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Mechatronic modeling of a 750 kW fixed-speed wind energy conversion system using the Bond Graph Approach

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A B S T R A C T

In this paper, we would like to focus on modeling main parts of the wind turbines (blades, gearbox, tower, generator and pitching system) from a mechatronics viewpoint using the Bond-Graph Approach (BGA). Then, these parts are combined together in order to simulate the complete system. Moreover, the real dynamic behavior of the wind turbine is taken into account and with the new model; final load simulation is more realistic offering benefits and reliable system performance. This model can be used to develop control algorithms to reduce fatigue loads and enhance power production. Different simulations are carried-out in order to validate the proposed wind turbine model, using real data provided in the open literature (blade profile and gearbox parameters for a 750 kW wind turbine).

1. Introduction

Many engineering activities, including mechatronic design, require that a multi-domain or multi-physics system and its control system should be designed as an integrated system [1]. Mechatronics is “a technology which combines mechanics with electronics and information technology to form both functional interaction and spatial integration in components, modules, products and systems” [2].

Wind turbine is a complex mechatronic system, in which different technical areas are involved (mechanics, aeronautics, electrical, among others). There is no doubt that a mechatronic approach is essential in the field of wind turbine design. This approach implies that a mechanic, aerodynamic, electric subsystems and eventually their control subsystem should be designed as an integrated system. This integration is important for a more accurate evaluation of the extreme loads and the fatigue life, and this might reduce the failure rate in the design stage. However, the aerodynamic, mechanical and electrical models should be usable for detailed control system design, which will be necessary as the design goes deeper. Indeed, linear simplified models, e.g., a simple aerodynamic, mechanical or electrical models, are not sufficient to take into account the necessary coupling effects among the components.

For the combined analysis of the aerodynamic, structural and control generating systems, or the mechanical, control and aerodynamic subsystems many works either use a very simple mechanical model with a detailed electrical model, or a complicated mechanical model with a simple control system model [3,4]. Hence, the interactions and the dynamics coupling cannot be accurately predicted. In [5] four different models of wind turbines are introduced. On one hand, two static models – the simple static model and the static mechatronic model – represent two different instances of a simplified behavior. On the other hand, two dynamic models – the mechanical model and the dynamic mechatronic model – describe the dynamic behavior of a wind turbine in more detail.

In [6] a control-generator-structure coupled with analysis in wind turbines using a monolithic modeling and simulation is proposed. The integrated system models were developed on Samcef for Wind Turbines (S4WT) through a nonlinear finite element method (FEM) formalism. Another contribution [7,8] reviews

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recent research of technical issues on the development of wind farms. These contributions highlight the importance of having a mechatronic model of the wind turbine, but the models lack some detail. In order to analyze the system in the same reference frame, there are several methods and tools for the modeling and the simulation of physical systems and their controllers, with parameters directly related to physical components. Moreover, it is desired that these (sub-) models should be reusable. Common Block-Diagram (CBD) or Equation-Based Simulation (EBS) packages do not easily support these features. The Energy-Based Approach (EBA) for modeling physical systems allows the construction of reusable and easily extendable models.

In this work, a fixed speed wind turbine mechatronic model has been developed. The main components of the system are modeled in detail using the Bond-Graph Approach (BGA). The implementation of the complete model has been carried out by means of the 20-*Sim* simulation program (a demo version is freely available on the Internet). Parameters of a 750 kW-power wind turbine were taken from NACA 4415 profile [9]. Verification of results is reported. Conclusions of the conducted research investigation are drawn.

2. Mechatronic modeling of the wind energy conversion systems

In the next sections, the mechatronic modeling of the main components of a WECS will be presented. Our first aim is to show the complete wind turbine in a unified framework. The WECS is organized into four main areas, namely the aerodynamic, mechanical, electrical, and pitch servo subsystems. The main components of a WECS are rotor, transmission system and power generator unit. The rotor comprises the blades where the aerodynamic conversion takes place, the hub that links the blades to the transmission and the pitch servos, which are located inside the hub that rotates the blades around their longitudinal axes. The transmission system transmits the mechanical power from the rotor to the electric machine. It comprises the low- and high-speed shafts, the gearbox and the brakes. The gearbox increases the rotor speed to values more suitable for driving the generator, typically from 20–50 rpm to 1000–1500 rpm. The electric generator is the device that converts mechanical power into electricity. Its electric terminals are connected to the utility network. In the case of variable-speed WECS, an electronic converter is used as interface between the AC grid and the stator or rotor windings.

A mechatronic model, that takes into consideration the dynamic behavior of the entire WECS, can be structured as several interconnected subsystem models as shown in Fig. 1. The aerodynamic subsystem describes the transformation of the three-dimensional wind speed field into forces on the blades that generate the rotational motion. The mechanical subsystem can be divided into two functional blocks, i.e., the drive-train and the support structure. The drive-train transfers the aerodynamic torque on the blades to the generator shaft. It encompasses the rotor, the transmission and the mechanical parts of the generator. The structure is made up of the tower and the blades. The electrical subsystem describes the conversion of mechanical power at the generator shaft into electricity. Finally, the actuator subsystem models the pitch servo behavior.

In order to analyze the system in the same reference frame, the Bond-Graph Approach (BGA) [10,11] is used.

2.1. Fundamental concepts of bond graphs

Bond graph is a graphical way of modeling physical systems. All these physical systems have in common the conservation laws for mass and energy. Bond graph, originated by Paynter [10] in 1961, deals with the conservation of energy. This gives a unified approach to modeling physical systems. Further follows a short introduction to this modeling tool, more information can be found in [9,10]. The bond graph based modeling has several advantages over conventional simulation methods as follows:

1. providing a visual representation of the design;
2. controlling the consistency of the topological settings of the design;
3. providing the hierarchical modeling of designs;
4. extracting the system equations symbolically in a structured way.

Within physical systems, energy is transported from one item to another. This energy is either stored or converted to other forms. But the important thing is that it does not dissipate. If the energy is changing in one place, it also changes in an opposite way at another location. The definition of power is the change in energy (E) with respect to time:

$$P = \frac{dE}{dt} \tag{1}$$

This power is transferred between the different parts in Bond Graph model with the use of power bonds, see Fig. 2. Power can be expressed as the product of an effort and a flow variable, thus the general expression:

$$P = e(t)f(t) \tag{2}$$

The symbols $e(t)$ and $f(t)$ are used to denote effect and flow quantities as functions of time. Table 1 shows that the effort and flow quantities can be in some familiar domains.

2.1.1. System elements

In Bond Graph modeling there are a total amount of nine different elements. We will also here introduce the causality assignments, but first we have to explore the cause and effect for each of the basic bond graph elements.

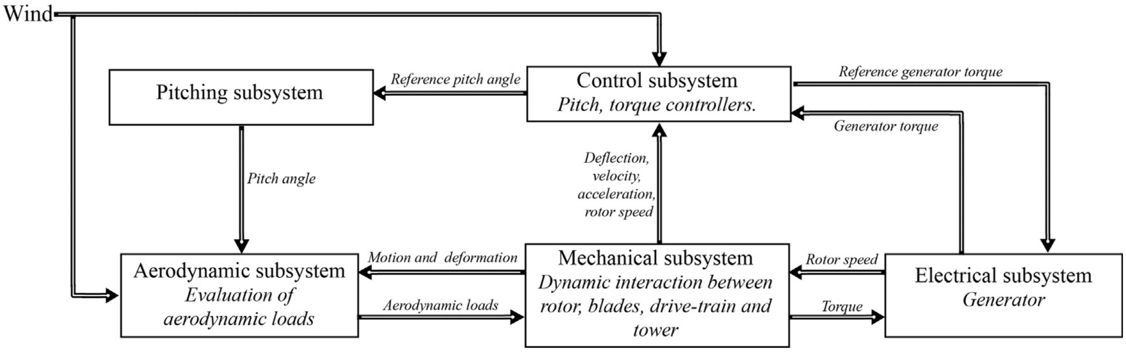

Fig. 1. Subsystem-level block diagram of a WECS.

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