Detection and classification of alarm threshold violations in condition monitoring systems working in highly varying operational conditions

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Abstract. All commonly used condition monitoring systems (CMS) enable defining alarm thresholds that enhance efficient surveillance and maintenance of dynamic state of machinery. The thresholds are imposed on the measured values such as vibration-based indicators, temperature, pressure, etc. For complex machinery such as wind turbine (WT) the total number of thresholds might be counted in hundreds multiplied by the number of operational states. All the parameters vary not only due to possible machinery malfunctions, but also due to changes in operating conditions and these changes are typically much stronger than the former ones. Very often, such a behavior may lead to hundreds of false alarms. Therefore, authors propose a novel approach based on parameterized description of the threshold violation. For this purpose the novelty and severity factors are introduced. The first parameter refers to the time of violation occurrence while the second one describes the impact of the indicator-increase to the entire machine. Such approach increases reliability of the CMS by providing the operator with the most useful information of the system events. The idea of the procedure is presented on a simulated data similar to those from a wind turbine.

1. Introduction
In the last several years we may observe a rapid growth of condition monitoring systems (CMS), employed nowadays in any field, where safety requirements meet a need to maximize the effectiveness of machinery operation. Regardless the area of usage, all CMS gather and process information from machinery residual processes, like vibration, oil or temperature, in order to reveal any sign of fault development. This information is often referred as diagnostic features (estimates), i.e. features that carry diagnostic information for the user of the system. The number of such diagnostic features to monitor is still increasing together with the advancement of signal processing techniques and computing capabilities. As stated in [1], in typically used wind turbine’s vibration monitoring process, there is nearly 150 diagnostic features monitored simultaneously and this number could rise if, for instance, additional sensors were installed or temperature

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features were taken into consideration. For a machinery park number of features to track reaches thousands [2], for example for new designs of wind farms.

In order to simplify decision-making process on such extensive amount of data, the statistical process control limits are set using various methods, such as presented in [3-5]. Moreover, for machinery working in varying operation conditions, the operational states were employed [6-8] to limit the number of false positive alarms resulting from high fluctuation of process parameters.

Nonetheless, diagnostic engineers responsible for operation of particular group of machines are still forced to deal with overwhelming number of threshold violations. This is due to several causes, besides the actual fault detection, just to name the most severe ones: improper or lack of threshold setup, irregular and unexpected behavior of machinery process parameters, technical problems not related to machinery condition, etc.

Many attempts were made in the field of alarm management starting from the early 80s [9-10], when first scientists pointed out a large number of alarms to be dealt with in rapidly growing power and process industries. They also noticed a need for distinguishing a crucial alarms to the entire system from less significant ones. In [11] the authors emphasize the difficulty with definition of the priority of particular alarms in operational context. Simultaneously they refer to the survey with process plant operators and claim that on average there are about 80 alarms in the first minute of a severe plant breakdown. The number of problems to be checked with no special priority for action is overwhelming to operators. Based on these conclusions the International Society of Automation developed the standard [12] that laid a foundation to the industrial applications, as mentioned in [13]. It assumed identification of necessary alarms and became the groundwork for this paper, in which the authors would like to discuss the idea of violation attributes and introduce the new approach – the violation priority coefficient (VPC) – for simplification of decision-making process. Although the proposed method is mainly focused on condition monitoring systems of wind turbines, it could be employed as well to other groups of rotating machinery.

This article is organized as follows. At first, the violation attributes are described to differentiate significance of various alarm features to the machine’s operation. Then, the methodology of reasoning is proposed. The case study on simulated data is presented step-by-step for several threshold violations of three, typically used in CMS, diagnostic features. Finally, the results are discussed and paper is concluded.

2. Violation attributes
Firstly it is essential to note that in the further discussion as a violation one should understand any singular crossing of defined threshold level by selected diagnostic estimator of rotating machine. We do not take into account the industrial practice of delaying the detection of an alarm or other practical modifications of the threshold violation management.

Every violation can be described using few attributes, that inform of a value that estimator reached, time when it happened, or what kind of estimator is above the limit. In authors opinion the listed details of violation may be used as a measure for the priority calculation.

2.1 Severity
The severity factor can be understood as level of the abnormal behavior compared to the acceptable, regular projection of particular phenomena (e.g. vibrations or temperature). In some cases, the distance from the normal operation can be fixed, as suggested in standards [14-15], where recommended vibration levels for rotating machines categorized into different classes based on their size and possible vibrations. Other approaches assume calculation of thresholds after ‘referential’ period of observation using various methodology [16-17]. For the typically used CMS common practice is to distinguish two basic levels of severity:

- Warning,
2.2 Time of occurrence
An attribute related to date is an important information for decision making process. Based on authors’
experience this parameter should modify its value in descending order. This is due to the fact that violation
that appears, e.g. today should have higher priority than the ones from 7 days ago. Therefore authors propose
to use gradual time of occurrence justification:
- 1 – old, e.g. older than 7 days,
- 2 – recent, e.g. between 2-7 days,
- 3 – new, e.g. until 2 days ago.

The problem of how to set the limits between particular levels can be solved in many ways. The values
proposed above are based on authors’ practice and should be treated merely as a starting point. Following
this manner will allow user to keep his insight about systems current performance up-to-date.

2.3 Type of feature
In the past few decades, a numerous health indicators (also called features) were proposed for a measure of
the machinery dynamic condition. For instance, for vibration-based condition monitoring, these indicators,
that could also be referred as ‘diagnostic features’, consists of two main groups: narrowband and broadband.
Narrowband features are calculated from a filtered band of frequency-domain signal, i.e. from the selected
row of spectral lines. In the contrary, broadband features does not require this specification as they are
obtained from a much wider band. Intuitively, the two groups of features have slightly different meaning.
According to [18], the narrowband group helps to localize the occurring fault since it focuses on observation
of characteristic frequencies related to individual rotating components. The increase of broadband features
usually appears sometime after the increase of narrowband features and bring information of a severe fault.
We propose that the broadband features have increased importance.

2.4 Type of element
Varying attention can be given to different kinematic elements based on e.g. statistics of failures. Gathered
statistical analyses are published frequently for certain types of machinery and carry information about
elements of that were mostly prone to damage in the period of time the report concerns. In [19] authors
presented statistics of causes of failure for offshore wind turbines. This information can result in
emphasizing selected threshold violations rather than the others. Another matter is length of a downtime
causd by the failure of a particular element [20] which may cause significant loss to the machine’s owner
and therefore should be taken into consideration.

3. Methodology
For the purpose of alarm classification, the authors propose to use the violation priority coefficient (VPC),
calculated for the individual violations using to the following formula:

\[ VPC_i = \prod_{j=1}^{k} A_j(s), \]

where \( i \) represents violation index, \( j \) – attribute index, \( k \) stands for total number of attributes used to describe
violation, while \( s \) is index of \( j^{th} \) attribute’s level, also referred to as ‘significance’. Values of \( A_j(s) \) could
be also understood as weights of particular levels and be designated based on the statistical estimations or
on the personnel’s experience.

Exemplary possible calculations of VPC for two attributes are presented in Table 1, where \( m \) is number
of levels of the first attribute, while \( n \) stands for number of levels of the second attribute.
In the final step, for the obtained sequence of VPCs: $\langle VPC_1, VPC_2, VPC_3, \ldots, VPC_n \rangle$, perform permutation to obtain new vector of VPCs: $\langle VPC'_1, VPC'_2, VPC'_3, \ldots, VPC'_n \rangle$, so that $VPC'_1 \geq VPC'_2 \geq VPC'_3 \geq \ldots \geq VPC'_n$. It is equivalent to sorting of violations in the descending order.

4. Case study

The authors would like to present the VPC properties via observing how the state-of-the-art CMS and proposed approach would categorize violations. The comparison is performed using simulated trend data presented in Figure 1. Although the trend plots were generated using MATLAB® software, yet it mimics diagnostic estimates behavior from a real life system – in this case from the wind turbine’s front bearing on generator. For the clarity purposes authors selected two narrowband features essentially used for bearing diagnosis, i.e. fundamental train frequency (FTF) and ball-passing frequency of outer race (BPFO), while as wideband one, the vibration energy estimate calculated as root-mean-square (RMS).
was selected. Please notice that although trends are plotted on separate figures they concern simultaneous events, what is denoted by the time axis. We did not assign any time to the observations, as the method can be adapted to different sampling frequencies. For this test we assumed that a significant change may happen between consecutive observations, so for clarity a reader can associate it with daily measurements.

The two levels of violations are set for the presentation purposes: warning (dotted line) and alarm (dashed line). They were designated using the two-step procedure presented in [5].

In order to highlight more important violations, the significance factors need to be adjusted. This can be done using either statistical approach as e.g. presented in [19-20] or from the experience of the responsible personnel. For the purpose of presentation, three attributes are distinguished, i.e. type of a feature under investigation, level of vibration understood as violation’s severity and novelty factor dependent on the date of violation’s occurrence. Values attached to each of the attribute levels, i.e. their ‘significance’, are presented in Table 2.

### Table 2 Attributes of violations with it significance factors

| Attribute | Type of feature | Novelty | Severity |
|-----------|----------------|---------|----------|
| Significance | Wideband | Narrowband | New | Recent | Old | Alarm | Warning |
|            | 9            | 3       | 10       | 4        | 1    | 10    | 5         |

As one may notice the highest attention should be given to wideband feature, i.e. RMS (over FTF and BPFO) and exceeding of level identified as ‘alarm’ (over ‘warning’). As for the novelty factor, violations occurring at the exact time should receive the highest priority, middle one should be given to events that happened one observation ago, and least importance is assigned to the older violations.

Base on this, the VPC is calculated on individual threshold violations. In the second step the violations are sorted in descending order to show the event with the greatest importance to the user.

The interesting events that are to be described in this section are ticked on Fig. 1 with letters A.-E. The first event, marked as Observation A. occurs in the moment of single warning-level violation on FTF estimate. This circumstance would be recorded similarly for the state-of-the-art approach and for the one proposed in this paper (Table 3). Instinctively, since there is only the individual violation, there is no difference between the results.

### Table 3 Comparison between alarm display for two approaches for Observation A.

| Event | State-of-the-art | Proposed |
|-------|------------------|----------|
| #     | Status | Date | Analysis | Value | Limit | #      | Status | Date | Analysis | VPC |
| A.    | 1      | warning | 22 | FTF | 0.0196 | 0.0179 | 1      | warning | 22 | FTF | 150 |

The first difference could be spotted for Observation B. In this case the three channels cross the threshold concurrently: RMS and BPFO their warning levels, while FTF its alarm level.

For the typical approach, all of this event are simply added to the list with no special remark (Table 4). In the contrary, the proposed technique positions the RMS on the top of the list since it might be indicating a serious threat to the objects performance. This is due to the higher VPC value related to high significance of wideband feature and its novelty factor. At the second place there is the alarm-level exceeding on FTF that should be treated with greater attention than warning-level violation of BPFO.

At Observation C. one may observe further violations on all three channels. For the state-of-the-art approach user needs to analyze the list seeking for channel that has the greatest importance for the machine’s maintenance while in the proposed approach, the VPC reaches maximum for RMS’s new
Table 4 Comparison between alarm display for two approaches for Observation B.

| Event | State-of-the-art | Proposed |
|-------|-----------------|----------|
|       | #   | Status | Date | Analysis | Value | Limit | #   | Status | Date | Analysis | VPC |
| B.    | 1   | warning | 22   | FTF     | 0.0196 | 0.0179 | 1   | warning | 23   | RMS     | 450 |
|       | 2   | alarm   | 23   | FTF     | 0.0280 | 0.0269 | 2   | alarm   | 23   | FTF     | 350 |
|       | 3   | warning | 23   | RMS     | 2.1015 | 2.0341 | 3   | warning | 23   | BPFO    | 300 |
|       | 4   | warning | 23   | BPFO    | 0.0251 | 0.0189 | 4   | warning | 22   | FTF     | 60  |

violation of alarm level (Table 5). RMS has supremacy over also alarm level exceeding, but by the narrowband feature of FTF. Recent alarms are pushed down the list with one exception, i.e. the RMS warning information is still more important than actual BPFO one.

Table 5 Comparison between alarm display for two approaches for Observation C.

| Event | State-of-the-art | Proposed |
|-------|-----------------|----------|
|       | #   | Status | Date | Analysis | Value | Limit | #   | Status | Date | Analysis | VPC |
| C.    | 1   | warning | 22   | FTF     | 0.0196 | 0.0179 | 1   | alarm   | 24   | RMS     | 900 |
|       | 2   | alarm   | 23   | FTF     | 0.0280 | 0.0269 | 2   | alarm   | 24   | FTF     | 300 |
|       | 3   | warning | 23   | RMS     | 2.1015 | 2.0341 | 3   | warning | 23   | RMS     | 180 |
|       | 4   | warning | 23   | BPFO    | 0.0251 | 0.0189 | 4   | warning | 24   | BPFO    | 150 |
|       | 5   | alarm   | 24   | FTF     | 0.0296 | 0.0269 | 5   | alarm   | 23   | FTF     | 120 |
|       | 6   | warning | 24   | BPFO    | 0.0288 | 0.0189 | 6   | warning | 23   | BPFO    | 60  |
|       | 7   | alarm   | 24   | RMS     | 2.5456 | 2.4111 | 7   | warning | 22   | FTF     | 15  |

During the Observation D. there were no new events upcoming to the list, nonetheless the Reader might notice that VPCs are actualized according to the novelty factor – previously new events became recent, while recent ones – old. This affected the VPCs values (Table 6).

Table 6 Comparison between alarm display for two approaches for Observation D.

| Event | State-of-the-art | Proposed |
|-------|-----------------|----------|
|       | #   | Status | Date | Analysis | Value | Limit | #   | Status | Date | Analysis | VPC |
| D.    | 1   | warning | 22   | FTF     | 0.0196 | 0.0179 | 1   | alarm   | 24   | RMS     | 360 |
|       | 2   | alarm   | 23   | FTF     | 0.0280 | 0.0269 | 2   | alarm   | 24   | FTF     | 120 |
|       | 3   | warning | 23   | RMS     | 2.1015 | 2.0341 | 3   | warning | 23   | RMS     | 60  |
|       | 4   | warning | 23   | BPFO    | 0.0251 | 0.0189 | 4   | warning | 24   | BPFO    | 45  |
|       | 5   | alarm   | 24   | FTF     | 0.0296 | 0.0269 | 5   | alarm   | 23   | FTF     | 30  |
|       | 6   | warning | 24   | BPFO    | 0.0288 | 0.0189 | 6   | warning | 23   | BPFO    | 15  |
|       | 7   | alarm   | 24   | RMS     | 2.5456 | 2.4111 | 7   | warning | 22   | FTF     | 15  |

There were six time intervals that passed between Observations C and E. This allowed all of the events on the list change its VPC to the minimum according to the novelty factor, i.e. all of them became ‘Old’. Therefore new violation appearing at Observation E, although coming from narrowband feature and is related ‘only’ to warning level of severity, for the system’s user is most important and thus is positioned at the top of the list. This is the opposite to the state-of-the-art approach, as presented in Table 7.

This mimics the situation in real CMS when, old and nearly forgotten events cover up the newest ones, and therefore delays the reaction.
Table 7 Comparison between alarm display for two approaches for Observation E.

| Event | State-of-the-art | Proposed | VPC |
|-------|------------------|----------|-----|
|      | Status | Date | Analysis | Value | Limit | Status | Date | Analysis | VPC |
| 1    | warning | 22   | FTF | 0.0196 | 0.0179 | 1    | warning | 30   | FTF | 150 |
| 2    | alarm     | 23    | FTF | 0.0280 | 0.0269 | 2    | alarm     | 24    | RMS | 90 |
| 3    | warning | 23    | RMS | 2.1015 | 2.0341 | 3    | alarm     | 24    | FTF | 45 |
| 4    | warning | 23    | BPFO | 0.0251 | 0.0189 | 4    | warning | 23    | RMS | 30 |
| 5    | alarm     | 24    | FTF | 0.0296 | 0.0269 | 5    | warning | 24    | BPFO | 30 |
| 6    | warning | 24    | BPFO | 0.0288 | 0.0189 | 6    | alarm     | 23    | FTF | 15 |
| 7    | alarm     | 24    | RMS | 2.5456 | 2.4111 | 7    | warning | 23    | BPFO | 15 |
| 8    | warning | 30    | FTF | 0.0220 | 0.0179 | 8    | warning | 22    | FTF | 15 |

5. Discussion and Conclusions
As presented in the above analysis, for CMS with multiple diagnostic estimates there is a need to introduce auxiliary method for categorizing the violations of threshold levels. Therefore the violation priority function (VPC) is proposed. Application of this approach to diagnostic reasoning may help to keep track to the new and crucial events in the monitored system, and thus enhance its performance, as presented in the discussed example. The undoubted advantages of the proposed method are its flexibility and intuitiveness. The first one is because it could be employed for monitoring of any sort of machinery or processes. The second comes from the idea that intuitively certain violations are more important to overall success of operation and maintenance process than the others. The VPC enables to reveal this fact.

The current shortcomings of the proposed method are simultaneously the challenges for nearest research. The authors note that there is a strong need for optimal weights justification in order to obtain more automatic way of violation organizing with limited human factor.

The second direction of study should be headed toward extension of violation types that might indicate fault development, e.g. the relative measure that takes into account any abrupt variation of diagnostic features.

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