Controller design for wind turbine load reduction via multi-objective parameter synthesis

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Abstract. During the design process for a wind turbine load reduction controller many different, sometimes conflicting requirements must be fulfilled simultaneously. If the requirements can be expressed as mathematical criteria, such a design problem can be solved by a criterion-vector and multi-objective design optimization. The software environment MOPS (Multi-Objective Parameter Synthesis) supports the engineer for such a design optimization. In this paper MOPS is applied to design a multi-objective load reduction controller for the well-known DTU 10 MW reference wind turbine. A significant reduction in the fatigue criteria especially the blade damage can be reached by the use of an additional Individual Pitch Controller (IPC) and an additional tower damper. This reduction is reached as a trade-off with an increase of actuator load.

1. Introduction

Control law design problems are often multidisciplinary in their nature where many, often conflicting design requirements, have to be fulfilled simultaneously. In the case of many design objectives, the control systems designer needs to compare design alternatives. Furthermore, he needs to know to which extent certain design objectives are satisfied. When conflicts arise, he requires quantitative information about the trade-off between individual objectives. Design objectives can usually be expressed as mathematical criteria representing quantities of achieved performance. The solution of such a control design challenge with many criteria can be carried out by solving a multi-objective optimization problem. As a computer-aided design technology, multi-objective optimization-based design is able to address all design requirements and constraints simultaneously, while balancing them individually according to given demands. Due to the complexity of the design task, a multi-objective optimization-based design usually involves experimenting with different set-ups for criteria formulation and weighting, different controller structures and parameterizations, as well as alternative (e.g. global or local) optimization methods [1].

A software environment called MOPS (Multi-Objective Parameter Synthesis), a multi-objective design tool for complex, multidisciplinary optimization problems, has been developed at the Robotics and Mechatronics Centre within the Institute of System Dynamics and Control, German Aerospace Centre, DLR. In this paper, MOPS is applied to design a multi-objective load reduction controller for the well-known DTU 10 MW reference wind turbine.

2. Multi-Objective Parameter Synthesis (MOPS)

This section is gathered from [1] and describes the software environment MOPS, which supports the control engineer in setting up his design problem as a properly formulated multi-objective optimization task. To this end, MOPS offers a basic control system criteria library, a generic multi-model structure for multidisciplinary problems and a generic multi-case structure for robust control law design, as well as visualization tools for monitoring the design progress, see figure 1. Several additional features for dealing with a large amount of parameters and criteria, distributed computation for time consuming computations and the use of external simulation and analysis servers are also provided. The user is provided with a clear application program interface and a graphical user interface both implemented in MATLAB. To solve the underlying optimization problem different powerful optimization procedures are available. For a more detailed description see [1], [2] or [3].
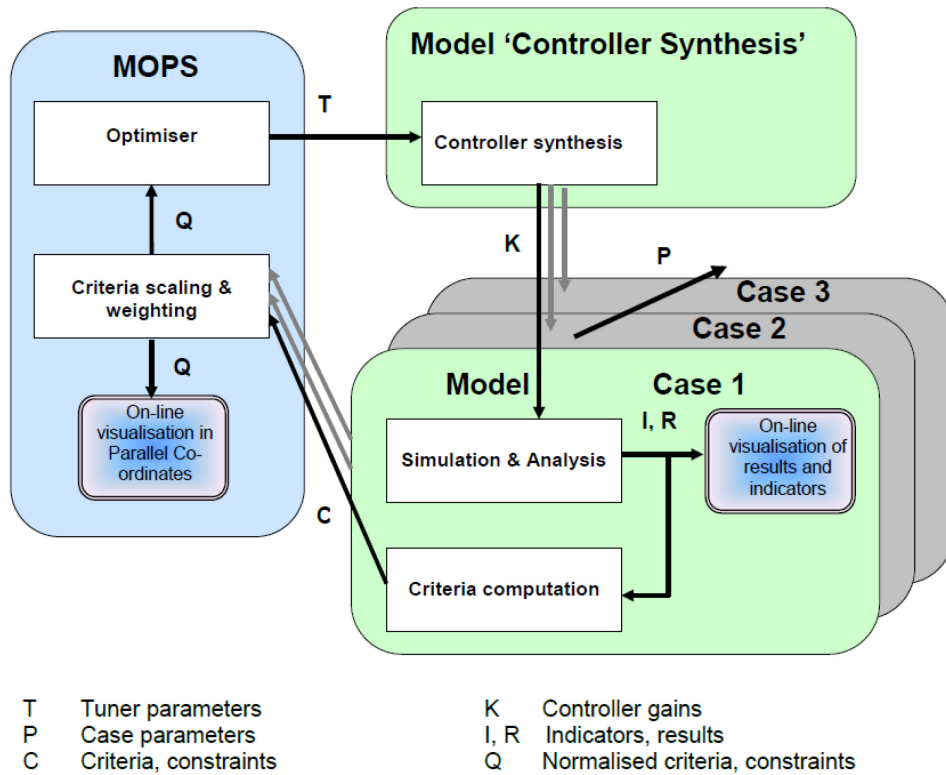

T	Tuner parameters	K	Controller gains
P	Case parameters	I, R	Indicators, results
C	Criteria, constraints	Q	Normalised criteria, constraints

Figure 1. Typical formulation of control design problems in MOPS for synthesis of controller gains [3]

2.1. Basic Problem Formulation

MOPS provides the following functionality to support the user in properly formulating multi-criteria control design problems

- *Definition of design criteria:* A set of basic functions for the most commonly used time and frequency domain criteria is provided within the MOPS criteria library. Customized criteria or the integration of not so common criteria for the standard controller design, e.g. criteria concerning the damage are possible.
- *Normalisation of criteria:* MOPS provides a convenient framework to automatically normalise criteria by generating appropriate scaling and shifting on the basis of specified good/bad limiting values (similar to fuzzy logic membership functions).

- *Multi-model based criteria evaluation:* MOPS explicitly supports the usage of different multidisciplinary model (non-linear simulation models, frequency domain models, etc.) to evaluate the design criteria.
- *Multi-case approach to robust control law design:* A kind of 'global' robustness can be achieved by using the multi-case approach. For example, for analysis models depending on uncertain parameters, the robustness against parameter variations can be achieved by trying to apply a unique controller to a whole set of model instantiations, corresponding to different values of physical parameters. Such a set of model instantiations is called a multi-case model and ideally characterises the whole range of dynamics variations over the parameter range.

2.2. Solving the basic optimisation problem

The multi-objective design problem arises by combining all criteria of all models and cases together an overall criteria vector. Such a vector optimisation problem is formulated in MOPS formally as [3]:

$$\min_T \max_{ijk \in S_m} \left\{ \frac{c_{ijk}(T, p_{ij})}{d_{ijk}} \right\}, ijk \in S_m \tag{1}$$

$$c_{ijk}(T, p_{ij}) \leq d_{ijk}, ijk \in S_i \tag{2}$$

$$c_{ijk}(T, p_{ij}) = d_{ijk}, ijk \in S_e \tag{3}$$

where ijk denotes the k-th criterion of the j-th case of the i-th model. The set of criteria to be minimized is S_m, S_i is the set of inequality constraints and S_e is the set of equality constraints. The k-th normalized criterion of the j-th case of the i-th model is c_{ijk}, d_{ijk} is the corresponding demand value which serves as a criterion weight and the vector T contains the tuning parameters. A parameter of the i-th model defining the j-th case is p_{ij}. The affiliation of a criterion to one of the groups S_m, S_i or S_e respectively can be changed at any time according to design progress. This ensures more flexibility in expressing design requirements. For example, a criterion c_{ijk} to be minimized, which satisfies the according demand d_{ijk} after an optimization run, can be set to an inequality constraint $c_{ijk} \leq d_{ijk}$ in further optimizations. This ensures that the demand for this criterion remains satisfied, while other criteria can be further improved.

The min-max multi-criteria optimization problem is solved by reformulating it as a standard non-linear programming problem (NLP) with equality, inequality and simple bounds constraints. This NLP-problem is then solved in MOPS by using one of several available powerful solvers implementing local and global search strategies, e.g.:

- gradient-based solvers (well-suited primarily for smooth problems),
- less efficient, but usually more robust gradient-free direct-search based solvers are available to address problems with non-smooth or noisy criteria.
- To overcome the problem of local minima to some extent, solvers based on statistical methods or genetic algorithms can be alternatively used.

The requirement of the designer is to know which optimal design alternatives exist and how they are related with each other. This information can be provided by a set of Pareto-optimal solutions from which the designer can select his preference solution [3]. Through the multi-objective min-max optimization of a criteria vector (i.e. with MOPS) it is feasible to find the Pareto-front. This front is a state of allocation of individual criteria in which it is impossible to increase one criterion without worse off another one.

Furthermore MOPS provide additional useful functions to enhance design productivity and control the tuning process, for more information see [2].

3. The DTU 10 MW reference wind turbine

The 10 MW DTU reference wind turbine (see [4] for more details) has been chosen as benchmark problem. The design summary is given in table 1.

Table 1. The DTU 10 MW 3 bladed reference wind turbine design summary.

Description	Value
Rating (MW)	10.0
Rotor diameter (m)	178.3
Hub Height (m)	119.0
Cut-in speed (m/s)	4.0
Rated speed (m/s)	11.4
Cut-out speed (m/s)	25.0

The DTU 10 MW reference turbine is implemented as a SIMPACK/AERODYN model and runs on a desktop computer (AMD Phenom IIX4 960T, memory 4 GB). A typical 10 minute simulation needs approximately one hour.

4. Controller structure and design criteria

This sub-section describes the control strategy, the blending functions and the controller structure as well as the design criteria.

4.1. Strategy

Variable-speed variable-pitch (vs-vp) wind turbines are usually controlled by two more or less independent feedback loops. These two feedback loops are the fast generator-torque control loop for the low wind speed region and the rotational-speed control loop via collective pitch control (CPC) for the high wind speed region at rated power P_0. Both feedback loops pursue different objectives; therefore the interference between both feedback loops has to be reduced.

This can be reached by a typical vs-vp control strategy which is plotted on the torque-rotational speed plane (the aerodynamic characteristics of a rotor are the light grey lines in the back), see figure 2. Interesting boundaries such as the maximum rotational speed Ω_{max}, the minimum rotational speed Ω_{min}, the maximum wind speed V_{max} (cut-out speed) and the rated power P_0, the maximum torque T_0 as well as the c_{pmax} curve (curve of maximised power output) are qualitatively shown.
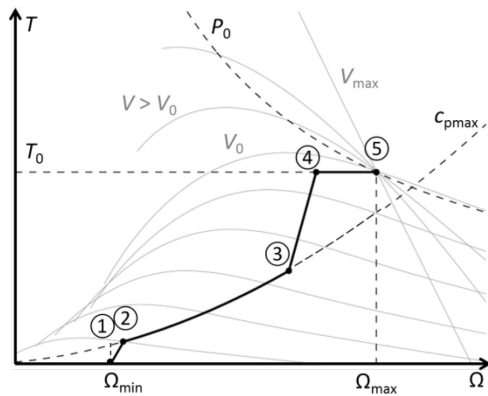

Figure 2. Modified control strategy with reduced interference, according to [5]
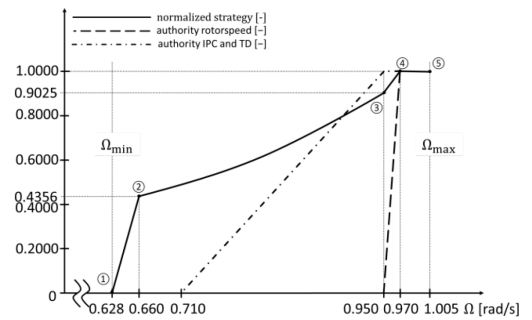

Figure 3. Blending functions [6]

The overall strategy can be decomposed in four steps

- $1 \rightarrow 2$: linear profil to start up the turbine at minimum rotational speed to reach the c_{pmax} curve
- $2 \rightarrow 3$: dynamical c_{pmax}-tracking by controlling the generator torque at partial load
- $3 \rightarrow 4$: to overcome the problem of infinite slope from c_{pmax} tracking to maximum generator torque at Ω_{max} a "ramp" command with finite slope is used.
- $4 \rightarrow 5$: In full-load operations, the generator power has to be limited. For a variable speed wind turbine this is realised by a constant generator torque command and a rotor speed controller which uses the collective pitch-angle.

4.2. Controller blending
According to the strategy it is reasonable that the different sub-controllers are not always active. The blending of each sub-controller depends on the low-pass filtered rotational speed. In figure 3 the blending functions for the sub-controllers are displayed and given by absolute values according to the normalized strategy (T/T_0) explained in sub-section 4.1.

4.3. Controller structure
The designed controller is a modified DTU controller [7]. Figure 4 shows the sub-controller used to fulfil the strategy and the load control loop as well as a tower damper (TD). Each sub-controller is explained hereafter. The individual pitch command saturations, the rate limitations and the blending functions for each sub-controller are shown in figure 4.

- *Generator torque control:* For partial load operation the generator torque T_G is controlled by the $k\omega^2$ approach which is widely used for tracking c_{pmax} in the low wind speed region, see [5]. Above rated speed the generator torque is held constant at T_0.

- *Rotor speed control:* Above rated power the rotor speed is controlled by a PI-controller $(K_{P,CPC}, K_{I,CPC})$ with an anti-windup scheme and a non-linear gain-scheduling, which is not explicitly shown, using collective pitch θ_{speed}^{CPC}.

- *Load control:* The "inner model principle" postulates that a model of the disturbance has to be included in the controller dynamics for good disturbance rejection. Therefore the out-of-plane blade root bending moments $M_{y,i}$ are fed into the individual pitch controller (θ_i^{IPC}) and filtered by a second order inverse-notch-filter with the notch frequency equal to the 1st rotor harmonics Ω_0 under full-load operation. Sinusoidal disturbances as well as disturbances regarding the "eddy slicing effect" can be modelled by an inverse-notch-filter. The damping ς_{IPC} of the second order inverse-notch-filter must be tuned. The filtered signals are transformed from the rotating to the non-rotating domain by using the multi-blade coordinate transform (MBC) and the rotor azimuth Ψ, see [6]. For each cyclic mode, indicated by sin and cos in figure 4, a PI-controller $(K_{P,IPC}, K_{I,IPC})$ and an anti-windup scheme is used.

- *Tower damper:* The control loops are extended by a tower damper using collective pitch θ_{TD}^{CPC}. To increase the damping of an oscillating body such as the tower a good feedback signal is the velocity of the tower top, which is in reality hard to measure. A sufficient approximation is the integrated tower top acceleration $\ddot{x}_{nacel}$. In a bias free simulation a numerical integration is quite right. Under real world conditions this signal has to be observed e.g. by a pseudo integration via a low-pass filter or typically a Kalman-Filter. In this paper, a numerical integration is used and the signal is filtered according to the "inner model principle" by a second order inverse notch filter, with the notch frequency Ω_{TW} of the

first tower for-aft bending mode. The filter steady state gain K_{TD} and the filter damping ς_{TD} are tuned.
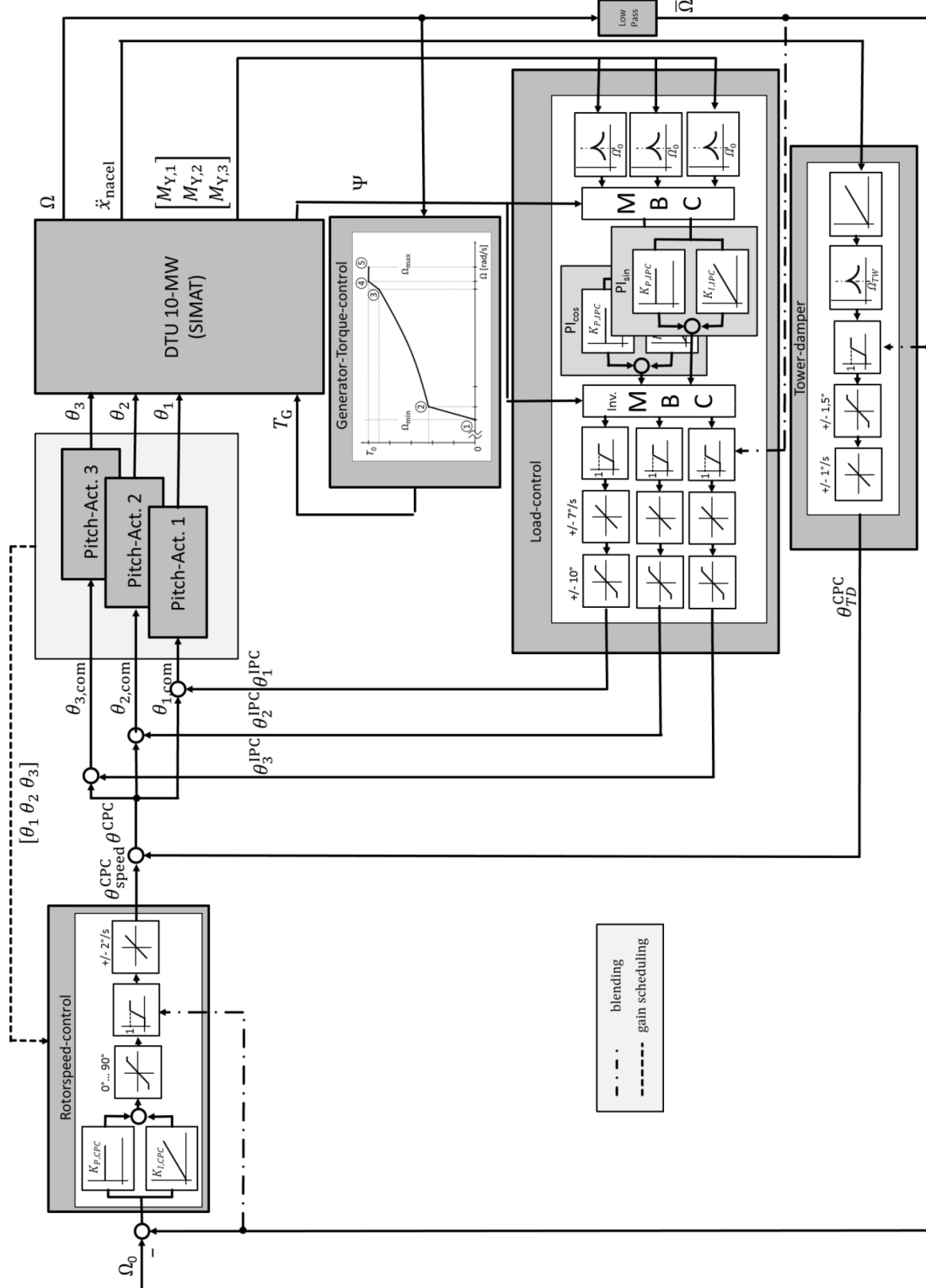

Figure 4. Controller structure, according to [6]

4.4. Design criteria

Reduction of the levelized cost of energy is the global goal for active load control. Through reduction in structural fatigue maintenance cost could be reduced, or lighter constructions of the major parts of the wind turbine are possible and therefore the levelized cost of energy could be reduced as well. The damage caused by fatigue loads of the blade root bending moments as well as the tower base for-aft bending moment are critical quantities for sizing and operating a wind turbine. So the blades root damage as well as the tower damage are well suited criteria ($C_{D,Blade}$; $C_{D,Tower}$) to tune a load controller.

In order to calculate the damage the number of load cycles l_i caused by a load spectrum from k different amplitudes σ_i must be distinguished by an algorithm, e.g. the rainflow algorithm which is used here. The Palmgren-Miner hypothesis assumes that the total damage D can be expressed as the sum of particular damages caused by the distinguished cycles [8].

$$D = const. \sum_{i=1}^{k} l_i \sigma_i{}^m \tag{4}$$

The Wöhler exponent *m* and the *constant term* are material properties. The third criterion $C_{Actuator}$ is the magnitude of the power consumed by the actuators. The fourth criterion $C_{\sigma(P)}$ is the standard deviation of the output power and thus the quality of the power to be fed into the grid. In the high wind speed region deviations from the reference output power P_{ref} have to be penalized. The penalization function principle (criteria five) is given by:

$$C_P = \left| \frac{P}{P_{ref}} - 1 \right| \; ; \; P_{ref} = \begin{cases} \frac{\rho}{2} \pi R^2 c_P V^3 & V \leq 11 \, m/s \\ P_0 & V > 11 \, m/s \end{cases} \tag{5}$$

4.5. Weighting

Due to required computational time, just three different evaluation wind speeds V_j (j = a, b, c) are feasible. Wind speeds less than 8 m/s are not examined because of negligible criteria quantities. Wind speeds above 18 m/s are unlikely to occur. The division of the enclosed wind speed range into 3 sectors, each represented by one wind speed V_j, is listed in table 2, for more information see [6].

Table 2. Sectors and representative wind speeds.

Sector j	Lower bound V_{low}	Upper bound V_{up}	Representative wind speed V_j
a	8 m/s	11 m/s	10 m/s
b	11 m/s	13 m/s	12 m/s
c	13 m/s	18 m/s	14 m/s

The $Q_{i,j}$ of the criteria C_i are chosen considering two aspects.

- The wind speed probability which is modelled by a Rayleigh density function *r(V)*.

- The dependence of criteria quantities on the wind speed which is gained in the form $C_i(V) / C_i(V_j)$ for one set of parameters during preliminary controller design.

It is assumed that although $C_i(V)$ changes during optimization, the ratio $C_i(V) / C_i(V_j)$ roughly remains constant. According to the above mentioned aspects, the weighting $Q_{i,j}$ of each sector j is computed by

$$Q_{i,j} = \int_{V_{low,j}}^{V_{up,j}} \frac{C_i(V)}{C_i(V_j)} \cdot r(V) \, dV. \tag{6}$$

The global criteria covering the entire wind speed range from 8-18 m/s are the sum of the weighted criteria, multiplied by a correction factor Z_i. For the starting point of optimization, Z_i is chosen such that $C_i = 1$ for each criterion. This equalization is one way to define the desired optimum on the Pareto front in the course of min-max optimization.

$$C_i = Z_i \cdot \sum_{j=a}^{c} Q_{i,j} \cdot C_{i,j} \tag{7}$$

5. Application of MOPS on a load controller design for the 10 MW DTU wind turbine

In this section a MOPS setup for the prior described controller and some results are shown. More information on the hierarchical data structure is provided in [3].

5.1. MOPS Setup

For a controller design typically different setups (complete optimization task consisting of one or several models), versions (configuration and complete problem description, ready for execution), tuner (optimization parameters), models, cases and counteracting criteria have to be handled.

The user is provided with a clear application program interface and a graphical user interface both implemented in Matlab [3]. The MOPS Setup Control Panel for wind turbine controller optimization is shown in figure 5. The list boxes of the upper row present all objects (Tuners, Models, Cases, Parameters, Results, and Criteria) defined in the set-up and its current version. In the row below the actual values and properties of the selected objects are displayed. Optimization method properties are set by the menu panel in the lower left corner [2].

The tuners which have to be determined through optimization are the damping of the inverse notch filters zetaTD (ς_{TD}) and zetaIPC (ς_{IPC}) for tower damping and individual pitch control, respectively. Furthermore, several controller gains (Ktd = K_{TD}, KPipc = $K_{P,IPC}$, KIipc = $K_{I,IPC}$, KPcoll = $K_{P,CPC}$, KIcoll = $K_{I,CPC}$), must also be optimized. As shown in the previous section, all other controller gains were assessed analytically. In order to reduce the computational cost during the optimization the criteria are computed for only one model and one case. For the shown optimization run, only the first three criteria CbladeDEL ($C_{D,Blade}$), CtowerDEL ($C_{D,Tower}$) and Caktuator ($C_{Actuator}$) are set active (labelled with + in front of the criteria in the last column) whereas the criteria Cpowermean (C_P) which penalize deviations from the reference output P_0 and standard deviation of the output power Cpowerstd ($C_{\sigma(P)}$) are set to be monitored only (labelled with - in front of the criteria in the last column).
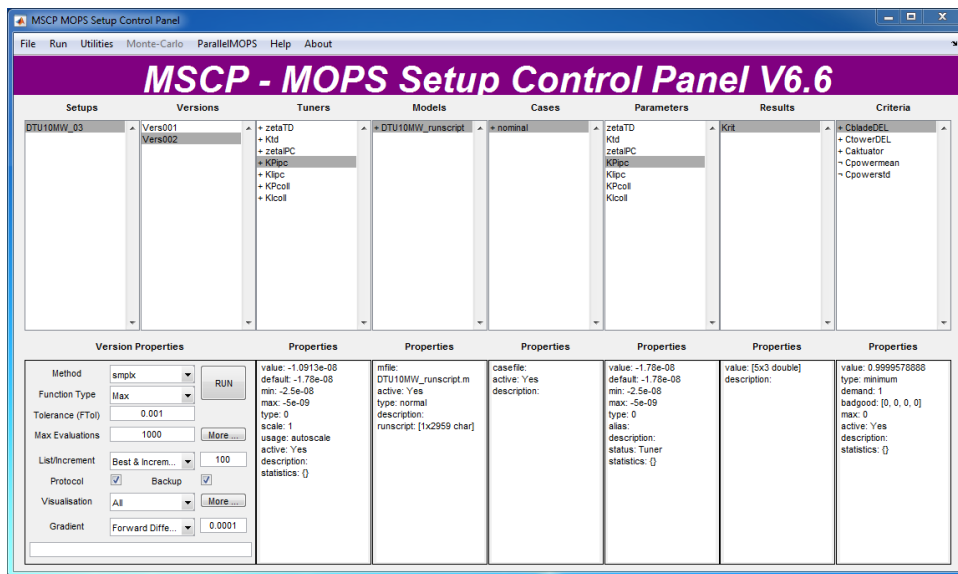

Figure 5. MOPS Set-up Control Panel

5.2. Results

Overall five optimisation runs were performed. The first two runs were performed with the first version and the last three runs were performed with the second version: the differences between the two versions are shown in table 3. These changes were necessary to reduce the computational cost and to increase the model representativeness.

Table 3. Version changes of the optimization.

Parameter	Version 1	Version 2
Sampling frequency [Hz]	1000	100
DOF	2 modes per flexible body	4 modes per flexible body
Actuator model	Rate saturation	Rate saturation and PDT_2-Dynamics
T_0 [Nm/(rad/s)^2]	$9{,}5\ 10^6$	$10\ 10^6$
Turbulence model	Risø-Smooth-Terrain	Kaimal IEC 1A

To show the influence and the improvement of the IPC-based load controller and the additional tower damper, these 2 sub-controllers are additionally activated and compared to the base controller, see figure 6. In this figure the criteria values are normalized to the values of the base controller. A decrease in the damage criteria ($C_{D,Blade}$, $C_{D,Tower}$), especially the blade damage and an increase of actuator load ($C_{Actuator}$) can be shown by the use of the additional IPC-controller and the additional tower damper. The quality of the power output described by $C_{\sigma(P)}$ is nearly constant for all configurations. The additional sub-controllers perform well and do what they were designed for.

These three configurations are compared to an analytical preliminary design which was used as starting point for the optimization. The optimized controllers are significantly, which shows how a well-formulated optimization outperforms the sole engineering judgment when dealing with many different and conflicting requirements. Therefore a multi-objective optimization environment such as MOPS proves useful on this example.

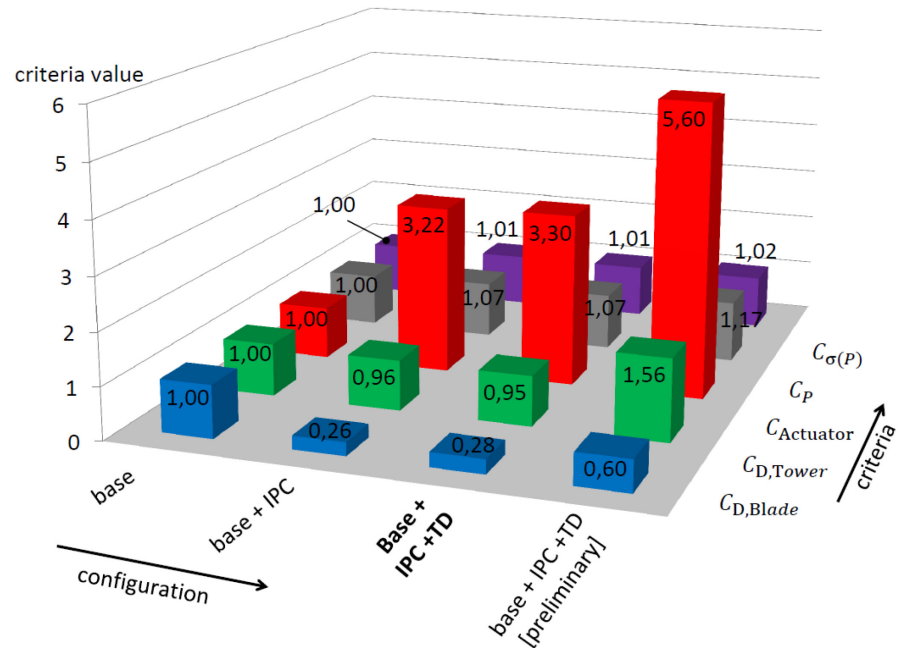For further information on the preliminary design and the detailed optimization process see [6] (in German)

Figure 6. Fulfilment of criteria for different controller configurations

To date, the full potential of MOPS for the design of controllers for wind turbines has not been exploited. This is due to the limitations related to the long simulation time on the desktop computer that was used. Furthermore, the parameters as well as the criteria space have also been limited in order to get also an acceptable workload for the optimization process on the desktop computer. It has to be emphasised that the limitation is not a problem of MOPS: these problems are already inherently solved by MOPS through parallelizing on multiple cores and computers. To overcome this problems in the close future and to perform a robustness assessment MOPS will be used on a more powerful computer.

6. Conclusions

The described software environment MOPS offers flexibility and visibility in controller design as well as during the formulation of the controller design problem itself. The formulation of design requirements as normalised criteria functions allows the multi-objective optimisation to investigating the possible design trade-offs and provides also a very comprehensive overview of the achieved performances to the designer.

The overview of the current design performances is not only useful to analyze the final design at the end of the design phase but supports the engineer in testing new designs with various criteria, controller structures and parameterizations in an interactive fashion during the entire design, which significantly ease achieving the best-possible performance.

The controller designed during the application shown (load controller design of a DTU 10 MW) already shows promising results. A significant reduction in the fatigue criteria, especially predicted blade damage, was reached.

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