CRANFIELD UNIVERSITY

STEFAN GUEORGUIEV IORDANOV

SELF-OPTIMIZING CONTROL FOR WIND TURBINE GENERATOR

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
ENERGY SYSTEMS AND THERMAL PROCESSES

MSc
Academic Year: 2015 - 2016

Supervisor: Dr Yi Cao & Dr Maurizio Collu
Septemeber 2016

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This thesis is submitted in partial fulfilment of the requirements for the degree of ENERGY SYSTEMS AND THERMAL PROCESSES
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

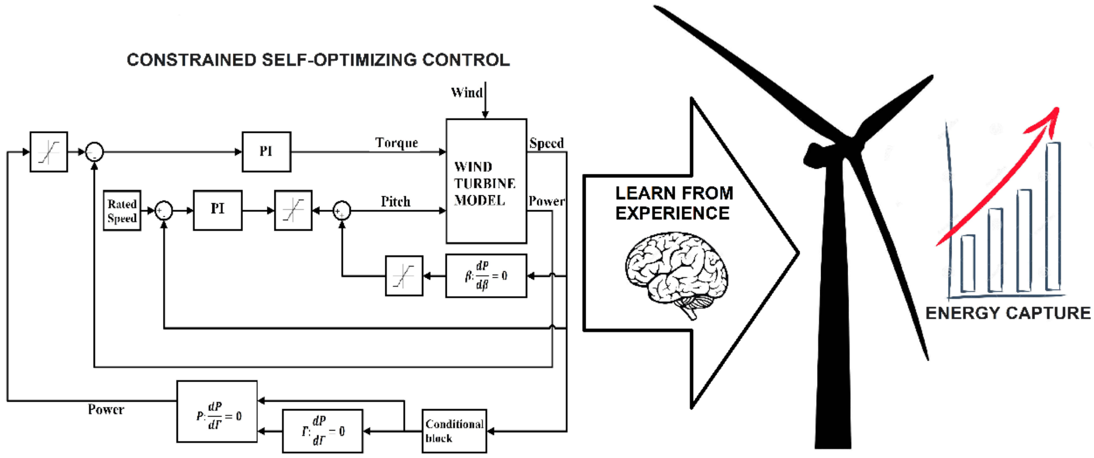
The fast development of the wind power technology is leading to larger and more expensive wind turbines which require increasingly advance control systems to achieve optimal or near optimal operation. However, the increased optimality of complex operation schemes, like real-time optimization approaches, incur in high implementation and maintenance costs. Furthermore, while the wind speed is a key variable for the wind turbine control, using it as a direct input leads to a poor response of the power control. This makes the industry focus on simpler control structures, considering wind as a disturbance [1]. Nevertheless, baseline control laws, which perform a deterministic control, require that complex aerodynamic properties are well-known to achieve the desired performance. But in practice, variability bounds the efficiency of the energy capture. Thus, a constrained self-optimizing control is proposed to regulate the wind turbine operation coping with wind speed uncertainty.

A data-driven self-optimizing control is proposed for the wind turbine control region where power is maximized (region 2). Operational data is extracted from a model off-line to examine the structure of the optimal solution. This insight is then transformed into a simple control structure capable of keeping the wind turbine to an optimal operation, in terms of maximizing power output. However, at high wind speed, wind turbine power output has to be maintained at its nominal rate. Thus, a cascade control structure for self-optimizing and constrained control is incorporated. The control structure is implemented in Simulink using as a model FAST v8 5MW onshore wind turbine model.

The proposed self-optimizing control learns the structure of the optimal solution off-line and then performs the optimization strategy, adjusting both torque and pitch to maximize energy capture. This control approach leads to an increase in power output when comparing it with the deterministic baseline control. Moreover, this heuristic control approach has the potential to take into account a higher number of inputs without compromising reliability. This property allows its future application for more advance control strategies.

Keywords: Data-drive, off-line, cascade control, control structure, optimal operation

GRAPHICAL ABSTRACT



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LIST OF ABBREVIATIONS

SOC	Self-Optimizing Control
BC	Baseline Control
WT	Wind Turbine
NCO	Necessary conditions for optimality
ESC	Extremum seeking control
CP	Coefficient of power
ANN	Artificial Neural Networks
CV	Controlled Variable
TSR	Tip Speed Ratio
NREL	National Renewable Energy Laboratory

1 INTRODUCTION

Wind turbine's capability of extracting energy from the wind has grown substantially over the last decades. This is thanks to the technological development of the numerous subsystems which compose the WT. In order to effectively and safely produce power, a WT requires a control system to manage the combined operation of all these units.

The two levels of control operation are known as supervisory and dynamic control. The supervisory control is responsible of monitoring and sequencing the control actions (safety systems, fault monitoring, grid connection and disconnection, etc.). The dynamic control regulates those features for which the outcome of the control action depends on the machine dynamics (torque and pitch control) [2]. This paper is focused on the torque and pitch dynamic control system's design.

The vast majority of large commercial WT are variable speed and pitch regulated. Thereby, the operation can be controlled by changing the speed or by regulating the blade pitch. The WT's operation is characterized by two main regions. At low wind speed (region 2), WT is operated in order to maximize energy capture. At high wind speed (region 3), when the WT reaches nominal power output, power is maintained constant by regulating the blade pitch.

The control method used to maximize power at low wind speed has a particular relevance. The essential input for controlling the WT operation is the wind speed. Johnson [3] proposes an adaptive controller which uses a simple gain adaptation law designed to track the optimal gain for maximizing WT power generation. In fact, it replaces the constant gain torque k, commonly used in WT baseline control, with a new adaptive gain, using turbine power and wind power measurements.

However, measuring wind speed and using it as a direct input for the control leads to significant problems. It is technically difficult to obtain a wind speed measurement anywhere in the WT that could be representative of the power generated by a large wind rotor. The consequence would be a poor response of the power control, as its performance is closely related to the quality of the input signals [1]. Therefore, there are preferred those feedback control structures which do not require wind speed as a measured variable, but those which assume it as a disturbance affecting WT operation and the value of which is unknown.

Thus, there have been proposed various approaches to make the WT perform at optimum or near optimum operation despite on the uncertainty of wind speed.

Work [4] investigates the implementation of extremum seeking control (ESC) to maximize energy capture at low wind speed. Torque and pitch are adjusted to achieve optimal operation via ESC based on the measurement of the rotor power. The simulations conducted with FAST show considerable improvement in energy capture compared to BC.

The study [5] presents the Takagi–Sugeno–Kang fuzzy model, which is able to estimate with high accuracy the maximum power output from a variable speed WT. Then, it is proposed a procedure to generate an adaptive fuzzy controller which can continuously optimize its internal parameters in order to achieve optimal operation.

Iyasere [6] presents a nonlinear controller to optimize energy capture. This control strategy allows blade pitch and tip speed ratio regulation in order to track the maximum power coefficient operating point.

Despite all these proposed novel solutions, the most extended control method used in industry to maximize energy capture is the one which adjusts the rotor speed in order to achieve the TSR at which the coefficient of power is maximized. This is due to its simplicity and simple implementation and maintenance.

Nonetheless, this method assumes that the TSR at which CP is maximized is the same for all wind speed. What’s more, it fixes the blade pitch at the reference angle 0º, leaving just one degree of freedom to achieve a maximum power output operation. This type of deterministic control is bound to be constrained to few input variables, as its complexity increases quickly, and with it its loss of reliability. The BC structure is described in chapter 3 and Appendix B.

Due to the limitation of this control approach when dealing with wind speed uncertainty in order to maximize energy capture, in this paper it is considered the concept of a self-optimizing control.

SOC is a method to achieve near optimal operation with an acceptable loss by keeping constant set points for particular CVs. This CVs are selected in order to minimize the loss of optimality with respect to a certain economic objective function. The objective is to find a simple control structure which gives a satisfactory economic performance without the need to re-optimize when disturbances occur. Skogestad [7] was the first who referred to this concept as 'self-optimizing control'.

SOC approach has been proposed for many control problems. A.S.Grema and Yi Cao [8] have moved the concept to the oil reservoir waterflooding process where a gain in net present value as high as 30.04% was obtained compared with the traditional open-loop method.

In Sayalero [9], a SOC control is applied to establish the plantwide control for a hydrodesulfurization HDS plant of a petroleum refinery with regards to hydrogen consumption optimization. It is achieved a simple and robust control structure which is able to assure the global optimum in most cases.

Jäschke and Skogestad present in [10] a SOC strategy for optimal operation of a preheating train of the crude oil unit at the Mongstad Refinery in Norway. In this work it is proved the effectiveness of the SOC for maintaining optimum operation by keeping heat exchanger temperatures despite uncertainties in flow rates, stream temperatures, and heat transfer coefficients. The proposed alternative is simpler than online real-time optimization method, cheaper to implement and easier to maintain.

Although the application of the SOC approach has been widely discussed for chemical plants and for the oil industry, still it has not been addressed for WT control. Thus, in this paper, a constrained self-optimizing control structure is proposed for maximizing WT power output at low wind speed.

The design of a control system which offers an acceptable performance requires a mathematical model containing the complex, non-linear dynamic effects of the WT. For this reason, the proposed constrained SOC structure is designed using as a model the software package FAST v8, NREL's main CAE tool for simulating the coupled dynamic response of a WT [11].

To sum up, the aim of the project is to design a SOC structure for the dynamic control of the WT through the whole operating region. Then, the resulting control scheme performance is compared with a BC. The study has been carried out as follows:

- A WT mathematical model containing the complex, non-linear dynamic aero-elastic effects, has been selected.
- The model is then adjusted to the required WT size and nominal power.
- Previously tested BC system is implemented in order to have a benchmark with which to compare the proposed SOC.
- CVs for SOC are selected through a data-driven approach, and hence operational data is obtained from the WT model in order to examine the structure of the optimal solution in WT control region 2.
- CVs are selected by performing a linear regression. Then, it is being tested the capability of the SOC to operate the WT at maximum power output when keeping CVs to zero setpoint.
- The resulting SOC is then incorporated into a cascade structure in order to maintain constant nominal power output above rated rotor speed.
- The behaviour of the resulting constrained SOC structure is tested at uniform and turbulent wind speed.
- Finally, it is carried out a comparison between the proposed constrained SOC and BC performance.

2 MODEL SELECTION

2.1 FAST v8

The design of a control system requires a mathematical model containing the complex, non-linear dynamic effects of the WT. The constrained SOC structure is designed using FAST v8 as a model, as it is a recognised and well-known model for WT control design.

The FAST (Fatigue, Aerodynamics, Structures and Turbulence) model was developed by the National Renewable Energy Laboratory as part of the U.S. Department of Energy sponsorship for software development for use by the wind power engineering community. FAST is the combination of an aerodynamic, control, electrical and structural dynamic models to facilitate non-linear aero-servo-elastic simulation in the time domain. The FAST v8 model architecture is illustrated in Figure 2-1.

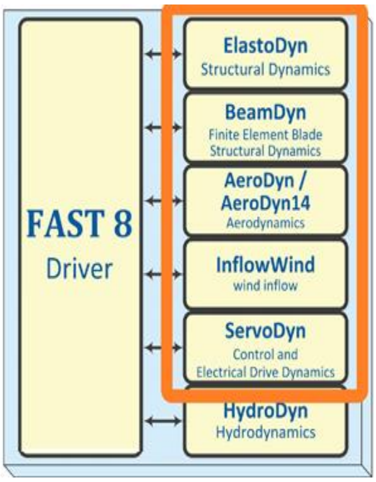

Figure 2-1 FAST v8 architecture [12]

Moreover, FAST includes an interface which links with Simulink® (Figure 2-2), allowing the user to develop advanced WT control systems in Simulink's block diagram form [12].

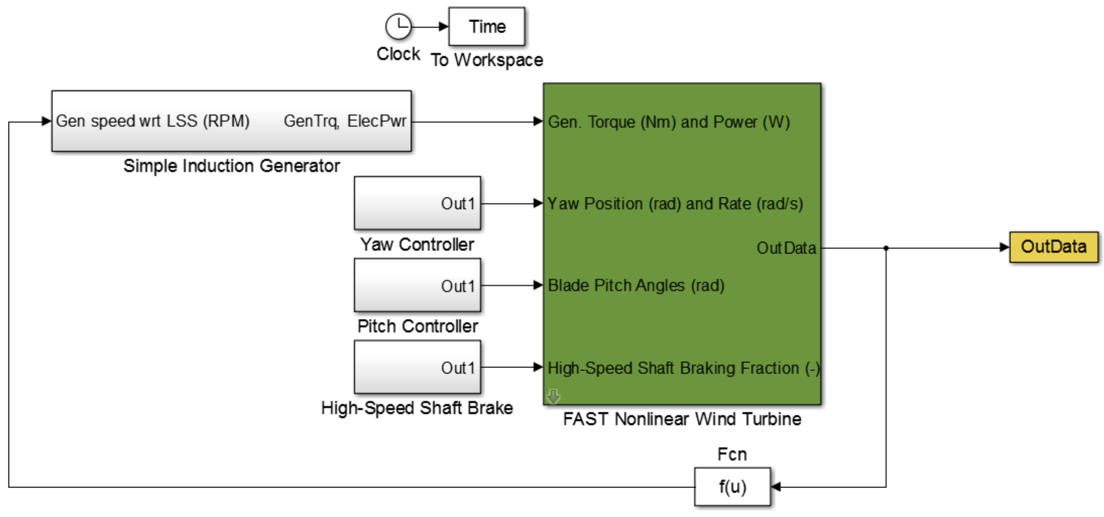

Figure 2-2 Simulink block diagram of the FAST wind turbine model

The main drawback of FAST version 8 with respect to previous version is the fact that it is still not possible to obtain linearized models for different operating points.

2.2 TurbSim

TurbSim is a stochastic turbulent wind simulator which uses a statistical model to simulate time series of three-dimensional wind speed vectors. These vectors are located at points in a vertical rectangular grid that is fixed in the space. TurbSim is used as a standalone programme to create the wind input files for the 5MW WT FAST simulations [13]. This wind files emulate the real turbulent wind regimes at which a WT is exposed.

2.3 5 MW reference wind turbine

To establish detailed features of a large multimegawatt WT and to promote studies aimed at assessing the offshore wind industry, NREL developed an offshore 5 MW baseline WT model. It is mainly based on the design information of the Repower 5M WT, although, it has also been considered publicly available features from conceptual models like WindPACT or DOWEC projects [14]. The main properties of the 5MW baseline WT are exposed in Table 2-1.

Rating	5MW
Rotor Orientation	Upwind
Configuration	3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor	126 m
Hub Diameter	3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg

Table 2-1 NREL 5-MW Baseline Wind Turbine specifications

The 5MW WT properties are stored as Fortran files which are read by the Simulink WT model block:

- Test 18.fst: FAST main input file for the NREL 5.0 MW Baseline Wind Turbine (Onshore) (A.1.1)
- NRELOffshrBsline5MW_Onshore_AeroDyn15.dat: Name of the file containing aerodynamic input parameters (A.1.2)
- NRELOffshrBsline5MW_Onshore_ServoDyn.dat: Name of file containing control and electrical-drive input parameters (A.1.3)
- NRELOffshrBsline5MW_Onshore_ElastoDyn.dat: Name of file containing structural input parameters of the WT (A.1.4)

3 BASELINE CONTROL SYSTEM

In order to have a regular WT control structure which can then be compared with the new designed SOC scheme, the BC system developed in [14] as a Fortran script, has been implemented in the Simulink interface for the 5MW onshore WT.

The WT operation region is strictly divided into 5 control regions: 1, 1 ½ , 2, 2 ½ and 3.

- Region 1 is the region before cut-in wind speed where generator torque and power are zero so that the wind is used to accelerate the rotor.
- Region 1 ½ is a linear transition region between region 1, where torque is zero, and region 2. Without this region the rotor would pass directly from torque zero to a considerably high torque which would slow down violently the rotor speed.
- Region 2 is the control region where generator torque is manipulated in order to maintain a constant TSR (λ) for which the coefficient of power (C_p) is optimal.
- Region 2 ½ is a linear transition between region 2 and 3. This region is needed to force the rated rotor speed (12.1 rpm) at the nominal power (5MW) as this operation point does not correspond to a point of maximum power.
- In region 3, at high wind speed, the blade pitch is regulated to reduce the aerodynamic efficiency (aerodynamic torque). This leads to a reduction in the rotor speed used to maintain constant power. Below rated power, the blade pitch is fixed at the design pitch angle (0 degrees) to limit pitch mechanism wear [2].

Figure 3-1 illustrates the different operating regions.

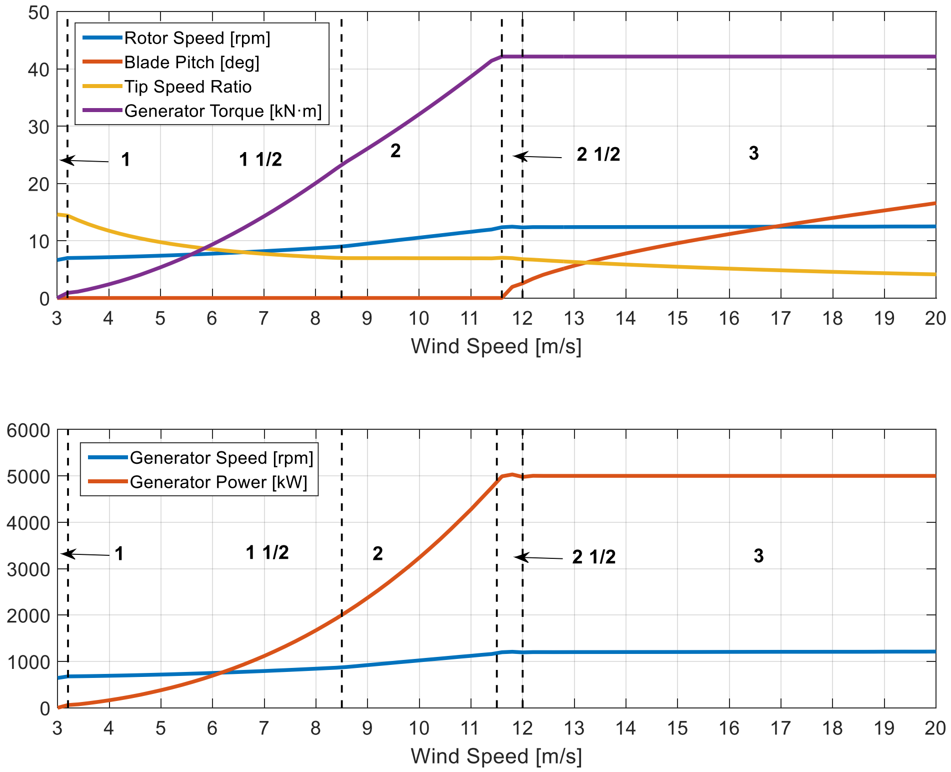

Figure 3-1 Wind turbine steady-state response as a function of wind speed

The baseline control system has been implemented considering the same properties as in [14].

Corner Frequency of Generator-Speed Low-Pass Filter	0.25 Hz
Peak Power Coefficient	0.482
Tip-Speed Ratio at Peak Power Coefficient	7.55
Rotor-Collective Blade Pitch Angle at Peak Power Coefficient	0°
Generator-Torque Constant in Region 2	0.0255764 N·m/rpm^2
Rated Mechanical Power	5.29661 MW
Rated Generator Torque	43093.55 N·m
Transitional Generator Speed between Regions 1 and 1 ½	670 rpm
Transitional Generator Speed between Regions 1 ½ and 2	871 rpm

Transitional Generator Speed between Regions 2 and 2 ½	1161.963 rpm
Maximum Generator Torque	47402.91 N·m
Maximum Generator Torque Rate	15000 N·m/s
Proportional gain at Blade-Pitch Setting	0.01882681 s
Integral gain at Blade-Pitch Setting	0.008068634
Minimum Blade-Pitch angle	0°
Maximum Blade-Pitch angle	90°
Maximum Absolute Blade-Pitch rate	8°/s

Table 3-1 Baseline control system properties

The Simulink implementation of the BC exposed in [14] is explained in Appendix B.

4 CONSTRAINED SELF-OPTIMIZING CONTROL STRUCTURE DESIGN

4.1 Self-optimizing control

As stated by Skogestad [7], the aim of a self-optimizing control structure is to achieve optimal or near optimal operation by keeping constant setpoints for the controlled variables (CVs). Therefore, a SOC structure is aimed to minimize the loss of optimality with respect to a particular cost function which is normally related to the cost of the system operation.

The main aspect of a SOC structure is that a model is used off-line to examine the structure of the optimal solution. This fact allows the achievement of simpler control structures, which on one hand may incur further losses compared to real-time optimization schemes, but on the other hand, can lead to lower development and operating cost when compared to complex control schemes [16].

4.2 Regression based controlled variables selection for a static data-driven self-optimizing control

As stated in section 2.1, FAST v8 does not allow the linearization of the model at certain operating points. To address this issue, it has been considered a model-free approach exposed by Yi Cao in [17]. The data-driven SOC method entirely relies on measurements to determine the CVs which approximate the unmeasured necessary conditions of optimality (NCO). By maintaining the CVs to zero setpoint, it is achieved near optimal operation over the entire operating region.

The objective function to be maximized can be represented as

$$J = \varphi(u, y, d) \quad \textbf{(4-1)}$$

The value of the objective function J depends on the value of manipulated variables (u), measurements (y) and disturbances (d).

The deviation of the objective function in a reference point with respect to a neighbourhood point can be approximated as

$$J_{i+1} - J_i = \sum_{j=1}^{n_u} \frac{dJ}{dU_j}(U_{i+1,j} - U_{i,j}) \tag{4-2}$$

where n_u is the number of manipulated variables.

As stated before, optimal operation ($\frac{dJ}{dU} = 0$) is achieved by maintaining the CVs to zero. The CVs can be linear or nonlinear measurement functions in the form of $CV = CV(y, \theta)$, θ to be obtained through regression such that

$$CV(y, \theta) = \frac{dJ}{dU} = 0 \tag{4-3}$$

Consequently, for a set of data u_i, y_i and J_i with d_i unknown, θ has to be obtained such that

$$min_\theta \sum_{i=1}^{N} \sum_{p=i_1}^{i_k} (J_p - J_i - \sum_{j=1}^{n_u} CV_j(y, \theta)\big(U_{p,j} - U_{i,j}\big))^2 \qquad i = 1, \dots, N \tag{4-4}$$

where $i_1, \dots, i_k$ are k neighbourhood points i.

4.3 Wind turbine generator case study

In the present case study, a SOC approach is considered for the operation region where WT power output is maximized. As shown in chapter 3, the maximization of power in a BC is achieved by just manipulating the generator torque, while blade pitch is fixed at 0°. Thereby, rotor speed (ω_R) is adjusted in order to achieve a TSR at which CP is maximum.

Thanks to the prior learning of the structure of the optimal solution, the data-driven SOC allows the system to regulate independently both pitch (β) and torque (Γ) in order to achieve the optimum in terms of maximum power output.

Furthermore, TSR is not restricted to a fix value for the whole control region. Instead, it slightly varies depending on current wind speed to achieve optimal operation despite wind speed uncertainty.

This is the fundamental difference with respect to BC. While for BC the optimum control law has been derived before and then imposed deterministically in the controller, in this case it is the controller itself deriving, from experience, the optimum control law.

The classification of manipulated variables U, measurements y and disturbance d are given as

$$U = [\Gamma, \beta], \quad y = [\Gamma, \beta, \omega_R, P], \quad d = [v] \tag{4-5}$$

where v corresponds to wind speed velocity and P to generator power.

Considering a generator efficiency (η), the objective function to be maximized is WT electrical power output defined as

$$P = \Gamma \cdot \omega_G \cdot \eta \tag{4-6}$$

Therefore, the deviation of power in a reference point with respect to a neighbourhood point can be expressed as

$$P_{i+1} - P_i = \frac{dP}{d\Gamma}(\Gamma_{i+1} - \Gamma_i) + \frac{dP}{d\beta}(\beta_{i+1} - \beta_i) \tag{4-7}$$

The data collection procedure is exposed in C.1. Then, the data pre-processing in order to design the CVs by performing a least-square regression is presented in Appendices C.2 and C.3.

4.4 Cascade structure for conditionally active constraints

The SOC approach is suitable for the control region at which power output is maximized. However, during control region 3, at high wind speed, the WT has to be maintained at nominal power and rated generator speed. This is achieved by increasing the blade pitch angle (i.e. moving the blade toward feather position) to decrease the aerodynamics torque.

In order to achieve a control structure capable of maximizing power through the SOC approach in region 2, and saturate at nominal power from a certain wind speed, it has been considered a cascade structure for self-optimizing and constrained control as proposed by Yi Cao in [18].

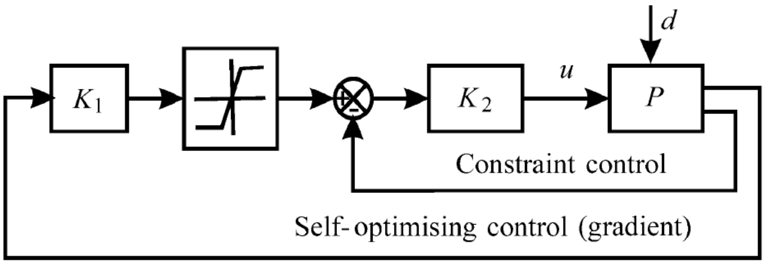

Figure 4-1 Cascade structure for constrained self-optimizing control

The setpoint of the inner loop is given by a saturation block in the outer loop. This limits the set point within the constraints when disturbance cause the process move outside of the SOC operating region. However, within the range of optimal operation, the setpoint of the inner loop is floating to perform a SOC.

4.5 Conditional block

As stated in section 3, the first operating section at low wind speed is divided into 4 regions: 1, 1 ½, 2 and 2 ½. The SOC approach is just suitable for region 2, where power is maximized. In control regions 1, 1 ½ and 2 ½, the turbine must be accelerated, then linearly brought to region 2 and then linearly brought again to region 3. For this reason, it is implemented a conditional block which adjust the SOC input value. The input variable of the SOC is the generator speed. To achieve the previously stated purpose, the generator speed reading is modified as shown in Figure 4-2.

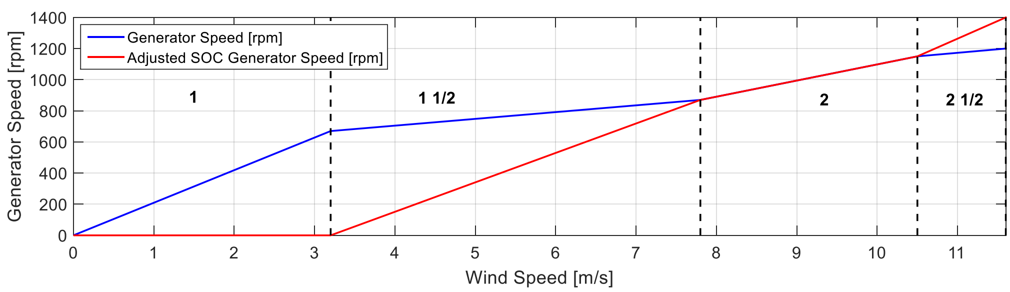

Figure 4-2 Generator speed adjustment by the conditional block

In region 1 (between 0 and 670 rpm), the input value of the SOC control is 0. Thereby, the power set point is 0 and therefore generator torque is also 0.

At region 1 ½ , the input generator speed of the SOC control is linearly adjusted from 0 rpm when real generator speed is 660 rpm, to 870 rpm when real generator speed is 870 rpm.

At region 2, the SOC has to keep the WT operation at maximum power output. During this region the SOC input is the real generator speed.

At region 2 ½ , the input generator speed of the SOC control is linearly adjusted from 1150 rpm when real generator speed is 1150 rpm, to 1404 rpm when real generator speed is 1200 rpm. This last region is needed to bring the WT to region 3 at an operating regime of nominal power at rated speed (5 MW and 1200 rpm), which is not an operating point corresponding to the optimal solution.

4.6 Necessary conditions for optimality approximation

Two different combinations of measurement functions have been considered for the CVs. Generator torque (Γ), generator speed (ω_G), blade pitch angle (β) and generator power (P) are the inputs of the SOC.

Measurement function 1:

$$CV_1 = \theta_0 + \theta_1 \cdot \omega_G + \theta_2 \cdot \Gamma \quad \textbf{(4-8)}$$

$$CV_2 = \theta_3 + \theta_4 \cdot \omega_G + \theta_5 \cdot \beta \quad \textbf{(4-9)}$$

Measurement function 2:

$$CV_3 = \theta_0 + \theta_1 \cdot \omega_G + \theta_2 \cdot P + \theta_3 \cdot \Gamma \quad \textbf{(4-10)}$$

$$CV_4 = \theta_4 + \theta_5 \cdot \omega_G + \theta_6 \cdot P + \theta_7 \cdot \beta \quad \textbf{(4-11)}$$

According to the analysis presented in [19], CVs can be chosen to approximate NCO over the whole operating region by using regression or other function fitting method such as ANN. The general procedure consists on sampling the whole operation space using independently generated inputs and disturbances. When all measurements are obtained for all samples, the system behaviour is fitted using a linear or non-linear function, $\hat{x}_i = \varphi(y_i, \theta)$ by calculating the parameter θ in order to minimize expression (4-4).

The simulation procedure is exposed in section C.1. Then the data pre-processing and the CVs design by performing a least-square regression is presented in Appendices C.2 and C.3.

4.7 Resulting constrained self-optimizing control structure

The WT model block has two inputs or manipulated variables, generator torque and blade pitch. Two outputs are measured, generator speed and generator power. Wind speed is defined as a disturbance which is not directly measured. The resulting control structure is characterized by two cascade loops which perform a SOC control on generator torque and blade pitch.

Torque is regulated by implementing a PI control on generator power. At the first control section, speed measurement is given to the conditional block (Figure B-12), which adjusts the value depending on the control region (1,1 ½, 2, 2 ½) (section 4.5). This value is then read by the two SOC blocks:

$$\Gamma: \frac{dP}{d\Gamma} = 0 \tag{4-12}$$

$$P: \frac{dP}{d\Gamma} = 0 \tag{4-13}$$

The SOC block (4-12) delivers the torque corresponding to maximum power output at the current wind speed. This value is then given to the SOC block (4-13) which provides the power setpoint for the inner loop. The saturation block fixes the maximum power setpoint at a nominal rate of 5MW. This allows to fix the generator torque at a constant value during the second control section, where power is maintained constant. Simulink block diagrams of the SOC blocks (4-12) and (4-13) are shown in B.2.4 and B.2.5.

During the optimization region, pitch is controlled by the SOC block (4-14), which regulates blade pitch to maximize energy capture. The saturation block in the outer loop restricts the actuation of the PI control. The Simulink implementation is shown in B.2.6.

$$\beta : \frac{dP}{d\beta} = 0 \tag{4-14}$$

Above rated power (5MW), the PI action overrides the SOC block (4-14) actuation and regulates the blade pitch to positive values in order to reduce WT aerodynamic efficiency and maintain at nominal speed (1200 rpm).

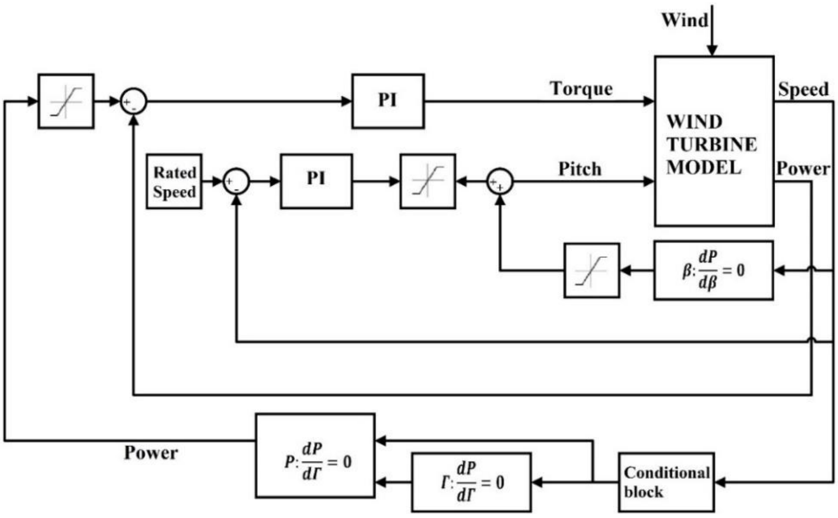

Figure 4-3 Block diagram of the constrained self-optimizing control structure

The Simulink diagram of the control structure is shown in Figure 4-4 and Figure B-10.

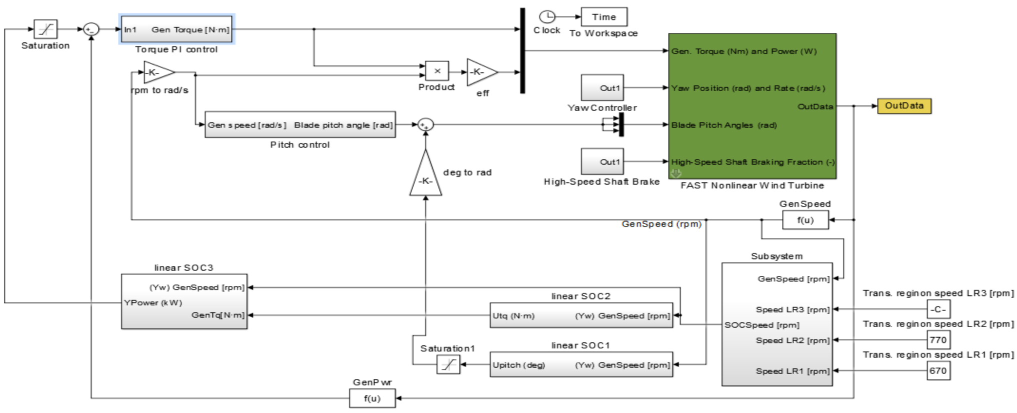

Figure 4-4 Simulink block diagram of the constrained SOC

The Simulink block diagram of the PI control for the generator torque is shown in Figure B-11. The PI control used for the blade pitch regulation when WT operates over rated power is the same as for the BC (Figure B-4 and Figure B-9).

5 RESULTS AND DISCUSSION

5.1 Controlled variables selection

As stated in section 4.6, two different measurement functions have been considered. First type of measurement function is required for the CV_1 (4-8) and CV_2 (4-9). The second measurement function is used for CV_3 (4-10).

As shown in section 4.7, the designed constrained SOC structure requires three different CVs to achieve the required control.

The two first control variables are obtained as stated in sections C.2 and C.3, since the only measurements required are generator torque and rotational speed.

$$CV_1 = -0.198297281 + 0.000442821 \cdot \omega_G - 0.000007996 \cdot \Gamma \quad \textbf{(5-1)}$$

$$CV_2 = 38.151847922 - 0.122050002 \cdot \omega_G - 45.786177285 \cdot \beta \quad \textbf{(5-2)}$$

The feedback control laws for torque and blade pitch used to achieve optimal operation are obtained by setting the CVs to zero.

$$\Gamma = -24800 + 55.3803 \cdot \omega_G \quad \textbf{(5-3)}$$

$$\beta = 0.8333 - 0.0026 \cdot \omega_G \quad \textbf{(5-4)}$$

In order to perform a constrained SOC, it is needed a third controlled variable used to determine the setpoint of the inner loop within the range of optimal operation. The input is the power regime needed to achieve an optimal operation. Therefore, the second measurement functions need to contain the generator power measurement.

$$\begin{aligned} CV_3 = 0.276306686 - 0.000209328 \cdot \omega_G + 0.000155259 \cdot P \\ - 0.000018256 \cdot \Gamma \end{aligned} \quad \textbf{(5-5)}$$

During maximum power operation the setpoint of the inner loop is given by the expression

$$P = -1779.65 + 1.3482 \cdot \omega_G + 0.1176 \cdot \Gamma \quad \textbf{(5-6)}$$

Table 5-1 shows the least-square error (R^2) for the regression corresponding to CV_1, CV_2 and CV_3.

Controlled Variables	CV expression	R^2
CV_1, CV_2	(4-8), (4-9)	0.697
CV_3	(4-10), (4-11)	0.797

Table 5-1 Least-square error for the CV resulting regressions

Additionally, there have been developed other regressions to test the fitting capability of other measurement functions.

CV expression	R^2
$CV_1 = \theta_0 + \theta_1 \cdot \omega_G + \theta_2 \cdot {\omega_G}^2 + \theta_3 \cdot \Gamma$ **(5-7)** $CV_2 = \theta_4 + \theta_5 \cdot \omega_G + \theta_6 \cdot {\omega_G}^2 + \theta_7 \cdot \beta$ **(5-8)**	0.764
$CV_1 = \theta_0 + \theta_1 \cdot \omega_G + \theta_2 \cdot P + \theta_3 \cdot {\omega_G}^2 + \theta_4 \cdot P^2 + \theta_5 \cdot P \cdot \omega_G + \theta_6 \cdot P \cdot {\omega_G}^2 + \theta_7 \cdot P^2 \cdot \omega_G + \theta_8 \cdot \Gamma$ **(5-9)** $CV_2 = \theta_9 + \theta_{10} \cdot \omega_G + \theta_{11} \cdot P + \theta_{12} \cdot {\omega_G}^2 + \theta_{13} \cdot P^2 + \theta_{14} \cdot P \cdot \omega_G + \theta_{15} \cdot P \cdot {\omega_G}^2 + \theta_{16} \cdot P^2 \cdot \omega_G + \theta_{17} \cdot \beta$ **(5-10)**	0.822
ANN (1 hidden layer with two neurons)	0.923

Table 5-2 Additional regressions to test the fitting capability of second order and ANN measurement functions

Even if measurement functions in Table 5-2 are obtained with lower least-square error, in this paper CVs are selected by using linear measurement functions in order to obtain a simple control law for the SOC system.

Moreover, second order polynomial measurement functions have not been implemented due to undesired control response. On the other hand, the implementation of a SOC using ANN is complex due to the lack of a global optimum.

Next, the performance of the proposed control structure is evaluated by comparing it with the BC (section 3 and B.1) at steady wind regimes and at turbulent low wind speed.

5.2 Results for steady wind speed

As shown in Figure 5-1, the steady state action of the proposed constrained SOC structure shows the desired response for the whole WT operating region.

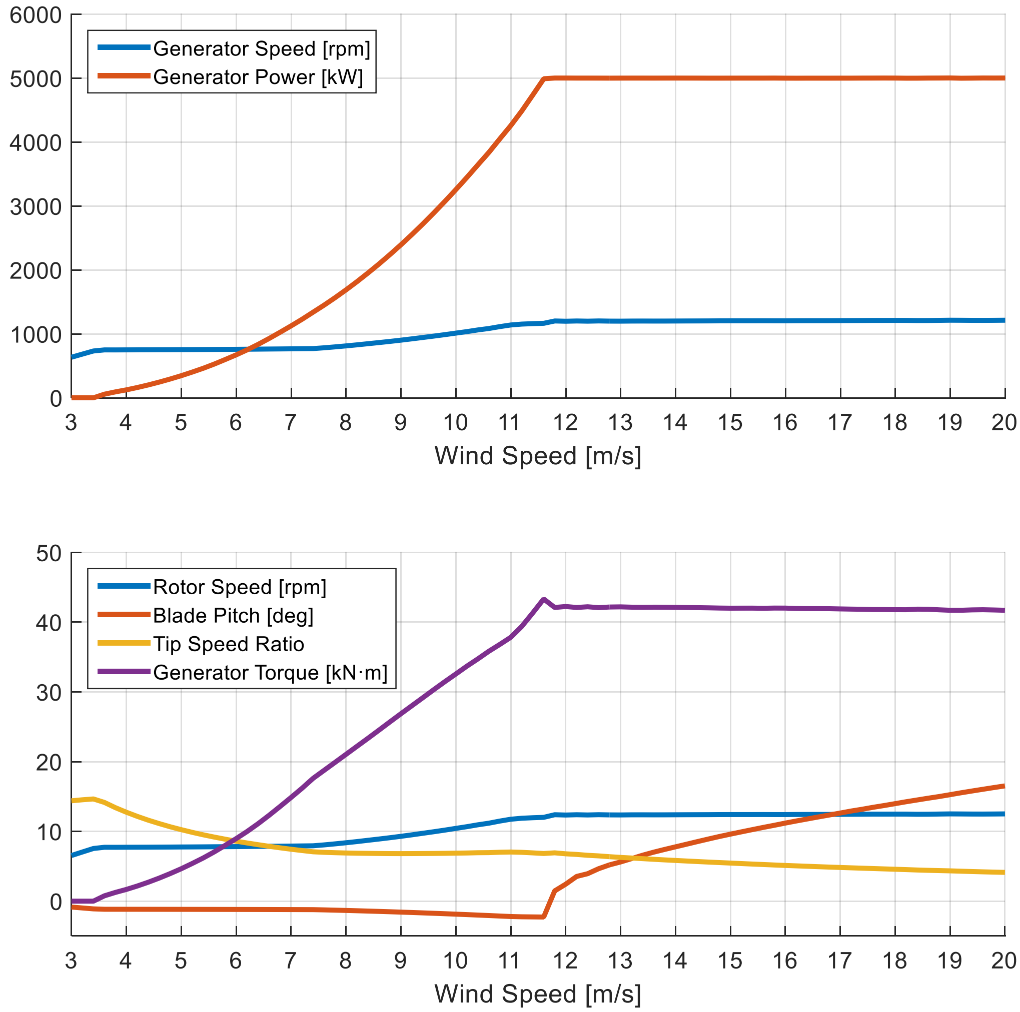

Figure 5-1 Steady-state response as a function of wind speed of the FAST 5MW wind turbine model implementing a constrained self-optimizing control.

Beyond nominal regime (1200rpm, 5MW), the conditional block adjusts the generator speed read by the SOC in order to perform control regions 1, 1 ½, 2, and 2 ½ (Section 3). During region 2, both blade pitch and generator torque are manipulated by the SOC in order to achieve maximum energy capture.

Figure 5-2 shows the CP versus blade pitch angle and TSR of the 5MW WT model for the wind speed range where power is maximized. The contour plot is illustrating the operational data obtained by running simulations (section C.1). As show in Figure 5-2, the maximum CP region is compressed for a blade pitch angle between -1 and -2 and a TSR ranged from 6.5 to 7.

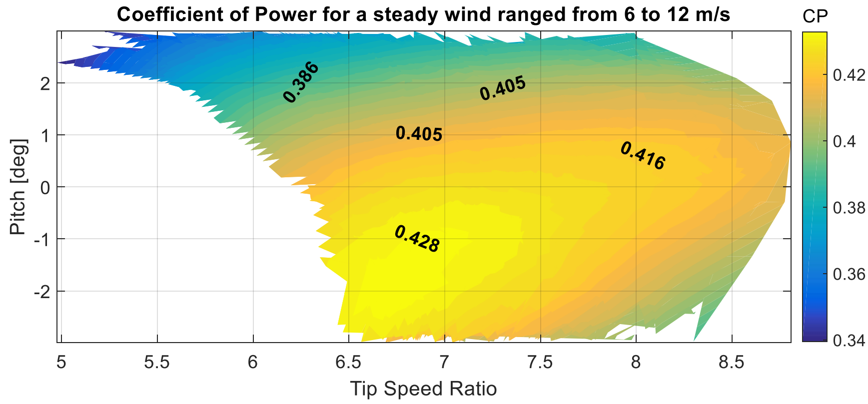

Figure 5-2 Coefficient of Power for a steady wind ranged from 6 to 12 m/s

The torque regulation performed by the SOC delivers a similar response compared with the deterministic BC. This is due to the fact that both control structures try to maintain an optimum TSR ranged between 6.5 and 7. While the BC structure has been designed focusing on keeping an optimal TSR (Appendix B.1.1), the SOC has learned by itself that this is the optimal solution.

However, by reviewing Figure 3-1 in section 3, the main difference that can be observed is that the proposed control structure makes use of the extra degree of freedom to maximize power during the first control section. The blade pitch is regulated to negative values ranged from -0.85° to -2.26°.

Instead, the BC structure operates the rotor with a constant blade pitch of 0°, as the loss of power due to this constraint is accepted in order to maintain the simplicity of the control structure. However, the great benefit of the SOC turns out to be that it is a simple control structure which is able to keep WT at optimal operation by manipulating both generator torque and blade pitch. This fact contradicts the common thought that the achievement of a control structure capable of operating with variable blade pitch without loss of power along the envelope of the CP-TSR characteristic, inevitably involves the implementation of a complex control structure (adaptive control approach) [1].

In order to evaluate the WT power output increase when implementing a SOC instead of a BC, the 5MW WT model has been tested for different wind speeds within region 2. The steady state power output for both control structures (SOC and BC) is exposed in Table 5-3. The power output increase in control region 2 ranges from 0.34 to 1.28 %.

Wind Speed (m/s)	Generator Power BC (kW)	Generator Power SOC (kW)	Power increase (%)
7,0	1117,43	1125,64	0,73
7,2	1217,90	1229,12	0,92
7,4	1322,64	1339,52	1,28
7,6	1432,66	1449,61	1,18
7,8	1549,06	1566,37	1,12
8,0	1670,47	1688,96	1,11
8,2	1798,39	1817,83	1,08
8,4	1931,05	1953,28	1,15
8,6	2072,58	2093,80	1,02
8,8	2218,18	2241,12	1,03
9,0	2372,29	2394,74	0,95
9,2	2531,38	2554,78	0,92
9,4	2697,20	2721,27	0,89
9,6	2871,93	2894,37	0,78
9,8	3049,88	3072,85	0,75
10,0	3236,72	3257,47	0,64
10,2	3431,47	3447,38	0,46
10,4	3631,35	3643,66	0,34

Table 5-3 Generator power increase with SOC with respect to BC

5.3 Results for turbulent low wind speed

The steady wind regime is just an idealisation to evaluate the steady state performance of the controller. In fact, the WT is constantly exposed to turbulent wind regimes. Thus, the performance of the proposed control structure is evaluated at turbulent wind speed.

Five turbulent wind input files have been created at average speeds contained within the optimal operating region. The turbulent wind input files creation is explained in section 2.1.

WT power generation is evaluated with both SOC and BC for the same wind speed files. The simulation time is 1300s, although the comparison is carried out avoiding the first 100s of simulation. This is done to avoid any outcome on the results due to the transitional period. The energy generated during this period is obtained by integrating the generator power output over time. The results are exposed in Table 5-4.

Average wind speed [m/s] of the turbulent wind input file	Energy capture with SOC [kJ]	Average power output for SOC (kW)	Energy capture with BC [kJ]	Average power output for BC (kW)	Energy capture increase [%]	Average power output increase (kW)
7.5	1780513.52	1483.761	1771633.15	1476.361	0.5	7.4
8	2142346.89	1785.289	2128426.81	1773.689	0.65	11.6
8.5	2550473.41	2125.394	2535149.56	2112.624	0.6	12.8
9	2987486.25	2489.572	2974047.12	2478.372	0.45	11.2
9.5	3564322.61	2970.269	3549302.30	2957.752	0.42	12.5

Table 5-4 Comparison of SOC versus BC for turbulent wind speed

Figure 5-3 and Figure 5-4 show the WT response for turbulent wind speed averaged at 7,5 and 8 m/s. In Appendix D is shown the performance for turbulent regimes at 8,5, 9 and 9,5 m/s.

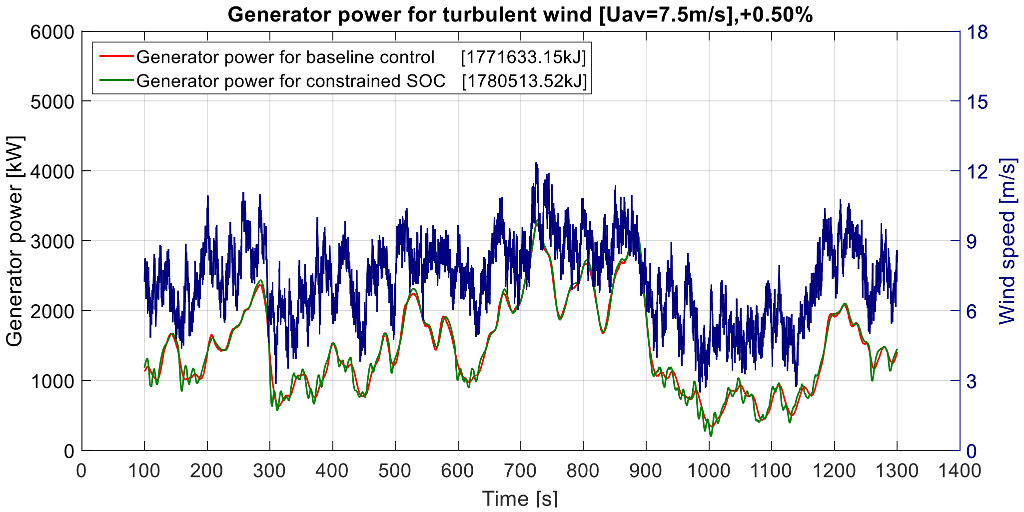

Figure 5-3 Simulation results of the WT generator power output implementing a BC versus SOC. Turbulent wind regime at average speed 7,5 m/s

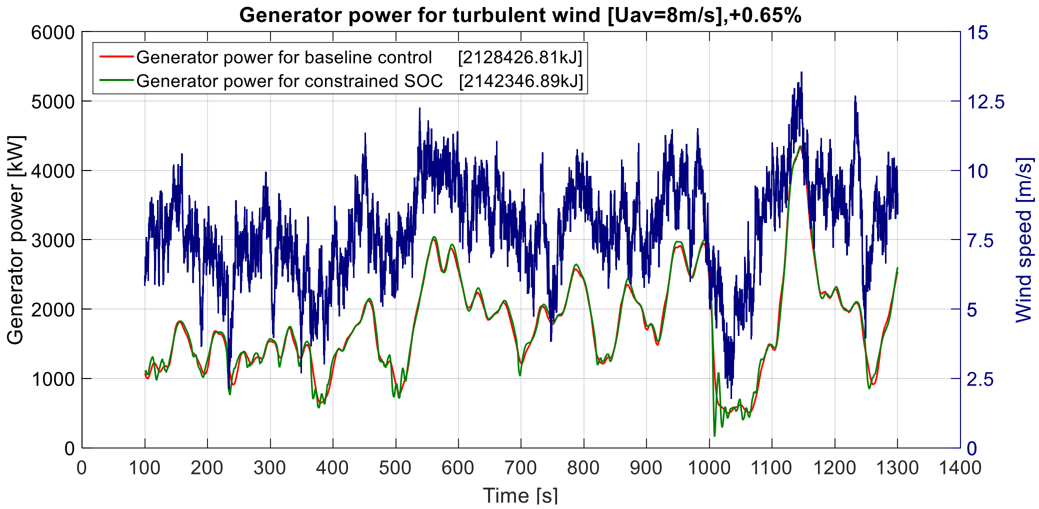

Figure 5-4 Simulation results of the WT generator power output implementing a BC versus SOC. Turbulent wind regime at average speed 8 m/s

In practice, when the WT operates at low turbulent wind regimes, the operating point is moving through the different control regions (1, 1 ½, 2, 2 ½ and 3). The real contribution of SOC is just limited to region 2, where WT is operated in order to maximize energy capture. That is way the average WT power output increase is lower compared to steady wind scenario (section 5.2).

When the turbulent wind average speed moves to values out of control region 2, the increase in energy capture decreases, as the time that the SOC is acting to keep the WT to optimal operation is being reduced.

Thereby, the SOC contribution on maximizing energy capture depends on the time that the wind turbine is operated in control region 2, and hence on the wind speed value over time. What's more, as illustrated in Table 5-3, even operating the WT at steady wind regimes, the increase in power output varies depending on where in region 2 the SOC is operating. As we go to wind speed values which are near the boundaries of the control region 2, the power increase is also being reduced.

As shown in Table 5-4, when comparing BC versus SOC performance, the higher energy capture increase is achieved for an average turbulent wind speed of 8.5 m/s (0.65% increase).

6 CONCLUSIONS

This project proves the benefit of employing the Self-Optimizing Control (SOC) approach for the wind turbine generator control. The potential of the SOC approach lies in the fact that it is not a deterministic control. Instead, it learns the structure of the optimal solution off-line and then performs the optimization strategy, adjusting both torque and pitch to overcome wind speed uncertainty.

The data collected from simulation to select the CVs has also been used to illustrate graphically the power regions of the WT. Figure 6-1 shows the power coefficient of the 5 MW WT vs TSR and pitch for a wind ranged from 6 to 12 m/s. The BC and SOC trajectories for the optimisation operation are illustrated as red and blue dots. The size of the markers symbolizes the increase in wind speed. The position in the contour plot illustrates the steady-state operating point.

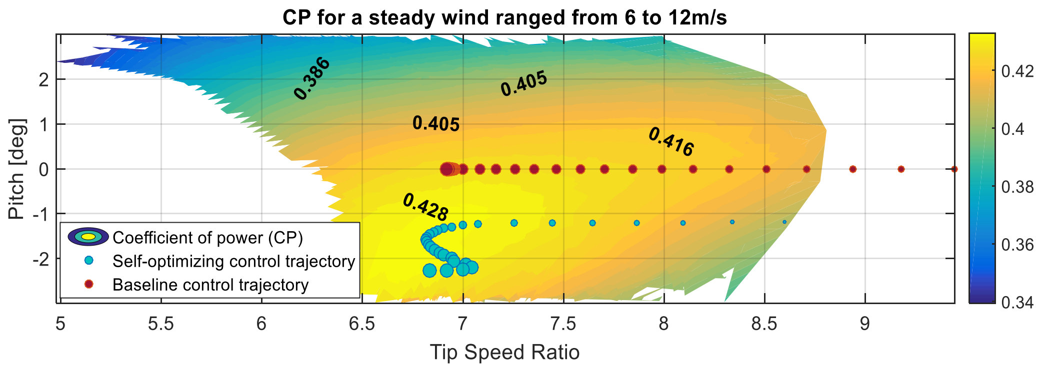

Figure 6-1 Comparison between BC and SOC trajectories for increasing wind ranged from 6 to 12 m/s

The deterministic behaviour of the BC can be noticed because of the straight trajectory that performs as blade pitch is fixed to 0º. This also limits the size of the operating region when trying to maximize power output as there is an important concentration of markers situated at the same TSR and pitch.

On the other hand, as the SOC is designed based on the previous knowledge of the structure of the optimal solution, the control laws used to regulate both pitch and torque perform an unpredictable trajectory which brings the WT operation to higher CP. The SOC structure is making use of both degrees of freedom to achieve optimal operation despite wind speed uncertainty.

Previous section 5.3 shows that power generation increases when operating at low turbulent wind speed. Although, it can seem that the power increase is negligible, we should focus on the fact that modern WTs are getting larger every time. As shown in Table 5-4, the average WT power output increase ranges from 7.4 to 12.8 kW. Considering that WT is working below rated power 50% of the time, it means an annual energy capture increase ranged from 32412 kWh to 56064 kWh. Assuming an annual average household electricity use in UK of 3300 kWh [20], the SOC implementation translates into covering the annual electricity demand of between 10 and 17 UK families, for each wind turbine.

7 FURTHER WORK

The benefits of SOC implementation on wind turbines is not just limited on the output power increase at low wind speed. The true potential of the SOC approach may deliver optimal operation in terms of other objective functions such as

- Considering load mitigations on the WT structure, reducing damaging fatigue loads [15].
- Controlling the power output in order to participate in frequency regulation for the utility grid [21].

In this project, the structure of the optimal solution for the WT maximum power operation is adjusted with a linear regression, since the CVs are defined as linear functions. As shown in section 5.1, the R^2 coefficient is relatively low. Further polynomial functions could be used to achieve a better adjustment of the CVs to the optimal solution, although the R^2 is still small for second order functions.

A real improvement is achieved by using cascade non-linear functions such as neural networks. In section 5.1, it can be seen that the adjustment achieved by a simple ANN with two neurons and one hidden layer is considerably higher compared to polynomial functions. The main disadvantage of using ANN as a fitting method is the fact that it is not a convex function, but it has many local optimums. This hinders the design of CVs using this kind of non-linear cascade fitting methods which, on the other hand, may adjust satisfactorily the control action to the real WT behavior.

Sampling data is also essential for the data-driven SOC approach. As exposed in Appendix C, operating data is obtained by running simulations of the FAST 5MW onshore WT model for different operating points near to the optimal solution. Even though, the number of samples is limited by the computational power. By using computers with faster processing speed, one could get much more operational data by dividing the disturbance range into much more sampling intervals.

What's more, the data-driven SOC allows a model free approach by obtaining operating data directly from the real system. This would require making the real

WT perform at different operating points in order to obtain a real representation of the system behavior and being able to obtain the structure of the optimal solution. The design of a data-driven SOC based on operational data from the real WT where the control is going to be implemented, undoubtedly entails significant advantages in terms of the control performance.

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APPENDICES

The next appendices complement the paper with additional information on:

- The FAST v8 input files needed to perform the MatLab simulations of the NREL 5MW wind turbine (Appendix A)
- The wind turbine baseline control exposed in [14], implemented as a Simulink block diagram (Appendix B).
- The constrained self-optimizing control implemented as a Simulink block diagram (Appendix B).
- The process of obtaining operational data by running simulations of the NREL 5MW wind turbine and then processing the data to design the controlled variables by performing a least-square regression (Appendix C).
- Additional figures evaluating the constrained self-optimizing control performance when comparing it with the baseline control, at low turbulent wind speed (Appendix D).

Appendix A

A.1 NREL 5MW Baseline Wind Turbine

A.1.1 Main input file

```
------- FAST v8.15.* INPUT FILE ----------------------------------------
-------
FAST Certification Test #18: NREL 5.0 MW Baseline Wind Turbine (Onshore)
---------------------- SIMULATION CONTROL -------------------------------
-------
false         Echo            - Echo input data to <RootName>.ech (flag)
"FATAL"       AbortLevel      - Error level when simulation should abort
(string) {"WARNING", "SEVERE", "FATAL"}
        60    TMax            - Total run time (s)
     0.005    DT              - Recommended module time step (s)
         2    InterpOrder     - Interpolation order for input/output time
history (-) {1=linear, 2=quadratic}
         0    NumCrctn        - Number of correction iterations (-)
{0=explicit calculation, i.e., no corrections}
     99999    DT_UJac         - Time between calls to get Jacobians (s)
     1E+06    UJacSclFact     - Scaling factor used in Jacobians (-)
---------------------- FEATURE SWITCHES AND FLAGS -----------------------
-------
         1    CompElast       - Compute structural dynamics (switch)
{1=ElastoDyn; 2=ElastoDyn + BeamDyn for blades}
         1    CompInflow      - Compute inflow wind velocities (switch)
{0=still air; 1=InflowWind; 2=external from OpenFOAM}
         2    CompAero        - Compute aerodynamic loads (switch)
{0=None; 1=AeroDyn v14; 2=AeroDyn v15}
         1    CompServo       - Compute control and electrical-drive
dynamics (switch) {0=None; 1=ServoDyn}
         0    CompHydro       - Compute hydrodynamic loads (switch)
{0=None; 1=HydroDyn}
         0    CompSub         - Compute sub-structural dynamics (switch)
{0=None; 1=SubDyn}
         0    CompMooring     - Compute mooring system (switch) {0=None;
1=MAP++; 2=FEAMooring; 3=MoorDyn; 4=OrcaFlex}
         0    CompIce         - Compute ice loads (switch) {0=None;
1=IceFloe; 2=IceDyn}
---------------------- INPUT FILES --------------------------------------
-------
"5MW_Baseline/NRELOffshrBsline5MW_Onshore_ElastoDyn.dat"    EDFile
- Name of file containing ElastoDyn input parameters (quoted string)
"5MW_Baseline/NRELOffshrBsline5MW_BeamDyn.dat"    BDBldFile(1)    - Name
of file containing BeamDyn input parameters for blade 1 (quoted string)
"5MW_Baseline/NRELOffshrBsline5MW_BeamDyn.dat"    BDBldFile(2)    - Name
of file containing BeamDyn input parameters for blade 2 (quoted string)
"5MW_Baseline/NRELOffshrBsline5MW_BeamDyn.dat"    BDBldFile(3)    - Name
of file containing BeamDyn input parameters for blade 3 (quoted string)
"5MW_Baseline/NRELOffshrBsline5MW_InflowWind_8mps.dat"    InflowFile
- Name of file containing inflow wind input parameters (quoted string)
"5MW_Baseline/NRELOffshrBsline5MW_Onshore_AeroDyn15.dat"    AeroFile
- Name of file containing aerodynamic input parameters (quoted string)
"5MW_Baseline/NRELOffshrBsline5MW_Onshore_ServoDyn.dat"    ServoFile
- Name of file containing control and electrical-drive input parameters
(quoted string)
"unused"      HydroFile       - Name of file containing hydrodynamic
input parameters (quoted string)
```

```
"unused"      SubFile         - Name of file containing sub-structural
input parameters (quoted string)
"unused"      MooringFile     - Name of file containing mooring system
input parameters (quoted string)
"unused"      IceFile         - Name of file containing ice input
parameters (quoted string)
---------------------- OUTPUT ------------------------------------------
-------
True          SumPrint        - Print summary data to "<RootName>.sum"
(flag)
          5   SttsTime        - Amount of time between screen status
messages (s)
      99999   ChkptTime       - Amount of time between creating
checkpoint files for potential restart (s)
"default"     DT_Out          - Time step for tabular output (s) (or
"default")
          0   TStart          - Time to begin tabular output (s)
          2   OutFileFmt      - Format for tabular (time-marching) output
file (switch) {1: text file [<RootName>.out], 2: binary file
[<RootName>.outb], 3: both}
True          TabDelim        - Use tab delimiters in text tabular output
file? (flag) {uses spaces if false}
"ES10.3E2"    OutFmt          - Format used for text tabular output,
excluding the time channel.  Resulting field should be 10 characters.
(quoted string)
---------------------- VISUALIZATION -----------------------------------
------
          0   WrVTK           - VTK visualization data output: (switch)
{0=none; 1=initialization data only; 2=animation}
          1   VTK_type        - Type of VTK visualization data: (switch)
{1=surfaces; 2=basic meshes (lines/points); 3=all meshes (debug)} [unused
if WrVTK=0]
true          VTK_fields      - Write mesh fields to VTK data files?
(flag) {true/false} [unused if WrVTK=0]
         15   VTK_fps         - Frame rate for VTK output (frames per
second){will use closest integer multiple of DT} [used only if WrVTK=2]
```

A.1.2 Aerodynamic input parameters

```
------- AERODYN v15.02.* INPUT FILE ------------------------------------
-----------
NREL 5.0 MW offshore baseline aerodynamic input properties.
======  General Options
========================================================================
===
False          Echo               - Echo the input to "<rootname>.AD.ech"?
(flag)
"default"      DTAero             - Time interval for aerodynamic
calculations {or "default"} (s)
         1    WakeMod             - Type of wake/induction model (switch)
{0=none, 1=BEMT}
         2    AFAeroMod           - Type of blade airfoil aerodynamics
model (switch) {1=steady model, 2=Beddoes-Leishman unsteady model}
         1    TwrPotent           - Type tower influence on wind based on
potential flow around the tower (switch) {0=none, 1=baseline potential
flow, 2=potential flow with Bak correction}
False          TwrShadow          - Calculate tower influence on wind
based on downstream tower shadow? (flag)
True           TwrAero            - Calculate tower aerodynamic loads?
(flag)
======  Environmental Conditions
==================================================================
      1.225   AirDens             - Air density (kg/m^3)
  1.464E-05   KinVisc             - Kinematic air viscosity (m^2/s)
        335   SpdSound            - Speed of sound (m/s)
======  Blade-Element/Momentum Theory Options
===================================================== [used only when
WakeMod=1]
         2    SkewMod             - Type of skewed-wake correction model
(switch) {1=uncoupled, 2=Pitt/Peters, 3=coupled} [used only when
WakeMod=1]
True           TipLoss            - Use the Prandtl tip-loss model? (flag)
[used only when WakeMod=1]
True           HubLoss            - Use the Prandtl hub-loss model? (flag)
[used only when WakeMod=1]
true           TanInd             - Include tangential induction in BEMT
calculations? (flag) [used only when WakeMod=1]
False          AIDrag             - Include the drag term in the axial-
induction calculation? (flag) [used only when WakeMod=1]
False          TIDrag             - Include the drag term in the
tangential-induction calculation? (flag) [used only when WakeMod=1 and
TanInd=TRUE]
"Default"      IndToler           - Convergence tolerance for BEMT
nonlinear solve residual equation {or "default"} (-) [used only when
WakeMod=1]
        100   MaxIter             - Maximum number of iteration steps (-)
[used only when WakeMod=1]
======  Beddoes-Leishman Unsteady Airfoil Aerodynamics Options
==================================== [used only when AFAeroMod=2]
         3    UAMod               - Unsteady Aero Model Switch (switch)
{1=Baseline model (Original), 2=Gonzalez's variant (changes in Cn,Cc,Cm),
3=Minemma/Pierce variant (changes in Cc and Cm)} [used only when
AFAeroMod=2]
```

```
True          FLookup           - Flag to indicate whether a lookup for
f' will be calculated (TRUE) or whether best-fit exponential equations
will be used (FALSE); if FALSE S1-S4 must be provided in airfoil input
files (flag) [used only when AFAeroMod=2]
======  Airfoil Information
=========================================================================
          1   InCol_Alfa        - The column in the airfoil tables that
contains the angle of attack (-)
          2   InCol_Cl          - The column in the airfoil tables that
contains the lift coefficient (-)
          3   InCol_Cd          - The column in the airfoil tables that
contains the drag coefficient (-)
          4   InCol_Cm          - The column in the airfoil tables that
contains the pitching-moment coefficient; use zero if there is no Cm
column (-)
          0   InCol_Cpmin       - The column in the airfoil tables that
contains the Cpmin coefficient; use zero if there is no Cpmin column (-)
          8   NumAFfiles        - Number of airfoil files used (-)
"Airfoils/Cylinder1.dat"    AFNames            - Airfoil file names
(NumAFfiles lines) (quoted strings)
"Airfoils/Cylinder2.dat"
"Airfoils/DU40_A17.dat"
"Airfoils/DU35_A17.dat"
"Airfoils/DU30_A17.dat"
"Airfoils/DU25_A17.dat"
"Airfoils/DU21_A17.dat"
"Airfoils/NACA64_A17.dat"
======  Rotor/Blade Properties
=====================================================================
True          UseBlCm           - Include aerodynamic pitching moment in
calculations?  (flag)
"NRELOffshrBsline5MW_AeroDyn_blade.dat"    ADBlFile(1)        - Name of
file containing distributed aerodynamic properties for Blade #1 (-)
"NRELOffshrBsline5MW_AeroDyn_blade.dat"    ADBlFile(2)        - Name of
file containing distributed aerodynamic properties for Blade #2 (-)
[unused if NumBl < 2]
"NRELOffshrBsline5MW_AeroDyn_blade.dat"    ADBlFile(3)        - Name of
file containing distributed aerodynamic properties for Blade #3 (-)
[unused if NumBl < 3]
======  Tower Influence and Aerodynamics
============================================================= [used only
when TwrPotent/=0, TwrShadow=True, or TwrAero=True]
         12   NumTwrNds        - Number of tower nodes used in the
analysis  (-) [used only when TwrPotent/=0, TwrShadow=True, or
TwrAero=True]
TwrElev        TwrDiam        TwrCd
(m)              (m)           (-)
0.0000000E+00  6.0000000E+00  1.0000000E+00
8.5261000E+00  5.7870000E+00  1.0000000E+00
1.7053000E+01  5.5740000E+00  1.0000000E+00
2.5579000E+01  5.3610000E+00  1.0000000E+00
3.4105000E+01  5.1480000E+00  1.0000000E+00
4.2633000E+01  4.9350000E+00  1.0000000E+00
5.1158000E+01  4.7220000E+00  1.0000000E+00
```

```
5.9685000E+01  4.5090000E+00  1.0000000E+00
6.8211000E+01  4.2960000E+00  1.0000000E+00
7.6738000E+01  4.0830000E+00  1.0000000E+00
8.5268000E+01  3.8700000E+00  1.0000000E+00
8.7600000E+01  3.8700000E+00  1.0000000E+00
======  Outputs
========================================================================
==========
True          SumPrint           - Generate a summary file listing input
options and interpolated properties to "<rootname>.AD.sum"?  (flag)
          0   NBlOuts            - Number of blade node outputs [0 - 9]
(-)
          1,          9,         19    BlOutNd             - Blade nodes
whose values will be output  (-)
          0   NTwOuts            - Number of tower node outputs [0 - 9]
(-)
          1,          2,          6    TwOutNd             - Tower nodes
whose values will be output  (-)
                   OutList           - The next line(s) contains a list
of output parameters.  See OutListParameters.xlsx for a listing of
available output channels, (-)
END of input file (the word "END" must appear in the first 3 columns of
this last OutList line)
------------------------------------------------------------------------
--------------
```

A.1.3 Control and electrical-drive input parameters

```
------- SERVODYN v1.05.* INPUT FILE ------------------------------------
-------
NREL 5.0 MW Baseline Wind Turbine for Use in Offshore Analysis.
Properties from Dutch Offshore Wind Energy Converter (DOWEC) 6MW Pre-
Design (10046_009.pdf) and REpower 5M 5MW (5m_uk.pdf)
---------------------- SIMULATION CONTROL ------------------------------
-------
False         Echo          - Echo input data to <RootName>.ech (flag)
"default"     DT            - Communication interval for controllers (s)
(or "default")
---------------------- PITCH CONTROL -----------------------------------
-------
          4   PCMode        - Pitch control mode {0: none, 3: user-defined
from routine PitchCntrl, 4: user-defined from Simulink/Labview, 5: user-
defined from Bladed-style DLL} (switch)
          0   TPCOn         - Time to enable active pitch control (s)
[unused when PCMode=0]
     9999.9   TPitManS(1)   - Time to start override pitch maneuver for
blade 1 and end standard pitch control (s)
     9999.9   TPitManS(2)   - Time to start override pitch maneuver for
blade 2 and end standard pitch control (s)
     9999.9   TPitManS(3)   - Time to start override pitch maneuver for
blade 3 and end standard pitch control (s) [unused for 2 blades]
          2   PitManRat(1) - Pitch rate at which override pitch maneuver
heads toward final pitch angle for blade 1 (deg/s)
          2   PitManRat(2) - Pitch rate at which override pitch maneuver
heads toward final pitch angle for blade 2 (deg/s)
          2   PitManRat(3) - Pitch rate at which override pitch maneuver
heads toward final pitch angle for blade 3 (deg/s) [unused for 2 blades]
          0   BlPitchF(1)   - Blade 1 final pitch for pitch maneuvers
(degrees)
          0   BlPitchF(2)   - Blade 2 final pitch for pitch maneuvers
(degrees)
          0   BlPitchF(3)   - Blade 3 final pitch for pitch maneuvers
(degrees) [unused for 2 blades]
---------------------- GENERATOR AND TORQUE CONTROL ---------------------
-------
          4   VSContrl      - Variable-speed control mode {0: none, 1:
simple VS, 3: user-defined from routine UserVSCont, 4: user-defined from
Simulink/Labview, 5: user-defined from Bladed-style DLL} (switch)
          1   GenModel      - Generator model {1: simple, 2: Thevenin, 3:
user-defined from routine UserGen} (switch) [used only when VSContrl=0]
       94.4   GenEff        - Generator efficiency [ignored by the
Thevenin and user-defined generator models] (%)
True          GenTiStr      - Method to start the generator {T: timed
using TimGenOn, F: generator speed using SpdGenOn} (flag)
True          GenTiStp      - Method to stop the generator {T: timed using
TimGenOf, F: when generator power = 0} (flag)
     9999.9   SpdGenOn      - Generator speed to turn on the generator for
a startup (HSS speed) (rpm) [used only when GenTiStr=False]
          0   TimGenOn      - Time to turn on the generator for a startup
(s) [used only when GenTiStr=True]
     9999.9   TimGenOf      - Time to turn off the generator (s) [used
only when GenTiStp=True]
```

```
---------------------- SIMPLE VARIABLE-SPEED TORQUE CONTROL -------------
-------
     9999.9   VS_RtGnSp    - Rated generator speed for simple variable-
speed generator control (HSS side) (rpm) [used only when VSContrl=1]
     9999.9   VS_RtTq      - Rated generator torque/constant generator
torque in Region 3 for simple variable-speed generator control (HSS side)
(N-m) [used only when VSContrl=1]
     9999.9   VS_Rgn2K     - Generator torque constant in Region 2 for
simple variable-speed generator control (HSS side) (N-m/rpm^2) [used only
when VSContrl=1]
     9999.9   VS_SlPc      - Rated generator slip percentage in Region 2
1/2 for simple variable-speed generator control (%) [used only when
VSContrl=1]
---------------------- SIMPLE INDUCTION GENERATOR -----------------------
-------
     1.5125   SIG_SlPc     - Rated generator slip percentage (%) [used
only when VSContrl=0 and GenModel=1]
     1200.0   SIG_SySp     - Synchronous (zero-torque) generator speed
(rpm) [used only when VSContrl=0 and GenModel=1]
      42149   SIG_RtTq     - Rated torque (N-m) [used only when
VSContrl=0 and GenModel=1]
          2   SIG_PORt     - Pull-out ratio (Tpullout/Trated) (-) [used
only when VSContrl=0 and GenModel=1]
---------------------- THEVENIN-EQUIVALENT INDUCTION GENERATOR ----------
-------
     9999.9   TEC_Freq     - Line frequency [50 or 60] (Hz) [used only
when VSContrl=0 and GenModel=2]
       9998   TEC_NPol     - Number of poles [even integer > 0] (-) [used
only when VSContrl=0 and GenModel=2]
     9999.9   TEC_SRes     - Stator resistance (ohms) [used only when
VSContrl=0 and GenModel=2]
     9999.9   TEC_RRes     - Rotor resistance (ohms) [used only when
VSContrl=0 and GenModel=2]
     9999.9   TEC_VLL      - Line-to-line RMS voltage (volts) [used only
when VSContrl=0 and GenModel=2]
     9999.9   TEC_SLR      - Stator leakage reactance (ohms) [used only
when VSContrl=0 and GenModel=2]
     9999.9   TEC_RLR      - Rotor leakage reactance (ohms) [used only
when VSContrl=0 and GenModel=2]
     9999.9   TEC_MR       - Magnetizing reactance (ohms) [used only when
VSContrl=0 and GenModel=2]
---------------------- HIGH-SPEED SHAFT BRAKE ---------------------------
-------
          0   HSSBrMode    - HSS brake model {0: none, 1: simple, 3:
user-defined from routine UserHSSBr, 4: user-defined from
Simulink/Labview, 5: user-defined from Bladed-style DLL} (switch)
     9999.9   THSSBrDp     - Time to initiate deployment of the HSS brake
(s)
        0.6   HSSBrDT      - Time for HSS-brake to reach full deployment
once initiated (sec) [used only when HSSBrMode=1]
    28116.2   HSSBrTqF     - Fully deployed HSS-brake torque (N-m)
---------------------- NACELLE-YAW CONTROL ------------------------------
-------
```

```
          0   YCMode        - Yaw control mode {0: none, 3: user-defined
from routine UserYawCont, 4: user-defined from Simulink/Labview, 5: user-
defined from Bladed-style DLL} (switch)
     9999.9   TYCOn         - Time to enable active yaw control (s)
[unused when YCMode=0]
          0   YawNeut       - Neutral yaw position--yaw spring force is
zero at this yaw (degrees)
9.02832E+09   YawSpr        - Nacelle-yaw spring constant (N-m/rad)
  1.916E+07   YawDamp       - Nacelle-yaw damping constant (N-m/(rad/s))
     9999.9   TYawManS      - Time to start override yaw maneuver and end
standard yaw control (s)
          2   YawManRat     - Yaw maneuver rate (in absolute value)
(deg/s)
          0   NacYawF       - Final yaw angle for override yaw maneuvers
(degrees)
---------------------- TUNED MASS DAMPER --------------------------------
-------
False         CompNTMD      - Compute nacelle tuned mass damper
{true/false} (flag)
"NRELOffshrBsline5MW_ServoDyn_TMD.dat"    NTMDfile     - Name of the file
for nacelle tuned mass damper (quoted string) [unused when CompNTMD is
false]
False         CompTTMD      - Compute tower tuned mass damper {true/false}
(flag)
"NRELOffshrBsline5MW_ServoDyn_TMD.dat"    TTMDfile     - Name of the file
for tower tuned mass damper (quoted string) [unused when CompTTMD is
false]
---------------------- BLADED INTERFACE ---------------------------------
------- [used only with Bladed Interface]
"ServoData/DISCON_win32.dll"    DLL_FileName - Name/location of the
dynamic library {.dll [Windows] or .so [Linux]} in the Bladed-DLL format
(-) [used only with Bladed Interface]
"DISCON.IN"    DLL_InFile    - Name of input file sent to the DLL (-)
[used only with Bladed Interface]
"DISCON"      DLL_ProcName - Name of procedure in DLL to be called (-)
[case sensitive; used only with DLL Interface]
"default"     DLL_DT        - Communication interval for dynamic library
(s) (or "default") [used only with Bladed Interface]
false         DLL_Ramp      - Whether a linear ramp should be used between
DLL_DT time steps [introduces time shift when true] (flag) [used only
with Bladed Interface]
     9999.9   BPCutoff      - Cuttoff frequency for low-pass filter on
blade pitch from DLL (Hz) [used only with Bladed Interface]
          0   NacYaw_North - Reference yaw angle of the nacelle when the
upwind end points due North (deg) [used only with Bladed Interface]
          0   Ptch_Cntrl    - Record 28: Use individual pitch control {0:
collective pitch; 1: individual pitch control} (switch) [used only with
Bladed Interface]
          0   Ptch_SetPnt   - Record  5: Below-rated pitch angle set-point
(deg) [used only with Bladed Interface]
          0   Ptch_Min      - Record  6: Minimum pitch angle (deg) [used
only with Bladed Interface]
          0   Ptch_Max      - Record  7: Maximum pitch angle (deg) [used
only with Bladed Interface]
```

```
          0    PtchRate_Min - Record  8: Minimum pitch rate (most negative
value allowed) (deg/s) [used only with Bladed Interface]
          0    PtchRate_Max - Record  9: Maximum pitch rate  (deg/s) [used
only with Bladed Interface]
          0    Gain_OM      - Record 16: Optimal mode gain (Nm/(rad/s)^2)
[used only with Bladed Interface]
          0    GenSpd_MinOM - Record 17: Minimum generator speed (rpm)
[used only with Bladed Interface]
          0    GenSpd_MaxOM - Record 18: Optimal mode maximum speed (rpm)
[used only with Bladed Interface]
          0    GenSpd_Dem   - Record 19: Demanded generator speed above
rated (rpm) [used only with Bladed Interface]
          0    GenTrq_Dem   - Record 22: Demanded generator torque above
rated (Nm) [used only with Bladed Interface]
          0    GenPwr_Dem   - Record 13: Demanded power (W) [used only
with Bladed Interface]
---------------------- BLADED INTERFACE TORQUE-SPEED LOOK-UP TABLE ------
-------
          0    DLL_NumTrq   - Record 26: No. of points in torque-speed
look-up table {0 = none and use the optimal mode parameters; nonzero =
ignore the optimal mode PARAMETERs by setting Record 16 to 0.0} (-) [used
only with Bladed Interface]
 GenSpd_TLU    GenTrq_TLU
  (rpm)          (Nm)
---------------------- OUTPUT ------------------------------------------
-------
True           SumPrint     - Print summary data to <RootName>.sum (flag)
(currently unused)
          1    OutFile      - Switch to determine where output will be
placed: {1: in module output file only; 2: in glue code output file only;
3: both} (currently unused)
True           TabDelim     - Use tab delimiters in text tabular output
file? (flag) (currently unused)
"ES10.3E2"     OutFmt       - Format used for text tabular output (except
time).  Resulting field should be 10 characters. (quoted string)
(currently unused)
          0    TStart       - Time to begin tabular output (s) (currently
unused)
               OutList      - The next line(s) contains a list of output
parameters.  See OutListParameters.xlsx for a listing of available output
channels, (-)
"GenPwr"                   - Electrical generator power and torque
"GenTq"                    - Electrical generator power and torque
"BlPitchC1"
"BlPitchC2"
"BlPitchC3"
END of input file (the word "END" must appear in the first 3 columns of
this last OutList line)
-------------------------------------------------------------------------
--------------
```

A.1.4 Structural input parameters

```
------- ELASTODYN v1.03.* INPUT FILE -----------------------------------
-------
NREL 5.0 MW Baseline Wind Turbine for Use in Offshore Analysis.
Properties from Dutch Offshore Wind Energy Converter (DOWEC) 6MW Pre-
Design (10046_009.pdf) and REpower 5M 5MW (5m_uk.pdf)
---------------------- SIMULATION CONTROL ------------------------------
-------
False         Echo        - Echo input data to "<RootName>.ech" (flag)
          3   Method      - Integration method: {1: RK4, 2: AB4, or 3:
ABM4} (-)
"DEFAULT"     DT          - Integration time step (s)
---------------------- ENVIRONMENTAL CONDITION -------------------------
-------
    9.80665   Gravity     - Gravitational acceleration (m/s^2)
---------------------- DEGREES OF FREEDOM ------------------------------
-------
True          FlapDOF1    - First flapwise blade mode DOF (flag)
True          FlapDOF2    - Second flapwise blade mode DOF (flag)
True          EdgeDOF     - First edgewise blade mode DOF (flag)
False         TeetDOF     - Rotor-teeter DOF (flag) [unused for 3 blades]
True          DrTrDOF     - Drivetrain rotational-flexibility DOF (flag)
True          GenDOF      - Generator DOF (flag)
True          YawDOF      - Yaw DOF (flag)
True          TwFADOF1    - First fore-aft tower bending-mode DOF (flag)
True          TwFADOF2    - Second fore-aft tower bending-mode DOF (flag)
True          TwSSDOF1    - First side-to-side tower bending-mode DOF
(flag)
True          TwSSDOF2    - Second side-to-side tower bending-mode DOF
(flag)
False         PtfmSgDOF   - Platform horizontal surge translation DOF
(flag)
False         PtfmSwDOF   - Platform horizontal sway translation DOF
(flag)
False         PtfmHvDOF   - Platform vertical heave translation DOF
(flag)
False         PtfmRDOF    - Platform roll tilt rotation DOF (flag)
False         PtfmPDOF    - Platform pitch tilt rotation DOF (flag)
False         PtfmYDOF    - Platform yaw rotation DOF (flag)
---------------------- INITIAL CONDITIONS ------------------------------
-------
          0   OoPDefl     - Initial out-of-plane blade-tip displacement
(meters)
          0   IPDefl      - Initial in-plane blade-tip deflection
(meters)
          0   BlPitch(1)  - Blade 1 initial pitch (degrees)
          0   BlPitch(2)  - Blade 2 initial pitch (degrees)
          0   BlPitch(3)  - Blade 3 initial pitch (degrees) [unused for 2
blades]
          0   TeetDefl    - Initial or fixed teeter angle (degrees)
[unused for 3 blades]
          0   Azimuth     - Initial azimuth angle for blade 1 (degrees)
          8   RotSpeed    - Initial or fixed rotor speed (rpm)
          0   NacYaw      - Initial or fixed nacelle-yaw angle (degrees)
```

```
         0   TTDspFA     - Initial fore-aft tower-top displacement
(meters)
         0   TTDspSS     - Initial side-to-side tower-top displacement
(meters)
         0   PtfmSurge   - Initial or fixed horizontal surge
translational displacement of platform (meters)
         0   PtfmSway    - Initial or fixed horizontal sway
translational displacement of platform (meters)
         0   PtfmHeave   - Initial or fixed vertical heave translational
displacement of platform (meters)
         0   PtfmRoll    - Initial or fixed roll tilt rotational
displacement of platform (degrees)
         0   PtfmPitch   - Initial or fixed pitch tilt rotational
displacement of platform (degrees)
         0   PtfmYaw     - Initial or fixed yaw rotational displacement
of platform (degrees)
---------------------- TURBINE CONFIGURATION ----------------------------
-------
         3   NumBl       - Number of blades (-)
        63   TipRad      - The distance from the rotor apex to the blade
tip (meters)
       1.5   HubRad      - The distance from the rotor apex to the blade
root (meters)
      -2.5   PreCone(1)  - Blade 1 cone angle (degrees)
      -2.5   PreCone(2)  - Blade 2 cone angle (degrees)
      -2.5   PreCone(3)  - Blade 3 cone angle (degrees) [unused for 2
blades]
         0   HubCM       - Distance from rotor apex to hub mass
[positive downwind] (meters)
         0   UndSling    - Undersling length [distance from teeter pin
to the rotor apex] (meters) [unused for 3 blades]
         0   Delta3      - Delta-3 angle for teetering rotors (degrees)
[unused for 3 blades]
         0   AzimB1Up    - Azimuth value to use for I/O when blade 1
points up (degrees)
   -5.0191   OverHang    - Distance from yaw axis to rotor apex [3
blades] or teeter pin [2 blades] (meters)
     1.912   ShftGagL    - Distance from rotor apex [3 blades] or teeter
pin [2 blades] to shaft strain gages [positive for upwind rotors]
(meters)
        -5   ShftTilt    - Rotor shaft tilt angle (degrees)
       1.9   NacCMxn     - Downwind distance from the tower-top to the
nacelle CM (meters)
         0   NacCMyn     - Lateral  distance from the tower-top to the
nacelle CM (meters)
      1.75   NacCMzn     - Vertical distance from the tower-top to the
nacelle CM (meters)
  -3.09528   NcIMUxn     - Downwind distance from the tower-top to the
nacelle IMU (meters)
         0   NcIMUyn     - Lateral  distance from the tower-top to the
nacelle IMU (meters)
   2.23336   NcIMUzn     - Vertical distance from the tower-top to the
nacelle IMU (meters)
```

```
    1.96256   Twr2Shft     - Vertical distance from the tower-top to the
rotor shaft (meters)
      87.6    TowerHt      - Height of tower above ground level [onshore]
or MSL [offshore] (meters)
         0    TowerBsHt    - Height of tower base above ground level
[onshore] or MSL [offshore] (meters)
         0    PtfmCMxt     - Downwind distance from the ground level
[onshore] or MSL [offshore] to the platform CM (meters)
         0    PtfmCMyt     - Lateral distance from the ground level
[onshore] or MSL [offshore] to the platform CM (meters)
         0    PtfmCMzt     - Vertical distance from the ground level
[onshore] or MSL [offshore] to the platform CM (meters)
         0    PtfmRefzt    - Vertical distance from the ground level
[onshore] or MSL [offshore] to the platform reference point (meters)
---------------------- MASS AND INERTIA ----------------------------------
-------
         0    TipMass(1)   - Tip-brake mass, blade 1 (kg)
         0    TipMass(2)   - Tip-brake mass, blade 2 (kg)
         0    TipMass(3)   - Tip-brake mass, blade 3 (kg) [unused for 2
blades]
     56780    HubMass      - Hub mass (kg)
    115926    HubIner      - Hub inertia about rotor axis [3 blades] or
teeter axis [2 blades] (kg m^2)
   534.116    GenIner      - Generator inertia about HSS (kg m^2)
    240000    NacMass      - Nacelle mass (kg)
2.60789E+06   NacYIner     - Nacelle inertia about yaw axis (kg m^2)
         0    YawBrMass    - Yaw bearing mass (kg)
         0    PtfmMass     - Platform mass (kg)
         0    PtfmRIner    - Platform inertia for roll tilt rotation about
the platform CM (kg m^2)
         0    PtfmPIner    - Platform inertia for pitch tilt rotation
about the platform CM (kg m^2)
         0    PtfmYIner    - Platform inertia for yaw rotation about the
platform CM (kg m^2)
---------------------- BLADE ---------------------------------------------
-------
        17    BldNodes     - Number of blade nodes (per blade) used for
analysis (-)
"NRELOffshrBsline5MW_Blade.dat"    BldFile(1)  - Name of file containing
properties for blade 1 (quoted string)
"NRELOffshrBsline5MW_Blade.dat"    BldFile(2)  - Name of file containing
properties for blade 2 (quoted string)
"NRELOffshrBsline5MW_Blade.dat"    BldFile(3)  - Name of file containing
properties for blade 3 (quoted string) [unused for 2 blades]
---------------------- ROTOR-TEETER --------------------------------------
-------
         0    TeetMod      - Rotor-teeter spring/damper model {0: none, 1:
standard, 2: user-defined from routine UserTeet} (switch) [unused for 3
blades]
         0    TeetDmpP     - Rotor-teeter damper position (degrees) [used
only for 2 blades and when TeetMod=1]
         0    TeetDmp      - Rotor-teeter damping constant (N-m/(rad/s))
[used only for 2 blades and when TeetMod=1]
```

```
          0   TeetCDmp    - Rotor-teeter rate-independent Coulomb-damping
moment (N-m) [used only for 2 blades and when TeetMod=1]
          0   TeetSStP    - Rotor-teeter soft-stop position (degrees)
[used only for 2 blades and when TeetMod=1]
          0   TeetHStP    - Rotor-teeter hard-stop position (degrees)
[used only for 2 blades and when TeetMod=1]
          0   TeetSSSp    - Rotor-teeter soft-stop linear-spring constant
(N-m/rad) [used only for 2 blades and when TeetMod=1]
          0   TeetHSSp    - Rotor-teeter hard-stop linear-spring constant
(N-m/rad) [used only for 2 blades and when TeetMod=1]
---------------------- DRIVETRAIN ----------------------------------------
-------
        100   GBoxEff     - Gearbox efficiency (%)
         97   GBRatio     - Gearbox ratio (-)
8.67637E+08   DTTorSpr    - Drivetrain torsional spring (N-m/rad)
  6.215E+06   DTTorDmp    - Drivetrain torsional damper (N-m/(rad/s))
---------------------- FURLING -------------------------------------------
-------
False         Furling     - Read in additional model properties for
furling turbine (flag) [must currently be FALSE)
"unused"      FurlFile    - Name of file containing furling properties
(quoted string) [unused when Furling=False]
---------------------- TOWER ---------------------------------------------
-------
         20   TwrNodes    - Number of tower nodes used for analysis (-)
"NRELOffshrBsline5MW_Onshore_ElastoDyn_Tower.dat"    TwrFile     - Name
of file containing tower properties (quoted string)
---------------------- OUTPUT --------------------------------------------
-------
True          SumPrint    - Print summary data to "<RootName>.sum" (flag)
          1   OutFile     - Switch to determine where output will be
placed: {1: in module output file only; 2: in glue code output file only;
3: both} (currently unused)
True          TabDelim    - Use tab delimiters in text tabular output
file? (flag) (currently unused)
"ES10.3E2"    OutFmt      - Format used for text tabular output (except
time).  Resulting field should be 10 characters. (quoted string)
(currently unused)
          0   TStart      - Time to begin tabular output (s) (currently
unused)
          1   DecFact     - Decimation factor for tabular output {1:
output every time step} (-) (currently unused)
          0   NTwGages    - Number of tower nodes that have strain gages
for output [0 to 9] (-)
        10,         19,         28    TwrGagNd    - List of tower nodes
that have strain gages [1 to TwrNodes] (-) [unused if NTwGages=0]
          3   NBlGages    - Number of blade nodes that have strain gages
for output [0 to 9] (-)
          5,          9,         13    BldGagNd    - List of blade nodes
that have strain gages [1 to BldNodes] (-) [unused if NBlGages=0]
              OutList     - The next line(s) contains a list of output
parameters.  See OutListParameters.xlsx for a listing of available output
channels, (-)
```

Appendix B

B.1 Baseline Control

B.1.1 MatLab Simulink implementation of a baseline dynamic control for wind turbine operation

The torque control is implemented in Simulink as shown in the diagram below (Figure B-1 and Figure B-7). Measured generator speed is passed through a low pass filter. Then, conditional blocks are used to select the torque operating region (1, 1 ½ , 2 or 2 ½) depending on generator speed. The third branch in descending order corresponds to region 2, where power output is maximized. Finally, torque variation rate is controlled by the scheme shown in Figure B-2 and Figure B-8.

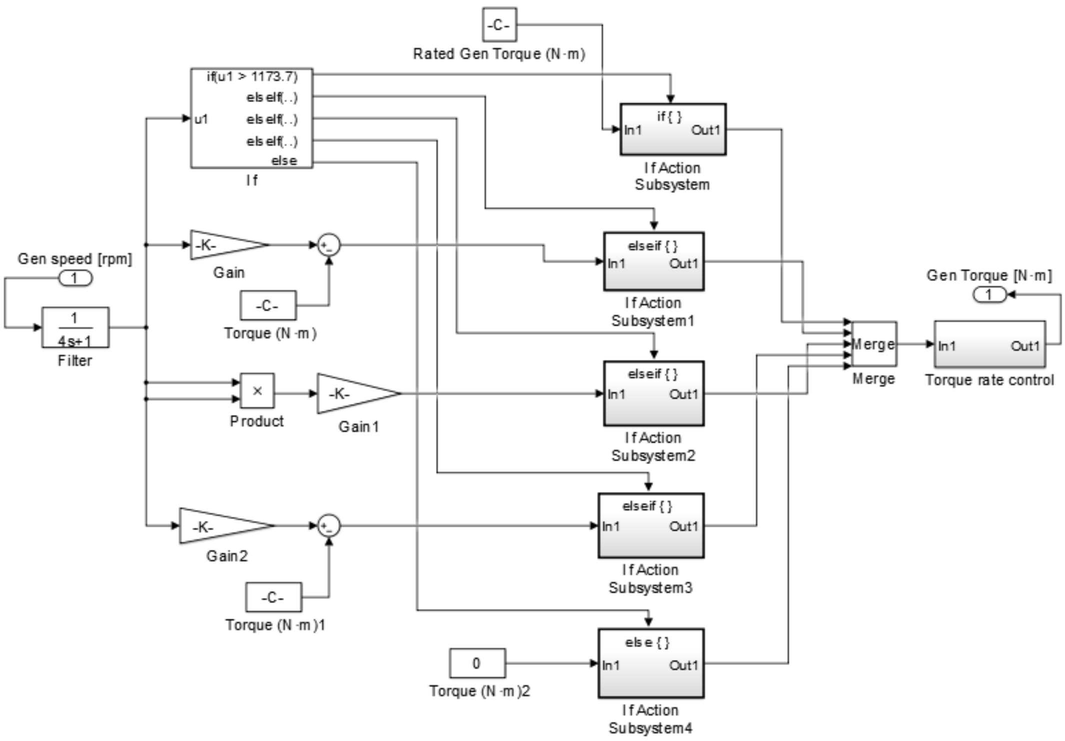

Figure B-1 Simulink block diagram of the baseline torque control

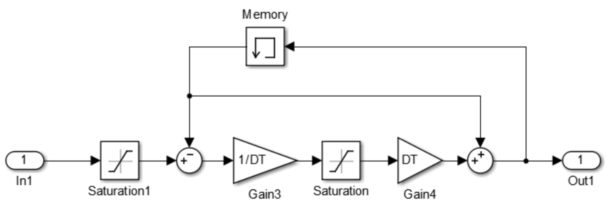

Figure B-2 Simulink diagram of the torque rate control

The peak power coefficient and tip speed ratio (λ_{opt}) at C_{pmax} is obtained as explained in [14]. The aerodynamic FAST module (AeroDyn) is driven as a standalone code to compute WT aerodynamic response in terms of coefficient of power at a number of given rotor speeds and blade-pitch angles for a constant wind speed of 8 m/s. The resulting surface is illustrated in Figure B-3. It is also specified the TSR corresponding to the maximum CP (C_{pmax}) at 0° pitch angle (λ_{opt}).

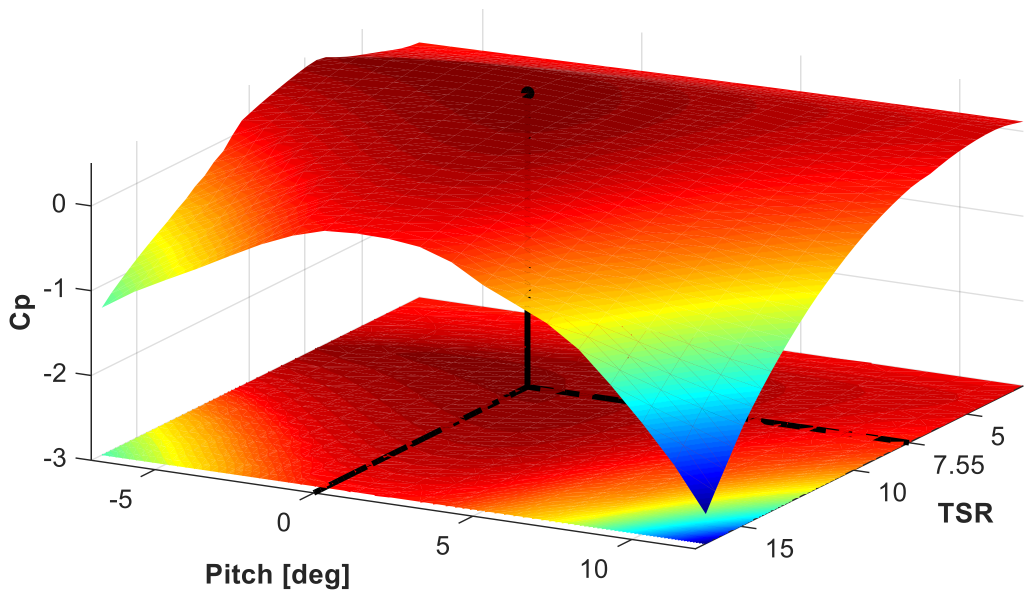

Figure B-3 Cp versus TSR and pitch for the 5MW wind turbine model

As exposed in [15], the gain law to track optimal torque used for Region 2 can be expressed as shown in

$$\Gamma_{R2} = k \cdot {\omega_G}^2 \quad \textbf{(0-1)}$$

where the generator torque varies as the square of the generator speed (expressed on the HSS side of the gearbox and in rpm). The generator-torque constant is calculated in

$$k = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^5 \cdot \frac{C_{pmax}}{\lambda_{opt}} \cdot \frac{1}{N_g^3} \cdot \left(\frac{\pi}{30}\right)^2 \quad \textbf{(0-2)}$$

Here, ρ is the density of air (1.225 kg/m^3), R is the rotor radius (63 m) and N_g is the gearbox ratio (97).

In region 2, blade pitch is not regulated to maximize power. Instead, it is fixed at the reference angle 0°. But at high wind speed, blade pitch is controlled to reduce aerodynamic torque and maintain the generator speed at the rated value. Figure B-4 shows the baseline pitch control diagram implemented in Simulink. To ease the comparison of the SOC with the BC presented in [14], it is assumed a generator nominal speed of 1200 rpm, corresponding to the synchronous velocity for a grid frequency of 60 Hz.

To compensate the negative error accumulation of the integrator while WT is not working in region 3, it has been implemented an anti-wind up control (green block in Figure B-4 and Figure B-9), as exposed in [15]. The blue blocks shown in Figure B-4 correspond to the non-linear compensation of the PI pitch control shown in [14]. Red blocks are the pitch rate implementation.

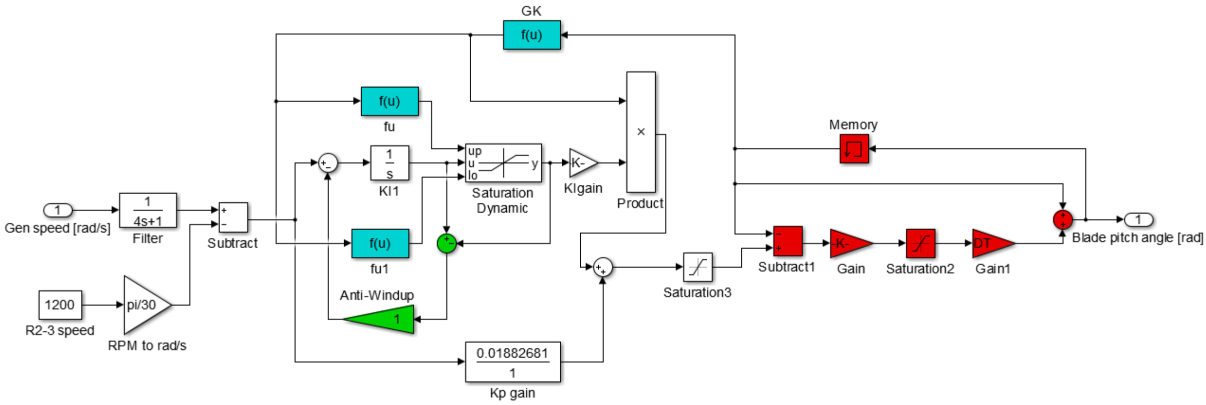

Figure B-4 Simulink block diagram of the pitch baseline control

The complete Simulink implementation of the BC on the FAST 5 MW WT model is shown in Figure B-5 and Figure B-6.

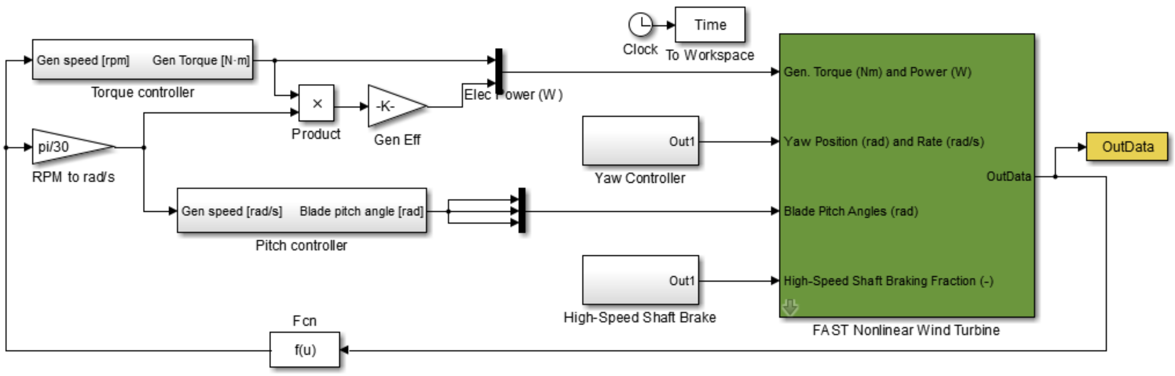

Figure B-5 Simulink block diagram of the baseline control implemented on FAST 5MW onshore wind turbine model

B.1.2 Simulink block diagram of a pitch and torque baseline control

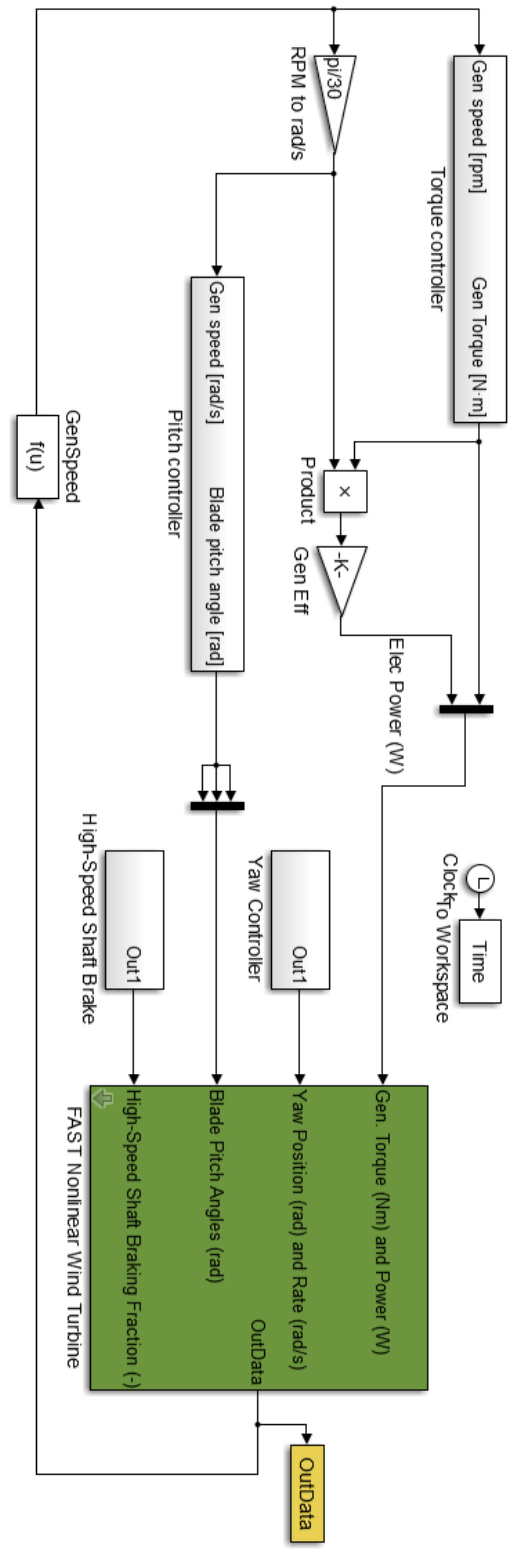

Figure B-6 Simulink block diagram of a pitch and torque baseline control

B.1.3 Simulink block diagram of the baseline torque control

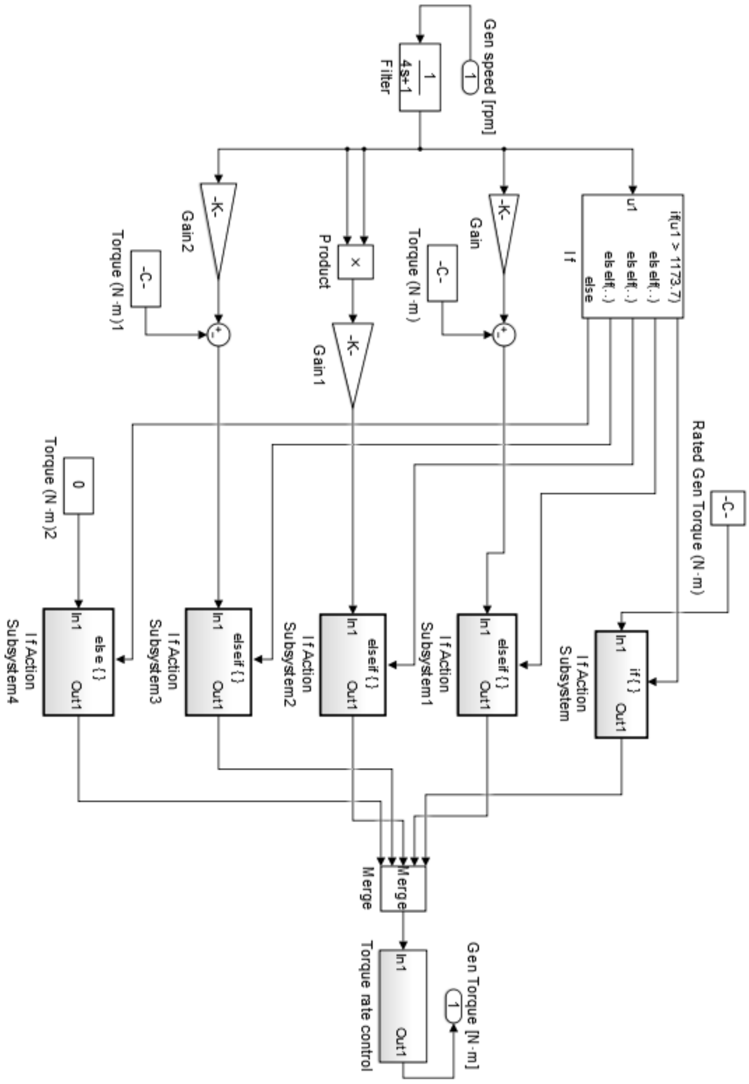

Figure B-7 Simulink block diagram of the baseline torque control

B.1.4 Simulink diagram of the torque rate control

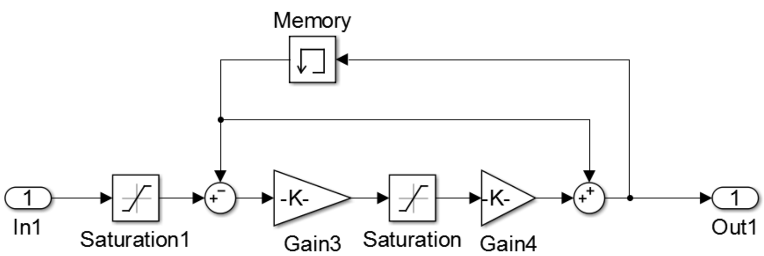

Figure B-8 Simulink diagram of the torque rate control

B.1.5 Simulink block diagram of the pitch baseline control

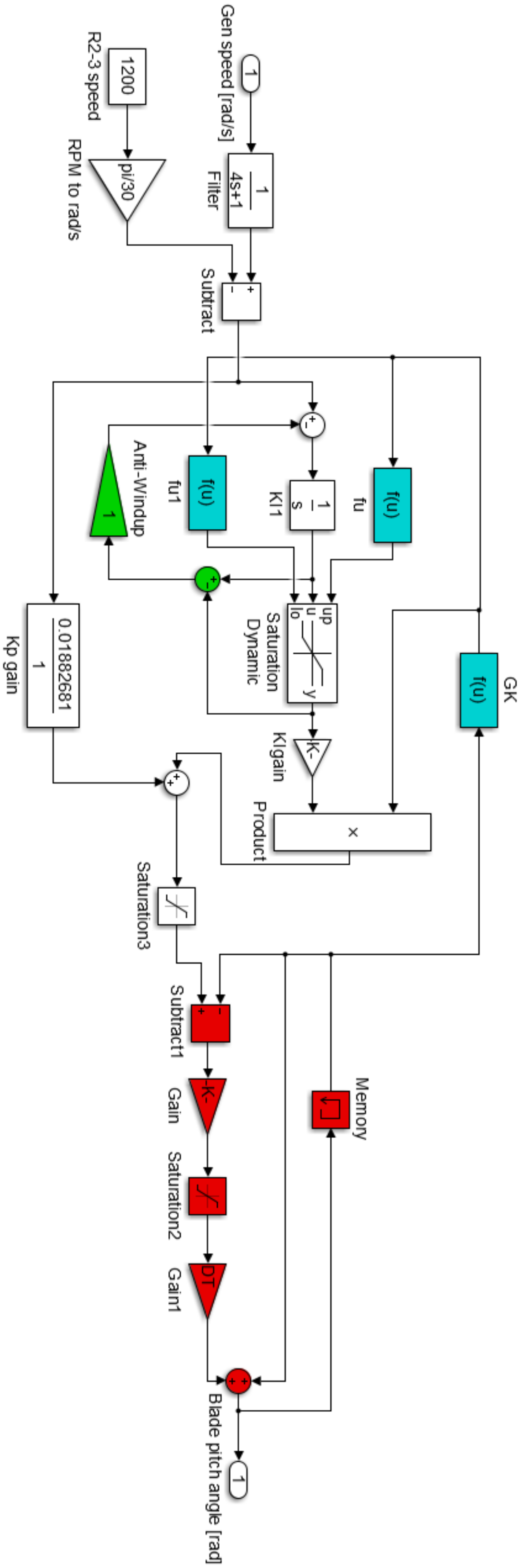

Figure B-9 Simulink block diagram of the pitch baseline control

B.2 Constrained Self-Optimizing Control

B.2.1 Simulink block diagram of a pitch and torque self-optimizing control

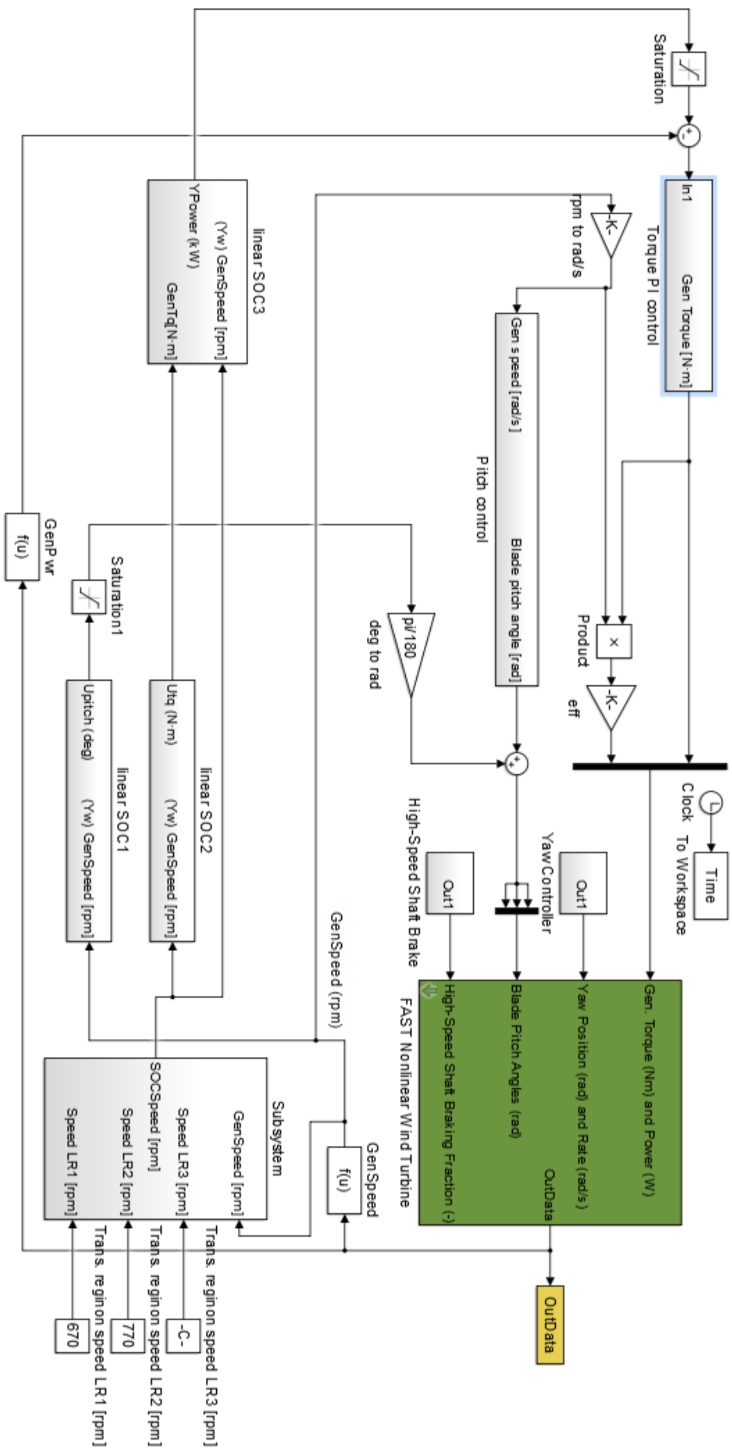

Figure B-10 Simulink block diagram of a pitch and torque self-optimizing control

B.2.2 Generator torque PI control

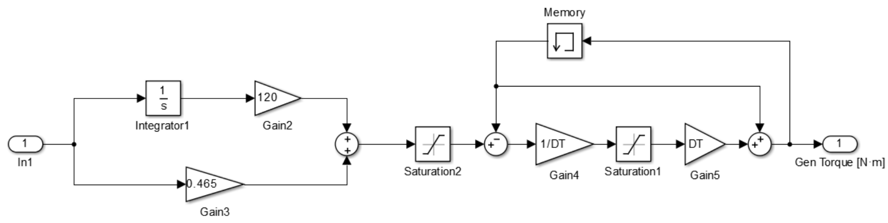

Figure B-11 Generator torque PI control

B.2.3 Simulink block diagram of the conditional bloc implemented in the constrained SOC structure

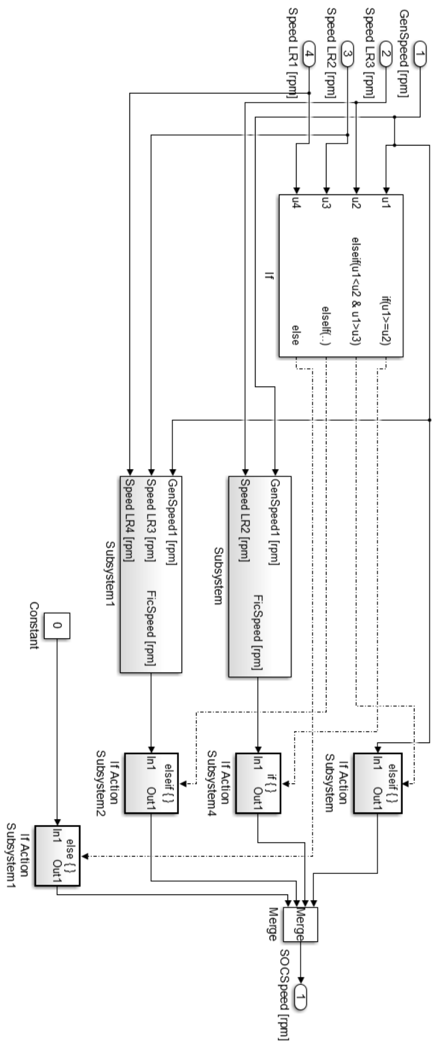

Figure B-12 Simulink block diagram of the conditional bloc implemented in the constrained SOC structure

B.2.4 Simulink block diagram of the SOC block (5-3)

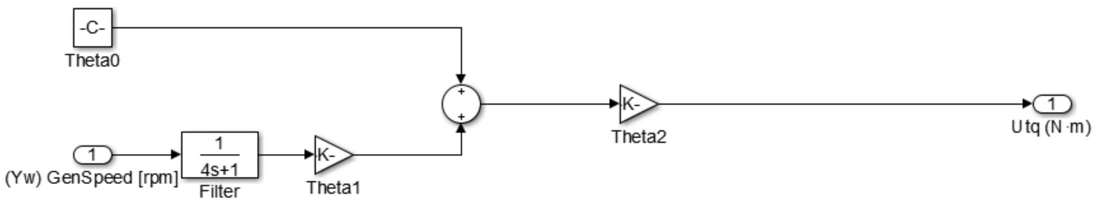

Figure B-13 Simulink block diagram of the SOC block (5-3)

B.2.5 Simulink block diagram of the SOC block (5-6)

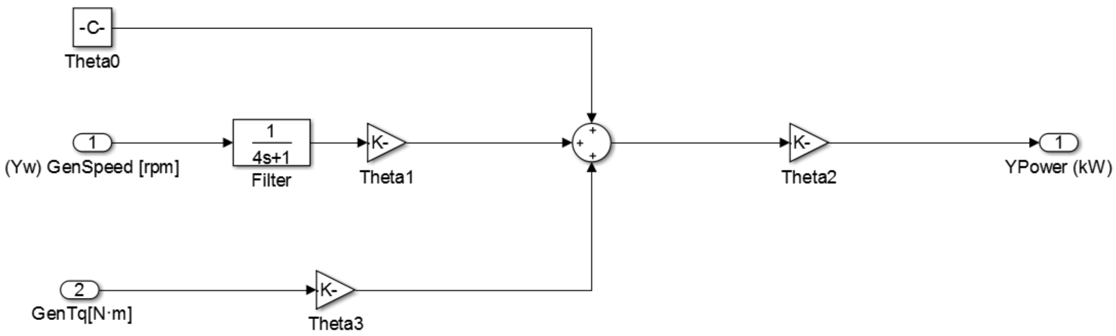

Figure B-14 Simulink block diagram of the SOC block (5-6)

B.2.6 Simulink block diagram of the SOC block (5-4)

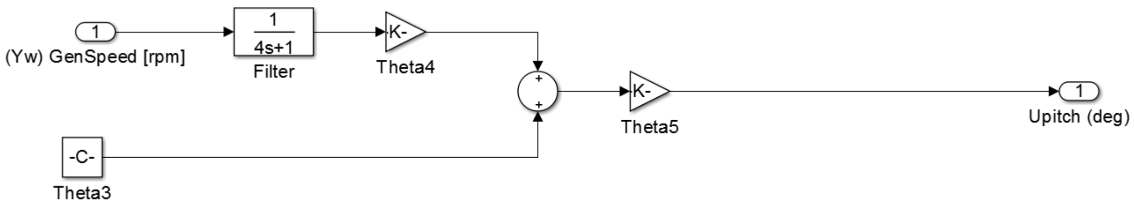

Figure B-15 Simulink block diagram of the SOC block (5-4)

Appendix C

C.1 Data collection from simulation

In order to select the CVs, process data is obtained from simulation. Simulations are carried out by fixing the value of disturbance. For each value of disturbance are taken 120 samples. Every 20 samples are taken at a constant blade pitch, between -3° and 2°, plus a random value between 0 and 1. In order to obtain sampling data near the optimum operating point and also to avoid applying higher generator torque than the aerodynamic torque, the initial torque for each 20 sample group is fixed following the expression (0-3), which depends on the disturbance value (wind speed). Then, torque is increased in each sample following the expression (0-4).

$$\Gamma_1 = -3193.9 + 167.5 \times wind + 307.4 \times wind^2 + U([0,10]) \quad \textbf{(0-3)}$$

$$\Gamma_{i+1} = \Gamma_i + 100 + U([0,80]) + U([0,120]), \quad i = 1, \dots, 20 \quad \textbf{(0-4)}$$

Torque and pitch increase from a reference sample to a neighbour is randomized to avoid that the regression coefficients get biased by constant increase in blade pitch or generator torque.

Figure C-1 illustrates the structure of the data collection.

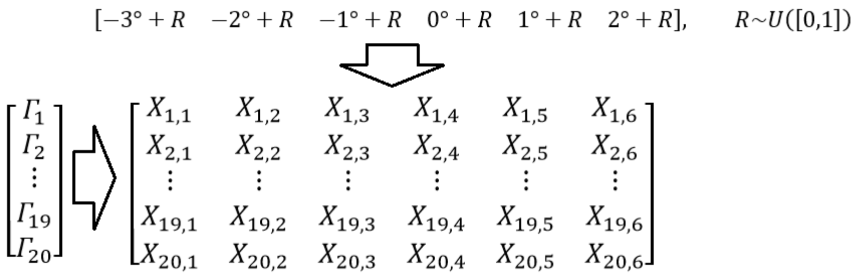

Figure C-1 Structure of the sample matrix for every disturbance value

Each disturbance step is composed of 5 matrices of 120 samples corresponding to generator power output, generator speed, generator torque, blade pitch and wind speed.

There have been collected 3720 samples, from a wind speed of 6 m/s to 12 m/s with a constant increase of 0.2 m/s, corresponding to 31 disturbance steps. Due to the high number of samples required and the long simulation time for each sample (because of a long transitional period), it has been developed a MatLab script to automatically run all simulations required (Appendix C.4). The script also allows simulations to run with all necessary degrees of freedom activated (Appendix A.1.4). When an error occurs due to uncoupled dynamics in the WT model, the script is recursively trying to find a rotor initial speed which allows the simulation to run without errors.

C.2 Data pre-processing for regression

As stated in section 4.2, the expression (4-2) represents the deviation of power in a reference point with respect to a neighbourhood point. This is the expression used to carry out the least-square regression and determine the CVs. Equation (4-2) is only valid for those neighbouring operating points corresponding to the same disturbance value.

CVs are defined as:

$$\frac{dP}{d\Gamma} = CV_1 = \theta_0 + \theta_1 \cdot \omega_G + \theta_2 \cdot \Gamma \qquad \textbf{(0-5)}$$

$$\frac{dP}{d\beta} = CV_2 = \theta_3 + \theta_4 \cdot \omega_G + \theta_5 \cdot \beta \qquad \textbf{(0-6)}$$

Whereby, (4-7) can be expressed as

$$P_{i+1} - P_i = (\theta_0 + \theta_1 \cdot \omega_G + \theta_2 \cdot \Gamma_i) \cdot (\Gamma_{i+1} - \Gamma_i) + (\theta_3 + \theta_4 \cdot \omega_G + \theta_5 \cdot \beta_i) \cdot (\beta_{i+1} - \beta_i) \qquad \textbf{(0-7)}$$

Considering a sample matrix (0-8) corresponding to the same disturbance value,

$$[X_{i,j}], \qquad i = 1, \dots, 20, \qquad j = 1, \dots, 6 \;\; Eq. 6 \qquad \textbf{(0-8)}$$

the torque and pitch increase of a reference point with respect to a strict neighbour can be expressed as

$$\begin{bmatrix} \Delta\Gamma_{i+1,j} \\ \Delta\Gamma_{i,j+1} \\ \Delta\Gamma_{i+1,j+1} \end{bmatrix} = \begin{bmatrix} \left(\Gamma_{i+1,j} - \Gamma_{i,j}\right) \\ \left(\Gamma_{i,j+1} - \Gamma_{i,j}\right) \\ \left(\Gamma_{i+1,j+1} - \Gamma_{i,j}\right) \end{bmatrix}, \quad \begin{bmatrix} \Delta\beta_{i+1,j} \\ \Delta\beta_{i,j+1} \\ \Delta\beta_{i+1,j+1} \end{bmatrix} = \begin{bmatrix} \left(\beta_{i+1,j} - \beta_{i,j}\right) \\ \left(\beta_{i,j+1} - \beta_{i,j}\right) \\ \left(\beta_{i+1,j+1} - \beta_{i,j}\right) \end{bmatrix} \tag{0-9}$$

Figure C-2 illustrates the concept of strict neighbour. Data samples for regression are obtained from the submatrix 19x5, as the elements of the last column and last row do not have the three neighbours with which to obtain the torque and pitch difference.

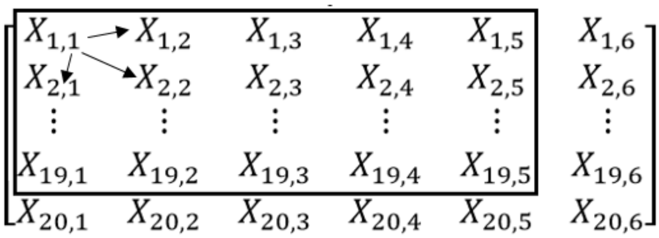

Figure C-2 Matrix element that have three strict neighbours

For each element of the submatrix indicated above, there are obtained three data samples for the regression . Thereby, from each sample matrix there are obtained 285 samples for the regression.

$$\begin{bmatrix} P_{i+1,j} - P_{i,j} \\ P_{i,j+1} - P_{i,j} \\ P_{i+1,j+1} - P_{i,j} \end{bmatrix} \tag{0-10}$$

$$= \begin{bmatrix} \Delta\Gamma_{i+1,j} & \omega_{i,j}\cdot\Delta\Gamma_{i+1,j} & \Gamma_{i,j}\cdot\Delta\Gamma_{i+1,j} & \Delta\beta_{i+1,j} & \Delta\beta_{i+1,j}\cdot\omega_{i,j} & \Delta\beta_{i+1,j}\cdot\beta_{i,j} \\ \Delta\Gamma_{i,j+1} & \omega_{i,j}\cdot\Delta\Gamma_{i,j+1} & \Gamma_{i,j}\cdot\Delta\Gamma_{i,j+1} & \Delta\beta_{i,j+1} & \Delta\beta_{i,j+1}\cdot\omega_{i,j} & \Delta\beta_{i,j+1}\cdot\beta_{i,j} \\ \Delta\Gamma_{i+1,j+1} & \omega_{i,j}\cdot\Delta\Gamma_{i+1,j+1} & \Gamma_{i,j}\cdot\Delta\Gamma_{i+1,j+1} & \Delta\beta_{i+1,j+1} & \Delta\beta_{i+1,j+1}\cdot\omega_{i,j} & \Delta\beta_{i+1,j+1}\cdot\beta_{i,j} \end{bmatrix} \cdot \begin{bmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{bmatrix}$$

C.3 Least-Squares Regression

The method of least squares is a standard regression approach where the overall solution minimizes the error sum of squares(S_E). It can be used for linear or non-linear fittings.

Partial Input matrix X_k corresponding to a sample matrix obtained at a constant disturbance value is defined as the vertical concatenation of the 285 previously stated elements.

$$X_{k,i,j} = \begin{bmatrix} \Delta\Gamma_{i+1,j} & \omega_{i,j}\cdot\Delta\Gamma_{i+1,j} & \Gamma_{i,j}\cdot\Delta\Gamma_{i+1,j} & \Delta\beta_{i+1,j} & \Delta\beta_{i+1,j}\cdot\omega_{i,j} & \Delta\beta_{i+1,j}\cdot\beta_{i,j} \\ \Delta\Gamma_{i,j+1} & \omega_{i,j}\cdot\Delta\Gamma_{i,j+1} & \Gamma_{i,j}\cdot\Delta\Gamma_{i,j+1} & \Delta\beta_{i,j+1} & \Delta\beta_{i,j+1}\cdot\omega_{i,j} & \Delta\beta_{i,j+1}\cdot\beta_{i,j} \\ \Delta\Gamma_{i+1,j+1} & \omega_{i,j}\cdot\Delta\Gamma_{i+1,j+1} & \Gamma_{i,j}\cdot\Delta\Gamma_{i+1,j+1} & \Delta\beta_{i+1,j+1} & \Delta\beta_{i+1,j+1}\cdot\omega_{i,j} & \Delta\beta_{i+1,j+1}\cdot\beta_{i,j} \end{bmatrix} \quad \textbf{(0-11)}$$

$$i = 1,\ldots,19, \quad j = 1,\ldots,5 \quad k = 1,\ldots,31$$

The total input matrix X is defined as the vertical concatenation of the partial input matrices X_k corresponding to the 31 step disturbance.

$$X = \begin{bmatrix} X_1 \\ \vdots \\ X_{31} \end{bmatrix} \quad \textbf{(0-12)}$$

In the same way, the partial output vector Y_k corresponds to the vertical concatenation of the 285 elements corresponding to the same disturbance value.

$$Y_{k,i,j} = \begin{bmatrix} P_{i+1,j} - P_{i,j} \\ P_{i,j+1} - P_{i,j} \\ P_{i+1,j+1} - P_{i,j} \end{bmatrix} \quad \textbf{(0-13)}$$

The total output vector Y is defined as the vertical concatenation of the 31 partial output vectors

$$Y = \begin{bmatrix} Y_1 \\ \vdots \\ Y_{31} \end{bmatrix} \quad \textbf{(0-14)}$$

Once the total input matrix X and total output vector Y are obtained, the regression coefficients θ is obtained by applying the least-squares regression expression

$$\theta = (X^T \cdot X)^{-1} \cdot X^T \cdot Y \tag{0-15}$$

The effectiveness of the regression is evaluated by using the R^2 parameter given by

$$R^2 = \frac{S_T - S_E}{S_T}, \qquad S_E = \sum_{i=1}^{N} (x_i - \hat{x}_i)^2, \quad S_T = \sum_{i=1}^{N} (x_i - \bar{x}_i)^2 \tag{0-16}$$

where S_T stands for the total sum of squares.

C.4 MatLab script for running FAST v8 simulations

```
wind=6; %Initial wind speed corresponding to first simulation
Power=[]; %Initialization of generator power matrix
Speed=[]; %Initialization of generator speed matrix
Torque=[]; %Initialization of generator torque matrix
Pitch=[]; %Initialization of blade pitch matrix
Wind=[]; %Initialization of wind speed matrix
w=0; %Initialization counter
TMax=130; %Fixing simulation time
filename = 'dataSOCautoMAX.xlsx'; %Creating an excel file to store
                                  %simulation data
while wind<12.1
    changewind(wind); % Change steady wind speed
    Pit=-3; % Fixing initial blade pitch angle
    cw=-3193.9+167.5*wind+307.4*wind^2;  %Calculating initial torque
    c=cw+rand(1)*10; %Randomize initial torque

    PPower=[]; %Initialization of generator power vectors
    PPPower=[];

    PSpeed=[]; %Initialization of generator speed vectors
    PPSpeed=[];

    PTorque=[]; %Initialization of generator torque vectors
    PPTorque=[];

    PPitch=[]; %Initialization of blade pitch vectors
    PPPitch=[];

    PWind=[]; %Initialization of wind speed vectors
    PPWind=[];

    inispeed=wind;
    %Change initial speed in the Elastodyn file
    change_initial_speed(inispeed);
                                    %exe file
    for j=1:6; %Run from blade pitch angles from -3 to 3 degrees
        % Open new figure to check the evolution of simulations
        figure(j)
        title(wind)
        hold on
        Tq=c;
        Piti=Pit+rand(1)*1; %Randomize blade pitch angle
        simdone=0;
        %Code to catch errors due to uncoupled dynamics
        while simdone==0;
            try
                sim('MODEL_SOC_DATA.mdl') %Run simulation
                simdone=1;
               % If an error is detected, change initial rotor speed
            catch
                  % and run simulation again
                if inispeed>(wind*0.8);
                    inispeed=inispeed-rand(1)*0.2;
                    change_initial_speed(inispeed);
                else
```

```
                inispeed=wind;
                change_initial_speed(inispeed);
            end
        end
    end
    % Operational data is saved
    GenPwr=OutData(:,strmatch('GenPwr',OutList));
    a=size(GenPwr);
    PPPower=vertcat(PPPower,GenPwr(a(1),1));
    GenSpeed=OutData(:,strmatch('GenSpeed',OutList));
    plot(GenSpeed)
    a=size(GenSpeed);
    PPSpeed=vertcat(PPSpeed,GenSpeed(a(1),1));
    PPTorque=vertcat(PPTorque,Tq);
    PPPitch=vertcat(PPPitch,Piti);
    Wind1VelX=OutData(:,strmatch('Wind1VelX',OutList));
    PPWind=vertcat(PPWind,Wind1VelX(a(1),1));
    for i=1:19;
        cond=0;
        while cond==0;
            Tq=c+100+rand(1)*80+120*rand(1);%Generator torque step
                                         %increse randomized
            Piti=Pit+rand(1)*1;          %Blade pitch angle randomized
            simdone=0;
            while simdone==0;
                try
                    sim('MODEL_SOC_DATA.mdl')
                    simdone=1;
                catch
                    if inispeed>(wind*0.8);
                        inispeed=inispeed-rand(1)*0.2;
                        change_initial_speed(inispeed);
                    else
                        inispeed=wind;
                        change_initial_speed(inispeed);
                    end
                end
            end
            %If the wind turbine starts to slow down due to high
            %generator torque, the simulation is run again.
            GenSpeed=OutData(:,strmatch('GenSpeed',OutList));
            if ((PPSpeed(end,1)-
GenSpeed(a(1),1))/PPSpeed(end,1))>0.08;
                cond=0;
            else
                cond=1;
            end
        end
        % Operational data are stored
        GenPwr=OutData(:,strmatch('GenPwr',OutList));
        a=size(GenPwr);
        PPPower=vertcat(PPPower,GenPwr(a(1),1));
        GenSpeed=OutData(:,strmatch('GenSpeed',OutList));
        plot(GenSpeed)
        a=size(GenSpeed);
        PPSpeed=vertcat(PPSpeed,GenSpeed(a(1),1));
        PPTorque=vertcat(PPTorque,Tq);
        PPPitch=vertcat(PPPitch,Piti);
        Wind1VelX=OutData(:,strmatch('Wind1VelX',OutList));
```

```
            PPWind=vertcat(PPWind,Wind1VelX(a(1),1));
            c=c+100+rand(1)*80+120*rand(1);

        end
        % Operational data are stored
        PPower=horzcat(PPower,PPPower);
        PSpeed=horzcat(PSpeed,PPSpeed);
        PTorque=horzcat(PTorque,PPTorque);
        PPitch=horzcat(PPitch,PPPitch);
        PWind=horzcat(PWind,PPWind);
        PPPower=[];
        PPTorque=[];
        PPSpeed=[];
        PPPitch=[];
        PPWind=[];
        Pit=Pit+1;
        c=cw+50*rand(1);
    end
    % Operational data are stored into the excel file
    close all
    numCell=num2str(w*21+5);

    cellWind=strcat('B',numCell);
    cellPower=strcat('J',numCell);
    cellSpeed=strcat('R',numCell);
    cellTorque=strcat('Z',numCell);
    cellPitch=strcat('AH',numCell);

    xlswrite(filename,PWind,1,cellWind)
    xlswrite(filename,PPower,1,cellPower)
    xlswrite(filename,PSpeed,1,cellSpeed)
    xlswrite(filename,PTorque,1,cellTorque)
    xlswrite(filename,PPitch,1,cellPitch)


    Power=vertcat(Power,PPower);
    Speed=vertcat(Speed,PSpeed);
    Torque=vertcat(Torque,PTorque);
    Pitch=vertcat(Pitch,PPitch);
    Wind=vertcat(Wind,PWind);

    PPower=[];
    PTorque=[];
    PSpeed=[];
    PPitch=[];
    PWind=[];
    % Wind speed step increase
    wind=wind+0.2;
    w=w+1;

end
```

Appendix D

D.1 Wind turbine simulations for turbulent wind regimes

D.1.1 Turbulent wind regime at average speed 8,5 m/s

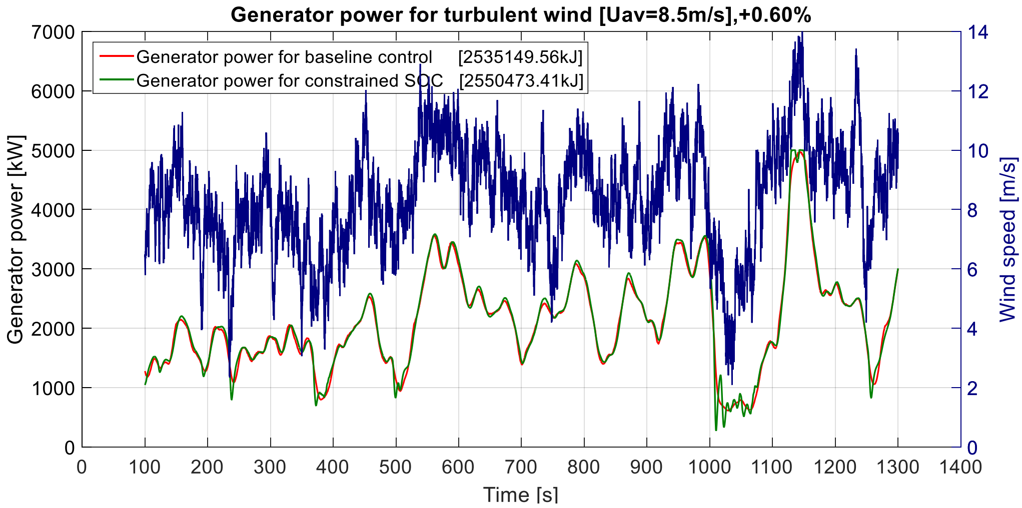

Figure D-1 Simulation results of the WT generator power output implementing a BC versus SOC. Turbulent wind regime at average speed 8,5 m/s

D.1.2 Turbulent wind regime at average speed 9 m/s

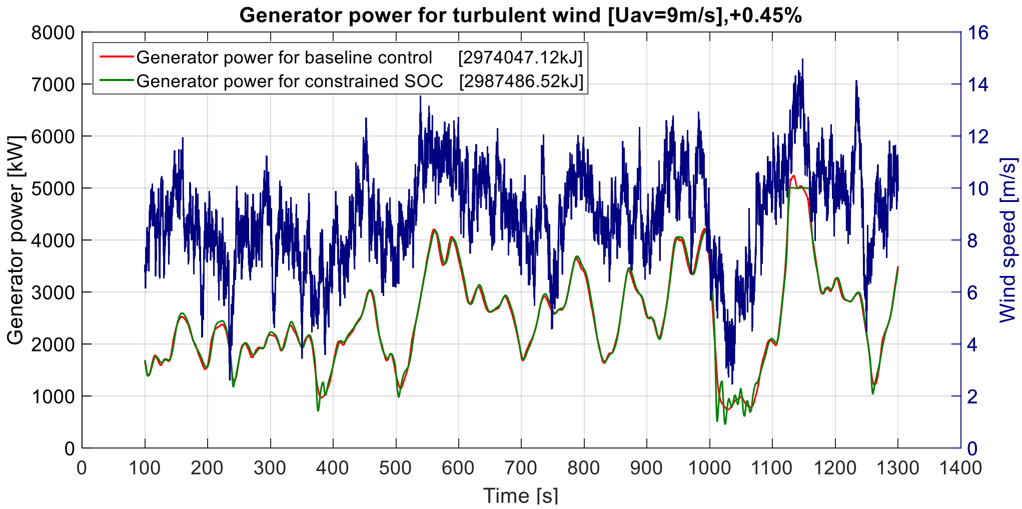

Figure D-2 Simulation results of the WT generator power output implementing a BC versus SOC. Turbulent wind regime at average speed 9 m/s

D.1.3 Turbulent wind regime at average speed 9,5 m/s

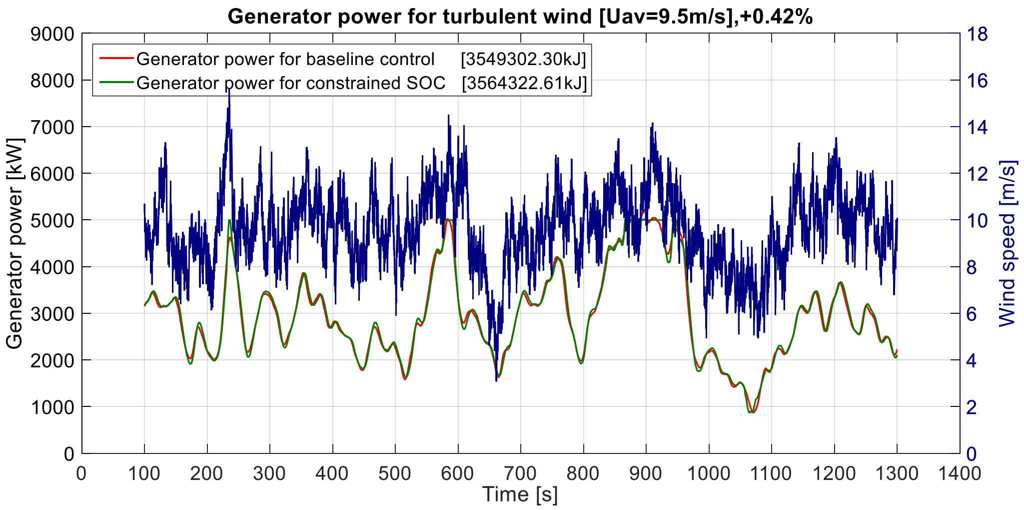

Figure D-3 Simulation results of the WT generator power output implementing a BC versus SOC. Turbulent wind regime at average speed 9,5 m/s