gap (2 - 3) between the repairs.

![Figure 4. 1,5-year trend of vibration acceleration on the centrifugal pump unit.](image)

Statistical analysis of the obtained by the expressions 8 and 9 arrays of failure rates $\lambda$ was carried out using R-Studio software package. As a result, the density distribution function $\lambda$ in the various states and various groups were obtained, as well as checking of $\lambda$ dependency on the factors like the machine type or size-power group was carried out.

Figure 5 shows the function of failure rate distribution density $\lambda$ in UAC state (red), ARQ (Yellow), ACC (green) by the vibration acceleration of the centrifugal pump unit (A - motor B - pump).
Figure 5 - Function of failure rate distribution density $\lambda$ in UAC state (red), ARQ (Yellow), ACC (green) by the vibration acceleration of a motor (A) and a pump (B)

It may be noted, that the distribution of $\lambda$ for ARQ and UAC states are multimodal, while the distribution of $\lambda$ for the state ACC is expressed in Weibull form. The numerical values of $\lambda$ for ARQ and UAC states are more than 100 times higher than the values of ACC state.

Since $\lambda$ is different from the normal distribution, to determine confidence intervals the distribution statistics, it is not appropriate to use the standard interval estimate by the Student ratio. To calculate the confidence intervals one may use the numerical method - bootstrap analysis [10], which is implemented in the R package.

To test the effect which various factors have on $\lambda$ value, the nonparametric Wilcoxon rank test (Mann-Whitney test) is used [11]. This criterion was used for pairwise checking whether two distributions belong to one, by taking samples with various factors.

An analysis of the data yielded the following results:

1 All $\lambda$ distributions are not subject to the normal law. Distributions for ARQ and UAC states has a multimodal form, distributions for ACC state are expressed in Weibull form.

2 Statistics of A, V, S of $\lambda$-parameters in ACC state (and therefore in ACC + ARQ and ARQ + ACC + UAC states) have identical values. This is due to the fact that in ACC state all the parameters have the same operating time. Differences in operating time for various signs appear only in the ARQ and UAC states.

3 An increase in the size-power group of the unit causes a slight decrease in $\lambda$-values in ACC state. On the contrary, for values of ARQ and UAC states the $\lambda$-values increase together with size-power group of unit.

4 The hypothesis of the equality of the distribution of $\lambda$ parameters in ARQ + UAC state and their independence from the size-cardinality group was validated.
state of machinery. The approach employed in the systems for continuous condition monitoring can significantly improve the effectiveness of their implementation and increase units’ turnaround.

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Welcome to CM 2016 and MFPT 2016

10-12 October 2016, Novotel Paris Sud, Porte de Charenton, Paris, France

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The British Institute of Non-Destructive Testing (BINDT) is pleased to invite you to this premier event, the Thirteenth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies.

The Conference is being organised by BINDT in close co-operation and partnership with the US Society for Machinery Failure Prevention Technology (MFPT). The combination of the efforts of two leading organisations creates the largest event of its kind at a truly international level and builds on the highly successful series of twelve international Condition Monitoring Conferences organised by BINDT and 70 Annual Conferences organised by the Society for MFPT.

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• Plenary distinguished invited presentations
• Specialised keynote addresses (for structured session organisers)
• Invited presentations
• Contributed presentations, including case-study presentations
• World-leading sessions for major industrial sectors, including a session for the BINDT certification scheme
• Expert panel sessions on hot topics in condition monitoring, organised by recognised scientists
• Extensive exhibition and vendor presentations
• Social events

The exhibition of around seven will take place alongside the conference and will provide an ideal opportunity to investigate the up-to-date technology available.

Sponsored by:
Session 2A – **Condition monitoring systems**  
*Chair: Professor V Kostyukov  Room: Decouverte 3 and 4*

**14.00**  
[127] *Assessment of failure probability and operational risks of process plants according to the data of condition monitoring systems*  
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