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AI supported maintenance and reliability system in wind energy production

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Abstract: The environmental effects of wind power are relatively minor, compared to those of more traditional energy sources. Among the renewable energy arts wind energy plays a significant role and, as forecasted its ratio within the total energy production will rapidly increase. Wind turbines are relatively complex electro-mechanical systems, their smooth functioning is an important economical factor. This is why monitoring and diagnosis of wind turbines and wind farms gained extreme importance in the past years. The ReliaWind EU 7th Framework Research project has set up ambitious goals, namely, optimizing wind energy systems design, operation and maintenance. The paper shortly underlines the importance of the wind energy, gives some facts on its growing penetration. The main goals and approaches of the ReliaWind project are introduced. Concentrating on monitoring, diagnosis and maintenance issues, the logical architecture of an advanced health monitoring system is described. Special attention is given on standardization issues. The results of the first investigations based on relative huge amount of data collected from wind turbines from different producers are highlighted. Further research issues are identified.

Keywords: artificial intelligence, system engineering, wind energy, maintenance and reliability

1. INTRODUCTION - WIND ENERGY PRODUCTION – STATUS AND CHALLENGES

Wind energy is one of the most promising branches today, e.g. in 2008 the market growth of this sector was above 20% [12]. Forecasts show that in Europe the share of wind energy will be between 5% and 20% of the total demand by the time [2][6][12], , while, e.g., currently the share of offshore electricity is around 1.3% representing that the growth of this sector is above the linear trend, it is nearly exponential [1]. This economical trend involve dramatic technical developments, and as result, e.g. today, a wind turbine produces 180 times more electricity, at less than half the cost per kWh than its equivalent type 20 years ago [2] and it decreases with 10% every time the total capacity is doubled. However 80% of the total costs is fix and arise then establishing the wind turbine generator (WTG), flexible cost, like operating and maintenance of wind farms pays more and more importance, especially when considering offshore turbines that have around 50% more preparation cost and far higher risk in operation than onshore [12] turbines. One of the most important challenges in comparison of cost at various producers and operators is the lack of universally agreed set of cost categories [12], however, some cost models are presented in [18].

Beyond the investment analysis one can identify that cost is only a factor among further important features listed here and analysed in [4] to compare the effects of different renewable energy sources.

- price of energy produced
- greenhouse gas emission during full life cycle of the technology
- availability of renewable sources
- efficiency of energy conversion
- land requirements
- water consumption

- social impacts

Taking the same weights for these evaluation aspects wind and hydro energies were found as best solutions. Various aspects are to be found at players of the value chain of wind energy, too [12]:

- Project developers which focus on planning and realization of wind farms
- Electric utility companies on buying and selling the electricity produced, while
- Grid operators on balancing and re-allocation of electricity in the electric net
- Manufacturers concentrate on technological developments

The increasing market share and growing number of wind farms in energy production, the growing rate of offshore installations having higher investment cost and risks and the variety of viewpoints when evaluating this branch indicates especial importance of maintenance and reliability of wind farms.

Wind turbine generators are data intensive information sources because they incorporate various sensors similar to other branches, e.g. like manufacturing [19]. This allows real condition monitoring and supervision of wind turbines and wind farms also from different locations and supports the preparation of reliability models with statistical information, too [5]. There are also some differences, e.g., wind turbines are operating in continuously changing environmental conditions with sometimes extreme circumstances [17] that is not typical e.g. in production system because they try to ensure stable and unchanging operation. This variety in environmental effects gives a great difficulty for handling changing conditions but it has also positive side: for statistical and further Artificial Intelligence (AI) analysis and modelling it can ensure a data set collected in various conditions. From the other side the data intensity requires sophisticated data processing techniques and knowledge related to them [9] [20][21].

Various condition monitoring and sensing techniques, ordered to different WTG components extended by some fault detection solutions with AI methodologies are enumerated and compared in [6][14] similar to [3] that explains the relation of condition monitoring to reliability modelling as a tool for handling the changes at the right/wearing out side of a bath curve. Combinations of turbine components and monitoring techniques are highlighted in [3], hybrid statistical modelling is introduced in [11] for special problem domains however one can find the lack of a comprehensive framework for handling orderings of

- turbine components
- failure modes
- detecting sensors
- appropriate data processing and monitoring
- field specific limits
- failure detection and prognosis tools
- efficient control modifications
- and appropriate maintenance and repair actions

to each-other. Even the internal structures of these components are not clearly defined up to now. The establishment of such a framework is one of the main targets of the ReliaWind project.

The paper is organised as follows: After introducing the project goals reported in the paper the description of its condition monitoring and artificial intelligence related work package is described. The introduction of the novel logical architecture of an advanced wind turbine generator health monitoring system is followed with the description of its harmonisation with the recent standard series on communications for monitoring and control of wind power plants. For putting concrete content to the defined architecture SCADA data collection and analysis were performed applying artificial intelligence methods. Conclusions close the paper.

2. RELIAWIND – EU 7TH R&D PROJECT: GOALS AND APPROACH

2.1. Overall project goals and measure

ReliaWind: Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation [16]. ReliaWind project's main goal is to usher in a new generation of more efficient and reliable wind turbines, providing practical results to be used in wind turbine design, operations and maintenance. The project aims to achieve better efficiency for wind turbines, through the deployment of new systems with reduced maintenance requirements and increased availability. To this end, the project proposes architecture directed at a modular design more immune to environmental conditions, permitting the replacement of components simply and quickly; to improve monitoring systems for components and thus achieve more accurate diagnosis; and to develop preventive maintenance algorithms for failure anticipation. These new technologies will be integrated in future generations of wind turbine components, wind turbines and wind farms.

Ten partners are taking part in this ambitious project, each of them leaders in technical and operational disciplines in the wind power generation value chain. This includes the Wind Industry itself, Gamesa and Alstom Ecotecnia are wind turbine producers, LM Glasfiber is producer of blades, Hansen Transmissions of gearboxes, ABB of generators and SKF of bearings for the turbine. Technology experts are Garrad Hassan as an engineering consulting firm and Relex Reliability Software and Services serving with a software and reliability modeling knowledge. Academia is represented by Durham University, UK and SZTAKI, the Computer and Automation Research Institute of the Hungarian Academy of Sciences.

Further the operative project members, a "Reliability Panel" has been established in order to interact with top-level experts in reliability worldwide, not necessarily from the wind energy sector, such as aerospace and other sectors where reliability is paramount. Its mission is to share conclusions, establish guidelines, etc. The first invitation to join the "Reliability panel" has been issued to NREL, the US National Laboratory. A "Users Working Group" has also been established in order to interact with top wind farm owners worldwide. Its mission will be to share experiences in wind farm operation and maintenance, providing feedback on "best practice". The first invitations to potential members will be issued shortly.

The project results improve the reliability of wind turbines and wind farms and have enhancement effect directly on Mean Time Between Failures (MTBF) and on Mean Time to Repair (MTTR) resulting improved availability of facilities of energy production. Finally the relative cost of energy by kWh is decreased. All of the target measures are differentiated whether considering onshore or offshore installations.

2.2. Work packages and approach

The deliverables of the project are [16]:

- Critical Wind Turbine Systems and failure modes identification, which will lead to the introduction of failure design compensating provisions, redundancy, back-up and reserve systems, etc.
- New design guidelines and tools, incorporating new features such as full lightning strike protection, wave loading of support structures, re-sitting of electrical units into an environmentally controlled section of the turbine, implementation of offshore corrosion protection technology, modular design to ease failure recovery, etc.
- Definition of new active control components required to control instabilities, reduce dynamic loads and extend components lives, increasing overall Wind Turbine availability. Advanced Troubleshooting and on-board / remote fault diagnose capabilities, decreasing the total number of false alarms reducing downtime following turbine failure and associated revenue losses.
- Enhanced predictive maintenance and prognosis of Wind Turbine allowing better maintenance planning and tasks sequencing. Maintenance planning guidelines.
- Support to the Maintenance & Operations decision making process, by the introduction of optimisation criteria and tools.

To achieve these provoking results, the following activities are carried out as WorkPackages (WPs):

- WP-1: Field Reliability Analysis. Identify Critical Failures and Components

Within any complex system, certain components will stand out as high-risk items, either because they are ‘weak points’ that are failure prone, or are absolutely essential for “normal” turbine operation, or are expensive and time-consuming to diagnose and repair. The aim is to capture, collect, and analyze historical wind farm SCADA (Supervisory Control and Data Acquisition) datalogs and maintenance data from several sources available to the project partners to determine which components and failure modes should be subject to a more detailed work during next project phases. Therefore, based on an empirical analysis, the project will determine the “high risk items” and failure modes.

- WP-2: Design for Reliability. Understand Failures and Their Mechanisms

Understanding the failure modes, their mechanisms and the physical and chemical magnitudes and variables that are involved in the phenomena allows the scientists to construct logical models of failure mode growth and propagation, both in two scenarios: Within the WTG architecture and along time. These reliability models will contribute to the main project objectives in two ways: 1) Design for Reliability and 2) Condition Monitoring. Each industrial partner will construct in a coordinated fashion its applicable subsystems and component functional and reliability models and one SME partner, acting as model integrator, will assemble all previous “building blocks” in order to attain a complete full WTG reliability model. Appropriate sensing devices will be selected and specified for capturing the aforementioned physical and chemical magnitudes. Signals coming from these devices will later act as inputs to the logical algorithms defined in WP3.

- WP-3: Algorithms. Define the Logical Architecture of an Advanced WTG Health Monitoring System

The aim is to define and integrate all the logic required to convert input signals (more than a hundred in a normal WTG) into appropriate actions. State of the art advanced expert systems and architectures will be used to detect actual failures, isolate these failures and assign them to an specific component, determine the residual life of components experiencing impending failures, define maintenance actions to be taken, schedule these actions in an optimum sequence and, finally, support maintenance technicians and managers to make the most adequate decisions concerning maintenance policies.

- WP-4: Proof of concept. Demonstrate the Principles of the Project Findings

All the results achieved during previous work packages will be integrated into a consistent set of tools and applications that can provide Condition Based Maintenance tools for wind turbines and wind farms. Existing protocols and standards for connectivity to current SCADA systems will be adopted and new extensions will be proposed to benefit from the findings of the project. Specific software components will be defined and integrated in an extensible software framework to create a multi-agent software platform to simulate each possible turbine operational condition and WTG configuration to be modelled. Finally, a holistic wind farm software model (virtual demonstrator) will be built and tested in order to verify and show the principles achieved by the project.

- WP-5: Training. Train internal and external partners

The aim is to provide training to the partners and other stakeholders (directly involved in wind turbine design, operation and maintenance) about the reliability, modelling and information tools needed to enable a more reliability-minded approach to be applied in the future to these activities.

- WP-6: Dissemination. Conferences, Workshops, Web Site and Media

The aim is to disseminate the findings to the Wind Energy Sector community in the European Union (e.g. wind farm promoters, regulatory bodies, financers, insurers, certification bodies, government bodies, associations, etc.). This will be achieved through a variety of Conference, Workshop, Web site and Media initiatives. In this respect the experiences in the offshore oil and gas industry to disseminate methods to improve plant reliability will be emulated.

2.3. Work Package 3 - Logical Architecture of an Advanced WTG Health Monitoring System

WP3 is targeting to develop the Logical Architecture of an Advanced Wind Turbine Generator (WTG) Health Monitoring System (AWTGHMS). It is not only an architecture design but active also in the field of idea approval. The Fig. 1 shows the architecture of the AWTGHMS. The different components of the system are developed in consecutive tasks comprehend by the Task 3.0 for guaranteeing the overall consistency of the monitoring architecture. Logical architecture definition of required hierarchical system breakdown guarantees a common WTG & Wind farm level integration from a diagnosis, prognosis & health monitoring point of view.

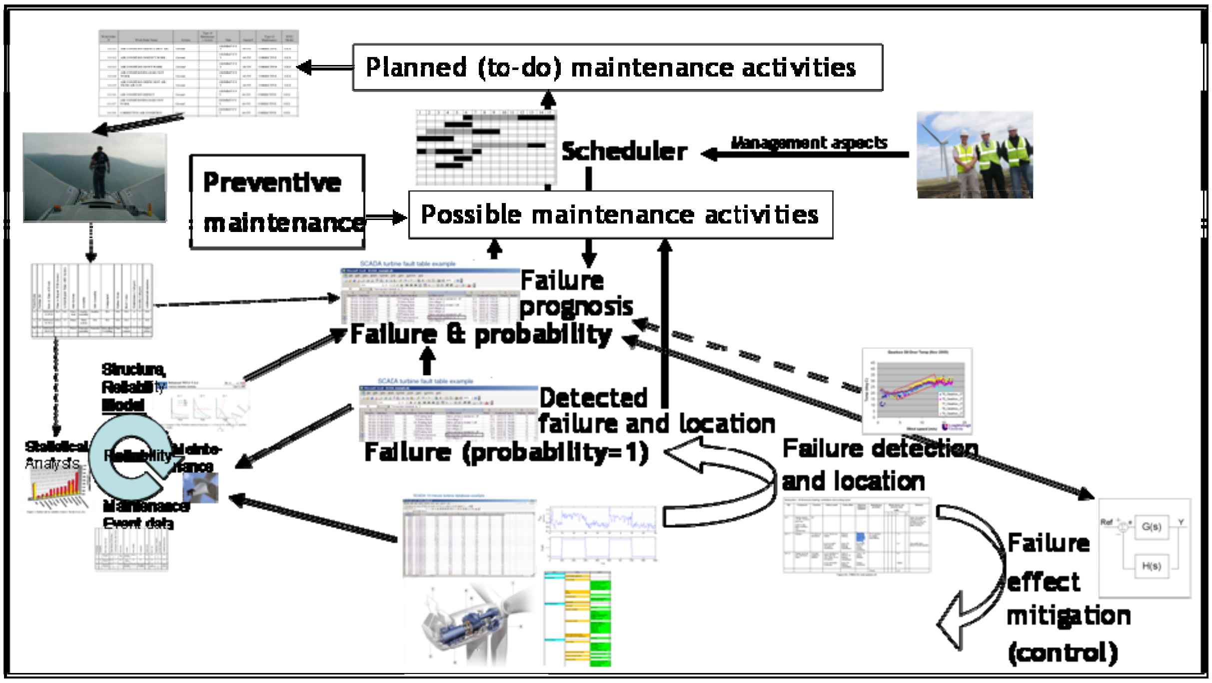

Fig. 1. The architecture of an Advanced Wind Turbine Generator (WTG) Health Monitoring System (AWHMS)

Improvements in the cost-effectiveness of wind turbines will drive designers towards more 'intelligent' control algorithms inside the Task 3.1 which play an important part in actively improving the reliability of components and sub-systems. Advanced controllers which receive multiple inputs and make use of this information for regulation of structural loads and vibrations as well as for maximization of energy output are already under development, test and, in some cases in commercial operation. The objective of the work to be conducted in this task is to investigate the extent to which such advanced control algorithms might be extended to address reliability issues. Changes to both closed loop and supervisory control will be considered. The former will include, for example, the active control of structural loads and vibrations by means of pitch activity in response to measured loading and vibrational motion whereas the latter might include supervisory control action, for example, to de-rate the torque transmitted through the gearbox in response to abnormal behaviour detected by appropriate sensors.

The purpose of the Task 3.2 is to develop agents for the detection of specific incipient failure modes in the whole turbine. The algorithms are developed from the analysis of indications extracted from different monitoring signals on each important turbine system including blades, nacelle, yaw system, drive train, turbine control system and electrical control system. The mission of these algorithms is to determine and identify which turbine system has progressed from a nominal to a malfunction condition.

The purpose of the Task 3.3 is to develop agents for the location of specific incipient failure modes identified before, integrated with the knowledge developed in failure effect mitigation and failure detection. The algorithms are developed from analysis of monitored variables on the turbine system. The mission of these algorithms is to locate which turbine system has progressed from a nominal to a malfunction condition. This includes design and development for the integration of detection and location agents with other global SCADA systems operating on the wind turbine and wind farm.

The aim of Task 3.4 is to develop algorithms which can provide a prognosis for the incipient failure modes detected and located before. In this way the algorithms attempt to predict the residual life and reliability of the components for which the incipient faults have been detected. This will form the basis for the repair and maintenance strategies of the next two tasks.

The purpose of the Task 3.5 is to generate maintenance activities based on the repair prognosis for the faults detected and located to effect improvements to the availability of the wind turbine.

Having a list of maintenance assignments is to plan maintenance activities based on the repair prognosis for the faults detected and located from and the maintenance activities generated. This Task 3.6 give maintenance operators the work plan of maintenance activities.

The feedback of operators and also the reliability model developed in the previous Work Package for design for reliability and understand failures and their mechanisms are also included among the inputs of the AWHMS realizing a closed loop for high system availability.

3. HARMONIZATION OF THE LOGICAL ARCHITECTURE OF AN ADVANCED WTG HEALTH MONITORING SYSTEM WITH THE RECENT STANDARD SERIES ON COMMUNICATIONS FOR MONITORING AND CONTROL OF WIND POWER PLANTS

Typically, any wind power plant component, which needs to exchange information with other components and actors, is equipped with a so-called intelligent electronic device (IED), which can send data to external receivers and receive data from external senders. Therefore the information exchange is already implement in currently working WTG systems, but these information models are proprietary and cannot be used in a research project like ReliaWind. To overcome the problems of the proprietary data models a standard data model is proposed to use, which is based on the IEC 61400-25 [7] standard.

This standard defines a communication model for monitoring and control of wind power plants. The communication model comprises three separately defined areas:

- Information model
- Information exchange model
- Mapping of the information model and the information exchange model to standard communication profiles.

The information exchange model and the mapping to standard communication profiles are concerned when a standard interface is implemented in the WTG system.

Unfortunately the IEC 61400-25 series leaves it open how and in which physical device the server is to be implemented in practice. The objective of IEC 61400-25 series is that the information associated with single wind power plant component is accessible through a standardized interface. This implies that the information model defined rather generally and in a way that supports the information exchange interface smoothly. If the standard is implemented in a specific WTG system it is the responsibility of the device owner to map their internal (and proprietary) data structure to the standardized information model [10][13]. This mapping is required only because of technical reasons, namely to define the information exchange function.

The information model defined in IEC 61400-25 series - and because this standard is heavily relies on the IEC 61850 [8] standard this two standard is concerned later on – provides a list of well organized named information. These pieces of named information are our main interest, since this gives us a way to define and communicate algorithms in a non-proprietary format even if the algorithms are developed on proprietary data sets. The following process is planned to implement in the project:

- Develop the algorithms based on field data or other proprietary data
- Map the data to the information model of IEC 61400-25 series.
- If the map is not possible extend the data model
- Deliver the developed algorithms using the standard naming strategies

The IEC 61400-25 series utilises the concept of object modelling to represent the systems and components of a wind power plants to communicate with. This means that all of the components in the real world are identified as objects that have data such as analogue values, binary status, commands and set points and these objects and data are mapped into generic, logical representations of the real world components as a wind power plant information model (see in Fig. 2).

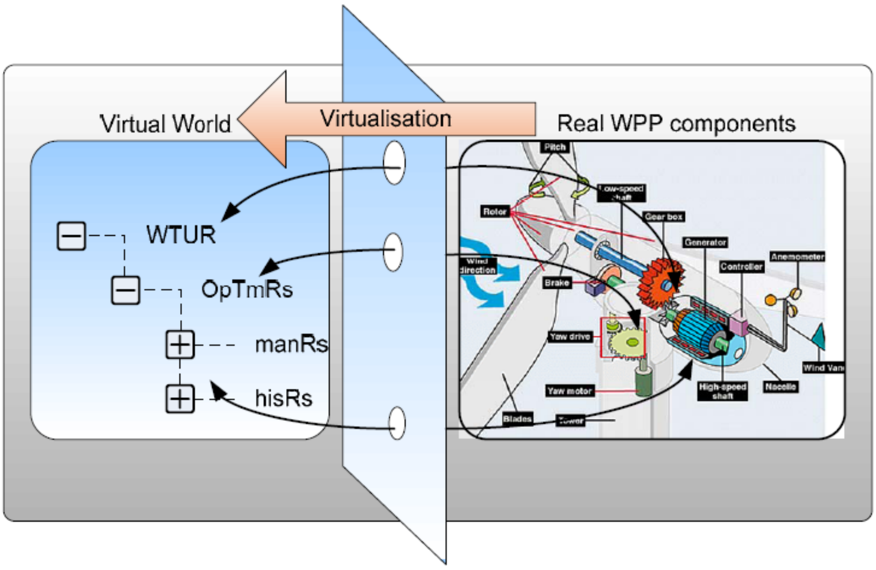

Fig 2: Mapping components to information model

The information model is principally a tree structured model that captures the assembly-subassembly-…- part structure of the real WTG system. The structure of this hierarchical tree is defined in the IEC 61850 standard. The name of the concept is Abstract Communication Service Interface (ACSI) and the basic conceptual class model of ACSI is displayed in Fig 2. The class model displayed in Fig. 3. is just a view of the complete data structure, because only the most important attributes of the classes are displayed [7][8]. For a complete list of attributes the reader should consult the standard.

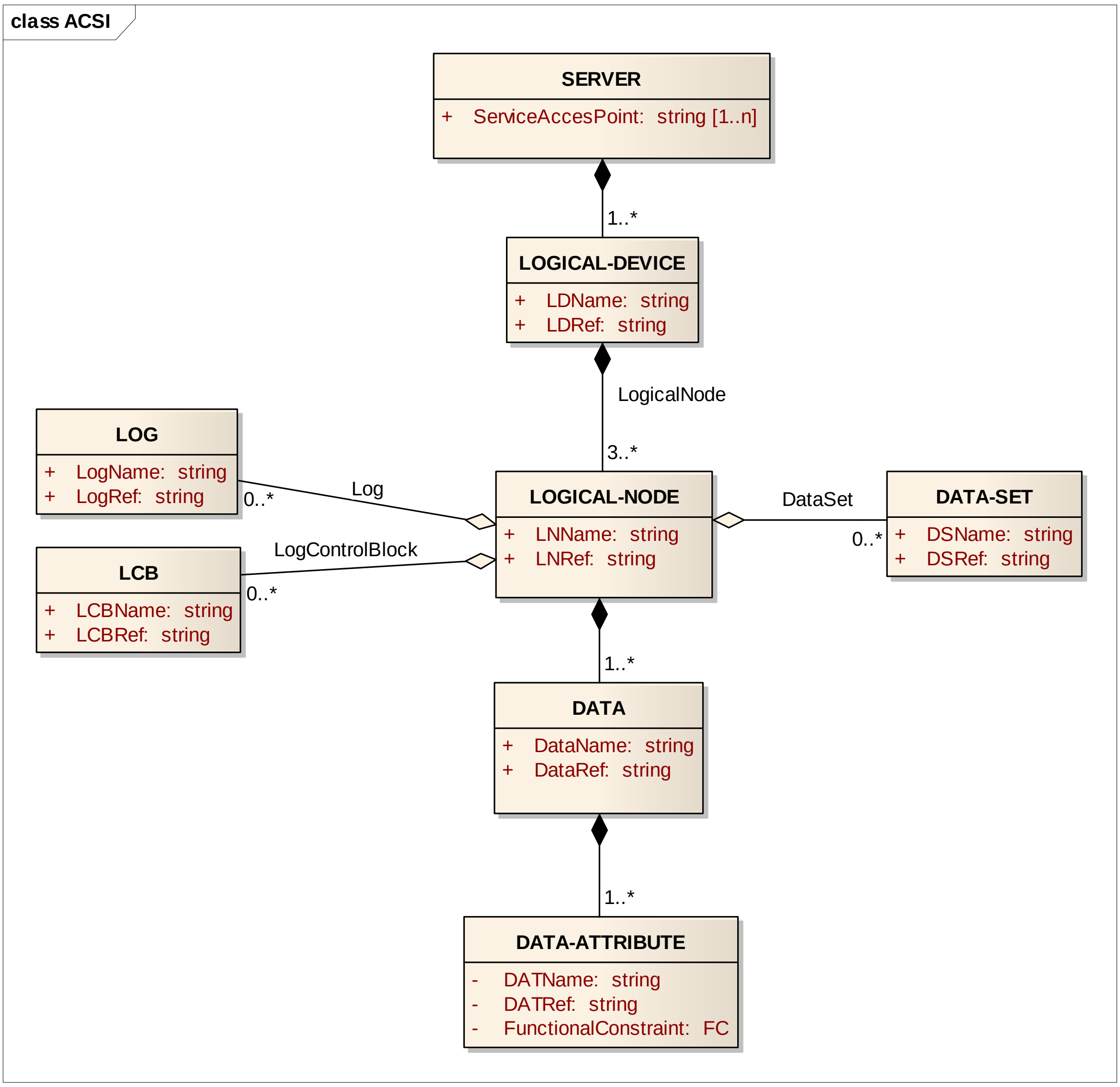

Fig 3: Conceptual class model of the ACSI

4. MONITONRING DATA COLLECTION AND ANALYSIS

4.1. Data structures, content and cleaning

In order to prepare the ground a data cleaning is implemented to provide high quality data for the forthcoming data analysis. The field data currently available for the analysis came from two sources:

- Work orders (some thousand records)
- SCADA data from central databases

The work orders store the repair works performed on the wind turbines. The SCADA data is available in 3 delimited text files. The data are available for the same wind turbines that were referenced in the Work Orders file. The three files contain the following information

- Alarm information (some ten thousand records)
- Wind information (some million records)
- Energy information (some million records)

The alarm information contains the trigger events of the different sensors in the wind turbine. The wind information stores averages of the wind speed measured at the different wind turbines. The energy information stores also averages of the energy produced on the different wind turbines. Because of the volume of the records and for having structural, consistent data structure the data was loaded into an Oracle database. This database could be queried during the data processing and analysis.

The work orders are edited by hand; therefore, it is highly possible that small syntax errors might occur during the editing phase. Since the failure modes are important piece of information in the later processing, it is very important that two different spellings of one failure modes are not considered as two failure modes.

The automatic filtering is realized applying AI techniques it is based on Porter's stemming and a clustering algorithm [15]. The algorithm works as follows:

- Divide every expression into words
- Drop the stop words (small words that does not influence the meaning)
- Find the stem of every word
- Add the word to the dictionary (in this case a list of words used at least once in an expression)
- Calculate the word vector of every expression. The word vector is a sparse vector that contains 1 only at positions where the dictionary stores the contained words.
- Cluster the identical vectors

The algorithm is applied to the corpus of all failure modes, sub-systems, assemblies, sub-assemblies, and part expressions. The clustering algorithm found some tens of clusters that have more than one member. Examples of clusters are displayed in Table 1 below. The identical expressions are filled in the database as identical records having the same index numbers.

Table 1. Example of identical expressions

Group No	Expression 1	Expression 2	Expression 3
6	BLADE REPAIR	BLADE REPAIRING	**BLADES REPAIRING**
7	ELEVATOR REPAIR	ELEVATOR REPAIRING	
8	VIBRATIONS SENSOR	VIBRATIONS SENSORS	
9	YAW SENSOR	YAW SENSORS	
...	...	...	**...**

4.2. Data analysis

As the preliminary task a clustering of the work orders was carried out. This analysis is a very simple way to find out dependencies between failures. Since every work order corresponds to a failure mode, therefore the work orders clustering is equivalent of the failure modes clustering. The idea behind the analysis is the following: let us assume that failure modes that regularly occur together have dependencies between each other. Visualizing these dependencies might immediately reveal some real – which means here accepted that by experts – dependencies between the different failure modes.

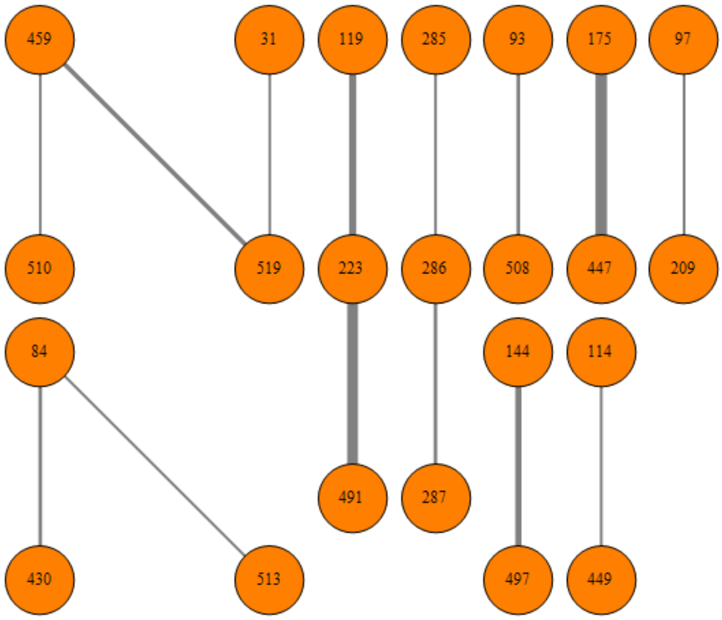

Fig. 4. Dependency graph with minimum edge weight = 3

In order to visualize the dependencies first the work orders are clustered into dependency groups. Dependency groups mean a set of work orders that have some connections between them. The dependency groups are determined in this analysis based on the date stamp. Two work orders are considered dependent if they occurred on the same turbine and the difference of the two date stamps is less than some days. In other words if two failure modes occurs close together, they most probably influence each other, e.g. they are dependent.

All work order pairs – or failure mode pairs – in a dependency group represent an edge in a dependency graph. As the graph is defined, every edge receives a weight, which is equal to the cardinality of the occurrences. If the weight of the edge is 2, then it means that the given pair of failure modes appear exactly twice on the same turbine within the time window prescribed.

To visualize the dependencies a minimum edge weight is defined to filter out the edges from the graph whose weight is less than the specified minimum. The reason behind this filtering is quite simple, the lower weight of the edges, the less probable the real dependency. In Fig. 4 a dependency graph is displayed with minimum edge weights equal to 3. Edges having bigger weight are drawn with thicker lines.

This simple dependency graph does not necessary reveal direct, real dependencies between the failure modes, but it definitely helps to build a better qualitative understanding of the provided information, consequently engineering check is needed using this result.

5. CONCLUSIONS

The environmental effects of wind power are relatively minor, compared to those of more traditional energy sources. Among the renewable energy arts wind energy plays a significant role and, as forecasted its ratio within the total energy production will rapidly increase. Wind turbines are relatively complex electro-mechanical systems, their smooth functioning is an important economical factor. This is why monitoring and diagnosis of wind turbines and wind farms gained extreme importance in the past years. The ReliaWind EU 7th Framework Research project has set up ambitious goals, namely, optimizing wind energy systems design, operation and maintenance. Concentrating on monitoring, diagnosis and maintenance issues the novel logical architecture of an advanced wind turbine health monitoring system harmonized with the recent standard series on communications for monitoring and control of wind power plants was introduced. Wind turbines have several built-in sensors measuring various physical characteristics during the operation and SCADA systems serve with huge amount of data. This allows applying artificial intelligence techniques for analysing the dependencies among data. Similar to other branches, e.g., to manufacturing [20], exploration of this new knowledge the necessary models for condition monitoring can be set up ensuring a part of the content for the introduced advanced wind turbine health monitoring system.

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