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Subspace predictive repetitive control to mitigate periodic loads on large scale wind turbines

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ABSTRACT

Manufacturing and maintenance costs arising out of wind turbine dynamic loading are one of the largest bottlenecks in the roll-out of wind energy. Individual Pitch Control (IPC) is being researched for cost reduction through load alleviation; it poses a challenging mechatronic problem due to its multi-input, multi-output (MIMO) nature and actuation constraints related to the wear of pitch bearings. To address these issues, Subspace Predictive Repetitive Control (SPRC), a novel repetitive control strategy based on the subspace identification paradigm, is presented. First, the Markov parameters of the system are identified online in a recursive manner. These parameters are used to build up the lifted matrices needed to predict the output over the next period. From these matrices an adaptive repetitive control law is derived. To account for actuator limitations, the known shape of wind-induced disturbances is exploited to perform repetitive control in a reduced-dimension basis function subspace. The SPRC methodology is implemented on a high-fidelity numerical aeroelastic environment for wind turbines. Load reductions are achieved similar to those obtained with classical IPC approaches, while considerably limiting the frequency content of the actuator signals.

1. Introduction

In the past three decades, wind energy has shown exponential growth, reaching an installed capacity of 282 GW in 2012, capable of delivering 3% of the global electricity demand. As a clean, resource-efficient source of energy, wind power is viewed as a viable complement to the current energy mix, with more than a 100 countries actively investing in large-scale wind energy [1]. A majority of commercial wind turbines are multi-megawatt grid-connected machines, installed onshore. It is expected that offshore siting of wind farms will gain further momentum in the future, as this affords the opportunity to tap higher wind speeds and relaxes the constraints imposed by sites close to densely populated areas. However, one of the main roadblocks to offshore wind energy development is the high capital cost associated with the design of a mechanical system able to withstand severe dynamic loading, of the order of 10^8 to 10^9 loading cycles, significantly higher than any other commercially produced mechanical component [2]. Further, the relative inaccessibility of the offshore environment exacerbates repair and maintenance issues.

Turbines are today instrumented with a variety of sensors and new actuators; thus mechatronics and control engineering form an integral part of wind turbine design. The highly coupled aerodynamic-structural interactions and the electromechanical conversion to grid-quality electrical energy requires sophisticated control strategies and the use of the latest advances in sensor and power electronics. One of the first comprehensive analyses of this mechatronic and control problem [3], highlights the need for optimal multivariable control design of modern wind turbines for load reduction and controller validation on high-fidelity simulators.

For load control, individual pitch control (IPC) is perhaps one of the most interesting and readily implementable extensions to the basic controller [4]. In recent literature, PI (proportional-integral) control has been used for implementing IPC on prototypes. However, since the system is periodic and multi-input, multi-output (MIMO) in nature, it is difficult to achieve the precise control within narrow frequency bands typically seen in wind turbine loads. Although important improvements have been made, at present the control techniques do not exploit the periodic nature of the disturbances. Hence, current control techniques cannot achieve the

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limits of performance, and require a significant amount of control effort across a broad spectrum of frequencies.

In control engineering literature, several high-performance approaches have been developed to specifically target periodic disturbances. Learning control, of the form first introduced in [5], achieves asymptotic rejection of periodic disturbances by “learning”, in real-time, the ideal feedforward control input sequence thereto. The term “Iterative Learning Control (ILC)” is used to designate those learning control problems where the initial conditions are reset at the end of each period, while “Repetitive Control (RC)” is used to designate those problems where the final conditions of the previous period are the initial conditions of the current period. Since a wind turbine does not undergo initial condition resets, load reduction forms an RC problem, but the two methodologies are very closely related. The survey paper [6] reviews the different approaches towards designing ILC controllers, and delineates conditions for satisfying the stability, performance and robustness criteria. ILC control has been shown to achieve performance superior to that of a traditional 2-DoF controller in tracking applications [7]. The use of ILC for vibration rejection of flexible structures using Hankel matrices has been shown in [8], with excellent potential for online adaptive control. The receding horizon principle of Model Predictive Control (MPC) has been combined with RC in [9] to obtain a predictive-repetitive controller capable of handling constraints. It should be noted, however, that all the RC methods mentioned above are model-based and cannot be directly applied to an unknown plant.

For the current application, model-based RC has been simulated in [10], specifically to target all periodic loads with a single control loop. It can easily deal with the MIMO problem with a transparent LQR formulation. RC design involves recursively optimising the lifted control input; for many systems this has a very high dimensionality. To robustify the performance of the RC, the dimensionality can be reduced by projecting the control input onto a basis function subspace, chosen such that the basis vector directions capture a large amount of energy content of the periodic disturbance [11,12]. In [13], load reduction was achieved by using RC with sinusoidal basis functions, on a scaled prototype wind turbine in a real-time wind tunnel experiment. Here, instead of using pitch actuation, active flaps located on the blades were used to control the aerodynamic flow and thereby achieve load reduction. As the number of actuators available for control increases, state-of-the-art decoupled PI controllers can no longer provide optimal control inputs, and a true MIMO strategy, like RC, seems to be necessary. However, in all the above cases, the RC control law was derived based on the assumption that the plant model is available and is perfectly LTI.

Although RC controllers can be substantially robust to model uncertainties, it may prove difficult in practical cases to arrive at an approximate system model of a wind turbine. Aerodynamic control authority is a strong function of mean free stream wind speed, a slowly varying environmental parameter, which currently cannot be reliably measured or estimated in wind turbines. Wind turbine dynamics also depend on turbine location and manufacturing discrepancies (e.g. rotor imbalance), and are hence unique to each turbine. So, an adaptive control strategy which is able to identify wind turbine dynamics online, would be most suitable for IPC.

Different adaptive methods have been explored for combining learning control with online identification. In [14], the concept of basis functions optimised for the unknown system directly from input–output data is introduced. In [15], offline system identification is done in the basis function domain and applied to a robotic arm for ILC position control. However, there has thus far not been a formalised combination of online system identification and learning control that would be amenable to further analysis as a fully adaptive control law.

Subspace identification, described in [16] can be readily adapted for online system identification of engineering systems in both open- and closed-loop settings. As introduced in [17], subspace identification can be integrated with receding horizon predictive control to achieve model-less online adaptive control; this control technique is called Subspace Predictive Control (SPC). This has been applied to aeroelastic vibration control of wind turbines in [18], and appears to be directly extendable to incorporate RC for suppressing periodic disturbances.

The key contribution of this paper is a novel RC approach that utilises online system identification to form an adaptive control law for periodic disturbances, the so-called “Subspace Predictive Repetitive Controller” (SPRC). This controller is formulated to asymptotically suppress the dominant periodic loads in the turbine, as per RC theory. Further, basis functions are used to enable tight control over the shape of the actuator signals, a significant advantage for limiting actuator stress. The integration with online system identification ensures that controller performance can be maximised irrespective of variations or variability in the dynamics of the wind turbine system. The validity of this approach is proved by application to the highly complex wind turbine mechatronic system, tested in a high fidelity numerical environment. As a predictive-repetitive scheme, SPRC can be directly extended to include constraints, however this has not been explored in the current paper.

The outline of the paper is as follows: in Section 2 the background for IPC is explained and the simulation environment is described. In Section 3 the methodology of SPRC is introduced. In Section 4, the results are presented, and conclusions drawn from these results will be discussed in Section 5.

2. Control of wind turbines

A modern wind turbine is a large-scale mechatronic system, with a complex interplay between actuating and power transfer mechanisms, the electrical drives and the control electronics. The main components relevant from the perspective of dynamic load alleviation are described below [19]:

- *Rotor* – The rotor consists of a hub supporting up to three blades, free to rotate on a horizontal axis. Aerodynamic torque is generated by wind flowing through the rotor disc.
- *Transmission* – The rotation of the rotor is transmitted by the main shaft, supported on the main bearings, to the generator located in the housing (nacelle) of the turbine. A gearbox may be used to change the speed of rotation if required.
- *Generator* – The generator converts the rotation of the output shaft into electrical energy. The generated electricity is then conditioned by a converter and a transformer to make it suitable for grid upload.
- *Support Structure* – This includes the tower and all other structural elements required to support the nacelle and the rotor, and withstand the loading over the lifetime of the wind turbine, typically taken to be 20 years.

These components can be seen in Fig. 1, which shows the prototype turbine XEMC-Darwind XD115 in full and cross-sectional views. This testing prototype has been constructed at Wieringerwerf in the Netherlands. A high-fidelity model of this turbine will be considered as our test bench in the rest of the paper.

The operation of a wind turbine is divided into two regions: the region where the wind speed is below the rated wind speed of the turbine, and the region where it is above the rated wind speed. In the below-rated region, the wind turbine is expected to maximise the energy that can be extracted from the air stream. In the