Use of VDI 3834-1 & DIN ISO 10816-21 for vibration monitoring of large wind turbine fleets

Thomas Gellermann, Ulrich Oertel und Holger Fritsch

Kurzfassung

Anwendung der VDI 3834-1 und DIN ISO 10816-21 für die Schwingungsüberwachung von großen Windanlagenflotten

Mit der Richtlinie VDI 3834 „Messung und Beurteilung der mechanischen Schwingungen von Windenergieanlagen und deren Komponenten" [1] ist seit 2009 ein Regelwerk für die Beurteilung der Schwingungen von Windenergieanlagen mit Getriebe verfügbar. In 2015 wurde das aktualisierte Blatt 1 nach umfangreicher Überarbeitung und Ergänzung veröffentlicht. Ebenfalls in 2015 konnte die Überführung der grundlegenden Inhalte in die internationale Norm ISO 10816-21 [2] erfolgreich abgeschlossen werden.

In dem Beitrag werden die wesentlichen Inhalte des Regelwerks und deren Zielrichtung, die Vereinheitlichung von Schwingungsmessung und -beurteilung, vorgestellt sowie der Unterschied zur Zustandsbeurteilung dargestellt. Gleichzeitig wird gezeigt, wie die Kenngrößen der VDI 3834 zur Schwingungsüberwachung genutzt werden können und so die Zustandsüberwachung sinnvoll ergänzen. Dies wird anhand von Felderfahrungen aus der Überwachung großer Anlagenpopulationen behandelt. Es werden die Schwingungswerte getrennt nach verschiedenen Triebstrang-Konzepten von Windenergieanlagen mit Getriebe dargestellt und basierend auf den Ergebnissen gezeigt, dass die gefundenen Verteilungen der Messwerte mit den Bewertungszonen der VDI 3834 Blatt 1 korrelieren.

Auf Basis der umfangreichen Datenbasis werden Beispiele von Anlagen mit auffälligem Schwingungsverhalten präsentiert. Dabei werden mittels der Schwingungskenngrößen erkennbare Fehler benannt und auf der anderen Seite Grenzen der Detektierbarkeit aufgezeigt. Letztere erfordern spezifische Analysemethoden, wie sie Condition Monitoring Systeme bereitstellen.

Authors

Dipl.-Ing. Thomas Gellermann
Allianz Zentrum für Technik
Allianz Risk Consulting GmbH
Munich, Germany

Dipl.-Ing. Ulrich Oertel
Dipl.-Phys. Holger Fritsch
Bachmann Monitoring GmbH
Rudolstadt, Germany

Introduction and definition of terms "vibration evaluation vs. condition assessment"

Modern wind turbines (WTs) are structures subject to highly dynamic loads and complex vibrations due to the use of rotor diameters and tower heights partly of over one hundred meters, as well as tower head masses of several hundred tons. They are exposed to a wide range of "external" vibration excitations as severe temporal and spatial fluctuations in wind speed as a result of gusts, turbulence and wind shear, as well as for offshore units excitations caused by sea swell. The variability of speed, aerodynamic and mass-related rotor imbalances and the large ratios of gear systems, as well as the misalignments to the generator also cause a number of "internal" vibration excitations. In the operational speed range it is also possible for drive train resonances and coupled vibration modes in interference to the rotor or tower to appear. The effect of these different vibration excitations may cause considerable additional dynamic loads, which can impair the reliability and lifespan of the turbine (cf. [3]).

This is where vibration evaluation is used. A key task of vibration evaluation is the measuring and evaluation of load relevant vibrations. A code of practice for the analysis of WTs has been missing for many years (cf. Overview of the code of practice in [4]). This gap was bridged with VDI 3834 standard "Measurement and Evaluation of the Mechanical Vibration of Wind Energy Turbines and Their Components" [1].

The purpose of this standard is vibration evaluation in which the measured load-relevant vibrations are evaluated through a comparison with defined reference values. The aim is to ensure the reliable and safe operation of the turbine without assessing the condition of the components themselves.

This is the task of condition assessment (cf. definition of terms in [5]), which requires extensive methods such as analyses in the frequency range. In the wind sector, appropriate analysis methods were integrated in vibration-based condition monitoring systems (CMS), which indicate deviations in condition and provide suitable diagnostic tools (cf. [6, 7]). Condition assessment is normally based on relative observations with regard to an individual installation, such as deviations of vibration characteristics from the reference value. CMS has hardly been used up to now for absolute or comparative observations, such as the vibrations of turbines within a wind farm or a special turbine type at different sites. The characteristic quantities defined in VDI 3834 and DIN ISO 10816-21 can be applied here.

Content of the VDI 3834 and DIN ISO 10816-21 Standards

A special feature of wind turbines compared to many other types of machinery are the considerable external vibration excitations caused by the fluctuations of the wind field, or in the case of offshore turbines, sea swell. These vibration immissions, which are transferred to the components from the tower and nacelle, are expressly included in the vibration evaluation in accordance with VDI 3834.

These have also been included with the transposition of the standard's contents to the new ISO 10816-21 standard. As a result, there is a key difference to other sections of the ISO 10816 normative series (cf. e.g. DIN ISO 10816-3 [8]), which restricts the vibration evaluation to vibrations generated by the machine set itself.

Part 1 of the standard was revised and extended in parallel with the international hearing process for ISO 10816-21. The update of VDI 3834 Part 1 issued in 2015 is thus complementary to ISO 10816-21 and the German translation DIN ISO 10816-21.

New features of the revised VDI 3834 standard

The revised VDI 3834 Part 1:2015-08 contains additional application notes and clarifications based on the experience gained from its application. It also contains a new annex covering the balancing of the rotor in situ. This provides basic information on the sources of rotary vibration excitations in order to calculate and evaluate the state

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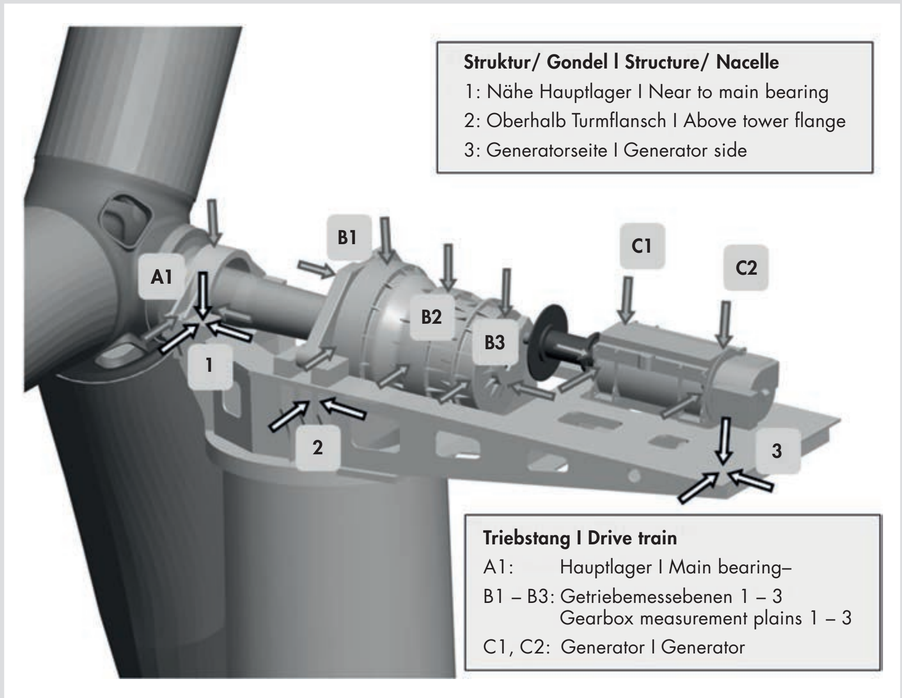

Fig. 1. Typical measuring points for evaluating the vibration of a WT with gearbox according to VDI 3834 Part 1.

of balance. Compared to the first edition, the initial intention to cover onshore and offshore wind turbines (WTs) in separate groups and standard parts was changed with this revision of Part 1. Now, this standard for turbines with gearboxes combines both locations in one group. The limitation of the scope of zone boundaries for WTs with nominal power ≤ 3 MW was also removed. Work on the planned Part 2 for WTs without gearboxes is currently in progress.

Characteristic quantities and evaluation period

To evaluate the vibrations in accordance with VDI 3834, both the assessment acceleration and the assessment velocity must be determined. Both evaluation values can be determined in practice on the basis of the vibration acceleration (vibration velocity through integration). The measurements are taken at defined measuring points on the drive train and the structure of the machine support (see Figure 1).

Due to the constantly changing wind conditions, a WT has a very dynamic operating behavior that cannot be compared to conventional power station turbines. The vibration behavior is consequently also subject to large deviations. However, in order to obtain representative vibration values, the evaluation values according to VDI 3834 are formed by means of “energy equivalent averaging” from the band-pass filtered time signal of the vibration acceleration and vibration velocity. If the evaluation period is used for the time interval, the averaging corresponds formally to the interval RMS value, such as described in DIN 45662 [9].

The evaluation period in which the averaging takes place depends on the evaluation value and the measuring conditions. The evaluation period for the aerodynamically excited vibrations of the nacelle, the tower and the components with frequencies between 0.1 Hz and 10 Hz should be 10 minutes. Shorter evaluation periods of 1 minute are sufficient for evaluating the type-related characteristic vibrations at the gears and generators with frequencies between 10 Hz and over 1,000 Hz.

Evaluation zones

The standard contains reference values in the form of the standard evaluation zones in ISO 10816 for evaluating the measured vibrations. These are divided into three zones B, C and D according to the following definition:

- WTs and components with vibrations in Zone B are regarded as suitable for running in long-term operation.
- WTs with vibrations in Zone C are normally not regarded as suitable for running in long-term continuous operation. It is recommended that the type and cause of the vibrations should be examined and whether the measured vibrations are permissible for unlimited continuous operation should be clarified, taking into account the particular design and operating conditions.
- Vibrations in Zone D are generally regarded as so serious that damage to the WT and its components can occur. An immediate analysis of the cause is recommended.

Zone A for turbines recently put into operation was not defined because a differentiation according to new and used installations was not considered necessary and was also not possible on the basis of the available pool of data.

In order to define the zone boundaries, vibration values were collected according to the defined characteristic quantities and conditions of over 1,000 correctly operating onshore WT with gearboxes by the members of the standard committee and statistically evaluated. The zone boundaries B/C were derived from the frequency distributions of the amplitude values at a frequency of 97.7 % of the particular measured value group.

If zone boundary B/C is exceeded, this is considered as an indication of increased vibrations and a possible risk to the relevant components of the WT or installation in its entirety. If the zone boundary B/C is not being exceeded, running behavior may well be normal but this does not rule out the possibility of individual instances of damage. Figure 2 shows this relationship by means of the idealized frequency distributions of the vibration values of turbines with and without “problems”. The zone boundaries C/D were defined from

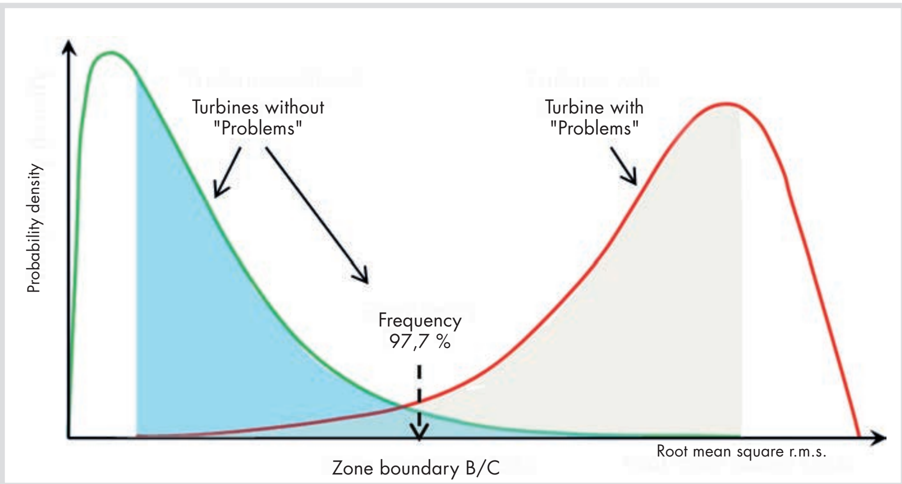

Fig. 2. Schematic diagram of the frequency distributions of vibration values of turbines with and without “problems” and derived zone boundary B/C according to a frequency of 97.7 % of turbines running fault-free (without “problems”).

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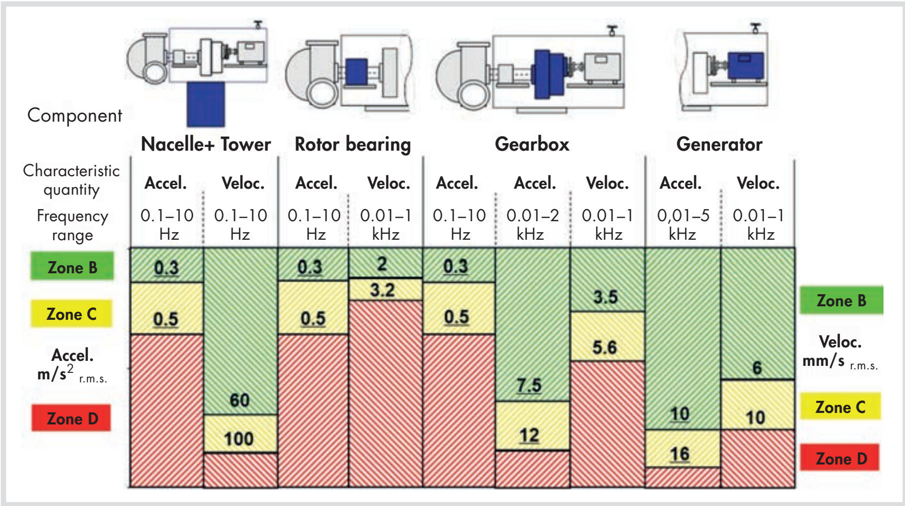

Fig. 3. Limit values of the evaluation zones of the evaluated acceleration and velocity in m/s^2 $_{rms}$ and mm/s rms according to VDI 3834 Part 1.

Detectable faults

Readers and users of the VDI 3834 standard are faced with the question which machine faults can be detected by the standard and where are any possible limits to its application. This question specifically refers to the boundaries and the main application areas for vibration and condition evaluation (cf. Chapter "1. >Introduction and definition of terms vibration evaluation vs. Condition assessment"). Figure 2 shows the idealized frequency distributions of the vibration values of turbines without and with "problems". Figure 2 clearly shows that there is an overlapping area that can be protected through the use of early fault detection systems (such as a conventional drive train CMS). This is illustrated with the following selected example.

zone boundaries B/C with an addition of around 60 %.

Figure 3 shows the limit values of the evaluation zones defined in VDI 3834 Part 1 for the evaluated acceleration and velocity. When the standard was revised, the zone boundaries were examined and confirmed on the basis of the extensive additional data collected since the first edition. The same zone boundaries were also transferred to the informative Annex of DIN ISO 10816-21.

Use for vibration monitoring

The standard describes how limit values for operation can be defined on the basis of the characteristic quantities and evaluation zones. As the evaluation zones consist of generally applicable approximate values for the evaluation of vibration behavior, individual limit values are required for the vibration monitoring. These are normally selected on the basis of reference values (baseline values) measured at the particular installation, taking recommended margins and the zone boundaries into account. This enables monitoring to be implemented that is adapted to the specific requirements of the particular installation. As the vibration behaviour of a WT is influenced by the operating state, the standard also stipulates that it may be useful to define the limit values according to the operating parameters, such as the power output.

The experience gained from the use of the characteristic quantities is the subject of the next section.

Field experience in monitoring a large turbine population

Aim of the integration in plant monitoring

The characteristic values defined according to VDI 3834 and provided by the CMS (example Bachmann CMS, Figure 4) can be integrated as signals and information in the controller of a WT and in the visualization (SCADA). This provides in future the far reaching possibility to create new characteristic values for the optimized operation of WTs, combining for example the know-how gained from the technical operational management and design parameters of the particular turbine type with characteristic quantities from the condition and vibration evaluation. This would have the following benefits:

- Possible prevention of adverse operating states of the WT
- Feed-in management, taking the current condition of the turbine into account
- Consistent service life management of turbine components

Ethernet-based fieldbuses are suitable for this as well as manufacturer-specific interfaces. Figure 4 shows the possible linking and visualization of the CMS data to the WT controller or a SCADA system (in the example: connection of the CMS via the OPC UA protocol to the Bachmann Wind Power SCADA).

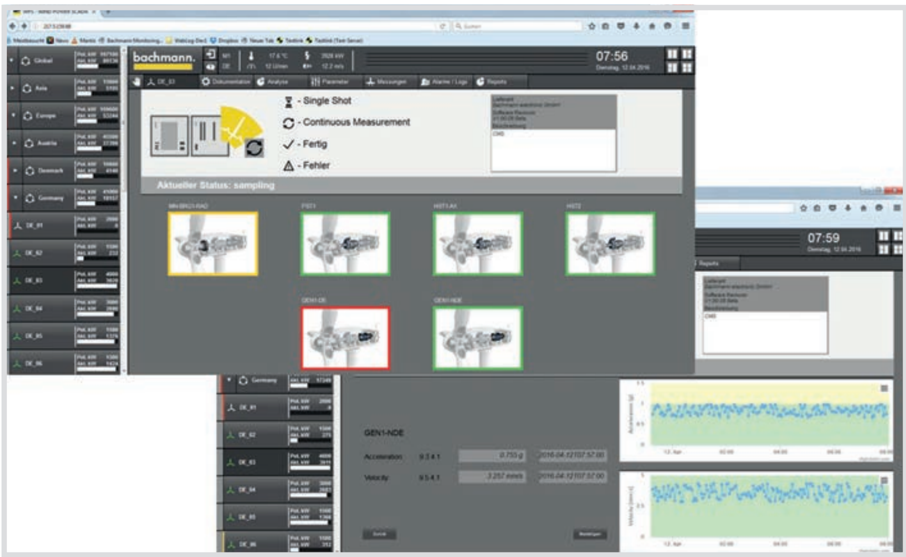

Fig. 4. Connection of the CMS to the Bachmann Wind Power SCADA (WPS).

When applied, RMS values are used within different frequency ranges, depending on the component to be analyzed (generator, gearbox, rotor bearings, tower and nacelle). The RMS value can be used as a measure of the energy content of a signal.

The example (Figure 5) shows the time signal of a fault-free gear system (black) and a gearbox with bearing damage (blue, red). The RMS value specified in the band range from 10 Hz to 1,000 Hz as defined by the standard for fault-free gearboxes is 2.3 m/s^2 $_{rms}$ in this case. The peaky signal (blue) is clearly distinguishable in the time signal of the gearbox with damage on the inner ring of the bearing. For the diagnostics technician a clear indication of a fault in the gearbox, which can also be detected acoustically.

The RMS value calculated here is 5.2 m/s^2_{rms} and is significantly higher but below the limit value of the B/C zone boundary of 7.5 m/s^2 $_{rms}$. This means that abnormal vibration behaviour cannot yet be detected by a comparison with the zone boundaries alone. Detection would be possible by

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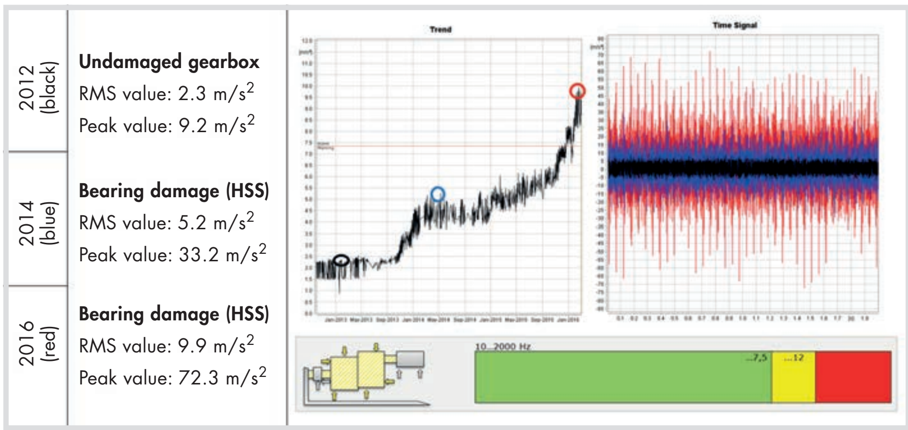

Fig. 5. RMS values (according to the characteristic values of VDI 3834) at the measuring point for gears.

defining individual limit values (cf. Chapter "Use for vibration monitoring") or by means of a trend representation or analysis. The zone boundary value itself is not exceeded until a considerable later point in time. In this case, condition monitoring methods, which can detect damage and diagnose the cause of the fault considerably earlier, are preferable. Figure 6 shows the envelope curve spectrum automatically created by the CMS, which indicates the fault at the inner ring of the bearing on the high-velocity shaft (HSS) before the trend rise of the RMS value.

The considerably earlier detection of the fault with a CMS is due to the shock excitations and peaky signals, which occur in the event of bearing or gear damage. These constitute only a minor contribution of the energy content of the signal and thus to the RMS value. Early fault detection in the sense of condition monitoring is therefore exclusively ruled out in VDI 3834.

Unlike the peaky signals, sinusoidal excitations, caused for example by installation and mounting faults through misalignment of the drive train, make a major contribution to the RMS value. These machine faults transfer a lot energy in components and can cause damage or a reduced lifespan of the components as a result of the increased stresses.

Distribution of the vibration characteristic values and influences

As part of the revision of VDI 3834 Part 1 Bachmann Monitoring analysed over a million data sets from approx. 1,000 WTs. The zone boundary limits were verified here in two stages.

Faults detected by remote monitoring were analysed first and characteristic values were defined according to VDI 3834. This first step aims to ensure that machine faults are detected with the limit values specified in the standard. The analysis showed that energy comprising machine faults, such as installation and mounting faults, can be reliably detected with the characteristic values of VDI 3834.

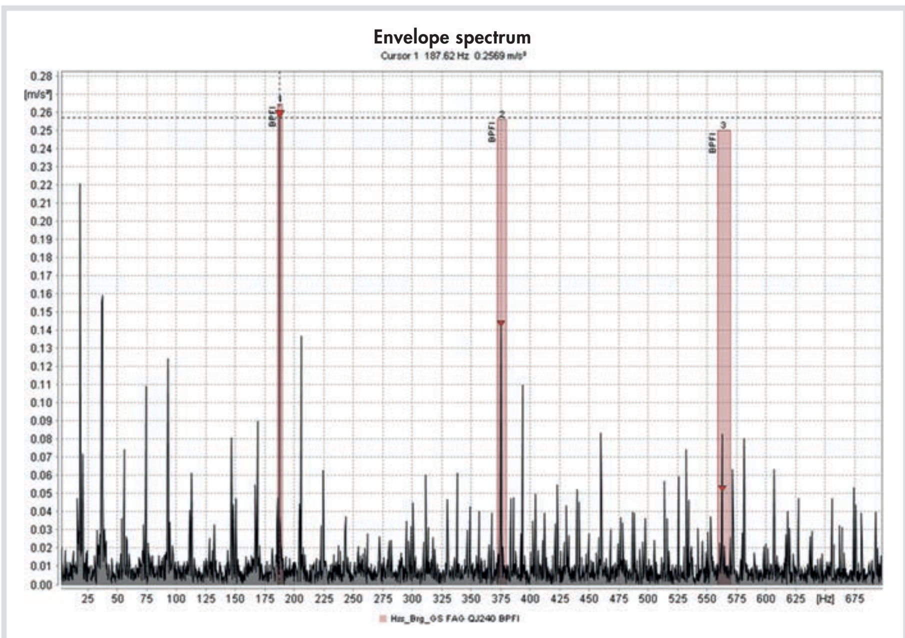

Fig. 6. Envelope curve spectrum in June 2013, clearly showing the fault at the inner ring of a gearbox bearing.

In the second stage, the data of approx. 1,000 WTs from different manufacturers and types have been analysed. This examination is required to check whether the zone boundary values can be applied and transferred to different turbines and drive train concepts of different manufacturers. This particularly focused on the following:

- Dependences on the operating state (e.g. the speed)
- Dependences on the turbine type
- Statistical evaluation and confirmation of the zone boundaries of VDI 3834

Mechanical vibrations depend considerably on the operating state of the turbine, therefore measurement in stable production operation with a rated output of at least 20 % is prescribed in the VDI. Online CMS acquire data in the entire operating range of WTs with outputs from a few kW up to several MW. The dependence on the operating state (output, speed) was therefore examined and statistically evaluated for different types of WT. This shows as expected a dependence on the operating point, which varies from type to type. This dependence is shown in Figure 7 for 2 different turbine types at the measuring point Generator "Drive End". The first zone boundary value B/C is shown in the figure in yellow, the statistically determined boundary, in which 97.7 % of the measured values are located, is shown in blue. Although some of the values measured exceed the zone boundaries, 97.7 % of the measured values are clearly below the valid zone boundaries B/C. This means that the characteristic values calculated according to VDI 3834 very well represent the vibrations present during the operation of the WT. If the characteristic values per VDI 3834 are exceeded, an analysis of the cause and, if necessary, repeat of measurement is always advisable and necessary. As already described, analysis by means of CMS provides information on changes in condition with a larger number of installations of this observation group. They can also be analyzed and tracked as part of the CMS Remote Service.

Conclusions and outlook

The systematic use of the characteristic quantities from VDI 3834 for the vibration monitoring of large turbine populations and different WT types has shown that the standardized evaluation values are well suited as a supplement to conventional condition monitoring. The evaluation zones used in the code of practice enable the vibration behaviour to be evaluated. This also enables the actual vibration values and the information whether the wind turbine can be regarded as suitable for continuous operation to be integrated in the controller or SCADA visualization and used for monitoring the vibration behavior.

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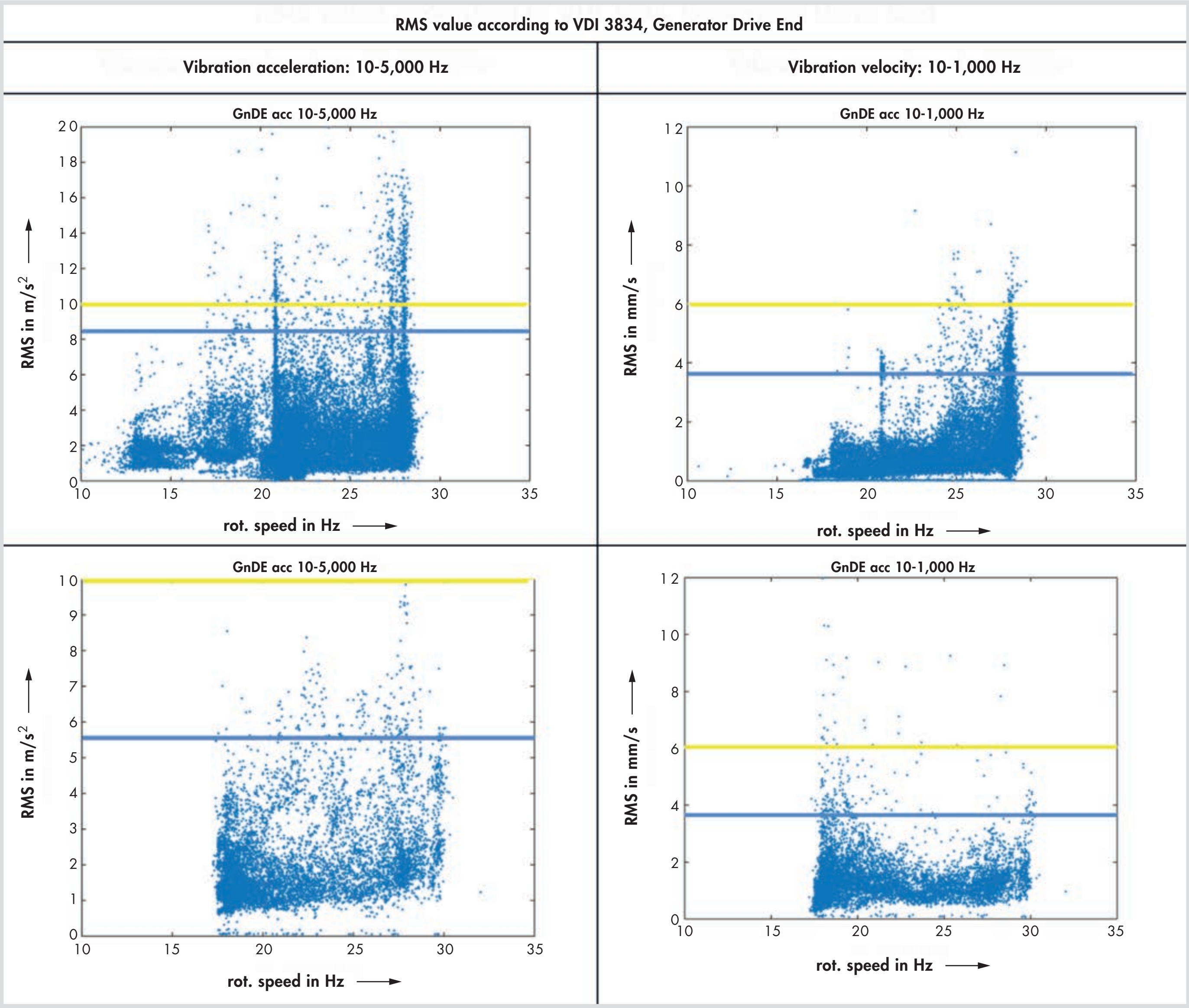

Fig. 7. RMS values at the Generator measuring point for two different WT types (yellow zone boundary per VDI 3834, blue: 97.7 % of the data records).

The examinations carried out confirm that the vibration evaluation based on VDI 3834 in combination with CMS brings the greatest benefit. This is particularly due to the fact that this method and consistent process implementation makes it possible to counteract the occurrence of damage early on through the use of new type comparative turbine information.

This therefore provides for the first time manageable variables for integration in "control center software" and SCADA software in web-based SCADA systems, which can be combined in particular with other process variables.

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