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# Enhancing Pumps Reliability in Redundant Systems: A Proposed Procedure Utilizing ISO 13373-3 and ISO 10816 Bearing Vibration Analysis

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## Abstract

Optimizing the arrangement of pumps in industrial complexes is paramount for enhancing system reliability. This study presents a novel methodology that seamlessly integrates vibration analysis into reliability calculations, leveraging the ISO 10816 standard for vibration zone classification and the ISO 13373-3 standard for vibration severity assessment. This research introduces reliability calculation relationships tailored for single pumps, as well as for parallel and standby configurations. A key innovation of this paper is the inclusion of vibration zone effects and vibration severity in these reliability relationships. The proposed methodology aims to identify the most effective configuration of active and standby pumps. Analysis of leaching pumps in the mining industry demonstrates that incorporating a standby pump can enhance reliability by up to 16%, achieving a remarkable reliability of 98%. Furthermore, deploying three pumps can push reliability beyond 99%. The application of this methodology extends to optimizing pump arrangements in water and sewage stations, showcasing its practical implications in industrial settings.

**Keywords**: Reliability; Redundancy; Vibration Analysis; Condition Monitoring.

## 1. Introduction

In modern industrial systems, reducing downtime is a key goal, necessitating the analysis of system reliability and the implementation of condition monitoring (CM) strategies. CM is essential for early failure detection, enhancing machine life and reliability while lowering repair costs. A prominent CM technique is vibration analysis, which monitors machines' vibrational behavior to identify faults, predict failures, and estimate remaining useful life (RUL). Rolling element bearings (REBs), commonly used in rotating machinery, are significant contributors to machine failures, representing 45-55% of breakdowns. Since REBs have a limited lifespan, timely replacement is critical to avoid catastrophic failures. This article explores the integration of vibration analysis and reliability metrics, creating a comprehensive method to improve industrial machinery performance and longevity.

To introduce the approach of this article, which combines vibration analysis and reliability analysis, the focus will be on industrial pumps. Pumps are integral to many industrial processes, including manufacturing, chemical processing, water treatment, energy generation, etc. The number of pumps utilized across different industries can be substantial, reflecting their critical role in various processes. For instance, in the oil and gas sector, thousands of pumps are employed for extraction, transportation, refining, and distribution. In water and sewage treatment, municipalities often operate hundreds to thousands of pumps to manage the water supply, drainage, and wastewater treatment systems. In conclusion, the importance of pumps in industrial applications cannot be overstated. Any failure in a pumping system can lead to significant disruptions, resulting in lost productivity, delayed operations, and potential financial losses. Ensuring pump reliability can reduce the total cost of ownership by minimizing maintenance expenses, energy consumption, and the need for frequent replacements. Therefore, industries must invest in high-quality pumps, regular maintenance, and effective monitoring systems to guarantee optimal reliability and performance.

In various industries, it is common to find configurations where multiple machines operate in parallel or are maintained as spare equipment, collectively referred to as redundant systems or standby machines. The term “$k$-out-of-$N$” is often used to describe these systems, where k denotes the number of machines actively in service and $N$ represents the total number of machines, including both primary and backup units. In the context of parallel systems, if a failure occurs in one line, the operation can continue through the other line, thereby preventing a complete halt in production. Spare equipment is activated when the main machinery can no longer operate at optimal efficiency. The effective design and arrangement of equipment that incorporates redundancy can significantly enhance both the efficiency and the lifespan of the machinery. However, fundamental questions arise regarding the optimal configuration of these systems. Specifically, given $N$ similar machines, what is the ideal number ($k$) that should be in service, and how many ($N - k$) should remain as standby units? Additionally, a critical consideration is determining the appropriate timing for activating spare machines and deactivating other equipment to maximize overall reliability.

The topic of replacement strategies for online and standby pumps, with a focus on vibration behavior, has been addressed in a few publications. In 2007, Shalev and Tiran [1] introduced a method for calculating the reliability of a pump with a standby unit, taking into account the vibrational stage of the bearings failure to enhance fault tree analysis. In 2019, Xing et al. [2] utilized a Hidden Markov Gaussian Mixture Model (GMM) and dynamic Bayesian network (DBN) for REB’s degradation state estimation based on CM data, applying the results for dynamic risk assessment. More recently, He et al. [3] proposed a real-time probabilistic risk assessment method based on vibration data, incorporating a DBN to integrate monitored data into risk assessment. Despite these advancements, many articles have yet to pursue the topic of bearing vibration analysis for fault diagnosis and prognostics to assess pump reliability in redundant systems. Soomro et al. [4] reviewed literature in the field of bearing fault diagnosis, while Singh et al. [5] and Bhandare et al. [6] focused on methods for predicting the RUL of bearings.

As previously mentioned, the objective of this article is to analyze the failure state of bearings in order to calculate the reliability of pumps. In this context, the article begins with the identification of the vibration zone of the bearing in accordance with ISO 10816 (20816) standard, followed by the determination of the severity of the bearing vibrations based on ISO 13373-3 standard. Subsequently, the reliability of the bearings, and by extension, the reliability of the pumps, is calculated. While this study employs standard-based methodologies to assess the bearing vibrations, it acknowledges that intelligent models utilizing machine learning and deep learning could be utilized as alternatives in this assessment. Furthermore, this paper examines the reliability of two and three similar pumps arranged in different configurations with distinct operational modes. It demonstrates how the inclusion of a parallel pump or a standby pump can significantly enhance the overall reliability of the system for a sample leaching pump in mining industry. The introduced approach discussed is applicable to both online and offline CM systems. Finally, the practical application of this approach is illustrated through an industrial case study involving several parallel pumps within the water and sewage system of a province.

This article is structured as follows: Section 2 provides a detailed, step-by-step description of the proposed reliability prediction approach, which is applicable to any number of available pumps. Section 3 presents calculations and analyses of the reliability for two available pumps and then, three available pumps in various configurations. Section 4 introduces an industrial case study and presents the findings associated with it. Ultimately, conclusions and future interests are given.

## 2. Proposed Reliability Prediction based on Vibration Analysis

The stages for assessing the reliability of each pump configurations based on vibration severity are illustrated in Figure 1. A detailed explanation of the calculation procedures for each step will follow.

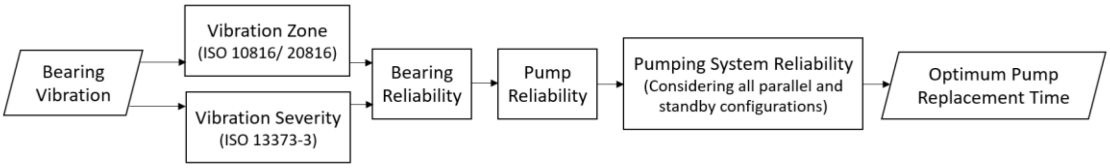


**Figure 1.** Flowchart of how to calculate reliability based on pump vibrations.

### 2.1 Bearing Vibration Zone

ISO 20816 (previously known as ISO 10816) is a standard that outlines guidelines for assessing the overall vibration of machinery, with a particular emphasis on rotating equipment. The standard establishes criteria for vibration measurement and evaluation, ensuring that machinery operates within acceptable vibration limits to mitigate the risk of damage and prolong operational lifespan. It delineates thresholds for safe machine operation and provides threashold on acceptable vibration levels according to the type of machinery and its operational conditions. ISO 20816 categorizes vibration severity into four distinct evaluation zones:

- Zone A (normal operation): Typically associated with newly commissioned machinery, which usually falls within this category.
- Zone B (under care): Designated for unrestricted long-term operation of machines, indicating satisfactory performance.
- Zone C (action required): Indicates that machines are experiencing unsatisfactory long-term continuous operation, warranting further investigation or corrective measures.
- Zone D (immediate action required): Represents a critical situation where vibration levels are high enough to potentially cause damage to the machinery.

Additionally, ISO 20816-7 [7] especifically addresses the evaluation of rotodynamic pumps within industrial applications, focusing on vibration measurements taken from non-rotating components. This standard serves as the reference framework for this research, aiding in the determination of vibration zones (A/B/C/D) for the pumps based on measurements carried out on each bearing (DE: drive-end and NDE: non-drive-end).

### 2.2 Bearing Vibration Severity

REB severity chart, presneted in ISO 13373-3 standard [8] is utilized to determine vibration severity. According to r.m.s. acceleration and maximum peak acceleration, vibration severity is described. By using severity chart vibration severity could be divided into bad (alarm- red region in

Figure 2), doubtful (alert- yellow region in Figure 2) and good condition (normal zone- green and blue regions in Figure 2).

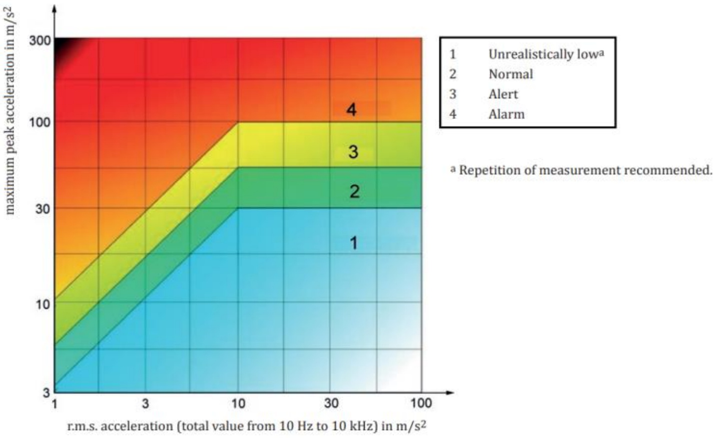


**Figure 2.** Rolling element bearing vibration severity chart based on ISO 13373-3 [8].

## 2.3 Bearing Reliability Prediction

The basic rating life of a bearing according to ISO 281 [9] can be expressed as:

$$L_{10} = (\frac{C}{P})^b \tag{1}$$

where $L_{10}$ is the basic rating life of the bearing (in millions of revolutions) at 90% reliability, $C$ is the dynamic load of the bearing (in kN) and is specified by the manufacturer for each particular bearing, $P$ is the equivalent dynamic bearing load (in kN) that the bearing is designed to withstand this load, and the exponent $b$ is an index that is equal to 3 for ball bearings and 10/3 for roller bearings.

If the speed is constant, it is often prefarable to calculate the life expressed in operating hours, using the following equation:

$$L_{10h} = \frac{10^6 L_{10}}{60n} \tag{2}$$

in which, $L_{10h}$ is the basic rating life of bearing (in operating hours) at 90% realibility, and $n$ is the rotational speed (in rpm).

The relationship between reliability and failure rate can be written as [1]:

$$R(t) = \exp(-\lambda t) \tag{3}$$

where $R$, $\lambda$, and $t$ respectively are reliability, failure rate, and time. The combination of Eq. (2) and (3) yields the following equation for determining the failure rate of a REB:

$$\lambda_{Bearing} = \frac{\ln(\frac{1}{0.9})}{\alpha L_{10h}} \tag{4}$$

It should be noted that basic rating life ($L_{10h}$) in the aforementioned relation refers to a bearing that has not yet entered the failure zone. Consequently, as damage within the bearing progresses, this parameter will undergo changes by the coefficient factor, $\alpha$, introduced in Eq. (4). Article [1] categorizes this rate distinctly across various stages of failure, neglecting the severity of failure associated with each vibration zone. In this article, the vibration zone of the bearing, as defined in Section 2-.1, along with the severity of vibrations calculated as outlined in Section 2.2, are utilized to derive the $\alpha$ coefficient, as presented in Table 1.

**Table 1.** Percentage of residual life of bearing associated with each vibration zone ($\alpha$ in Eq. (4)).

| **Bearing Vibration Zone** | **Vibration Severity** | | |
|---|---|---|---|
| | **Good (*)** | **Doubtful (**)** | **Bad (***)** |
| Zone A | 20 | 15 | 10 |
| Zone B | 10 | 7.5 | 5 |
| Zone C | 5 | 3 | 1 |
| Zone D | 1 | 0.5 | 0.1 |

## 2.4 Pump Reliability Prediction

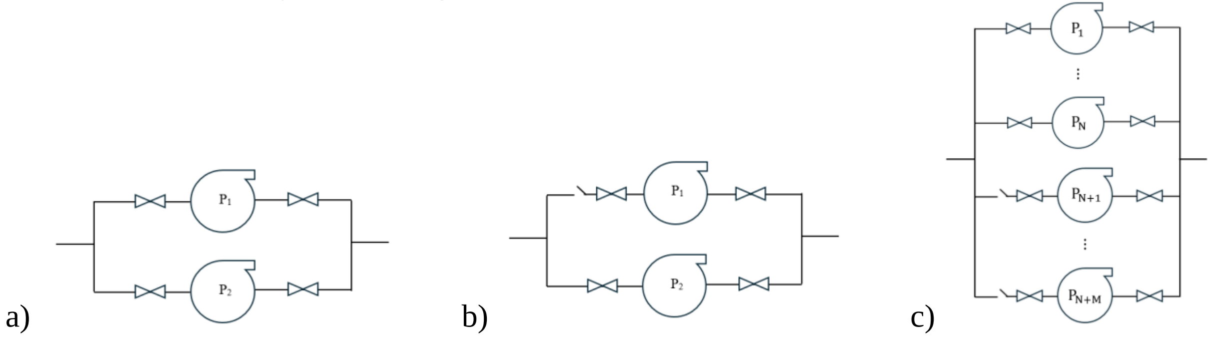
Pump assemblies are comprised of many component parts including sealing, shaft, casing, fluid driver, and bearings. The equivalent failure rate for a pump is obtained by adding up the failure rates of each component of the pump [1]:

$$\lambda_P = \lambda_{sealing} + \lambda_{shaft} + \lambda_{ca\sin g} + \lambda_{fluid-driver} + \sum \lambda_{Bearing} \tag{5}$$

In light of bearings being identified as the components with the highest failure rate of industrial pumps, the failure rates of the other parts of the pump may be regarded as equivalent to their nominal values. Consequently, the overall failure rate of the pump is influenced by the vibration state of the bearing, and any changes in the failure rate of the bearing are proportional to these vibrations. This relationship can be calculated in accordance with the equations presented in Section 2.3. Substituting the failure rate derived from Eq. (5) into Eq. (3) yields the reliability of a single pump.

## 2.5 Pumping System Reliability Prediction

This section presents the methodology for calculating the reliability of the pumping system across three configurations, including parallel pumps, single pump with a standby, and a combination of active and standby pumps (Figure 3).



a) b) c)

**Figure 3.** Schematic of pumping system configurations: a) parallel pumps b) single pump with a standby c) combintaion of active and standby pumps

### 2.5.1 Parallel Pumps

In parallel pumps structure (Figure 3.a), both pumps are active, and system operates if either one or both pumps work properly. The reliabilities of two pumps can be evaluated using the procedure decribed in Section 2.4 and then, the equivalent reliability for this configuration is defined by [10]:

$$R = 1-(1-R_1)(1-R_2) \tag{6}$$

### 2.5.2 Single Pump with a Standby

Standby redundancy structure is attained when a single pump works, and the other pump is not active as illustrated in Figure 3.b. In this configuration an operator can decide when to switch these pumps and this decision is of particular importance in order to obtain maximum reliability. Equivalent reliability for this structure is evaluated as [10]:

$$R = \begin{cases} \dfrac{\lambda_2 R_1 - \lambda_1 R_2}{\lambda_2 - \lambda_1} & \lambda_1 \neq \lambda_2 \\ \exp(-\dfrac{\lambda_1 + \lambda_2}{2} t) + \dfrac{\lambda_1 + \lambda_2}{2} t \exp(-\dfrac{\lambda_1 + \lambda_2}{2} t) & \lambda_1 = \lambda_2, \lambda_1 \approx \lambda_2 \end{cases} \tag{7}$$

### 2.5.3 Combination of Active and Standby Pumps

By intergrating Eqs. (6) and (7), the reliability of a confuguration comprising $N$ active pumps and $M$ standby pumps (as illustrated in Figure 3.c) can be derived. Initially, the individual reliabilities of all active pumps and all standby pumps are calculated as follows:

$$\begin{cases} R_a = 1 - \prod_{i=1}^{N} (1 - R_i) \quad ; \quad \lambda_a = -\dfrac{\ln(R_a)}{t} \\ R_s = 1 - \prod_{i=1}^{M} (1 - R_i) \quad ; \quad \lambda_s = -\dfrac{\ln(R_s)}{t} \end{cases} \tag{8}$$

Subsequently, these computed reliabilities, along with the failure rates, are substituted in Eq. (7) to ascertain the overall reliability of the pumping system.

## 3. Pumping System Reliability Analysis

This section addresses two key questions: How does the failure of individual bearings, or the simultaneous failure of both, impact the overall reliability of a pump? How does the implementation of parallel pump configurations or the presence of a standby pump enhance reliability, and what constitutes the optimal arrangement of pumps? First, relevant data from a sample industrial pump is presented to explore these questions, followed by an analysis that answers the above questions based on this specific pump case.

### 3.1 Data Introduction

The pump analyzed in this section pertains to the electropump utilized in the leaching unit of a mining industry (Figure 4), with technical information provided in Table 2. This table outlines the failure rates associated with the sealing, shaft, casing, and fluid-driver of the pump. Additionally, the vibration trend of the pump over time, as well as the time of bearing replacement, are illustrated in Figure 5. The vibration zone and severity for both bearings of the pump have been calculated using the methodology outlined in Section 2. The results are presented for various dates in Table 3.

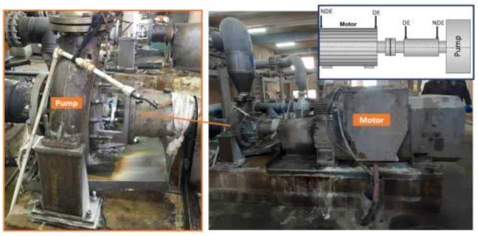


**Figure 4.** Leaching process electropump.

**Table 2.** Technical information of a pump analyzed in this research.

| Power [kW] | 200 |
|---|---|
| Speed [rpm] | 1415 |
| Pump DE Bearing | 6226-C3 Timken, C = 165 kN |
| Pump NDE Bearing | 6226/C3VL0241 SKF, C = 156 kN |
| Equivalent dynamic bearing load [N] | 419 |
| Sealing failure rate | 8e-6 |
| Shaft failure rate | 6e-6 |
| Casing failure rate | 5e-6 |
| Fluid-driver failure rate | 3e-6 |

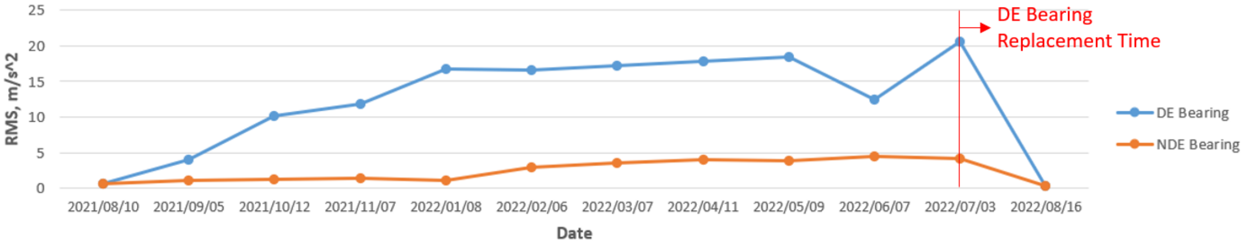


**Figure 5.** Vibrational trend of the pump (RMS, m/s$^2$, 1-8 kHz): a) DE bearing b) NDE bearing.

**Table 3.** Vibration zone and vibration severity of the leaching pump's bearings.

| Date | Pump DE Bearing | | Pump NDE Bearing | |
|---|---|---|---|---|
| | Vibration Zone | Vibration Severity | Vibration Zone | Vibration Severity |
| 2021/08/10 | A | * | A | * |
| 2021/09/05 | B | * | A | * |
| 2021/10/12 | D | * | A | * |
| 2021/11/07 | D | * | A | * |
| 2022/01/08 | D | ** | A | * |
| 2022/02/06 | D | ** | B | * |
| 2022/03/07 | D | ** | B | * |
| 2022/04/11 | D | ** | B | * |
| 2022/05/09 | D | ** | B | * |
| 2022/06/07 | D | * | B | * |
| 2022/07/03 | D | *** | B | * |

## 3.2 Impact of Bearing Failures on Pump Reliability

In order to calculate the reliability of a single pump configuration, $L_{10h}$ should be evaluated for both bearings in each failure stage as illustrated in Table 3. Modified $L_{10h}$ is used to obtain failure rates for each of bearings and equivalent failure rate for pump by utilizing Eqs. (3) and (5), respectively. Reliability of this structure in each failure stage can be attained by using Eq. (4). Figure 6 illustrates reliability changes in term of bearings condition. As shown in the figure, due to the presence of two distinct bearings in the pump, variations in the failure stage of each bearing will produce differing effects on the overall reliability of the pump.

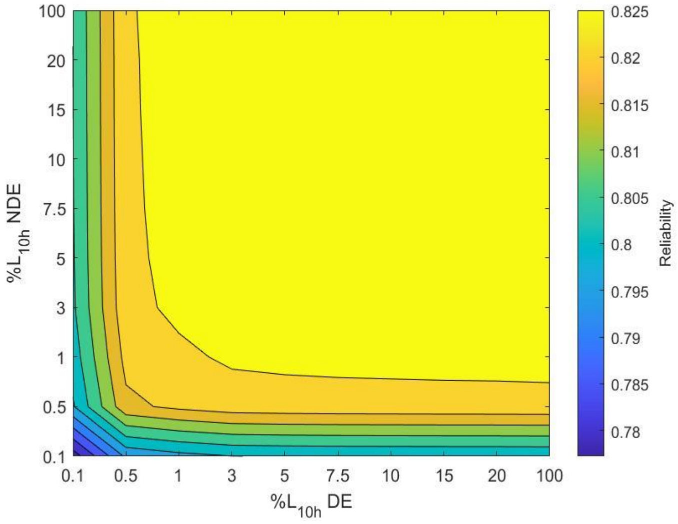


**Figure 6.** Effect of bearings' failure (in terms of the percentage of bearing life) on the pump's reliability

## 3.3 Optimal Configuration of a Two-Pump System

In scenarios where the provision of two pumps is feasible, three configurations can be considered: (1) only one pump is operational, (2) both pumps are operational, or (3) one of the pumps is designated as standby within the circuit. In the case of parallel pumps, it is assumed that the bearings in both pumps change their failure phase simultaneously. However, solving the problem for other situations is also possible with the proposed formulation of this article. In this configuration, the modified $L_{10h}$ should be multiplied by the number of pumps to accurately simulate the operational conditions, as pumps arranged in parallel experience reduced load.

Figure 7 shows the variation of reliability at different failure levels (mentioned in Table 3) for the three configurations. The average reliabilities for single pump, parallel pumps, and standby configuaration are respectively 82.4%, 97.0%, and 98.3%. So, the optimal configuration for a two-pump system is to save a pump as a standby in the circuit.

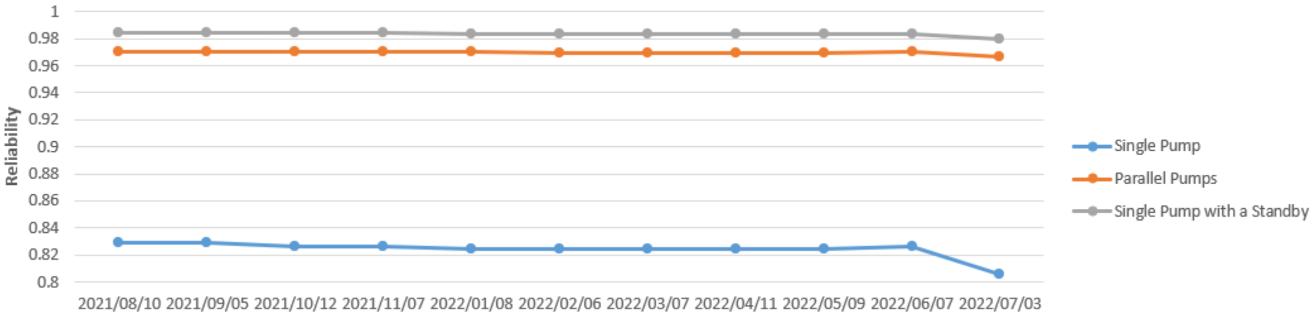


**Figure 7.** Reliabilities for various configuration of a two-pump system

### 3.4 Optimal Configuration of a Three-Pump System

In scenarios where the deployment of three pumps is feasible, three distinct configurations may be considered: (1) all pumps are operational, (2) one pump is designated as standby, or (3) two pumps are regarded as standby within the system. The minimum and maximum reliabilities of the mentioned arragaments at different failure stages (reported in Table 3) are given in Table 4. It can be observed that for the pump under investigation, when three pumps are available, the reliability exceeds 99%, regardless of the configuration employed.

**Table 4.** Maximum and minimum reliabilities for various configuration of a three-pump system.

| Configuration | Minimum Reliability (%) | Maximum Reliability (%) |
|---|---|---|
| Three parallel pumps | 99.4 | 99.5 |
| two active pumps and one standby pump | 99.7 | 99.7 |
| One active pump and two standby pumps | 99.8 | 99.9 |

## 4. A Practical Application of Approach

In water and sewage systems, it is typical for each water supply station to be equipped with multiple pumps. The selection of a specific number of these pumps to be engaged in the operational circuit is determined by the water level in the reservoir. The responsibility of the line operator is to select the appropriate pumps to be activated during each operational time interval. However, by calculating the reliability of each potential configuration using the proposed procedure in this paper, it is possible to optimize the overall reliability of the pumping system.

Figure 8 depicts four parallel pumps situated within a water and sewage station. The power and rotational speed of the electromotors are 90 kW and 1481 rpm, respectively. Vibration signal analysis of the electropumps' bearings has been performed, and the vibration zones along with their severity have been calculated in accordance with the methodology outlined in Section 2 and are presented in Table 5.

**Table 5.** Vibration zone and vibration severity of the water and sewage pumps.

| Pump | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Vibration Zone and Severity | C* | D** | B* | C* |

**Figure 8.** Water and sewage parallel electropumps.

In the water supply system under consideration, it is typically recommended that two pumps be operational in the circuit to meet urban water demands, while the remaining two pumps are maintained in standby mode. Table 6 presents the reliability for various types of active pumps. It is evident that by activating pumps 1 and 4 within the circuit, the highest level of reliability is attained. Consequently, the methodology detailed in this article provides guidance for operators in selecting optimal active pumps.

**Table 6.** Reliability for various configurations of a four-pump system in a water and sewage company- considering two active and two standby pumps.

| **Active Pumps** | 1-2 | 1-3 | 1-4 | 2-3 | 2-4 | 3-4 |
|---|---|---|---|---|---|---|
| **Reliability (%)** | 96.5 | 98.4 | 99.6 | 98.4 | 96.5 | 98.4 |

## 5. Summary/Conclusion

The objective of this article is to present a novel methodology for calculating and then enhancing the reliability of pumping systems based on the zone and severity of vibrations. This methodology is grounded in ISO 10816 and 13373-3 standards and has been initially analyzed through an analysis of the failure status of pump bearings concerning their reliability. Subsequently, a comparative analysis has been conducted between two-pump and three-pump systems, specifically focusing on leaching electropump within mining industry. The findings indicate that the incorporation of one standby pump can enhance system reliability to 98%, and the implementation of three pumps can elevate reliability to over 99%. Moreover, the study has addressed the identification of optimal active pumps within parallel pumping systems, with particular attention to water and sewage applications to increase overall system reliability. While this work has developed reliability analysis, future research is required to implement smart online systems that decides when to activate which pump in a set of several parallel pumps to reach the maximum reliability, using the procedure introduced in this paper.

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