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ASPECTS REGARDING OPERATION PREDICTABILITY OF WIND TURBINES

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Abstract: *As the wind turbine blades are one of the most difficult parts to monitor, it reliability is vital in the operation and maintenance of a wind turbine. A possible way to intelligently monitor the condition of the blade is to acquire and process data on the current strains inside the blade structure. The aim of the work is determination of the critical areas via simulations. In those areas is proposed to integrate micro-wire strain sensors. A typical mega-watt wind turbine (≈1.5 MW) was considered for simulations under various boundary conditions. The maximum equivalent stress in the blade (≈ 48 MPa) occurs at the wind speed of 16 m/s. The extreme strain values (0.00032 and 0.00062) occurred at locations ≈ 0.18 and 0.7 of the rotor radius.*

Key words: *Wind turbine blades, operation predictability, predictive maintenance, numerical simulation, critical areas.*

1. INTRODUCTION

In the context of the current energy crisis, extending the operating life of wind turbines is welcome in order to reduce energy costs. Therefore, the reduction and optimization of maintenance costs represent the largest share of operating expenses. As is well known, wind turbine blades are the most exposed to mechanical and environmental loads that include complex and cyclic deformations, temperature and humidity variations, electrical discharges, precipitation, and impact with erosive particles or birds [1, 2].

Monitoring and control of blade failures can be achieved to some extent if their degradation and failure mechanisms are known. This is necessary for predicting failure events, planning maintenance activities and reducing degradation processes.

As the size of wind turbines increases, additional loads occur on the structure and other components of the turbine. It is estimated that globally there are over 3,800 blade failure incidents each year [2].

In order to keep under control the safe operation of wind turbines, several methods are proposed. One of the most advanced methods is predictive maintenance. This consists in monitoring the structural condition of the blade with the use of special sensors embedded in the material.

2. ASPECTS REGARDING FAILURE MECHANISMS OF WIND TURBINE BLADES

2.1 Failure analyzing methods

Wind turbine blade damage occurs in various forms such as surface damage (microcracks), damage in the composite laminate (resin defects, delamination) and structural damage (fiber breakage or bending) [1, 2]. Blade surface defects are generated by erosion (precipitation, sand and hail) or impacts with small objects.

The analysis methods of wind turbine blade failures are as follows:

- post-destruction analysis of damaged blades;
- real-scale testing of blades in special laboratories equipped with structural condition monitoring systems;
- collecting incident reports and analyzing databases;

- observing blade behavior during operation using non-destructive testing and structural condition monitoring methods;
- testing the constructive elements of the blade such as the spar, the reproduction of some component elements of the blade assembly such as the adhesive joints, the composite laminate of the blade shell;
- numerical simulation of the blade behavior under complex loads.

Direct monitoring of blade behavior and failure is of particular interest. It can be done using non-destructive testing methods and structural health monitoring methods [3]. To monitor deformation and damage events special sensors are mounted in the blades.

With the development of software and hardware, computational modeling of wind turbine blade degradation has become a viable method for failure mechanism analysis. The analysis involves a series of static load simulations to determine the sensitive areas in the blade and then simulating the fatigue conditions in those areas. Numerical models have a wide range of applications and adequate efficiency, and their application requires prior knowledge of the failure criteria according to which damage will occur.

2.2 Determination of sensitive areas

The most vulnerable areas in the blade structure are the segments subjected to the most intense loads (the tip and the leading edge), the transition zone (for example, the transition zone from the cylindrical section to the airfoil and the thickness reduction of the composite laminate), the interfaces bonded with adhesive. The research results presented in the work [4] show that the most affected areas of the blade are: near the root (30–35% of the rotor radius) and near the tip (≈70% of the rotor radius), the leading edge and at the rotor hub.

The damage mechanisms in sensitive areas:

The blade tip. In this area, the wear is very intense because the speed of the tip is the highest, and the erosion affects almost half of the blade airfoil section. At the same time, electric discharges occur at the tip, which cause composite layer separation near the tip [5].

The leading edge. It is affected by raindrops, hail, sand and repeated impacts. As a result, cracks and water ingress may occur in the joint area [5].

The trailing edge. It can fail by peeling of the adhesively bonded composite laminate or by buckling of it. Adhesive joint can fail permanently at less than maximum loads because of buckling.

Thickness transition zones, hub section. The transition from the circular section to the airfoil represents an area with sudden variation in the thickness of the composite layer and complex geometry that may be sensitive to buckling [5].

Adhesive joints/Connecting lines. The bonds between the shell and internal ribs and spar can deteriorate, resulting in buckling of the entire structure [5]. If the blade skin detaches from the internal stiffening ribs the spar blade destruction may occur.

In addition to those mentioned, the occurrence of damage can also be influenced by manufacturing faults and complex blade loads [4]. Figure 1 shows the sensitive areas where frequent damage mechanisms of wind turbine blades take place.

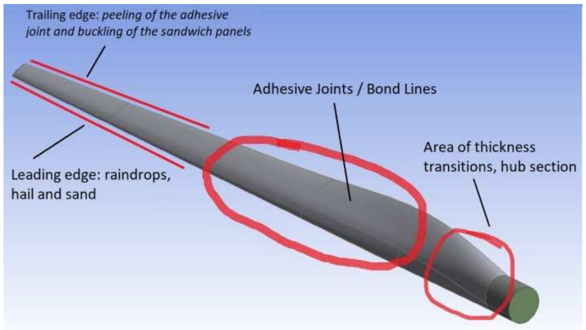

Fig.1. Sensitive areas of blade damage mechanisms

Thus, the fortification of the mentioned vulnerable areas can increase to some extent the reliability and operating time of wind turbine rotors.

For example, in figure 2, some representative images of damaged wind turbines with a power greater than 1 MW have been selected. Actually, the sensitive zone is located in the buckling area of the blade (≈ 0.35 … 0.4 of the rotor radius). The research presented in the paper [2] indicates that blade destruction occurs at nominal operating parameters (wind speed and operating time).

a.

b.

c.

Fig.2. Appearance of damage on actual wind turbines blades: a*) https://nawindpower.com/;*
b) https://www.saurenergy.com/;
c) https://stopthesethings.com/.

A numerical model for evaluation the behavior of a megawatt-scale wind turbine blade has been developed and is set out in the next paragraph. The purpose of Finite Element Analysis (FEA) is to establish the critical zones where equivalent stress and strain concentrations occur.

3. COMPUTATIONAL MODELING OF A BLADE AND DETERMINATION THE CRITICAL AREAS

The wind turbine rotor was modeled in SolidWorks software and later imported into the ANSYS Workbench environment, where the fluid flow domain was developed and the settings for the Computational Fluid Dynamics (CFD) analysis were prepared. To save computational time, a CFD volume was modeled that includes 120° of the rotor (1/3 of the entire domain) giving periodic conditions. Tower and ground influence on blade aerodynamics were not considered. The parameters of the numerical fluid domain were correlated following the recommendations proposed in the paper [6]. The input parameters for wind turbine modeling and simulation are presented in Table 1.

Table 1

Input parameters of the analyzed rotor

Nominal power, MW	1,5 - 3
Nominal rotor speed, min^{-1}	18 - 20
Wind speed, m/s	10 - 20
Rotor diameter, m	83
Variation of shell and spar thickness, m	0,1 – 0,005

Since the real structure of a blade is very complex, some idealizations were accepted in the calculation model that does not significantly affect the results. One of them is the homogenization of the composite material from which the blades are made. The orthotropic properties of the used material are presented in Table 2. These are the typical values that are most often encountered.

There are various homogenization methods. For example, direct homogenization is based on averaging field variables such as stress, strain, and energy density. Actual properties can be calculated from their definitions. The method Finite Element Analysis allows the calculation of variable fields and the geometry and microstructural properties can be generalized to real composite materials.

Table 2

Material mechanical properties

Density (kg/m^3)	1550
Young-X Modulus (Pa)	1,1375E+11
Young-Y Modulus (Pa)	7,583E+09
Young-Z Modulus (Pa)	7,583E+09
Poisson's ratio-XY	0,32
Poisson's ratio-YZ	0,37
Poisson's ratio-XZ	0,35
Shear modulus-XY(Pa)	5,446E+09
Shear modulus-YZ (Pa)	2,964E+09
Shear Modulus-XZ (Pa)	2,964E+09

It should be mentioned that the accuracy of the FEA analysis is affected, first of all, by the mesh quality and the nodes distribution in the key areas of the model geometry. Sensitive areas are found on the blade surface, where the boundary layer is constituted. Significant variations in aerodynamic parameters can be captured with finite element refinement in the areas of interest.

After several meshes at different parameters to increase the simulation results accuracy, the calculation model was divided into ≈3000 000 elements. For this purpose, the recommendations presented in the tutorials [7] for megawatt-scale wind turbine blade simulation were useful. Figure 3 shows the details of the discretization of the blade shell.

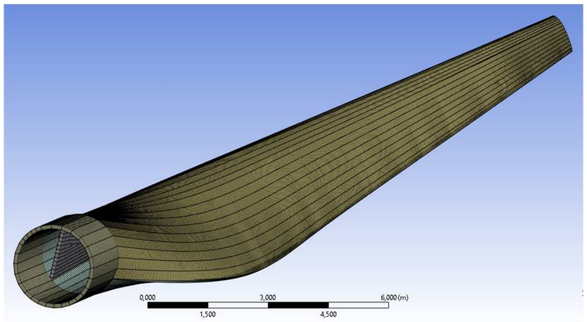

Fig.3. The meshed blade model

The following boundary conditions were considered in the simulation: wind speed range 10 – 20 m/s and corresponding rotor speed 18 – 20 min^{-1} respectively. To monitor the veracity of the simulation input data, a diagram illustrating the velocity distribution along the blade was elaborated (figure 4). The wind turbine is set at the nominal operating speed 18 min^{-1} and wind of 10 m/s, respectively.

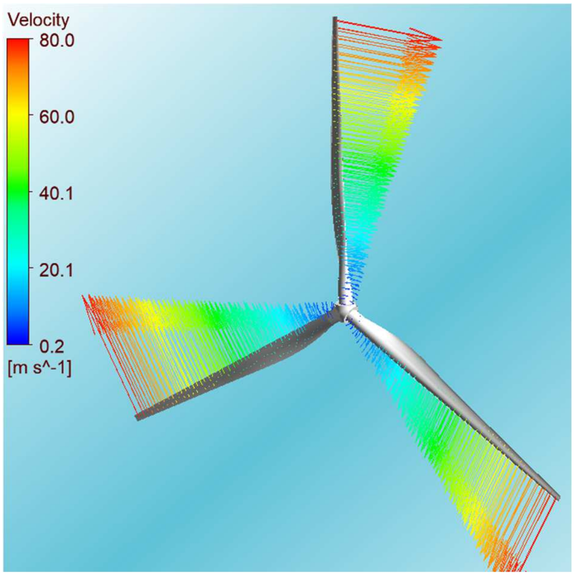

Fig.4. Relative velocity distribution on the blades (wind speed of 10 m/s)

As the blade in real conditions is subjected to complex bending-torsional loads as a result of aerodynamic effects these loads were analyzed. In figure 5 the pressure distribution on the blade surface for nominal wind speed (10 m/s) is presented. The study was done for the entire range of wind speeds (10 - 20 m/s). The gravity force was neglected in the simulations because this is not a wind blade design study.

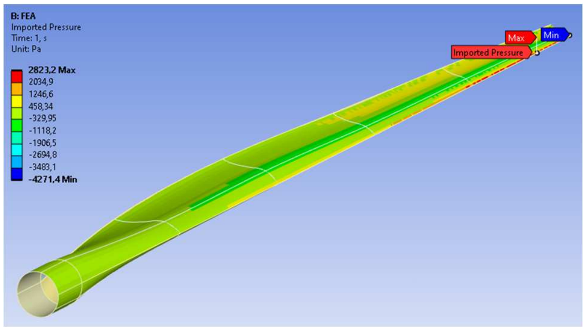

Fig.5. Pressure distribution on the blade surface

The necessary results of numerical analysis are the following: equivalent stress (von-Misses) and equivalent elastic strain distribution. Figure 6 shows the location of stress concentrations.

The maximum value of ≈48 MPa occurs at the wind speed of 16 m/s. For the wind speed of ≈11 m/s the equivalent stress is ≈ 35 MPa. For instance, the maximum tensile stress of adhesive based on epoxy resin used in blade manufacturing is 30 – 40 MPa. It follows that the operation of megawatt-scale wind turbines at wind speeds exceeding the rated values must be limited.

Figure 7 shows an illustrative case of the loaded blade at 12 m/s wind speed. Several nodes with elastic strain concentrations in the blade casing were marked. It should be noted that for the entire range of wind speeds, the critical areas are in the same positions. This facilitates the implementation of the predictive maintenance system that will be presented in the next paragraph.

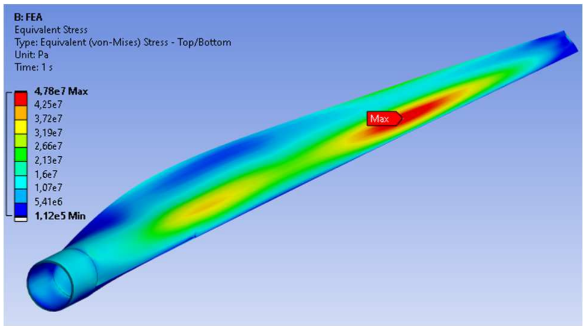

Fig.6. Equivalent stress distribution in the blade shell

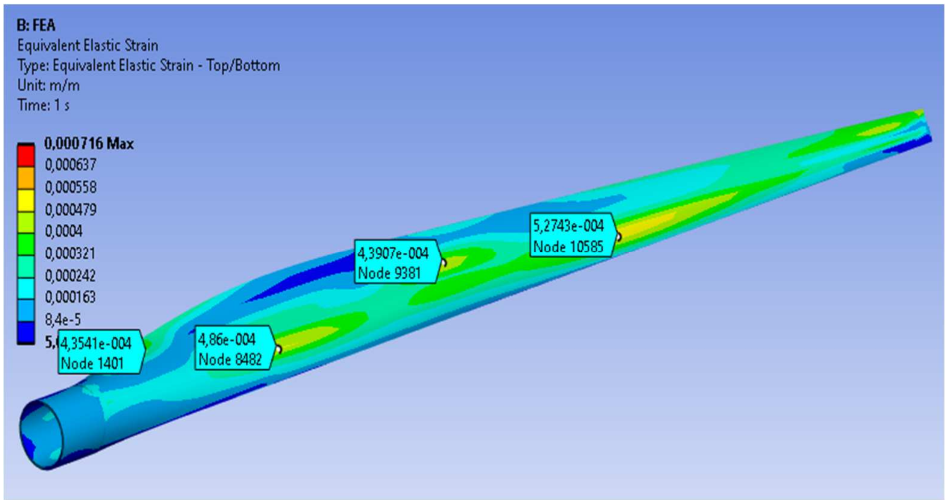

Fig.7. Equivalent strain distribution in the blade shell (a case for V =12 m/s)

4. ASPECTS REGARDING THE INTELLIGENT MONITORING OF THE BLADES STRUCTURAL CONDITION

4.1 Conditions and means of intelligent monitoring

As already mentioned, blade reliability is vital in the operation and maintenance of a wind turbine. On the other hand, the turbine rotor blades are one of the most difficult parts to monitor. A common approach for monitoring the condition of the rotor blades is to use vibration sensors [8-12], mounted one on each blade. Vibration analysis is usually presented as the most effective condition monitoring method, especially for rotating equipment, because it produces vibration that is specific in its behavior and character. A new wind turbine has an associated relatively smooth vibration signal during normal operation, but as it degrades due to wear and tear, it will change the characteristics of the signal. Turbine integrity can be assessed by detailed comparison of new and old vibration spectra. Since the small damaged spots do not cause significant changes in the course of rotation or in the aerodynamic behavior, it follows that there are also no indications in the noise spectra of the origin and/or extent of any damage spot located in the area of the rotor blades.

Strain measurement is a common technique [12] and calculates the level of mechanical stress, for example in turbine blades. As sensors, resistive type sensors are proposed for use, the most common material used to be constantan alloy. However, it should be noted that resistive sensors have a number of disadvantages, including low sensitivity. Considering the extreme importance of wind turbine blade reliability, it is very important to study and propose new solutions for non-contact condition monitoring. Next, this problem is approached from the perspective of using microwire based strain sensors with positive magnetostriction.

As is well known, an intelligent turbine condition monitoring system involves the acquisition, processing, analysis and interpretation of data. Given that such a system aims to monitor wind turbine blades in particular, data acquisition must include measurement of blade strain as well as other variables of interest. In the light of the adopted approach, the intelligent monitoring of the condition of the wind turbine requires the acquisition and processing of data on the current strain inside the blades.

To meet this challenge effectively, first of all, the judicious choice of priority (vulnerable) locations is needed. The results obtained by the numerical modeling of the wind turbine blade strength allow the determination of the coordinates of the locations for mounting a suitable number of non-contact strain sensors.

Second, it is important to choose sensors that lend themselves to the application under consideration. Since in our case it is necessary to measure the strains in multiple locations of the blade, a suitable choice refers to strain measurement sensors based on micro-wires with positive magnetostriction [13, 14]. It should also be mentioned that the tensile strength of the material for the amorphous Fe-based alloy micro-wires is approximately 1.5 GPa [14], a value that far exceeds the values of the maximum stresses in the blade shell (≈ 48 MPa) and which correspond to the wind speed of 16 m/s.

Figure 8 shows a plot containing all values of equivalent strains as a function of wind speed. The minimum and maximum strain values (0.00032 and 0.00062) occurring at locations (0.18 and 0.7 of the rotor radius) along the blade longitudinal axis are shown.

The diagram also shows the power potential of the wind turbine rotor, calculated with the relation:

$$P = \omega \cdot T, \qquad (1)$$

where ω = 2 rad/s is kept constant at wind speeds greater than 12 m/s;

T – torque developed by the turbine rotor.

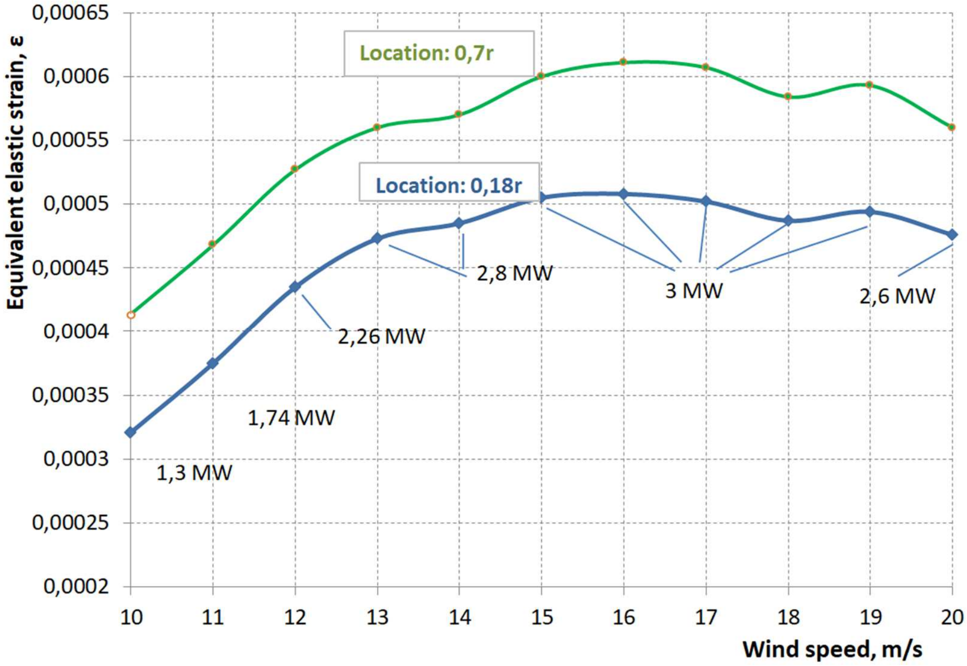

Fig.8. Equivalent strain depending on the wind speed and location of occurrence

Accurately determining the location of the sensitive areas for a particular blade model requires their appropriate modeling and simulation. However, the information in Figures 1, 2 and 7 can be useful for establishing priority locations for the purpose of implementing the wind turbine blade condition monitoring system.

Based on the particularities of the considered application, the non-contact strain sensor can be considered as a suitable sensor for implementation [15]. Such a sensor contains at least two segments of micro-wire, made on the basis of ferromagnetic alloys with an amorphous structure, which must be mounted on the surface of a solid body. One micro-wire segment is used as the sensing wire and at least one other micro-wire segment is used as the reference wire. The basis of the sensor's operation is the application of an external magnetic field and the analysis of the system's response to the applied magnetic field. The magnetic response of the sensor to the applied alternating magnetic field depends on the tensile strain. In other words, the change in the magnetic characteristics of the hysteresis loop is correlated with the strain to which the magnetic material is subjected. So the magnetic response of the sensor can be determined by detecting the electromagnetic pulses induced upon remagnetization and calculating the numerical value of the ratio of the hysteresis loop area of the sensing wire to that of the reference wire. The resulting value must be recalculated as a function of the stretch sensitivity coefficient of the sensitive wire with a built-in algorithm on a signal processing unit. The result obtained from the calculations will represent the size of the strain, which does not depend on the distance [15, 16].

In order to achieve the best possible coverage of the assessment of mechanical stresses in the critical locations of the blade, it is welcome to install as many strain sensors as possible, considering the vulnerable locations. Using multiple strain sensors can be an advantage in terms of reliability. Let's say we want to read every revolution all the sensors embedded in the blades of a wind turbine. Let us also assume that successive measurements of the sensors magnetic response will be made. Then, in the case of a turbine with three blades and the rotor speed up to 40 min^{-1} (at nominal wind speeds of 10 – 25 m/s), the maximum number of strain sensors that can be incorporated in one blade will not exceed 10 units (at a magnetic sensor response processing time of 50 ms). This amount may be sufficient to monitor the most critical locations of the blade.

4.2 The structure of the monitoring system and the operation algorithm

The decision-making process implemented in a system for monitoring the functional state of the wind turbine blade can follow two distinct paths. The first of these concerns the evaluation of the current state, that is, it refers to the current diagnosis of the blade. The second decision-making branch is much more sophisticated and involves the development and incorporation of a predictive model that provides the prognosis of the future state.

Figure 9 shows the structure of the monitoring system in the blade diagnosis variant.

The reading of the strain sensors and the determination of their magnitude is carried out with the help of an appropriately designed computing device. The processing and control unit ensures the execution of the strain monitoring algorithm in the turbine blade (figure 10), respectively the provision of the necessary commands for system operation in the diagnosis mode of the blade condition.

The structure of the system in figure 9 follows the monitoring concept presented in [17] and also includes the necessary elements for the implementation of countermeasures. For this purpose, the processing and control unit ensures the location of the blade defects, identifies the type and form of countermeasures in accordance with the established diagnosis, and respectively generates the commands (signals) to perform the countermeasures. The commands generated are interpreted and executed by means of an actuator control device, available at the level of the turbine maintenance system.

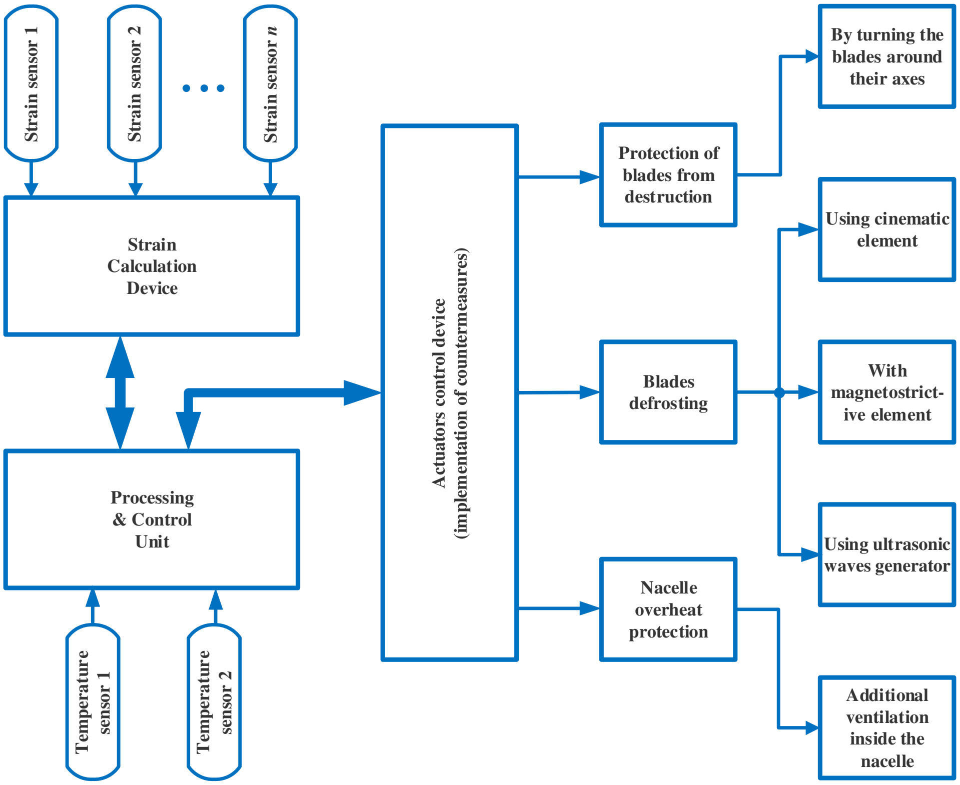

Fig.9. Monitoring system: *diagnosis and implementation of countermeasures*

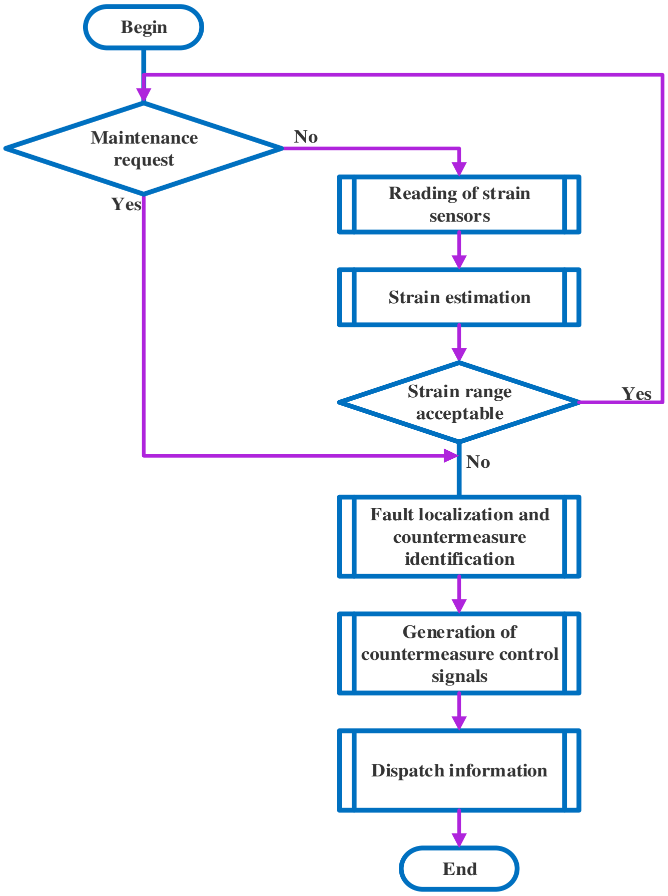

Fig.10. Strains monitoring algorithm of the wind turbine blade

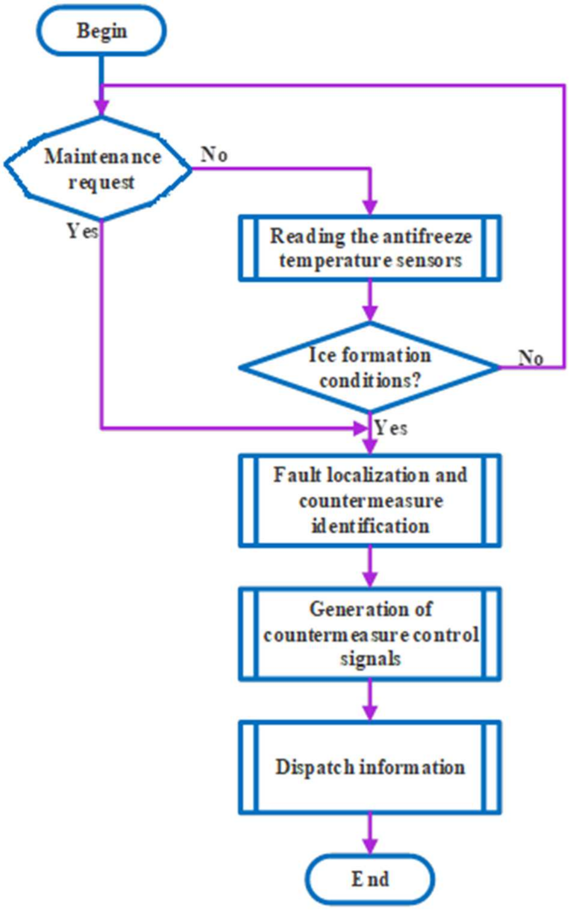

Fig.11. The blade defrosting process monitoring algorithm

On the other hand, the processing and control unit ensures the reading of the temperature sensors (figure 9) and the analysis of the ice formation condition on the blade surface. The algorithm for monitoring the blade defrosting process is presented in figure 11. Similar to the case of strain monitoring, the processing and control unit executes the appropriate algorithm, identifies the countermeasures to be implemented (in correlation with the established diagnosis), and generates the countermeasures implementation commands.

5. CONCLUSION

Based on the research, a new method of predictive maintenance is proposed for monitoring the structural health of wind turbine blades. For this purpose, the FEA calculation model of the rotor of a mega-watt wind turbine was developed and determined the locations of the critical areas where blade strength is affected. In these locations, it is proposed to integrate strain sensors based on micro-wires with positive magnetostriction. The tensile strength of the material for the amorphous Fe-based alloy micro-wires is approximately 1.5 GPa, a value that far exceeds the values of the maximum equivalent stress in the blade shell (≈ 48 MPa) and which correspond to the wind speed of 16 m/s. The minimum and maximum strain values (0.00032 and 0.00062) occurring at locations (≈ 0.18 and 0.7 of the rotor radius) along the blade longitudinal axis.

The structure of the intelligent monitoring system of the structural condition of the blades and the operation algorithm was elaborated. The proposed algorithms aim to strains monitoring and blade defrosting, identifying and generating of countermeasures.

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Aspecte privind predictibilitatea funcționării turbinelor eoliene

Deoarece palele turbinei eoliene sunt una dintre cele mai dificile părți de monitorizat, fiabilitatea acestora este vitală în funcționarea și întreținerea unei turbine eoliene. O posibilă modalitate de a monitoriza în mod inteligent starea palelor este achiziționarea și procesarea datelor privind deformațiile curente din interiorul structurii lamei. Scopul lucrării este determinarea zonelor critice prin simulări. În acele zone se propune integrarea de senzori de deformare cu micro-sârmă. O turbină eoliană tipică de ordinul megawaților (≈1,5 MW) a fost luată în considerare pentru simulări în diferite condiții la limită. Tensiunea maximă echivalentă în paletă (≈ 48 MPa) apare la viteza vântului de 16 m/s. Valorile extreme ale deformațiilor specifice (0,00032 și 0,00062) apar în locații 0,18 și 0,7 ale razei rotorului.

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