Modern wind turbine controller design

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Abstract The ECN Control Design Tool (CDT) is used to design wind turbine feedback control algorithms. Due to its automated code generation it combines high level development with seamless integration with aero-elastic codes and PLC hardware. TURBU greatly enhances the range of controllers that can be developed with the CDT (like individual pitch and vibration damping) by providing linearized, complete aero- and hydro-dynamic turbine models. Both software tools are implemented in Matlab/Simulink and distributed as open source.

Key words Wind turbine control, Aero-elastic modeling, Load reduction

1. Introduction

Current trends in the wind turbine market show an ever increasing turbine size as well as a growing interest in off-shore farms. These developments call for a greater emphasis on control design aimed at load reduction and robust operation. Balancing these requirements against power production demands an integrated assessment of control and aero-elastic stability. Furthermore, as turbines are often designed for specific site conditions, this balancing problem does not have a generic solution.

To increase the level of knowledge in the wind turbine industry and research centres on these subjects, the non-profit organisation ECN developed two software tools: the ECN Control Design Tool (CDT) and TURBU. They demystify the control design process and facilitate the optimization of a modern wind turbine controller.

In this paper the ECN control design software is presented. Section 2 gives an overview of the CDT. In section 3 TURBU is introduced. Finally, section 4 outlines the current highlights and development.

2. Control Design Tool

This section describes the function of the CDT and its connection to other aero-elastic code.

2.1. Control problem and approach

The Control Design Tool [1] is used to design a controller for modern, large wind turbines. This means it targets horizontal axis, variable speed, active pitch to vane regulated turbines. The controller contains the feedback algorithms for pitch and generator actuation. Their main purpose is to control the rotor speed and power production respectively.

Additionally, the control actions can be used for active damping of resonances. E.g. the generator torque may also be used to damp drive train vibration and lateral tower displacement. This control problem is multivariable in nature, because a contribution to the control output aimed at damping a phenomenon influences the main control goal. However, from a design point of view it is undesirable that the frequency ranges involved overlap. This makes it possible to separate these phenomena by applying turbine-specific filters to the measured signals (especially rotor speed). The advantage is that the control problem is split up into several simple, physically interpretable control loops that can be designed individually.

2.2. Control design process

Controller design with the CDT is a three-stage process. The first stage is the controller synthesis. In this stage user input is converted into control parameters. The second stage is frequency-domain analysis, followed by the last stage: time-domain evaluation. The process is not sequential, meaning that it is possible to start time-domain evaluation with only a minimal amount of synthesis complete. This allows for short design iterations right from the start of the design. Figure 1 gives a global overview of the whole controller design process.

The synthesis and analysis stage are completely implemented in Matlab® (using the Control System Toolbox™ and Signal Processing Toolbox™). The evaluation stage is performed in Simulink®. All of which are products from The Mathworks™, a well established industry standard.

Synthesis

This design stage comprises the modelling of the turbine, wind and aerodynamic effects as well as the calculation of all control parameters. The end result is a fully parameterized controller and turbine model. The latter is used for the time-domain evaluation.

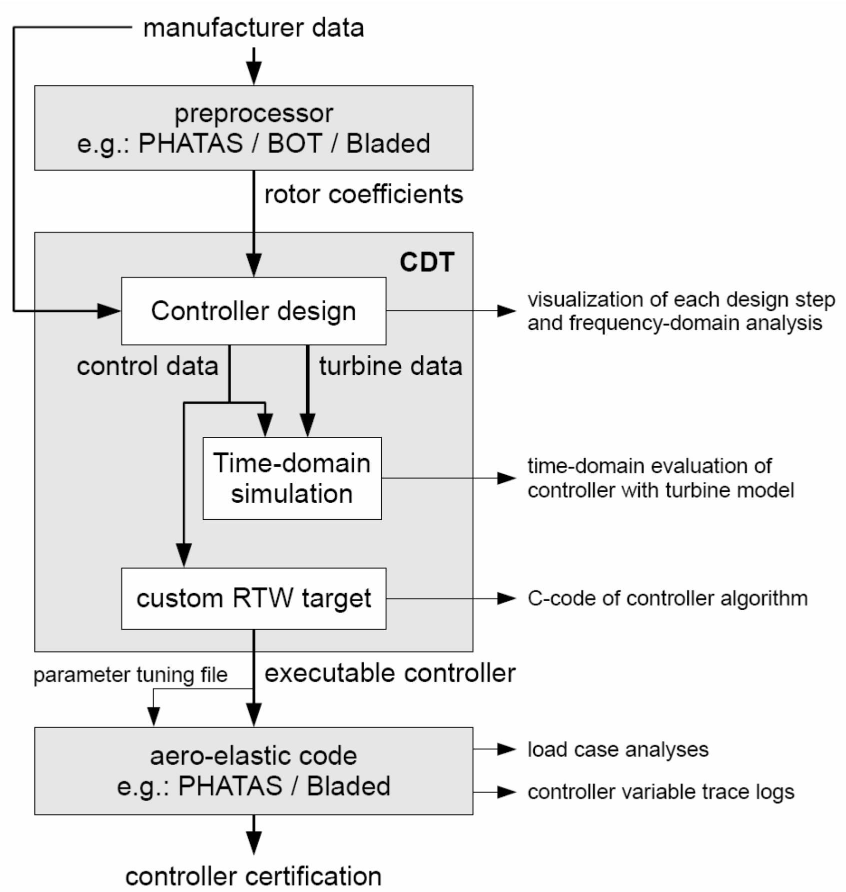

Figure 1: Overview of the CDT work flow (left) and information output (right)

The basis for the design consists of a list of turbine specifications and controller settings. Besides these, the CDT requires the input of rotor coefficients tables. The power and thrust coefficients describe the aerodynamic behaviour of the rotor (at various pitch angles and tip speed ratios). These tables are calculated by a pre-processor, based on the rotor blade design. ECN provides two tools that can be used as a pre-processor: PHATAS [2] and the Bladed Optimization Tool (BOT) [3]. An example of external tools that may be used as a pre-processor is GH Bladed.

The synthesis stage is built in a modular fashion. Some modules are optional. The major modules deal with the topics below.

Model parameterization:

- stochastic turbulence effective wind generation
- rotor aerodynamics and dynamic inflow effect
- first bending mode of the tower and first torsion mode of the drive-train
- generator torque servo behaviour and pitch actuation (including friction)
- delay and quantization effects of measurements

Controller parameterization:

- gain scheduled rotor speed control with setpoint adaptation
- low pass and band pass filter design
- generator torque/speed operation and dynamic shifting thereof [4]
- tower resonance bridging [5]
- smooth transitions between partial load and full load operation
- non-linear estimated wind speed feed-forward control [6]
- dynamic inflow compensation [7]
- drive-train damping
- adaptation of filters and control parameters for turbine commissioning

The modular approach provides a good overview of the design process. It is convenient to locate, study and modify functionality. And thanks to the well-structured data management even the addition of new modules is easy.

Once the CDT is started, it runs through the calculations of all modules automatically, producing graphical output of the intermediate results for each module. These visualizations provide the control engineer with insightful information as the design advances.

Analysis

In order to allow for input and model uncertainty, assessment of the robustness of the controller design is required. Therefore, stability analysis is a vital part of the CDT.

In the analysis stage open loop transfer functions are generated for the integrated model of the controller and wind turbine. This is achieved by linearization of the non-linear model in many turbine operating points. The non-linear model that is used for linearization of the full-load controller is depicted in figure 2. The frequency-domain analysis consists of calculating the frequency response of the cascade of controllers and linear models in the set of operating points. As is common in the industry, the results are presented as a Nyquist diagram.

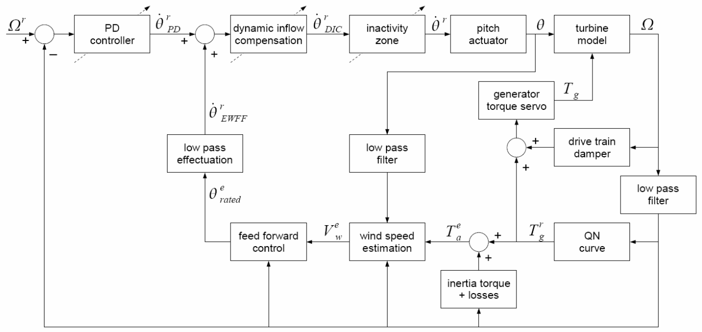

Figure 2: Full load controller schematic. Superscript ‘r’ and ‘e’ designate reference and estimated values respectively. An arrow indicates that a function block is scheduled (using at least the pitch angle as a scheduling variable).

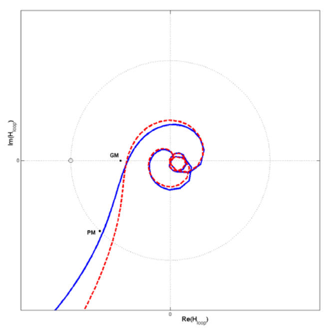

Figure 3: Nyquist diagram showing stability without (solid) and with (dashed) EWFF control enabled.

A particularly useful feature is that many control loops and effects can be disabled to observe their influence on the stability, as illustrated in figure 3 for a single operating point. The trained eye immediately makes out that the estimated wind speed feed forward (EWFF) control has a significant positive effect on the phase margin (PM) at the expense of a marginal reduction of the gain margin (GM).

Evaluation

The CDT offers a highly flexible and fast simulation environment for comfortable time-domain evaluation of the controller performance. Wind speed input can be selected from a range of predefined deterministic and stochastic profiles or defined by the user. Both the wind turbine model and control algorithms are implemented in a hierarchical, graphical structure, making it convenient to analyse or modify a certain part of the controller.

Time series can be generated for any turbine or controller variable. They provide invaluable insight into the real-world performance of the controller. Many parameters can be tuned in the simulation without the need to redesign the controller.

Figure 4 visualizes the combination of time series from two simulation runs using the same wind speed profile. It compares the performance of the ‘standard’ controller to a controller that anticipates wind gusts. It can be seen that in the onset of the gust the anticipation algorithm achieves a reduction in rotor over-speed and maximum pitch rate at the expense of some generated power and a slightly longer pitch activity.

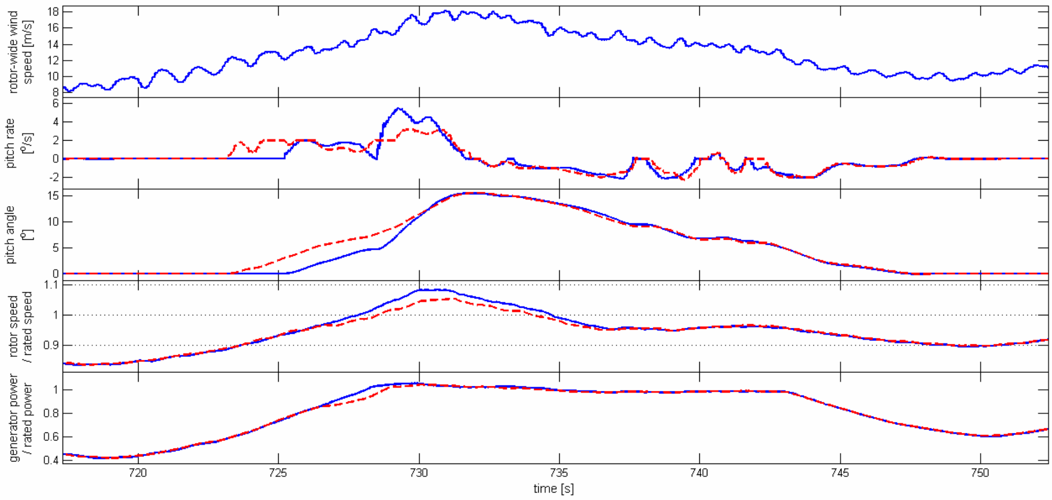

Figure 4: Time series showing a ‘normal’ partial load to full load transition (solid) and a gust anticipation algorithm (dashed)

2.3. Code export

One major advantage of having the control structure implemented in Simulink is that it enables the use of Real-Time Workshop® (RTW) for automatic code generation. RTW translates the Simulink model to C-code, allowing it to be implemented on most controller hardware.

The CDT furthermore supplies custom targets for RTW, resulting in automatically generated executable controller code (in the form of a dynamic link library) for seamless integration with aero-elastic codes. Currently PHATAS and GH Bladed are supported. The executable controller can still be tuned using an auto-generated parameter file. Also, Matlab format data files may be generated during the aero-dynamic simulations, enabling extensive logging of the controller variables.

Another advantage of the Simulink implementation is that it is an attractive open standard for third party vendors. Companies like Bachmann provide software for auto-generating a PLC task directly from the Simulink model.

2.4. Current development

The currently distributed CDT targets collective blade pitch designs only. However, with the ever increasing size of wind turbines, load reduction techniques are receiving a lot of attention. One of the more promising techniques is individual blade pitching.

ECN has developed individual pitch control (IPC) algorithms and reworked the stochastic wind generation to support per-blade wind signals. Besides this, in order to model the phenomena and observe the effect of control actions involved with load reduction, a much more sophisticated aero-elastic turbine model is required. To meet this end, TURBU [8] was developed.

3. TURBU

To the CDT, TURBU is a multi-body modelling tool that provides *linear wind turbine models* capable of capturing the structural dynamics required for developing IPC algorithms. But it is much more than that.

The TURBU code was developed to allow for the analysis of advanced control algorithms on complex wind turbine models. It does so by producing full aero- and hydro-elastic models of the turbine that are linearized around the average deformed state; these models are driven by wind, waves, gravity and actuator signals. They will be used in the CDT to generate transfer functions for the frequency-domain analysis of the control loops. The models will also be used in the time-domain evaluation of the controller.

Since TURBU provides linear models, the calculations are very fast, which is ideal for scoping simulations. Moreover, TURBU is completely implemented in Matlab, which allows for seamless interoperability with the CDT.

Besides its symbiotic link to the CDT, the fast computation that its models allow gives rise to other applications, such as fatigue scoping, power spectra production and analysis of aero-elastic stability.

4. Advantages and development

The CDT and TURBU have been under active development for many years as in-house tools, but only made commercially available in 2007 and 2008 respectively.

Key advantages

The CDT can be offered together with a two-week course aimed at knowledge transfer, rather than software training. Using Matlab and Simulink for the implementation of our knowledge, allows our customers to tap into existing user experience, as control engineers are often familiar with the products from The Mathworks. These tools emphasize on productivity and flexibility, combining high level development with effortless translation to low level implementation.

What really sets the CDT and TURBU apart is the fact that all software is provided as *open source* Matlab and Simulink code. This gives customers the opportunity to fully understand and extend both the design tools as well as the control algorithms. And because Matlab can be run on several platforms, so can the CDT. This includes code generation and even running aero-elastic simulations with PHATAS on Windows® and Linux®.

The architecture of the CDT is designed to give early feedback on the design progress. This allows for short design iterations, so most of the design issues can be dealt with before relatively slow aero-elastic calculations are needed. And although the CDT was never optimized for speed, the use of aerodynamic tables, a rotor-wide wind signal and simple turbine model allow very fast redesigns. On average hardware a complete redesign will take around ten seconds, simulations run over fifty times real-time and a code export including compilation is performed within a minute.

The CDT and TURBU have been sold to several manufacturers and knowledge institutes worldwide. The controllers designed by the CDT have been implemented in several megawatt-class wind turbines. The CDT has been extensively validated by non-linear simulations with the authorised aero-elastic code PHATAS.

Current development

Apart from the process of integrating TURBU and existing IPC algorithms into the CDT, current development is aimed at two areas: IPC for damping of higher order blade vibration modes and damping of lateral tower vibration. The latter is of special interest for off-shore turbines where waves can hit the tower from different direction than the wind.

TURBU is currently being applied in the research of distributed blade control (each blade having multiple actuators along its span). It is also being coupled to aero-dynamics software for fast scoping simulations.

Conclusion

The CDT is a proven tool for developing production quality wind turbine controllers. Thanks to its high level, open source implementation, it is also a strong education and development platform. It allows the engineer to fully understand and support the controller and implement novel control concepts.

The CDT provides feedback to the engineer at several stages during the design, resulting in short design iterations. And when aero-elastic calculations are needed for optimization, no time is wasted thanks to the automated code export options.

TURBU is a unique tool that combines state-of-the-art aerodynamic and structural mechanic modelling with the possibility to extract linear models aimed at control analysis. In time-domain TURBU models achieve much faster simulation than non-linear aero-elastic codes; in frequency-domain the analysis options are unprecedented.

Acknowledgement

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