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Structural health management utilization for lifetime prognosis and advanced control strategy deployment of wind turbines: An overview and outlook concerning actual methods, tools, and obtained results

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A B S T R A C T

In this contribution, Structural Health Monitoring (SHM) systems applied to wind turbines (WTs) are considered. Challenges resulting from contradictions between requirements related to efficient operation with respect to energy production costs and those related to lifetime and maintenance are discussed. Especially pronounced in larger WT systems, structural loads contribute to lifetime shortening due to damage accumulation and damage-caused effects influencing subsystems of the wind turbine. Continuous monitoring of the WT system concerning State-of-Health is necessitated to provide information about the condition of the system guaranteeing reliable and efficient operation, as well as efficient energy extraction. In recent years, structural health monitoring of WT systems is significantly improved through automated on-line fault detection and health or condition monitoring (CM) system integration. In this contribution the focus is given to hardware components (mainly sensor technologies) and methods used for change evaluation, damage detection, and damage accumulation estimation. Accordingly, this contribution comprises recent knowledge about methods and approaches of handling structural loads with emphasis on offshore wind turbine systems and applied sensing technologies (especially with respect to wind turbine blades, gearboxes, and bearings) and partly hardware. Moreover, a brief sketch of an advanced concept is developed concerning structural load examination affected by operating conditions. Key idea of the introduced approach is to use the operating conditions to control and especially to extend system's lifetime. The review presents an actual state-of-the-art and overview related to the use and application of SHM-related technologies and methods. Especially in combination with the briefly introduced lifetime extension concept, the contribution gives comprehensive and detailed overview in combination with an outlook to upcoming technological options.

Contents

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1. Introduction

As the demand on energy production from renewable sources constantly increases, recent developments in wind turbine design are enforced by changed requirements reflected in Wind Turbine (WT) size increase (harvesting more energy), applied advanced control strategies, and improved Structural Health Monitoring (SHM).

Apart from aforementioned requirements, the costs of energy production have to be at least comparable with the costs of energy production from conventional sources to make wind turbine system commercially acceptable [1].

Wind turbine system is exposed to harsh environment and fluctuating load affecting system's performance and ultimately causing the loss of functionality. Not only the fluctuating load but also environmental conditions (humidity, salinity, changeable temperature, ice, etc.) have a strong impact on WT performance in terms of damage initialization/propagation and have to be considered. Due to changes in material properties occurring over the system usage and subsequently decreasing components reliability, continuous monitoring of critical wind turbine system parameters is inevitable targeting to detect system State-of-Health that differs from an initial (considered as undamaged) State-of-Health [2]. In these terms, fault is defined as a significant change of system parameters beyond acceptable/allowed limits reflected in the negative influence on overall system performance. As such, fault is closely related to damage occurred in the system but still cannot be understood as system failure [3]. Even the fault is present in a system, the impact on system performance can be tolerable. Contrary, system failure is defined as complete loss of functionality whereas the system is not capable to perform predefined functionalities [4]. As noted in [4], fault detection includes the statement about whether a fault in a system is present or not. Whenever the fault is occurred, fault diagnosis has to be carried out targeting to identify fault type, fault location, as well as fault criticality. Accordingly, suitable maintenance action has to be applied. In these terms, continuous health monitoring of the system is indispensable.

The decision about suitable actions according to detected faults belongs to one of the tasks of SHM systems. Depending on the fault and related criticality, the required actions may include corrective maintenance intending to restore the system state to the previous (undamaged) state or emergency maintenance targeting to avoid failures of components and systems. Nevertheless, if corrective or emergency maintenance is applied, an approach considers the maintenance decision made at the point of fault detection, but not before the fault is indicated. Conversely, it is possible to carry out preventive maintenance. Here, the action is required before the failure occurs (for instance: preestablished maintenance interval or elapsed predefined service time). Structural health monitoring therefore plays an important role to avoid system premature breakdowns, as well as reduction of system downtimes [5] possibly reducing at the same time operating and maintenance costs [6].

In spite of that, recent effort in SHM development focuses on condition-based and reliability-based maintenance. Decision to perform the maintenance in condition-based maintenance strategy is system specific and based on the system state observation as well as on fulfillment of predefined conditions (for instance predefined limit reached, high vibration index, temperature out of acceptable boundaries, etc.) [7]. Contrary, reliability-based maintenance combines the knowledge of the current system health state with the previous health state to infer the probability of failure; it includes the estimation of system reliability and prediction of system health state in terms of making decision on whether the maintenance action will be performed or postponed [8]. It may be concluded that methods applied and used for diagnosis and prognosis incorporated in SHM are primarily related to decisions about maintenance and replacement actions, but in this context can also be used as required module within a reliability-oriented control scheme, as depicted in Fig. 1. Remarkable benefits of reliability-based maintenance are especially pronounced in offshore WT systems concerning hampered approach to offshore site.

Regardless of applied maintenance strategies, SHM also aims to find a cost-effective solution for system operation/health monitoring. The importance of SHM development can be clearly seen from the fact that the maintenance costs contribute between 11% and 30% of the overall wind turbine costs [9]. From the other point of view, operation and maintenance costs are especially pronounced in offshore WT installments as individual costs of replacement and maintenance actions are in general higher compared to the associated costs for onshore installments.

As an example, a feasibility study done for offshore wind farms in Germany inferring potential fields for improvements concerning Operation and Maintenance (O&M) costs reduction is discussed briefly [10]. An analysis in aforementioned study belongs primarily to an analysis of expected wind farm installment/operation costs in dependence on expected benefits and energy generation costs. Moreover, the feasibility study considers different wind farm