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Modelling of a chaotic load of wind turbines drivetrain ☆

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ABSTRACT

The purpose of this paper is to present a model of the load of the wind turbine gears for simulation of real, varying operational conditions for modelling of wind turbine vibration. The characteristics of the wind, which generates chaotically varying loads on the drivetrain components generating load in teeth and bearings of gears during torque transfer, are discussed. A generator of variable load of wind turbines drivetrain is proposed. Firstly, the module for generation of wind speed is designed. It is based on the approach in which the wind speed was considered as a time series approximated by the Weierstrass function. Secondly, the rotational speed of the main shaft is proposed as a function of the wind speed value. The function depends on a few parameters that are fitted by using a genetic algorithm. Finally, the model of torque of the main shaft is introduced. This model has been created by using a multi-layer artificial neural network. The results show that the proposed approach yields a very good fit for the experimental data. The fit brings about the proper reproducing of all the aspects of the load that are crucial for causing fatigue and, as a consequence, damaging of gears of the wind turbines.

1. Introduction

We have been witnessing a rapid growth of the wind power generation all over the world for recent years. In the recent 15 years the actual cumulative growth rate was about 28%. The installed wind farms had reached the capacity of 237 GW by the end of 2011. It is going to increase in future and in 2020 it will have achieved 587 GW, according to the pessimistic scenario, 759 GW according to the moderate scenario, and 1150 GW according to the optimistic scenario. The decrease of the amount of CO_2 emission in 2020 will be 863 Mio t, 1118 Mio t and 1692 Mio t, respectively [1]. It is estimated that by 2020, about 12% of the worlds electricity will have been supplied by wind generation [2].

Electric power from the wind energy is different from the one obtained from conventional resources. Unpredictability and variability of the wind power generation are the fundamental difficulties that power system operators faced [3]. The ability to balance the power grid, i.e. to match the amount of generated energy with the consumed energy, is the main problem regarding this variability. Growing amount of the wind power sources creates significant pressure on the power system control [4–6]. A combination of predicting the wind speed and controlling other units of power generation, in such a

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Nomenclature

List of mathematical symbols

diam U the diameter of the set U.
$\mathcal{H}^s(F)$ the s-dimensional Hausdorff measure of the set F.
$\dim_H(F)$ the Hausdorff dimension of the set F.
$\dim_B(F)$ the box-counting dimension of the set F.
$f_{\lambda,s}(t)$ the Weierstrass function having parameters λ and s.

way that they carry the burden of balancing the grid, is one of possible solutions to this problem. This is the main reason for which the forecasting and modelling tools are being developed with the aim of the efficient reintegration of wind farms into the power system [7,8]. Especially, forecasting of the power generated by wind farms is taken into consideration [9–12].

However, the model of wind speed variability, introduced in [13,14] and briefly recalled in this paper, see Section 3, was created for quite other reasons. Studies showed that approximately 80% of all fractures were caused by machinery fatigue and only 20% by a static overload. That is why the studies concerning variability of operational conditions in wind turbines are crucial for their engineering. Therefore, modelling of the load of wind turbine gears for simulation of real varying operational conditions for modelling of the wind turbine vibration is the main goal of this paper. This is a crucial problem for the development of algorithms for fault detection which will operate successfully in the presence of large and random load changes. Such algorithms have important practical application because maintenance of the wind turbine generates the largest part of the cost of its operation [15]. A condition monitoring, first of all continuous monitoring of the drivetrain of wind turbines, is a common technique to decrease this cost [16–22]. Furthermore, condition monitoring of wind turbines, including fault diagnostics, especially at the early stage of a fault occurrence, is an essential problem in the wind turbines engineering in particular [18,23–25] and in rotating machinery engineering in general [26–32]. Development of condition monitoring systems requires validation of the applied algorithms for the fault detection. This can be accomplished by using the data from real faults or from test rigs. Such data are very difficult, or even impossible, to obtain and they cover only one or a few turbine types. In order to be able to collect practically unlimited amount of the seeded fault data one can develop a numerical drivetrain model, where it is possible to introduce one or more faults and various magnitudes. Using mathematical models for this task requires reconstruction of the real conditions in the model. Modelling of gearboxes and bearings is an important field and it has been investigated by many authors [33–37]. Behaviour of the drivetrain becomes much more complex when the machine is subjected to a varying load, as it is in the case of the wind turbines (and many others, e.g. open pit mining). Modelling of such a machinery was researched for a relatively short time, with significant contributions of [38–40]. Later, it has been followed by several other papers [41–45]. Analytical models for varying load require the function which generates the load, or torque, to the model. Therefore, the research has been focused on the software module which could act as a load generator to the drivetrain model.

The model of the chaotic variability of wind speed was proposed in [13,14]. The authors introduced the mathematical model which is capable of generating series of the wind speed. In order to develop fault detection and validate the methods of fault detection it is necessary to work out the adequate wind model which represents the most crucial components of the system input load. Such a model should be an integral part of a cybernetic model for wind turbine. We intended to increase the understanding of the wind variability. That was the reason why we did not use other – data driven – methods, like, for example, Markov chains, spectral analysis or simply feeding the recorded wind data into the mechanical drivetrain model [46,7].

The creation of the model of input load of wind turbines drivetrain and the implementation of the simulator of input load were the main goals of this paper. In order to apply the wind speed model to the model of the drivetrain load, the wind speed should be converted into the torque on the shaft. Since the model is intended to simulate the load of turbine gears, not of rotor blades, the wind speed is much more important parameter than its direction. Furthermore, modern wind turbines, including the ones from which we received the data for simulation, have wind direction sensors that control yaw drives. The sensors enable the turbines to orient automatically the blades perpendicular to wind direction. Additionally, it weakens the influence that the wind direction has on turbine gears. Therefore, we could neglect the wind direction in the model without loss of its utility.

The paper is organized in the following way. In Sections 2 and 3 the wind speed model, introduced in [13,14], is briefly recalled. The new results are presented in Section 4 which is the essential part of this paper. First of all, a module for generating wind speed values is described – see Section 4.1. Modules for converting wind speed values into a rotational speed and a torque, and generating drivetrain load are described in detail in Section 4.2. They are the second element of the introduced model of a chaotic load of the mechanical systems of wind turbines. The comparison of the results obtained from the introduced model with the measured loads is shown in Section 4.3. The discussion and conclusions are presented in Sections 5 and 6 respectively.

2. Wind speed model mathematical foundations

There are many examples of sets in $\mathbb{R}^n$ which have an irregular structure. The topological methods, however, are far insufficient to describe the irregular structure in detail. The fact that the topological dimensions [47] can be equal only to integral numbers or infinity is one of the important limitations. Such irregular sets are called fractals. Fractal dimensions, for which nonintegral values are permitted, are the basic tools that allow us to express the irregular set properties accurately. It should be mentioned that the idea of fractal dimension has nontrivial applications in the identification and the assessment of bearing degradation in rotating