

Control Design Toolbox for Large-Scale PRVS Wind Turbines

Sergio Dominguez and Prof. W.E. Leithead

Abstract—The trend towards large multi-MW wind turbines has given new impetus to the development of wind turbine controllers. Additional objectives are being placed on the controller making the specification of the control system more complex. A new toolbox, which assists with most of the control design cycle, has been developed. Its purpose is to assist and guide the control system designer through the design cycle, thereby enabling faster design. With the choice of control strategy unrestricted, the toolbox is sufficiently flexible to support the design process for the aforementioned more complex specifications.

Keywords: Fatigue loads, feedback, control, pitch, fundamental limitations, right half-plane zeros, time delay, bandwidth

I. INTRODUCTION

In recent years, with the trend towards large multi-MW wind turbines, the role of the control system, and so its design, has become increasingly important. The realisation, that not only the performance of the machine but also the optimisation of the structural design depends on the controller has given research into the control of wind turbines a new impetus as is evident from the recent increase in publications addressing this issue. The extension of the role of the controller to alleviate structural loads has motivated the exploration of novel control strategies, which seek to maximise load alleviation by exploiting the blade pitch system. Wind turbine controllers are consequently attaining a degree of complexity such that advanced control methods are required. The design of the controller for a wind turbine is no longer a simple task that can be carried out by a non-specialist. The range of existing machines, for instance the variation in the drivetrain characteristics, has the consequence that the controller must be tailored for the specific machine being considered if maximum performance and load alleviation are to be achieved. It is no longer advisable to adopt a particular controller and then tune it for different machines. The direct relationship between the dynamics of the machines and the dynamics of the controller and the effect the latter can have in modifying the former, implies that control should be an integral part of the design process of a wind turbine from its earliest stage. The purpose of this paper is not to discuss a general controller for wind turbines, but to introduce a toolbox that enables the control designers within the wind turbine manufacturers to optimise their task.

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The design of a control algorithm has four stages; construction of suitable dynamic models of the wind turbine, design of the set of controllers required to cover the operational envelope, determination of a suitable realisation that addresses the implementation issues (including the non-linear aspects) and evaluation and performance assessment of the controller. The design cycle is thus extensive and includes several well-defined stages for which different specific skills are required. At the University of Strathclyde, in collaboration with the Kelvin Institute (KI), a new toolset has been developed which assists with three of the above stages of control design. Incorporating a particular implementation structure for the controller, the Control Design Toolbox guides the control designer through the following aspects: the construction of dynamic models for a particular wind turbine using generic models requiring only the assignment of suitable physical parameter values; the design of the set of linear controllers over the operational envelope with sufficient flexibility to cater for any control strategy that the designer might choose; the interfacing with some of the most commonly-used wind turbine simulation packages to facilitate rapid prototyping and tuning of the controller.

The organisation of this paper follows the aforementioned stages of the control design process: Section II describes the model embedded in the Control Design Tools©(CDT); Section III defines the facilities of the CDT related to the design of the linear controllers for the different operating modes; Section IV deals with the non-linear design aspects of the controller; Section V describes the set of tools dealing with controller implementation issues and the implementation of the controller in programmable form and its debugging; Section VI discusses the tools which interface with the aero-elastic packages on which the controller performance might be evaluated and the post-processing capabilities included for this purpose; lastly, Section VII draws some conclusions from this paper and outlines some future research lines.

II. MODELLING

For control analysis and design purposes three different dynamic models of the system under consideration are required, namely, the simulation model, the linearisation of the simulation model and the control model. The simulation model includes all the relevant dynamic aspects of the wind turbine. The simulation model is non-linear and constructed such that its parameters correspond to physical parameters of the wind turbine. This makes the parametrisation of the model relatively straight forward requiring little effort from the user. In particular, all the parameters included in the control simulation model have a counterpart in the

parameter files used for FLEX¹ and Bladed², which makes the construction of the simulation model straight-forward when one of these models is available. The simulation model assists with solving the non-linear aspects of the controller implementation. It serves as a test-bed for controller designs. In addition, the simulation model enables the sensitivity and dependence of dynamic behaviour on physical parameters to be investigated. It, thus, supports a more complete investigation of the control design task and enables greater insight and understanding of it to be developed. Nevertheless, a rule of parsimony must be maintained since the analysis of non-linear systems becomes increasingly difficult the more detailed they become.

The simulation model for a wind turbine has a very different role to a full aero-elastic package. Only those aspects of the structural dynamics of direct relevance to the control system design task are included. For example, it can not be used to assess the fatigue of components absolutely. When the control specification includes a fatigue aspect, only a relative assessment is required or practical. Hence, only basic models of the relevant dynamics are used. The controller design process is often iterative involving the investigation of several candidate designs. Once this process nears completion, a fuller assessment using a detailed aero-elastic model becomes appropriate and necessary.

As alluded to above, the analysis of a non-linear dynamic system is not easy. The linearisation of the control simulation model is employed to assist with this analysis. It consists of a set of linear dynamic models, each valid in the neighbourhood of some operating point. They provide a bridge between the simulation model and the control model.

III. LINEAR DESIGN

A. System Identification

A fundamental part of the modelling process is the validation of the model against the real system. However, this is a difficult and laborious process for which, in the context of validating the models for a real wind turbine, there is as yet no clear procedure. The KI, building on previous experience of wind turbine System Identification, see [1], has developed a procedure for system identification based on FLEX and Bladed. The models embedded in the CDT can, thus, be adjusted to be a very accurate representation of the models included in these two widely accepted aero-elastic simulation packages. The procedure exploits frequency-domain system identification methods [2]. Although it has currently only been applied to the afore-mentioned aero-elastic packages, there is no *a priori* reason why it should not be applied to a real machine. Some identification results are shown in Figures 1 and 2, which depict the dynamics from pitch angle to tower speed and generator speed obtained from both the

linear models and from applying the system identification procedure to the aero-elastic packages. The close agreement is clear.

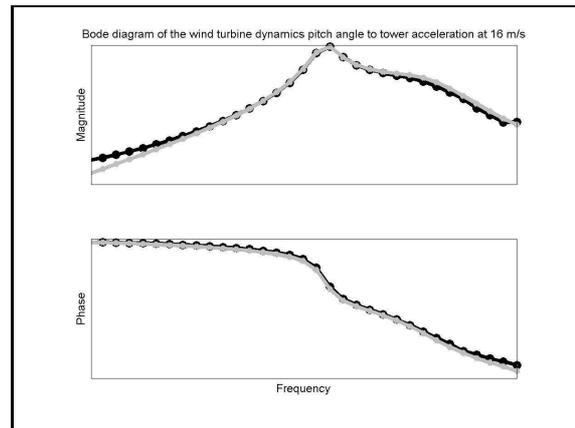


Fig. 1. Comparison of the dynamics from pitch angle to tower speed for the identified FLEX dynamics and the CDT linear model

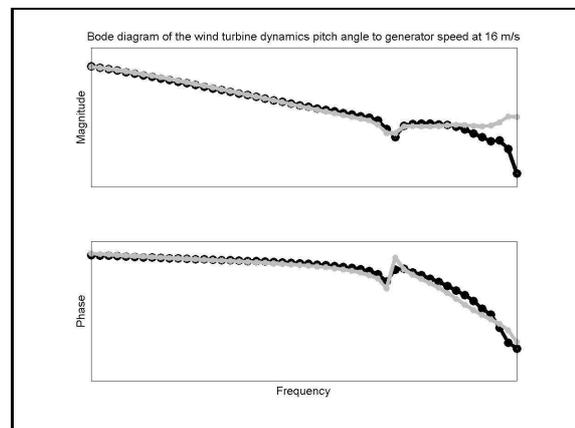


Fig. 2. Comparison of the dynamics from pitch angle to generator speed for the identified FLEX dynamics and the CDT linear model

B. Fatigue estimation via linear transfer functions

Fatigue load calculations are a fundamental part of the design of any wind turbine, especially for the off-shore, multi-MegaWatt market, for which the fatigue loads are generally accepted to be a design driver. Although there are several methods for estimating fatigue loads, rain-flow counting is widely used and achieves good results [3]. Obtaining fatigue estimations via rain-flow counting is, however, time-consuming involving the simulation of a full set of load cases. When tuning a controller for fatigue reduction this process must be repeated until the fatigue reduction results have been optimised. From a control viewpoint, it would be much more convenient to have frequency domain methods for fatigue estimation. However, although these methods are used in other fields, see for example [4], [5], and some specific procedures have been developed for the wind turbine context, see [6], fatigue estimation for wind turbines has

¹FLEX is an aero-elastic package developed at Delft University and is one of the most widely used packages used for wind turbine design and evaluation

²Bladed is an aero-elastic package developed at Garrad-Hassan and is one of the most widely used packages used for wind turbine design and evaluation

certain characteristics that reduce the effectiveness of these methods.

It is well known that the integral of the power spectral density (PSD) provides a rough estimate of fatigue [7], [8], which, while not providing accurate estimates of absolute fatigue damage, is quite useful in assessing the relative influence of different controllers on fatigue. If a frequency domain signal is the product of a transfer function times another frequency domain signal, then the PSD for the first signal, is the PSD for the second signal scaled by the squared magnitude of the transfer function; that is, for the situation depicted in Figure 3, the spectra are related by

$$S_y = |G(j\omega)|^2 \cdot S_x \quad (1)$$

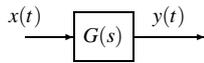


Fig. 3. Block diagram including disturbances

The frequency domain output for a closed-loop system is the frequency domain output for the open-loop system scaled by a transfer function; for example, when a feedback loop is used to actively regulate tower loads, the tower speed is modified by the tower feedback loop sensitivity function, see Figure 4.

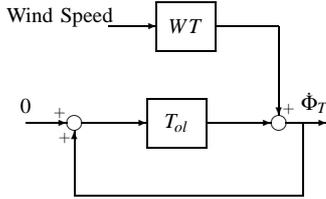


Fig. 4. Block diagram including disturbances

This simple rescaling of PSDs can be exploited to provide quick and direct estimates of loads arising from different controllers, e.g. the tower loads, and thereby, assist controller tuning. This procedure is included and automated in the CDT having proved in practice to be a good guide to controller tuning.

C. Estimation of RMS values of output variables

Parseval's Theorem [9] states that the integral of the PSD of a frequency domain signal is equal to the variance of the corresponding time domain signal. Hence, when the spectral density function is available, an estimate of the variance of the corresponding time domain signal can be determined by following the above procedure; for example, the variance for the generator speed or electrical power obtained by a particular controller. Once again, these estimates are not to be used as absolute measures of performance, but as relative measures. This procedure is also included and automated in the CDT .

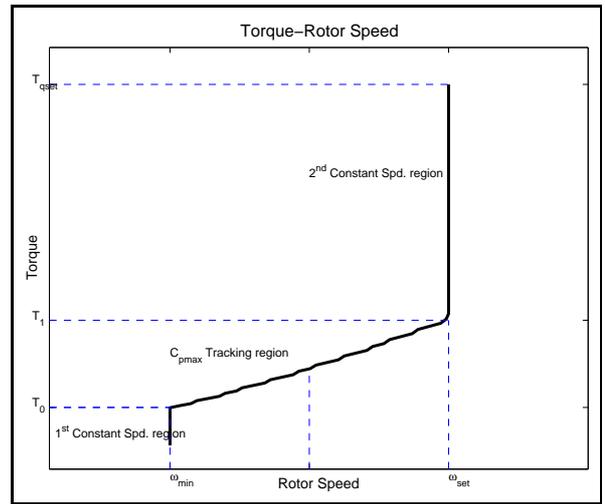


Fig. 5. Below rated classical strategy

D. Control Limitations

As previously reported, see [10], the achievable closed-loop bandwidth of the pitch control algorithm becomes more restricted as the size of the wind turbine increases. These unavoidable restrictions are due to the presence of right half-plane zeros in the dynamics connecting generator speed to pitch angle. In [10], a procedure for estimating the maximum achievable bandwidth for any particular wind turbine is developed. This procedure has been included within the CDT . Because it requires only a small number of physical parameters, the procedure provides useful guidance regarding the controller performance at an early stage of the design cycle.

E. Linear Controller Design

The availability of linear models obviously facilitates the design of linear controllers. Assuming that the non-linear aspects and implementation issues are resolved through the realisation adopted for the controller, only local linear controllers for a specific set of wind speeds remain to be designed. The design of these local linear controllers can then be addressed without further reference to the wind turbine context. In general, the individual controllers for wind turbines are quite low order, and in most cases a simple PI controller, in combination with some filters to mitigate particular frequency related features, is effective. Consequently, the design of the linear aspects of the controller tends to be straightforward. A generic realisation for the controller, that resolves the non-linear aspects and implementation issues, is incorporated within the Integrated Control Platform (ICP) described below.

The linear design process for the controller is supported in the CDT by the inclusion of a dedicated linear control design interface to MATLAB and the wind turbine control models. This interface permits a flexible choice of controller structure, thereby, avoiding unnecessary restrictions on controller design. A snapshot of the linear control design interface included in the CDT is depicted in Figure 6. When defining the

control system feedback structure, a comprehensive choice of plant input and output variables is available through the GUI with the individual control elements entered using the dialogue boxes to the left of Figure 6. The usual control design and analysis options are available, open and closed-loop analysis, sensitivity analysis, frequency domain plots, time domain plots, etc: all options are readily accessible from the Control Design GUI for any combination of control system inputs and outputs that might be of interest. When designing the individual control elements, the modification to the open loop dynamics, that would arise from changes to the controller parameters, can be explored through an interactive menu with a pole/zero drag-and-drop facility.

IV. NON-LINEAR DESIGN

A. Gain scheduling

In above rated conditions, when the wind turbine is being pitch controlled, the aerodynamic torque can be separated into two components. The first component is a function of the wind speed and the second is a function of the blade pitch angle and rotor speed. This separation enables a global linearisation of the aerodynamic non-linearity by means of a non-linear gain in the controller independent of wind speed. A linear control design undertaken at a specific wind speed is, thereby, valid for all above rated wind speeds.

The CDT includes a tool that, given the wind turbine plant dynamics for the different wind speeds, determines the above linearising non-linear gain. Assuming that the controller maintains an almost constant rotor speed in above rated conditions, the dependence of this gain on rotor speed can be ignored. Its inclusion in the controller is, formally at least, very similar to classical gain scheduling yet is globally linearising. Nevertheless, it is not sufficient just to include this linearising gain in the controller. Its location is important to ensure accurate compensation of the non-linear dynamics of the rotor. Moving its position can cause a marked deterioration in performance. The linearising gain is correctly implemented within the ICP to ensure precise cancellation of the non-linearity over the whole above rated operating range, thereby preserving the relevance of the linear analysis.

B. Operational curves

A fundamental aspect of the control design task is the choice of operational strategy for the wind turbine. The chosen strategy in essence defines the overall control objective; that is, the controller must cause the wind turbine to follow the strategy. The most typical operational strategy for PRVS machines, at which this tool is directed, is similar to that depicted in Figure 5. This simple strategy is currently standard in the industry and its description can be found in a number of sources, see for example [11]. However, modified versions of it are extant such as the reduction in the controller set-point at high wind speeds.

As seen from Figure 5, the operational strategy can be defined with respect to the set of switching points in the torque-speed plane. Outcomes that arise directly from the definition of this strategy are the ideal power curve for the

wind turbine, the steady state operating points and loads and the energy capture that is, of course, dependent on the site wind speed distribution. The CDT incorporates this basic strategy as the default strategy but it can be modified when required. It is straightforward to input all the parameters necessary to specify the operational strategy and obtain the corresponding outcomes. The outcomes are made available during system performance analysis, Section VI, to enable automatic comparison of these theoretical measures of performance to those obtained from evaluating the performance of the controller by means of the aero-elastic packages.

C. Annual Power and Energy Capture curves

Given the wind turbine aerodynamic characteristics, the operational strategy and the wind distribution of the site at which the machine is located, the nominal annual power and energy capture curves to benchmark the controller performance are readily obtained using the CDT. The post-processing analysis capability to provide comparable results from the aero-elastic packages simulations is discussed in Section VI.

D. Switching

The simulation model supports the implementation and rapid testing of different switching strategies. Measurement of the performance of different switching strategies is not trivial. Within the CDT two measures of performance are used, the ITSE and the ITE. These two measures of performance measure the speed at which the controlled system attains steady state in response to a step change. Therefore, in order to measure switching performance, the system must be subject to a wind speed step input that causes a change in operating region of the wind turbine, e.g. from below rated to above rated. Whereas the ITSE penalises more the long term deviations from the equilibrium state, the ITE penalises more the initial overshoots. Hence, a trade-off between both measures of performance might be necessary on a case-by-case scenario basis. The traditional form of these measures, widely used in the control literature to measure switching systems, need a small adjustment to work in this context due to the controllers for the wind turbine being type 1.

V. IMPLEMENTATION

A. Integrated controller platform

Ideally, the non-linear and linear design aspects of the wind turbine controller would be undertaken separately. To achieve this, one approach is to make use of a platform within which generic solutions to the non-linear design issues, that render the wind turbine control difficult (gain-scheduling, switching and rate constraints), are embedded. The individual linear controllers would be designed independently for insertion into the platform without any contingencies, in particular, without loss of performance from unexpected interactions. Just such a platform is the integrated controller platform (ICP) developed by the KI. It is integrated into the CDT. The ICP is sufficiently flexible to accommodate a broad range of wind turbines and operating strategies. These solutions to the non-linear design issues are clearly dependent on

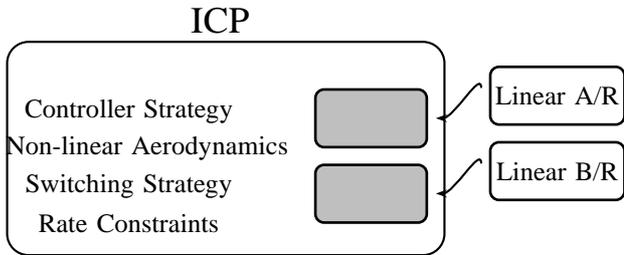


Fig. 7. Integrated controller platform

the control strategy, which is an input into the ICP, see Section IV-B. Once the wind turbine details and the operating strategy are specified, the individual linear controllers for the different operating regions, can be determined using the Control Design GUI, see III-E. These linear controllers are external inputs to the ICP, see Figure 7, and can be designed independently using any preferred design tool.

B. Implementation aids

Once the controller is fully designed within the context of the CDT the final step is to fully test it in an aero-elastic environment. These environments normally permit simulation with the controller implemented externally in *.dll* form or coded in a programming language of choice. In order to ease the transition from the Simulink [12] development environment to the aero-elastic environment³, the CDT enables direct testing of the code for the controller under Simulink using a MATLAB [14] *s-function*. It can thereby be checked that the implementation of the controller in code produces the same results as the implementation in Simulink blocks.⁴

VI. PERFORMANCE AND POST-PROCESSING

A. Rain-flow counting

As mentioned before, the rain-flow counting algorithm is generally recognised to provide the best estimates of fatigue damage. A MATLAB rain-flow counting algorithm running based on the WAFO, see [15], is included in the CDT giving the capability not only of estimating the life-time fatigue damage from a given simulation, but of comparing the percentage reduction in fatigue from running the simulation with different controllers or configurations of the wind turbine. Estimates of the contribution of every wind speed to the overall fatigue damage are also provided.

B. Level-crossing/binning

When dimensioning gearboxes, fatigue is not the main driver. Rather it is the time the input torque to the gearbox stays at the different load levels. A tool to quickly analyse the input loads to the gearbox and, therefore, give a first estimate of the effect of different controllers on the gearbox, is available within the CDT .

³MATLAB Real Time Workshop enables automatic code generation from Simulink models [13]

⁴An interface to have the controller in Simulink running under the aero-elastic packages FLEX and BLADED is under development, although not fully functional

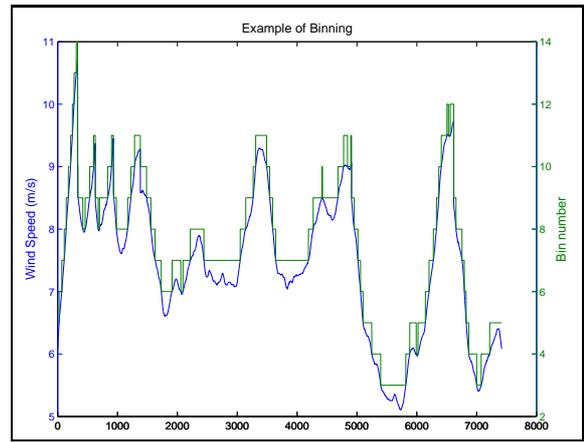


Fig. 8. Example of wind binning

C. Dynamic curves

To assess the performance of a wind turbine relative to wind speed, according to [16], the measurements should be collated in $0.5m/s$ wind speed bins, as depicted in Figure 8. By binning the wind in this way and determining the value of the measure to analyse while the wind is in the different bins, see Figure 9, the performance curves for a particular measurement, for example generated power or C_{pmax} tracking efficiency, consisting of the average and standard deviation with respect to wind speed, are obtained. Dynamic performance curves are provided by the CDT , an example of which can be seen in Figure 10.

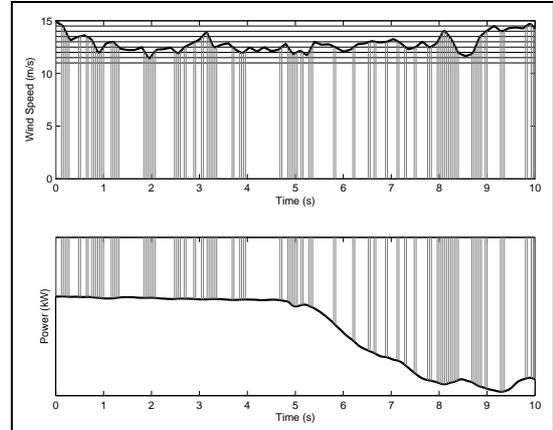


Fig. 9. Example of power binning

These performance curves, obtained from simulations run with different control strategies, are a reliable source of information regarding the comparative behaviour of the controllers when implemented on the actual machine.

D. Data Analysis GUI

To enable the CDT to be a self-contained tool, it has the capability of importing the results from the preferred aero-elastic package. For convenience, a suitable graphical interface, see Figure 11, that permits the simultaneous exploration of up to

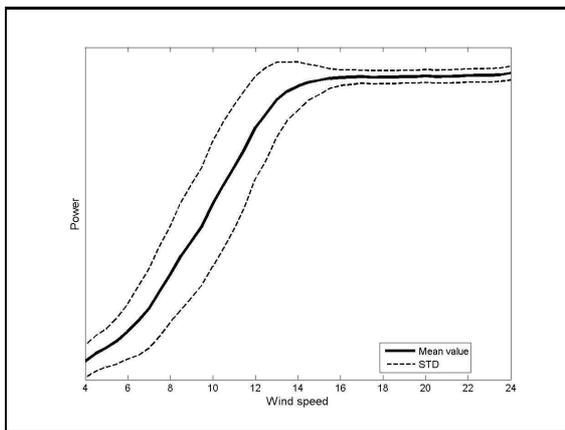


Fig. 10. Dynamic power curve

three different runs from the aero-elastic package, is included in the CDT. Since there is a strong frequency domain aspect to the wind turbine behaviour [17], it is always useful to have PSDs available. Accordingly, the graphical interface at all times depicts the time series, the PSD and the cumulative PSD for the chosen signals. The commonly required statistics for these signals are also displayed automatically. The imported data is also made available in the MATLAB workspace so that all the signal processing and analytic capability of the MATLAB environment can be exploited.

E. Parameter optimisation using MATLAB

One of the most time consuming aspects of controller design is tuning the different controller parameters. Given the excess of processing power available today, it seems appropriate to develop computer-based automatic tuning procedures. To do this the measures of performance, on which tuning is to be assessed, must first be defined. Whether standard deviation of generator speed, tower fatigue, the K_{opt} to obtain maximum below rated energy capture or some other alternative, the task of determining the controller parameters which optimises the measures of performance is straightforward in the CDT. The CDT incorporates a procedure that automatically executes a particular simulation run, or a batch of simulation runs, of the preferred aero-elastic package (Flex or Bladed), read the output, calculate the measures of performance chosen, and subsequently modify the controller values in order to improve on these performance measures. The procedure does not require user intervention and the optimisation continues until the improvement is within a specified tolerance. The optimisation routine included in the CDT is valid for most circumstances but, given the full integration of the CDT with MATLAB, it is straightforward to change that optimisation routine to be any included in the MATLAB Optimisation Toolbox [18].

VII. CONCLUSIONS

The aim of this paper is not to offer yet another tool in an already over crowded market. From the authors experience, the control designer often needs to use a variety of

tools from different sources. In addition, different companies use different aero-elastic packages. It seemed pertinent to incorporate all necessary tools for the control designer in a single independent framework and to make that framework compatible with any of the aero-elastic packages commonly used. The CDT is just such a framework. Furthermore, the fact that it is coded in Matlab makes it simpler for the control designer to embed in-house developments as extensions to this tool.

The CDT uses a set of well-tested solutions to some of the issues faced by the wind turbine control designer, whilst leaving room for modifications, improvements and adjustments to meet the specifics of any turbine when necessary. The CDT is, thereby, designed to be an aid to the control engineer.

Future Work

As the scope for the role of control changes, so the scope and sophistication of these tools evolves. One of the utilities, now under development at the KI, most demanded by control designers is an interface for Bladed and FLEX with Simulink to speed up the controller development by enabling controllers to be implemented in the aero-elastic environment in block diagram form.

A tool to directly parametrise the linear models within the CDT directly from the Bladed parameter files is also under construction. Unfortunately due to the extent of individual manufacturers have modified FLEX and created different versions of flex parameter files, implementing such a tool to extract the parameters from the FLEX parameter files is not possible. However, for a particular version of FLEX, a FLEX component files parser that would extract the necessary parameters is trivial.

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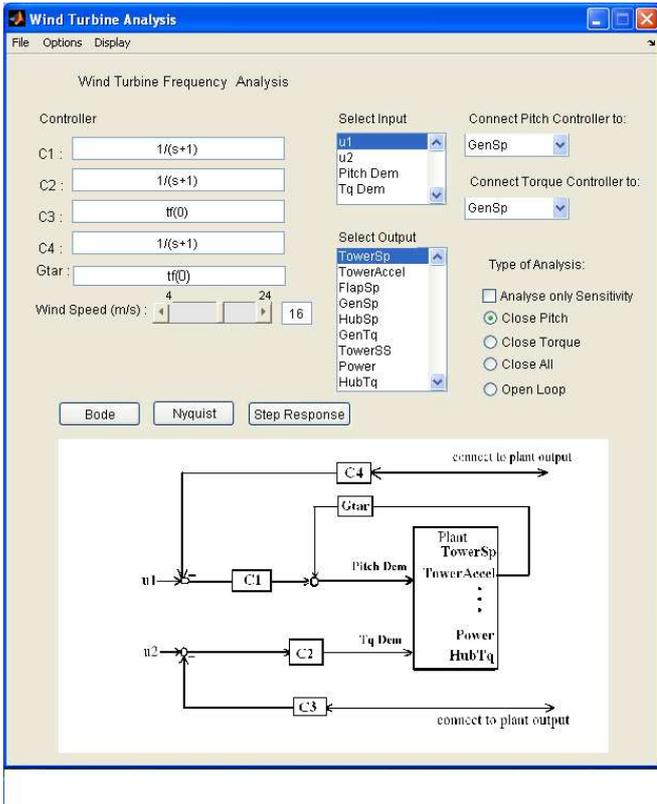


Fig. 6. Control Design GUI

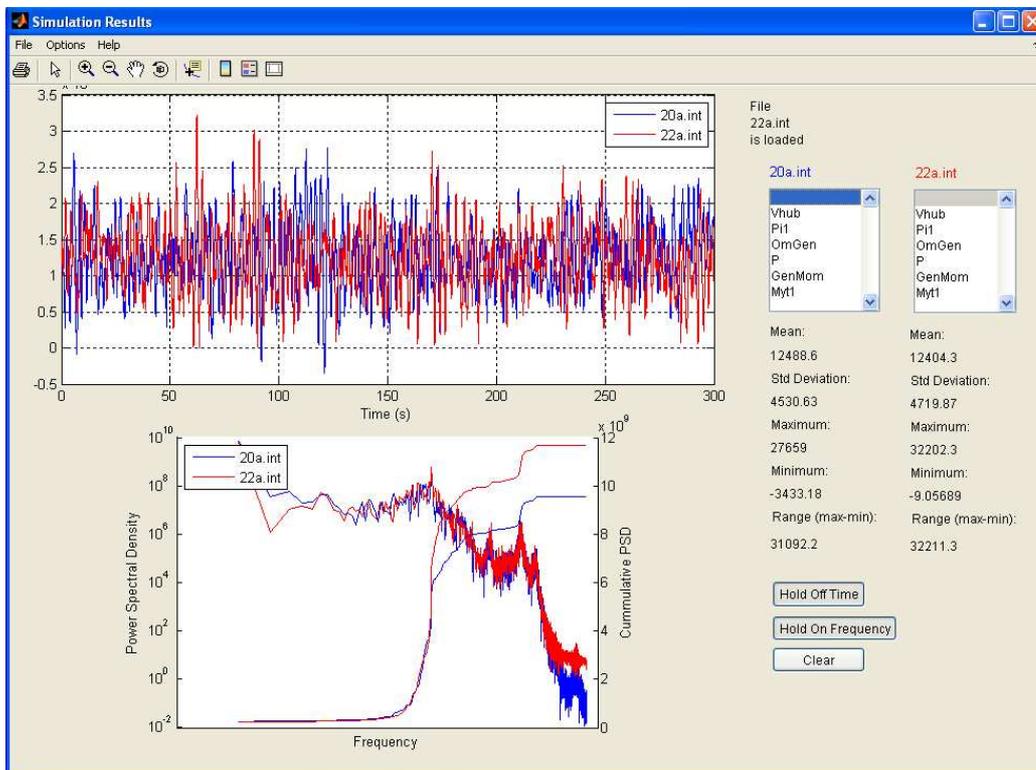


Fig. 11. Data Analysis GUI