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Fault Diagnosis approach based on a model-based reasoner and a functional designer for a wind turbine. An approach towards self-maintenance

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Abstract. The objective of this on-going research is to develop a design methodology to increase the availability for offshore wind farms, by means of an intelligent maintenance system capable of responding to faults by reconfiguring the system or subsystems, without increasing service visits, complexity, or costs. The idea is to make use of the existing functional redundancies within the system and sub-systems to keep the wind turbine operational, even at a reduced capacity if necessary. Re-configuration is intended to be a built-in capability to be used as a repair strategy, based on these existing functionalities provided by the components. The possible solutions can range from using information from adjacent wind turbines, such as wind speed and direction, to setting up different operational modes, for instance re-wiring, re-connecting, changing parameters or control strategy. The methodology described in this paper is based on qualitative physics and consists of a fault diagnosis system based on a model-based reasoner (MBR), and on a functional redundancy designer (FRD). Both design tools make use of a function-behaviour-state (FBS) model. A design methodology based on the re-configuration concept to achieve self-maintained wind turbines is an interesting and promising approach to reduce stoppage rate, failure events, maintenance visits, and to maintain energy output possibly at reduced rate until the next scheduled maintenance.

1. Introduction

Offshore sites differ from onshore sites especially because of their exposure to extreme weather conditions, remote location, and of their difficult to impossible accessibility in certain periods of the year. Consequently, the availability levels of offshore wind turbines become near to unacceptable, and the need of research to improve reliability becomes evident. These differences give rise to a significantly lower availability and hence lower energy production. The high level of offshore site inaccessibility, especially in winter, makes it difficult, or even impossible for conventional maintenance methods to provide the high availability levels (~98%) achievable in an onshore wind turbine.

There are different approaches to solve specific problems related to operation and maintenance of offshore wind turbines. Solutions can be found by improving reliability of the system or sub-systems. Other approaches target the accessibility of the site, for instance: finding more adequate boats that can travel faster, or at higher wave heights, or with more transport capacity, or using helicopter access for which heliports need to be built at the wind farm sub-station or at each nacelle of the wind turbines; or tools such as the Amplemann (http://ampelmann.nl/) to improve the access to the tower. Other approaches range from protective measures for certain components against the harshness of the sea weather to some changes in design of the nacelle to allow maintenance work or even temporary accommodation of crew, crane installation at the nacelle, etc. Availability can be increased by optimization of maintenance strategies, by fault diagnosis capabilities built in the supervisory controller, and by operation of dynamic controllers for specific subsystems, usually to make continuous high-speed adjustments in order to react to high speed changes, such as gusts [1]. These are meant to provide a safe, efficient, and/or smooth operation. Safety is also considered by design methodologies or tools (i.e. failure mode and effect analysis (FMEA)). However, there is still a percentage in which the wind turbine fails. A failure event can occur for instance at wintertime, where the energy production should be at its maximum, but also when the site is inaccessible for a couple of weeks, generating high losses of expected energy production. This creates the need of a new approach to handle shutdowns due to faults.

This work is part of an on-going research that intends to deal mainly with these offshore challenges, aiming at an increased availability. Facing the accessibility problem of offshore, it is proposed to look for ways of dealing with faults within the system, through reconfiguration of subsystems or components (see Section 3) to keep wind turbine operation until maintenance can be performed.

Research close to this work is about fault detection and fault tolerance. Fault diagnostic systems intend to identify what the failure or failures, in the case of a multiple faults event, are. Conventional techniques such as pattern matching to derive root cause of a failure or fault propagation graph to describe the propagating behaviour of the fault through the system, require a great deal of hand work, especially due to simulation process. More sophisticated techniques in the area of AI are rule-based approach, expert systems and model-based reasoning [2]. Comparing the MBR with the other approaches for fault diagnosis, a great advantage of the MBR is that it provides automation capabilities in the simulation process [2,3,4].

Expert systems use information collected from experts on how the system works, it is often about subjective knowledge and human analytical skills. This approach is a step forward with regards to conventional maintenance, however, it is not always easy to find the expertise and to translate it to computer language; moreover, the system is not easily adaptable to changes in the design due to the nature of its knowledge.

A model based diagnostic system uses a model of the system (product, service, software, etc.) to reason about its behaviour. It simulates what the system is supposed to do based on this model, and compares it to what it does in reality. The diagnosis is giving as the system being faulty or healthy. Possible faulty components are suggested by the system based on their probability of failure and the reasoning process. In this way, expected faults are detected. The use of a model makes this approach more robust in comparison with the expert system.

The proposed methodology differs from previous work mainly in two aspects: the qualitative reasoning system that allows to deal with unexpected faults and the reconfiguration concept that can be used as a repair strategy. This methodology is based on the design process, with the aim of equipping the wind turbine with the required capabilities to deal with faults and failures in a different and innovative way, in which the main purpose is to maintain operation and to lose some degree of dependency from the maintenance crew. This is a first step towards self-maintained wind turbines.

The Self Maintenance Machine (SMM) [5] concept has been already applied to other technology fields such as the photocopier industry. The idea of SMM is to design and build a machine using embedded intelligence together with sensors and actuators that can operate maybe not fully functionally but at a designated level (e.g. 50%), thereby adding robustness, and fault tolerance.

This paper intends to present a design methodology that makes use of existing functional redundancies within the system and sub-systems to keep the wind turbine operational, even at a reduced capacity if necessary. The methodology is based on qualitative physics (QP), which is the area of artificial intelligence that reasons about the behavior of a physical system. It describes behavior of the system in terms of qualitative characteristics of changes over time, and predicts the magnitude of these changes. This approach opens up many other possibilities to model systems that have higher complexity. Moreover, it reduces the amount of information that is needed for decision-making processes.

The first part of the methodology, which is based on the SMM, consists of a functional redundancy designer (FRD) [6] that targets the design process and collects information that will be useful during the operational stage. The second part of the methodology consists of a fault diagnosis system, a qualitative physics simulator, and two types of repair methods: control type and re-configuration (functional redundancy type) [6]. This structure provides the system with the capabilities of dealing with unexpected faults and allowing easy access to knowledge (see Section 5.2). Model-based reasoning (MBR) and FBS modelling constitute the foundation of the methodology. The functional approach is used mainly for the advantage of robustness in terms of usability and its direct congeniality with qualitative physics.

Additionally, a fault diagnostic system based on MBR provides reusability of knowledge about different objects, robustness of the reasoner against unknown faults, and easy knowledge acquisition [7]. Knowledge is structured using a FBS model, which supports conceptual design [6]. In other words, it supports the function definition process on its own, without referring it to behaviors or structure. Through simulation processes the methodology intends to allow the operator (or system itself if coded for online operation) to find out behaviors that can be used to perform the required function. Therefore, when a fault occurs, the fault diagnostic system identifies the faulty component or un-performed function, and looks for alternative behaviors that can realize such function.

Part of this research is also to understand faults and failures, understand the role of different technologies in the reliability of the wind turbine, and consequently, to identify the best designs and configurations of the systems and sub-systems.

Within the system, there are different levels at which this reconfiguration concept can be applied. Possible solutions can range from using information from adjacent wind turbines to setting up different operational modes. Nonetheless, there is no aim or intention of adding redundant components, unless it is necessary to satisfy operational requirements of alternative configurations.

The results of this design methodology intend to decrease stoppage rate, reduce number of failure events, maintain energy output possibly at reduced rate until the time of a scheduled maintenance, and reduce maintenance visits.

This paper will give the scope of the research project. More detailed explanation is given on the reconfiguration concept and design tools such as MBR, FBS and FRD, followed by the description of the proposed methodology for intelligent maintenance. Conclusions on the advantages of the design tools with respect to wind energy are presented at the end.

2. Scope of the methodology

An *offshore wind farm* is defined under the scope of this methodology as *system* that consists of more than one wind turbine and with the end-point at its land-based substation (excluded). The following main level is the wind turbine, the subsequent level corresponds to the major components of the wind turbine such as rotor (blades and supporting hub), drive train (low speed shaft, gearbox, high speed shaft, couplings, mechanical brake, and generator), yaw system, controller, electrical system (transformer, switchgear, cables, power electronic converter), etc. Each of these components or sub-systems has other components and so forth.

The starting point is to acknowledge and accept that faults happen. Therefore, knowledge on the system and its behaviour is needed to generate a methodology to deal with these faults. Usually information is not available at the required detail to understand how and where the system fails. Therefore, the methodology uses qualitative physics with the purpose of providing reasoning capabilities, with that level of information, as perceived by humans (qualitative information).

The first step is to describe the system at the first layer of complexity using the FBS model. In other words, information is defined and structured for the upper level of the wind turbine, which corresponds to the major components such as blades, generator, gearbox, transformer, etc. The system description within the FBS model must provide connectivity among all components at each level, within the desired scope of interest.

As depicted in Figure 1, the FBS model is built using information from the system and its technology, failure understanding, and knowledge about Reliability, Availability, Maintainability, and Safety mechanisms (RAMS) of the system.

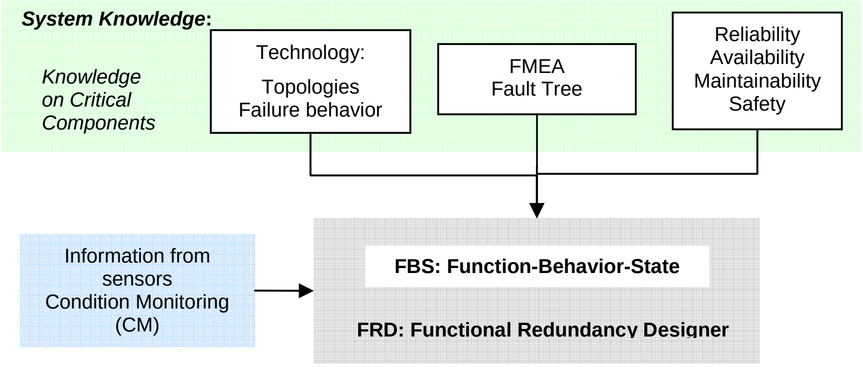

Figure 1. Desired knowledge for building FBS and FRD tools.

The failure of a system provides information about the operation and interaction among parts that is usually not intended by the designer. To understand failures it is important to understand how the system works, and what the main interactions between domains are, for instance mechanical and electrical. Additionally, tools such as a tree-fault diagram or even going in more detail a FMEA are useful to identify connectivity and criticality of components that compromise the reliability of the system. This information provides the designer with a prioritized agenda when selecting sub-systems. In other words, it points out critical components for the designer to give special attention when locating functional redundancies within the system. This criticality of components is representative of the functional hierarchy at the operational level and of fault frequency. Furthermore, sensor input provides information on where the system is evaluated, therefore parametric conditions can be compared as per what they should be and what they really are during online operation.

The methodology is not intended for improvement of materials or components. Nevertheless, it may incorporate some redundancies in the design to achieve re-configured states. The outcome is therefore a design methodology to deal with faults by providing alternative operational modes in terms of reconfiguration of the sub-systems within the wind farm. In the following section explains how the reconfiguration concept can be perceived within the wind turbine.

3. Reconfiguration concept

The reconfiguration concept applies to all structural levels of the wind farm. It can be perceived in 3 different manners, as per described in table 1. Reconfiguration based on information is expected to be more common at upper levels of detail such as wind farm level, and/or related to failure of sensors. Today many wind turbines stop due to nuisance alarms and making use of redundant available information even from adjacent wind turbines can help to reduce the stoppage rate. The behaviour type is based on the adjustments on control systems to adapt to a new operational mode, such as lower output, fix pitch angle, etc. Physical reconfiguration implies re-connectivity, re-wiring of components. Usually, control strategies and parametric adjustments are consequences of physical reconfiguration.

Table 1. Reconfiguration types

Reconfiguration type	**Comments/examples**
1. Informational	Wind speed can be known from adjacent wind turbines, or from sensor information on the same wind turbine by knowing torque, pitch, power curve.
3. Behavioural	Control strategy change to adjust to reduced operational conditions
4. Physical	Re-wiring, re-connecting, etc.

4. Design phase: FBS model and FRD tool

Funtion-behavior-state (FBS) is a functional model based on Artificial Intelligence (AI) intended to help the designer in the synthetic tasks of the design. The FBS model supports conceptual design [8] based on definition and decomposition of functions. The system is described by a network of functions: intended functions by the designer are decomposed into sub-functions until such a detail that they can relate to *physical features*. These *physical features* correspond to a set of descriptions of *entities*, *relations*, and *physical phenomenon* representing a specific interest. This modeling structure incorporates all the information of the system in a modular representation and keeps it in a knowledge base for easy access.

Figure 2 shows a descriptive scheme for the 3 main components of the FBS model [5,8]: *function, behaviour, and state*. Looking at Figure 2, from left to right, it begins with the intended *function* defined by the designer. Behaviour answers to the question *how to* accomplish the unintended function [8]. Besides, by definition behaviour is the change of *state of an entity*, which directly refers to the structure of the system. Furthermore, the state of an *entity* contains *attributes* and relations among them. Each *state* defines steady qualitative conditions and parametric values that do not change.

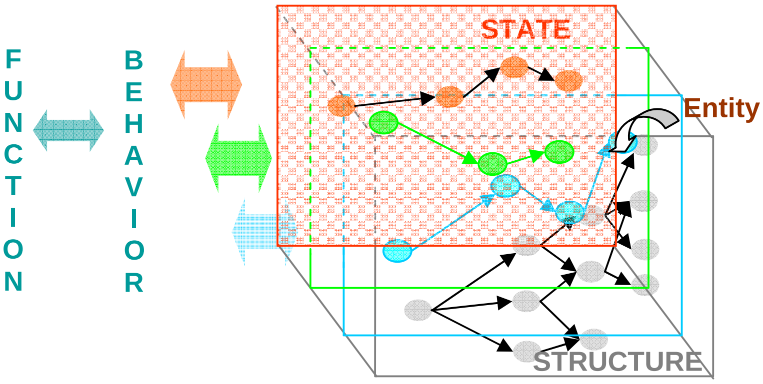

Figure 2. FBS Modeler scheme

On the other hand, time is divided in intervals and it is the analogy of a clock in a computer. It gives a time step in which parameters do or do not change. Therefore, in Figure 2 looking from right to left, it can be seen how a system or general *structure* is defined by interconnected *entities*. Each of them are characterized by *attributes* and *relations* defined at each *state*, and that can change from one interval to another. *Behaviour* is the change of *state* of an *entity* and relates to functions by activating the *physical phenomena* contained in a *physical feature* that is part of the function.

All this information belongs to a system and needs to be taken into account at the time of designing it. The FBS model provides the framework to structure this knowledge. As the complexity of the system increases the decision-making process when selecting components becomes more difficult. The FBS model helps the designer to visualize the existing relations among components, possible failure events due to lack of connectivity, or provides information on redundant functionality that can be useful to increase the reliability of the system. Additionally, unpredictable problems caused by inter-disciplinary relations can be detected sooner, at an early stage of the design process, by making use of functional modelling, such as FBS. For instance, vibration of mechanical component can affect electronic components placed nearby. Furthermore, at the basic or upper level of the wind turbine layout has a very straight forward design. However, it comprises specialized fields such as aerodynamics, mechanics, and electrical. Each main sub-system in the wind turbine is complex and represents a transformation process, at a multi-disciplinary level. For instance, kinetic energy from the wind is absorbed aerodynamically by the blades and transformed into rotational energy by the rotor. The gearbox amplifies that rotational speed and transfers the energy into the generator, which transforms it into electricity. Each field has a space domain that characterizes it, including governing set of equations, relevant as well as negligible parameters. However, by combining all these fields in this interaction of components not only all parametrical conditions need to be satisfied but also the domain characterization needs to be taking into account. Even though there are operational conditions that are not important or are negligible in a specific field, they are not for other fields. The functional modelling provides also the framework to facilitate the description of the system from the various disciplines since it describes the system based on functionalities. On the other hand, there is also information about the system in terms of functionality of components that is not initially intended by the designer but exists. These functionalities represent redundancy built in the system, since they belong to each entity (object or component), that can be used in the event of a fault.

5. Operational phase: Intelligent maintenance

The intelligent maintenance system is a methodology under study that intends to diagnose the system, identify a fault, find alternative solutions for continuing operation, and plan a repair strategy until maintenance can arrive. This methodology is part of an on-going research at TU Delft (NL). There are different design tools that come together to provide structured knowledge that can be used to generate these alternative solutions. Figure 3 shows the scheme of the methodology.

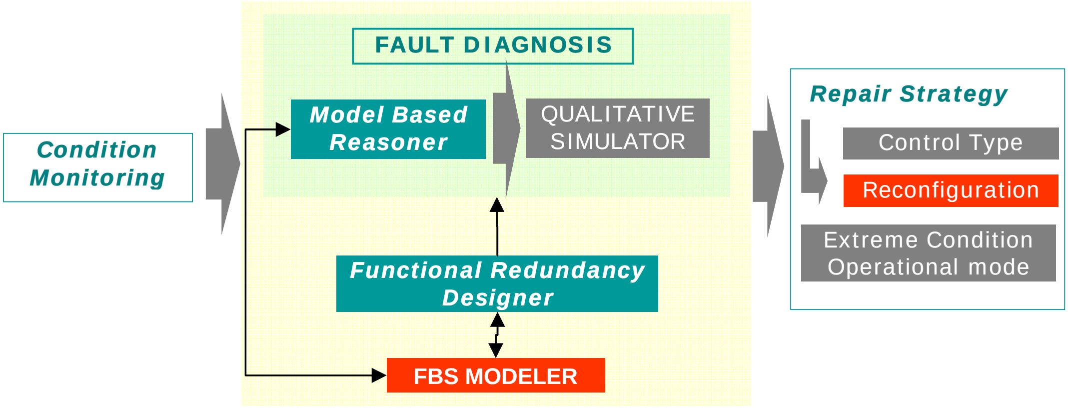

Figure 3. Intelligent Maintenance Methodology

The intelligent maintenance methodology involves two main modules: one applied at the design stage and the second one at the operational stage. At the design stage, the FBS model feeds the *Functional Redundancy Designer* (FRD), which is the responsible for systematically providing the designer with information on potential existing redundancies of the system. This is intended to help on the decision making process, with respect to the component selection. In this way, the designer knows what functional redundancies he/she is including in the system. At the operational stage, the methodology consists on a fault diagnosis system supported by a qualitative physics simulator and the FRD, and two types of repair methods: control type and re-configuration (functional redundancy type). A qualitative physics simulator consists on a reasoning engine based on qualitative physics.

As per described in Section 2, different knowledge is required to build the system. Tools from control theory, condition monitoring (CM), maintenance strategies, knowledge on offshore conditions together with qualitative physics theory and other design tools are used to develop an intelligent maintenance system. The first step to structure this knowledge is to translate or express this information into a qualitative language to obtain a non-quantitative perspective on how the wind turbine works and fails. Qualitative physics at this level is used to subtract only the valuable information and at the same time to be able to use it with the little amount of detail available. In a practical manner, this knowledge is represented as humans perceive the world, by common sense and logic statements, when not all the information is available to us. In the following sub-sections, the two main design tools of the intelligent maintenance methodology are described:

5.1. *Functional Redundancy Designer - FRD.* There are existing redundancies in the system provided by its components, which are overlooked due to lack of information. Each component is selected by the designer to perform a specific task. However, most of the components can be used for other purposes not specified in this particular design.

A functional redundancy designer is proposed to systematically find these existing redundancies based on information inherent in each component. On one hand, it intends to provide the designer with the information about the functional redundancies he/she is adding to the system by selecting a specific component, this facilitates decision-making processes. With this information, the designer can identify required redundant functions especially for critical components, and adapt the design to make possible re-configurations of the system providing additional operational modes to be used in the event of a fault. By doing this there may be the need of some additional parts, but usually parts that provide connectivity which are expected to be inexpensive compared to redundant components. Also, different operational modes can be the solution to deal with many different faults, whereas a redundant component would be needed in an individual basis. On the other hand, it aims to store this information to make it available to the fault diagnosis system. In a further step, the fault diagnosis system could use this information in its simulation to find candidates for possible solutions to the fault by identifying other components that can perform the faulty function, and/or by finding alternative operational modes.

5.2. Model-Based Reasoner - MBR. A model-based reasoner is part of artificial intelligence field that describes the physical word by representing knowledge using rules. In this application, these descriptions are qualitative. The MBR consists in an *entity* and *connectivity* model, *functional* description and *parametric model*, which corresponds to the physical or *object model*. Figure 4 shows a scheme of what the MBR comprehends.

Knowledge about physical laws and principles serves as a tool to help to determine what is possible and what is not during the simulation in the physical world, helping the diagnosis and repair simulations. Structural information of the system is contained in the object model including not only physical parts and connections but also information on parameters and mathematical relations. This provides the system with flexibility and robustness making it capable of dealing with unexpected faults, and allowing easy access to knowledge. The functional redundancy designer contains information on existing functional redundancies built into the system as a result of the component selection made by the designer.

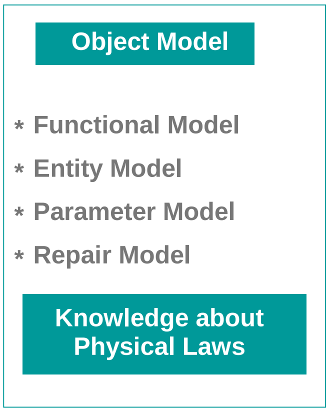

Figure 4. Model-based reasoner scheme

Figure 3 shows a link between the FBS model and the MBR. Considering the information contained in the FBS model and the MBR system, there are common elements that can be used. The FBS model is a functional modeling that structures the knowledge by a hierarchical network of functions. The model-based reasoner can take advantage of this structure to build the object model, which results in simplification of knowledge. This is accomplished by the separation of the knowledge from the object and physical laws and principles. An advantage of the FBS model is that functional representation can be used by all disciplines.

A fault diagnosis system should be able to detect fault of all components, including sensors, and implicitly, it should be able to identify the operational conditions, especially beyond operational limits [1]. However, once the fault is identified there is a large number of alarms for which the system shuts down, waiting for maintenance to come. The fault diagnosis system making use of the FRD provides additional information to the system to deal with faults. Also, it provides a different reasoning approach (qualitative reasoning) that allows the handling of information that is complex to deal with in common mathematical approaches.

The use of these two modules provides robustness and flexibility to the diagnosis system and includes maintenance and operation strategies from an early stage in the design process. When a fault occurs, this information will be used by the system to diagnose itself and to find/reconfigure other components that can execute the un-performed function.

In order to obtain an insight on the impact on the availability of the wind farm using this methodology, simulations can be compared using actual maintenance strategies and the proposed intelligent maintenance system. CONTOFAX [9], a Monte-Carlo simulation code written at TU Delft, provides the possibility to simulate stochastically weather conditions and the effect of different factors acting around the wind farm that directly affect its availability, such as crew, transport, maintenance procedures, reliability figures (mean time between failures - MTBF, mean time to repair - MTTR, etc).

6. Conclusions

Offshore wind turbines differ on operational conditions compared to onshore. This raises a problem that represents a high cost on the loss of energy production. Currently solutions involve maintenance strategies, increase of reliability of components, improve of accessibility, etc. A methodology to target the design of the wind turbine to provide alternative configurations is an innovative approach.

Describing the system in the base of functionalities provides robustness in the design process that help the designer in the decision making process. By decomposing the functions in sub-functions the system has the potential to visualize interactions among components that may not be intended by the designer, it can also alert about conditions that are not satisfied by using knowledge based systems from previous designs.

Functional knowledge described qualitatively provides a new approach on analyzing information. Qualitative physics deals with incomplete information, which allows reasoning at earlier stages of the design, if compared with a quantitative analysis. This increases the analytical capabilities of the reasoning system.

Optimizing the capabilities of the existing components of the wind farm provides a wider opportunity to deal with faults. There are existing redundancies in the system inherent in the components that are not included or used in current design processes, from the informational, behavioral, and physical point of view.

Functional Redundancy Designer (FRD) is a tool responsible for systematically providing the designer with information on potential existing redundancies of the system. This targets operational and maintenance needs from the design stage.

A fault diagnosis system supported by a qualitative physics simulator and the FRD represents an innovating and promising approach for offshore wind farms to deal with faults, with the aim of reducing stoppage rate, failure events, maintenance visits, and/or maintaining energy output even at reduced rate until the next scheduled maintenance.

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