Vibration-based condition monitoring, structural health monitoring, population monitoring – Approach to a definition of the different concepts by means of practical examples from the field of wind energy

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Abstract

Monitoring of machines and structures is more and more becoming state of the art in industrial application. Nevertheless, especially in practice, the terms condition monitoring (CM) and structural health monitoring (SHM) are often used synonymously for quite different topics. Furthermore, a new monitoring type regarding the comparative monitoring of a large number of machines or structures is also affected by the confusing perception of CM and SHM. Following the term used in biology, population monitoring (PM) or fleet monitoring is proposed to define this kind of comparative monitoring.
The main purpose of this paper is to clarify the terms and to explain their differences and their commonalities by means of useful examples from monitoring projects in the wind energy sector.
The umbrella term for CM, SHM and PM is monitoring, this will be exemplified by means of SCADA-data. An inner ring damage identification of a roller bearing is used to exemplify the CM. Since SHM serves to ensure the load-bearing behavior and integrity of large and civil engineering structures, this will be shown by means of the damage detection with a rotor blade of a wind turbine. The PM and thus the capability of individual machines (e.g. wind turbines) within a population (e.g. wind farm) of comparing themselves with each other by means of monitoring solutions is illustrated by the comparative monitoring of different rotor blades in various wind farms. Here the objective is optimized operation for maximum operating lifetime and also maximum electricity production.

Keywords: Structural health monitoring, condition monitoring, fleet monitoring, population monitoring, wind turbines

1 INTRODUCTION

The terms condition monitoring, CM, and structural health monitoring, SHM, are often used synonymously for quite different topics. To give an example for this “Babylonian confusion” a typical situation in the field of foundation monitoring with offshore wind turbines is described. Wölfel Engineering has performed SHM in the industrial field for more than 10 years (e.g. Wölfel developed a product SHM.Blade®, a SHM system for rotor blades of wind turbines). Thus the engineers at Wölfel are very familiar with the terms “SHM” and

"CM", see [1], to [4]. Nevertheless, two years ago, a customer asked for a monitoring system for offshore foundations. At the end and at customer's option, the system was called FCMS – "Foundation condition monitoring system". This name was given in spite of its application for monitoring the load-bearing capacity of the foundation and for early damage detection of structural components: is FCMS the wrong name for an important application?

There are a lot of other examples, such as the German standard DIN ISO 17359 [5] defining condition monitoring as superordinate concept of all activities leading to a description of the technical status of machinery or plants. Included are monitoring, assessment, diagnosis and prediction. Another example is the Proposal NP & 1CD 16079-1 "Condition monitoring and diagnostics of wind turbines - Part 1: General guidelines", this International Standard gives guidance for choosing the condition monitoring methods used for failure mode detection/diagnostics and prognostics of wind turbine components. Here are included also the structural parts of the plants like foundation, tower and rotor blades.

At the end that means SHM is treated today like a "subset" of CM. No international SHM rule exists to date. In our opinion those terms should be separated. This paper will contribute to the disambiguation and it should stimulate the professional discussion concerning vibration-based condition monitoring, structural health monitoring and population or fleet monitoring. It has to be pointed out that this discussion is only related to vibration-based monitoring!

2 MONITORING

Monitoring is the superior hierarchy element about the three terms "condition monitoring", "structural health monitoring" and "fleet" respectively "population monitoring". Therefore, we should first expose our understanding of monitoring. The word "monitor" originates from the Latin verb "monere" which means "to remind someone", "to exhort" or "to prompt". In the 17^{th} century in German language we can find the meaning "supervisor" and "admonisher". Today the word monitor names a screen which is used for observation. A second meaning is watching persons or processes or other variables to describe its development or its variation over time.

Depending on the application domain, monitoring has different meanings. In technical sense monitoring is the act of observing (sometimes also recording) a process, a machine, a device, a plant, etc. regarding activity or performance. In most of technical cases monitoring is a continuous observing process. The monitoring objects may be singular ones or a plurality of similar engines, buildings or plants. The motivation for monitoring is to maintain the nominal condition of the monitored objects or to get information about deviation from the nominal state respectively. With this information maintenance actions or warnings can be initiated. Thus, monitoring is more than a long lasting measurement campaign resulting in terabytes of measured data which never will be analyzed.

The information about the monitored object or process is gained by sensors embedded in the observing process or extracted from the operational characteristics. In this case it is important that the measured data is free of sensor errors. This can be guaranteed either by a self-test of the sensors or by a plausibility check of this data.

For technical applications, typical monitoring data is e.g. the SCADA-data, SCADA stands for "Supervisory Control and Data Acquisition". It consists of operational data and its statistics (e.g. statistical values of operational conditions like temperatures, kinematics, etc.) and information about the plausibility of the data, see Figure 1. Warnings or alarms can be initialized manually or automatically, depending on the significance of the data deviation from expected values. In this context, monitoring is a combination of data acquisition, well known thresholds, signal analysis, statistics, change detection algorithms, diagnosis procedures and assessment of the monitoring object. Usually, for the operational data thresholds are predefined. E.g. temperature exceeds the upper limit, pressure drops under the minimum, etc.

Depending on the monitoring system design, the monitoring process often means that the data collected by different sensors like e.g. pressure, oil temperature, generated power etc. is reported to a control panel or switch room. In this control room the operator of the machine or plant is analyzing the incoming data. The engineer in the control room is familiar with the plant or machine he is operating and he knows the thresholds of all monitored variables. On the basis of his knowledge and experience he is able to take actions when necessary.

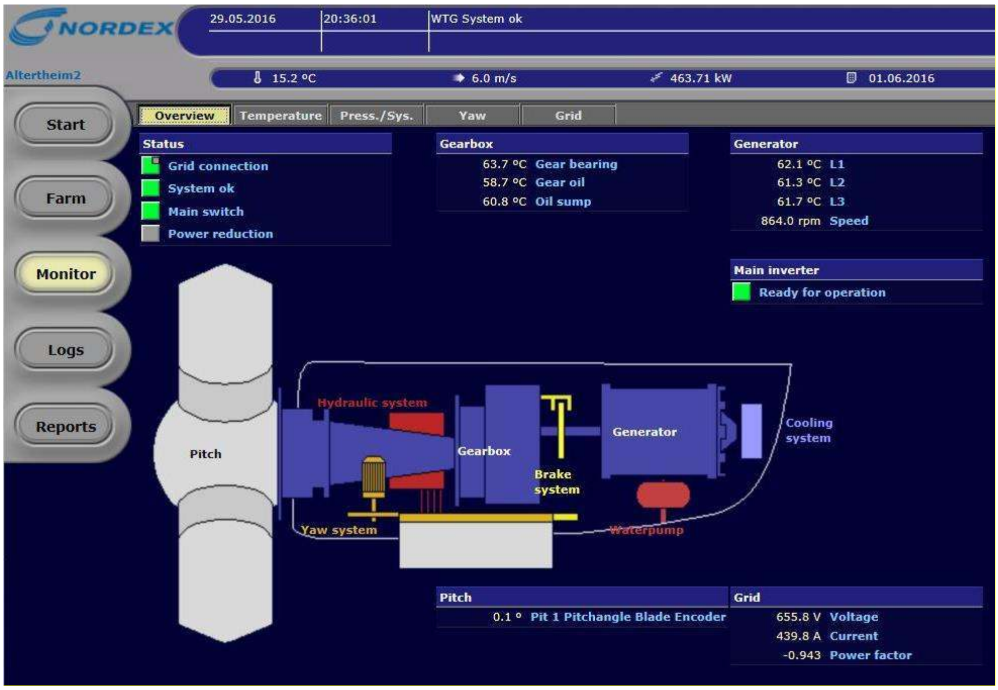

Figure 1: Standard monitoring system of a wind turbine, SCADA: Source: BEA

However, very often it is not possible to have an expert as decision-maker available, especially when the monitoring system also has a control function which automatically starts or stops other processes. One example is the vibration-based monitoring of icing of rotor blades [4]. If dangerous icing occurs the turbine has to be stopped; when the blades are defrosted the turbine should be restarted again to produce power. The decision whether there is ice at the rotor blades or not must be taken automatically. This ice monitoring can be done e.g. by assessing meteorological data only. This means that we get information about the conditions when ice can occur. If due to such assumption the turbine is stopped, this can cause financial loss in the event that there is no ice! Therefore, other additional criteria are needed to find out that a specific – dangerous – amount of ice is at the rotor blades. For this detailed statement that indeed ice is at the blade, sensors related to structural mass changes, e.g. accelerometers, are needed!

In our opinion vibrations and especially the structural response of a machine or structure to an external excitation delivers the missing integral values which can be used to get further knowledge about upcoming events. Vibration-based CM and SHM means early detection of upcoming damage using vibration data in addition to the operating parameters. CM and SHM together with a mechanical understanding of the monitored structures deliver additional assessment with the target of early damage identification (detection, localization, extension of damage, development and damage causes) and try to create a forecast of the remaining life time. Damage identification with CM and SHM is a continuous process with permanently installed sensors/actuators and autonomous decision-making. Both methods are able to detect changes and to give early warning, whereas non-destructive testing (NDT) is a singular inspection giving a snapshot of the status of a machine or a plant.

Thus, most of the tools used for vibration-based CM and SHM are basically the same: continuous vibration measurement, signal/data analysis and assessment. Maybe this commonality is the cause of the confusion? Both disciplines, CM as well as SHM, have the same goal, but different "kinds" of monitoring subjects.

3 CONDITION MONITORING

3.1 Objects of Condition Monitoring

Generally, the monitoring subject of CM-systems is machinery which is put into motion by means of energy supply (e.g. engines), parts of rotating machines (bearings, gear boxes, shafts, etc.), different mechanical energy converters (e.g. mechanical to electrical power converter: generator) or fluid machines (e.g. fluid to mechanical power converter: turbines), etc. The objects to be monitored are precise fabricated and standardized machine parts like bearings with tolerances in the range of micrometers or smaller. For gearboxes the distribution of masses and stiffness is more or less exactly the same. That means e.g. eigenfrequencies, roll-over frequencies and/or other modal characteristics of such machines are well known and the vibrational behavior of a gearbox in general is known (see Figure 2).

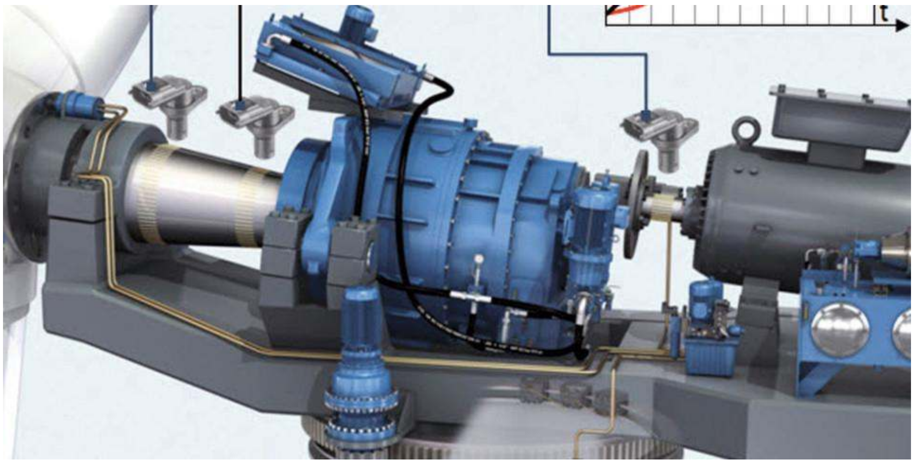

Figure 2: Drive train of a wind turbine. Source: konstruktionspraxis, Vogel

The CM monitoring objects (e.g. machine components) are related to geometric and kinematic constraints (e.g. rotational constraints), which are very closely linked to certain damage characteristics. Thus, in the classical way of CM the damage features often are related to "roll-over frequencies" (e.g. roller bearing damage), "meshing frequency" (damage to the toothing of gears). This makes the data-driven localization and identification of the damage type possible. E.g. the appearance of an outer race frequency can be associated with an outer race damage of a roller bearing by the kinematics, geometry and number of rolling elements. The objective of CM is the proper functioning of machines.

In the context of machine learning, the damage detection within CM can often be related to the model-based supervised learning procedure, because the appearing frequencies can be directly classified to one damage “class” or another. Today the most industrial CM applications for damage detection are based on interpretation of parameters like temperature, oil quality, torsional load (e.g. shafts) and especially kinematic related frequencies. However, further approaches like model-based CM are known.

Today CM belongs to the well established procedures for the monitoring of machines and engines in industrial application, see [5] to [14]. The CM “ingredients” are sensors, measurement systems, signal processing methods and thresholds for alarms. Even a selection of proper procedures by means of Failure Mode and Effects Analysis, FMEA, is described in very well established standards.

3.2 CM applied to damage identification of a roller bearing

Faults in the rotating machines occur as short impulses in the measured signals, which are usually accelerations. Through transformations of the envelope of the measured signals in the frequency domain it is possible to identify frequency peaks related to a certain fault type, for example an outer or inner race fault of a bearing, etc.. Typical frequency peaks induced by faults are knows as fault frequencies or fault signatures. These frequencies are in strong dependency on the kinematics of the machine components and can be calculated by specific formulae, see Figure 3 for the roll-over frequency f_A of an inner race fault.

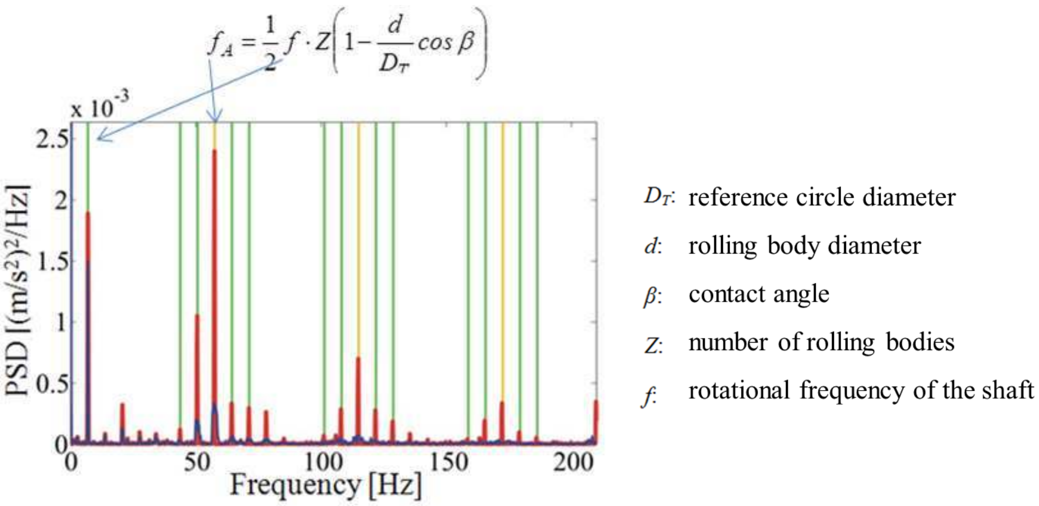

Figure 3: Example of inner race damage identification by means of CM

In the following example for CM the inner race fault at a bearing of the intermediate shaft of a pitch controlled turbine is shown. This fault was detected at an early stage by very complicated approaches like “cyclo coherence spectra” [15], here only the fault in a late stadium is exemplified by means of envelope spectra interpretation, see Figure 3. The yellow vertical lines represent the damage frequency and its harmonics. The green vertical lines correspond to the rotational speed of the shaft, the red line to the envelope spectra. If an inner race fault occurs, harmonic frequencies and side bands related to the shaft speed meet the damage pattern, as shown in Figure 3.

Such machines equipped with CM systems are called smart machines with self-diagnosis capability.

4 STRUCTURAL HEALTH MONITORING

4.1 Objects of Structural Health Monitoring

The monitoring subject of SHM is load-bearing structures or supporting structures like buildings, bridges, towers, antennas and supporting parts of machinery and vehicles like aerospace structures, ship structures, rotor blades of wind turbines (see Figure 4), etc. which may be considered as mainly statically loaded. However, they often are subject to ambient excitation (e.g. wind, waves) or operational loads (from supported machines). Most of the objects of structural health monitoring are manually manufactured. The accuracy of the manufacturing process is more in the range of centimeters or decimeters. The masses of such structures and the stiffness are varying in percent range. E.g. for a rotor blade of a wind turbine with a length of 40 m and a weight of about 7 tons a difference of mass of 50 to 100 kg is permissible. The target of SHM consists in the assessment of the load-bearing capacity and the stability of the structure. However, usually no information about the ultimate limit state of the structure is available in the SHM system. Another very important topic is the remaining life time of supporting structures at the end of the design life. The reason for this is the permission to extend the operating period of the structure.

Often the structural response to ambient, operational or targeted induced (e.g. by actuators) excitation is used to detect changes in mass, damping or stiffness which can be related to damage. In most of the cases the changes caused by damage cannot be predicted or localized by means of expected specific feature changes (like the appearance of kinematic constraint frequencies in case of CM). Each monitoring subject is individual. For a SHM-system to be installed at such an individual the first task is to become familiar with the subject to be supervised. That means to get reference values first. In this context, the damage identification within SHM often is related to novelty detection, consisting in algorithms for unsupervised learning of the undamaged state, and is followed up by the application of change detection algorithms during the monitoring process.

Figure 4: Rotor blade of wind turbines are typical SHM-structures. The length of the blade is about 59 m, the diameter of the rotor is 117 m

With vibration-based SHM a data driven damage detection is possible if the ambient and operational conditions are taken into account. For damage localization and extent identification model-based approaches are needed (data driven methods for damage localization are known, which require a large number of sensors, e.g. modal curvatures, etc.). The assessment of the life time expectation is possible only with vibration-based monitoring systems.

A further reason for the confusion with the classification of monitoring systems as CM or SHM originates from the fact that some monitored devices/plants, consist of machine and structural components at the same time. One very good example is the wind turbine consisting of structural parts (foundation, tower, blades) and machine components (main shaft, further shafts, gear box, roller bearings, generator, pitch and azimuth engines, etc.). It is a matter of fact, that for one and the same system mechanical engineers dealing with CM systems call this system “wind turbine” (considering more the machine parts and the generator) and civil engineers dealing more with the SHM of structures call the system “wind power plant”.

In general, the complexity of damage detection algorithms often is higher than common CM algorithms.

4.2 SHM for damage detection of a rotor blade

In the definition presented in this paper it is not a contradiction that rotor blade monitoring systems of wind turbines are assigned to SHM, although the blades are rotating, which seems to be a case of machine monitoring. However, not the rotation, but the load-bearing capacity and stiffness of the blade are monitored!

This example is based on a long-time vibration-based monitoring of a rotor blade of 40 m-class. The SHM system measures mainly accelerations. The blade is subject to stochastic excitation. Initially the blade was intact, during the time a fatigue crack at the trailing edge occurred (at the end of the measurement the crack was about 40 cm). As damage sensitive features the blade eigenfrequencies (which contain information about stiffness and/or mass changes) were used. Further influences on the eigenfrequencies, e.g. the blade temperature, were compensated by means of principal component analysis. The trend of the damage indicator, see Figure 5, reflects very well the development of this damage. The problem, however, is to get information about the ultimate limit state. Up to now a SHM-system is able to detect changes and to describe e.g. the velocity of such changings. To get information about the ultimate limit state of a structure a finite-element model should deliver the missing values.

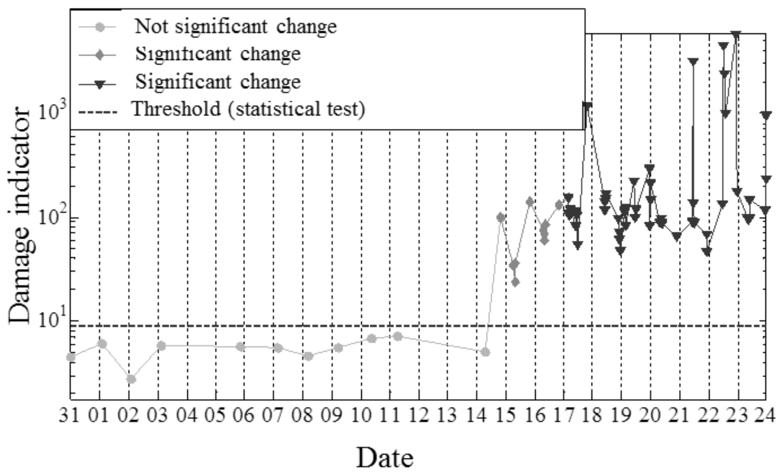

Figure 5: SHM of rotor blade; damage indicator

Structures equipped with SHM systems are called smart structures with self-diagnosis capability.

5 FLEET OR POPULATION MONITORING

Machines and structures produced in series can be monitored not only for themselves, but also in comparison to similar machines or structures. This kind of monitoring is called fleet or population monitoring. Monitoring subject is a plurality of machines or structures of similar type (Figure 6). The monitoring purpose is to maintain the nominal condition of the fleet or the population or to get information about deviations from the nominal state respectively, in terms of optimal operation, energy output (when dealing with systems for energy generation), damage state and life time consumption, by comparison between the monitored objects.

When only SCADA-data is used it is monitoring in the sense of chapter 2. When additional sensors like accelerometers, etc. are used fleet or PM is more in the sense of CM or SHM as per chapters 3 and 4.

Figure 6: Offshore wind farm Meerwind Süd | Ost. Source: WindMW

There are two different possible setups known:

1) The fleet of machines/structures is monitored by means of a control center; and the members of the fleet are compared to each other within the control center. We call it centralized fleet or population monitoring.
2) A control center is not available. Every member of the fleet is comparing itself with its neighbors and detects whether it is "above" or "below" the neighbors or fleet. We call it decentralized fleet or population monitoring.

The monitoring objects are equipped with CM and/or SHM systems. In addition to the "stand-alone" CM/SHM solution, within PM the systems are capable of communicating with each other or with the monitoring center. At least the monitored features are compared between systems. The comparison leads to the following benefits:

- The systems can be classified with respect to optimal operation.
- The systems can be classified with respect to remaining life time compared to each other.
- The visual or standard inspections can be better planned by means of systems classifications (first the suboptimal system, then the others are inspected).
- Missing features of systems (e.g. through a monitoring system with a lower number of sensor than others) can be estimated through correlation and extrapolation of the available features from other systems. This leads to cost effectiveness of PM, since not all systems have to be installed with the same amount of sensors.

- Causes of suboptimal operation or high life time consumption can be better identified and eliminated.
- Influences of position of monitoring object and their specific operating conditions on systems can be identified and changed with respect to optimal operation and increase of life time expectation.

Thus fleets of machine or structures equipped with PM can be called smart fleet.

5.1 Fleet or Population Monitoring of different WTs in a wind farm

The PM and its benefits are exemplified by the comparative monitoring of a plurality of rotor blades of the same class belonging to the same production series, but not in the same wind farm. The monitoring period here considered is about half a year. The SHM basic monitoring system installed on each plant is Wölfel's SHM.Blade®.

Figure 7 shows that different blades have different vibration levels, due to different wind conditions, quality of aerodynamic balance, goodness of pitch angle setting, position of the plant in the farm, etc. However, the vibration level stays in direct connection to the life time of the blade. Thus it is possible to predict which blade has higher life time consumption. In case of necessary inspections, these can "enjoy" a certain priority.

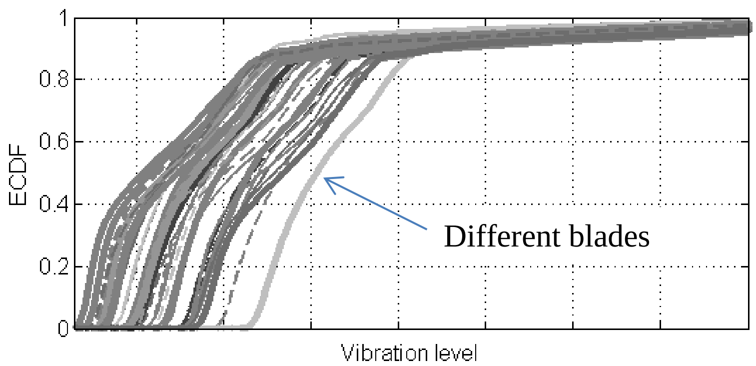

Figure 7: Empirical probability of vibration level for different blades on different WTs

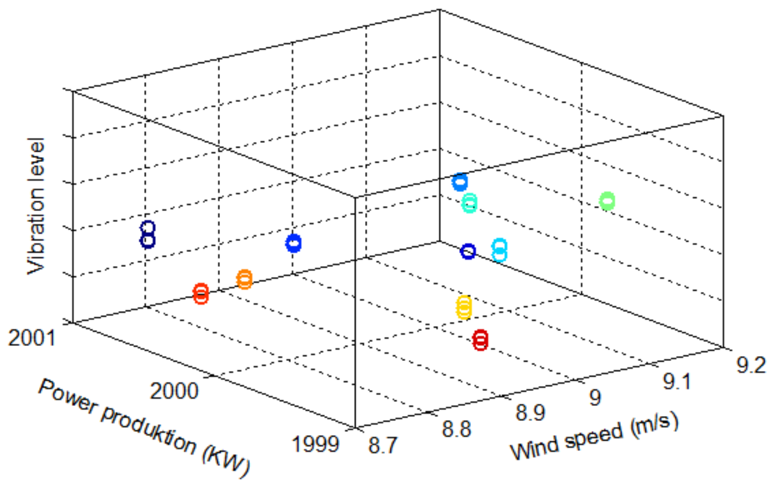

Figure 8: Relationship between vibration level, power production and wind speed at different blades on different WTs

Also questions regarding the optimal operation of the plants can be answered by easy correlation analysis between the vibration level, power production and further operational conditions of the plant (e.g. wind speed). Figure 8 shows some correlations between groups of blades (same colors) of different plants (different colors). Here the following questions are answered: How big is the vibration level of a plant at a power production of 2 MW? How much wind is necessary for one plant or another to produce 2 MW? What is the relationship between the wind speed, energy production and the blade vibration level? Knowledge about these correlations leads to information regarding the possibilities for a better (individual?) control of the plants with regard to the following pareto-optima: maximizing the energy production and the life time expectation.

6 CONCLUSIONS

In the course of the upcoming cyber physical systems (CPS) where all devices are communicating via sensors and data networks, the role of population monitoring is becoming more and more important! This also corresponds to the rules of cognition; in keeping with these rules correct information can be better obtained from associations through cross-correlations than from individual/limited sight of views.

Consequently, the future of monitoring e.g. in the wind energy sector lies in the PM of the farm. By means of classifying the individual plants with respect to their characteristics and "problems", see Figure 9, the plants can be better controlled with the purpose of increasing the energy production and the life time, also the necessary maintenance, repairs and inspections can be better planned.

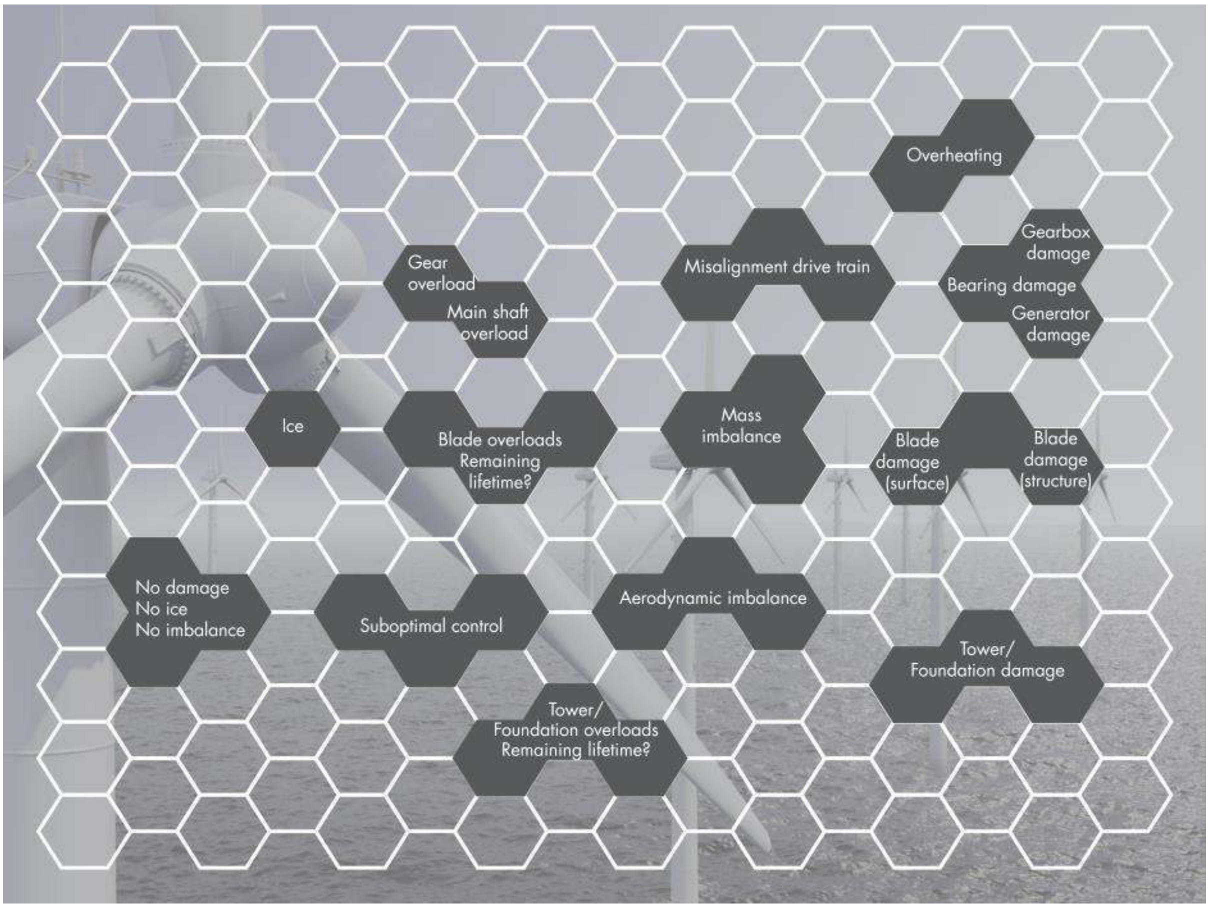

Figure 9: CM, SHM and PM in wind farm

REFERENCES

[1] P. Kraemer, H. Friedmann: Vibration-based structural health monitoring for offshore wind turbines structures – Experimental validation of stochastic subspace algorithms, Wind and Structures, An International Journal, 21(6), 693-707, 2015.

[2] H. Friedmann, P. Kraemer, C. Ebert: Vibration Based Structural Health Monitoring (SHM) for Offshore Wind Turbines – from Monitoring the Blades to a Concept for Foundation Structures, IWEC, International Wind Engineering Conference, Hannover 2014.

[3] P. Kraemer: Damage diagnosis approaches for structural health and condition monitoring of offshore wind energy plants, PhD Thesis, University of Siegen, 2011.

[4] P. Kraemer, H. Friedmann, C. Ebert: Vibration-based Ice Detection of Rotor Blades in Wind Turbines - The Industrial Realization of an SHM-System, 10th International Workshop on Structural Health Monitoring, Stanford University, USA, 2841-2848, 2015.

[5] ISO 13379: Condition monitoring and diagnostics of machines -- General guidelines on data interpretation and diagnostics techniques.

[6] ISO 12482-1: Cranes -- Condition monitoring.

[7] ISO 13373-1 and 2: Condition monitoring and diagnostics of machines -- Vibration condition monitoring.

[8] ISO 13374-1 and 2: Condition monitoring and diagnostics of machines -- Data processing, communication and presentation.

[9] ISO 13380: Condition monitoring and diagnostics of machines -- General guidelines on using performance parameters.

[10] ISO 13381: Condition monitoring and diagnostics of machines – Prognostics.

[11] ISO 16587: Mechanical vibration and shock -- Performance parameters for condition monitoring of structures.

[12] ISO 17359: Condition monitoring and diagnostics of machines.

[13] ISO 18436-1, 2, 3, 4, 6 and 7: Condition monitoring and diagnostics of machines -- Requirements for training and certification of personnel.

[14] ISO 19860: Gas turbines -- Data acquisition and trend monitoring system requirements for gas turbine installations.

[15] P. Kraemer, D. Lautenschlager, C.-P. Fritzen, U. Oertel: Condition Monitoring Methods for Machine and Drive Train Components of Wind Energy Plants, German Wind energy Conference, DEWEK, Bremen, Germany, 2008.