ECN
Energy research Centre of the Netherlands

Heat & Flux

Enabling the Wind Turbine controller

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Acknowledgement/Preface

My colleagues Eric van der Hooft and Tim van Engelen are gratefully thanked for relieving my professional loads during this project by always being there for me. Furthermore Tim and Eric facilitated the use of ECN's Control Tool for designing wind turbine controllers. Their presence has been very important for the realisation of this project.

My colleagues Koert Lindenburg and Edwin Bot are thanked for running simulations by respectively the aero-elastic wind turbine code Phatas and farm performance code FluxFarm.

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Abstract

In the years 1999-2003 ECN invented and patented the technique 'Heat & Flux'. The idea behind Heat & Flux is that tuning turbines at the windward side of a wind farm more transparent than usual, i.e. realising an axial induction factor below the Lanchester-Betz optimum of $^1/_3$, should raise net farm production and lower mechanical turbine loading without causing drawbacks. For scaled farms in a boundary layer wind tunnel this hypothesis has been proved in previous projects.

To enable alternative turbine transparencies, the wind turbine controller must support the additional control aim 'desired transparency'. During this study we have determined a general method to design a transparency control algorithm. This method has been implemented in ECN's 'Control Tool' for designing wind turbine control algorithms. The aero-elastic wind turbine code Phatas has been used to verify the resulting control algorithm.

Heat & Flux does not fundamentally change the control of horizontal axis variable speed wind turbines. The axial induction can be reduced by an offset on blade pitch or generator torque. Weighing reliability against performance profits, it appeared to be advisable to adapt only blade angle control.

Contents

Summary

In the years 1999-2003 ECN invented and patented the technique 'Heat & Flux'. The idea behind Heat & Flux is that tuning turbines at the windward side of a wind farm more transparent than usual, i.e. realising an axial induction factor below the Lanchester-Betz optimum of $^1/_3$, should raise net farm production and lower turbine loading. For scaled farms in a boundary layer wind tunnel this hypothesis had been proved in previous projects.

A pitch to feather variable speed wind turbine is tuned more transparent by pitching the blades to feather or raising the generator torque. Analysis learned that raising the generator torque above usual levels could realise only minor improvements to the Heat & Flux objectives. Alternative torque control has been abandoned for reasons of simplicity and thus reliability. So a conventional turbine controller becomes a Heat & Flux controller by implementing an algorithm that regulates blade angle on the basis of the additional control aim 'desired turbine transparency'.

The determinative property for wind turbine transparency is the turbine's induction factor, usually indicated by a. We found a general method to derive the relation between blade angle and induction factor, while remaining conventional torque control (and thus changing the tip speed ratio). Herewith the Heat & Flux control parameters could be calculated straight forward from the parameters already used for conventional control. The key for deriving these Heat & Flux turbine settings followed by using the feature that the same torque - rotor speed settings are applicable for both conventional and Heat & Flux control. The resulting method to design a Heat & Flux wind turbine controller has been implemented in ECN's 'Control Tool' for designing wind turbine control algorithms.

Further a transition mechanism between Heat & Flux and conventional operation, a wind direction signal, a yaw control algorithm and a simple Heat & Flux farm controller have been developed and implemented in the Control Tool. Herewith it became possible to verify the controller design by simulations within the Control Tool, including the wind direction dependent behaviour. Before the design of rotor speed control and power control did not depend on the direction of the wind.

Using ECN's Control Tool we designed a Heat & Flux wind turbine controller for a typical offshore multi-MW wind turbine. FluxFarm has been used to determine the parameters of the simple farm controller, i.e. the induction factor per yaw angle, for the case that the turbine would be part of the Horns Rev wind farm. The resulting Heat & Flux wind turbine control algorithm has been verified by the authorised aero-elastic wind turbine code Phatas.

The risks of applying a suitable Heat & Flux turbine controller appeared to be limited to some lack of production, in case the farm controller would misuse the introduced turbine control options. The only thinkable safety risk would follow by human failure while adapting the control code, although the code adaptations are very straightforward.

Simulations showed that both turbine production and turbine loading decreased, which is in conformance with increasing the turbine's transparency, by applying Heat & Flux turbine control. Concerning the situation behind the turbine, we still expect a net raise of farm production and a lowering of turbulence by applying Heat & Flux in wind farms. With reservation of full-scale farm and turbine experiments, we propose to implement Heat & Flux turbine control algorithms in wind turbines intended for wind farms.

1. Introduction

In the years 1999-2003 ECN invented and patented the technique 'Heat & Flux' [1-3]. The idea behind Heat & Flux is that tuning turbines at the windward side of a wind farm more transparent than usual, i.e. realising an axial induction factor below the Lanchester-Betz optimum of $^{1}/_{3}$, should result in 3 advantages without causing drawbacks (see figure 1.1). For scaled farms in a boundary layer wind tunnel this hypothesis has been proved already [4,5].

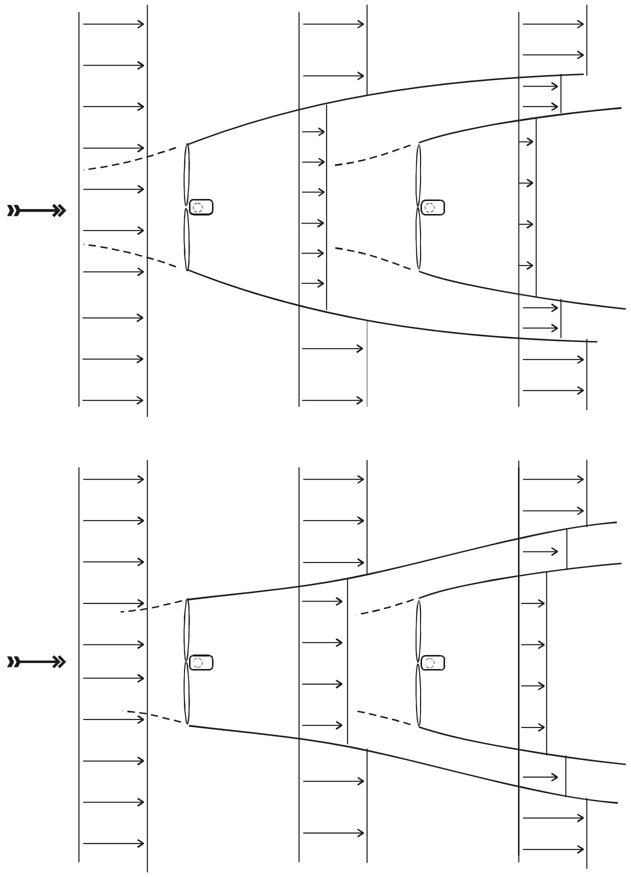

***Figure 1.1**: Wake representation of two turbines in a row. Above: usual operation. Below: "Heat & Flux" operation, i.e. the upwind turbine is more transparent [1].*

The advantages are:

1. The average axial loading of the turbines at the windward side decreases.
2. The fatigue loading of turbines under the lee decreases, because the upwind turbines generate less turbulence.
3. The net production of the farm slightly increases, because the profit of higher wind speeds in the downwind part of the farm exceeds the production offered by the upwind turbines.

At present the dominant turbine concept on the market is power regulation by variable speed and pitch to vane control. The Heat & Flux concept is applicable to other concepts also, but the research described in this report focuses at wind turbines applying variable speed and pitch to vane control. Heat & Flux does not fundamentally change the control of these horizontal axis wind turbines. Electric power and rotor speed are controlled conform the scheme of figure 1.2. Pitch angle and generator torque are set on the basis of the measured rotor speed. When aiming at more transparent turbine settings than usual, an offset must be applied to the blade angle and / or generator torque.

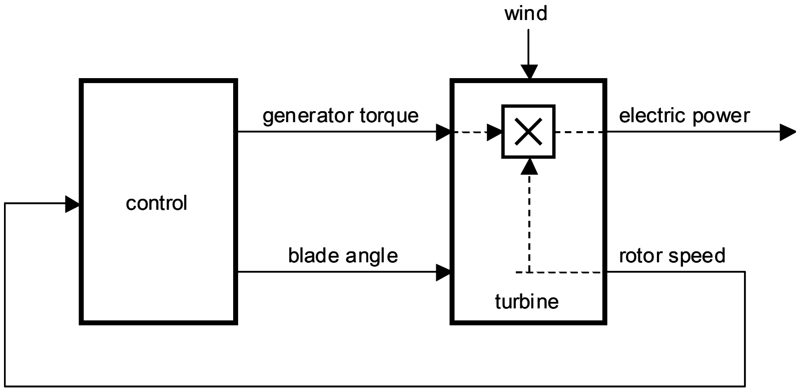

Figure 1.2*: High level control scheme of a variable speed, pitch to feather, horizontal axis wind turbine.*

To enable alternative turbine transparencies, the controller must support the additional control aim 'desired transparency'. During this study we determine a general method to design a transparency control algorithm. This method will be implemented in ECN's 'Control Tool' for designing wind turbine control algorithms [6-11]. The aero-elastic wind turbine code Phatas [12] will be used to verify the resulting control algorithm.

2. Analysis

A more transparent tuning of turbines at the windward side of a farm will be applied at wind speeds for which the turbines conventionally are tuned for maximum production. This only is the case when the turbines are not fully loaded because of a wind speed below the nominal wind speed. Then the wind turbines are controlled by setting the blade pitch angle θ and generator torque T as a function of the rotor speed. Commonly the blade angle remains (nearly) constant and the rotor speed and thus blade tip wind speed ratio λ are controlled by setting the generator torque. The resulting power coefficient $C_\mathrm{p}(\lambda,\theta)$ and thrust coefficient $C_\mathrm{t}(\lambda,\theta)$ follow from the blade characteristics. Typical $C_\mathrm{p}(\lambda,\theta)$ and $C_\mathrm{t}(\lambda,\theta)$ characteristics are given in figure 2.1.

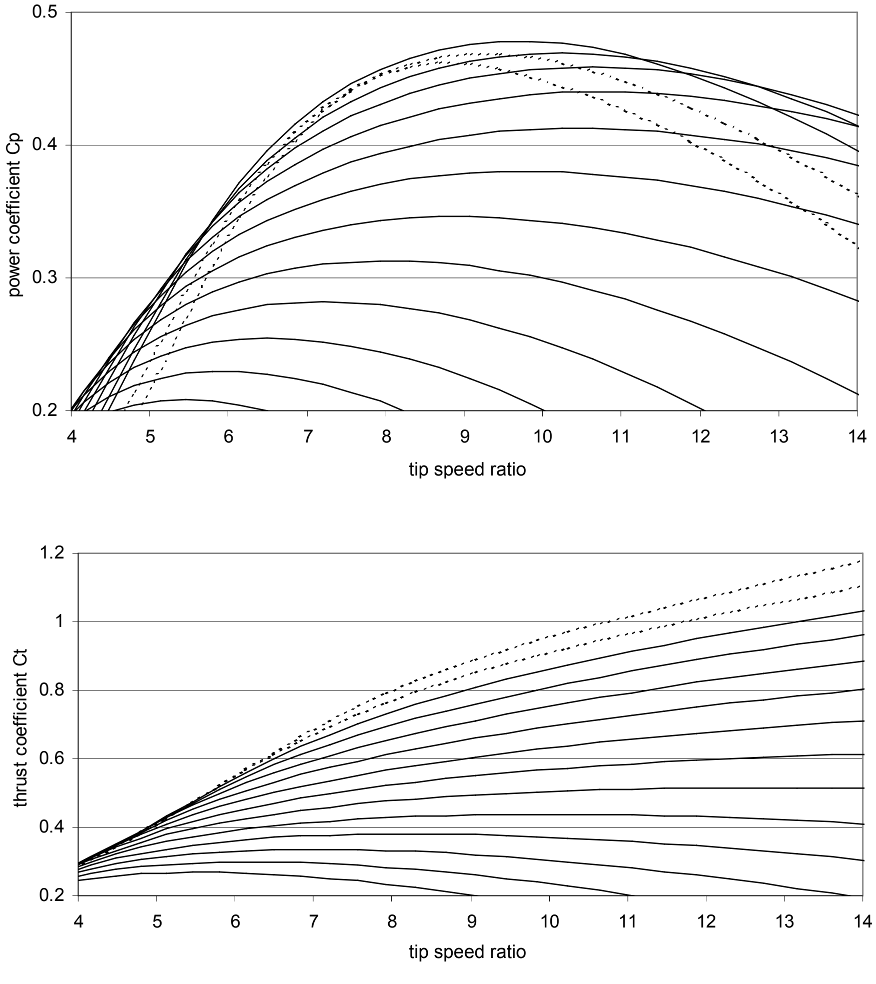

Figure 2.1: *Typical $C_p(\lambda,\theta)$ and $C_t(\lambda,\theta)$ characteristics of an offshore multi-MW wind turbine. Each curve represents a blade pitch angle setting.*

Conventionally turbine controllers aim to realise the maximum power coefficient and nearly pay attention to the accompanying thrust coefficient. Significant reduction of thrust coefficients at the windward side of a farm realises the Heat & Flux advantages. The accompanying lowering of power coefficients also contributes negatively by offering energy yield of those turbines. So the optimal Heat & Flux turbine controller always aims to tune the tip speed ratio λ and blade angle θ such that:

- $C_p(\lambda,\theta)$ is maximal given the value of $C_t(\lambda,\theta)$
- $C_t(\lambda,\theta)$ is minimal given the value of $C_p(\lambda,\theta)$

To determine how to modify the controller of a conventional turbine to become a Heat & Flux controller we studied the following strategies to obtain alternative realisations of power and thrust coefficient:

- Control λ conventionally and θ alternatively
- Control θ conventionally and λ alternatively
- Control both λ and θ alternatively

We applied those strategies for the blade characteristics of two typical multi-MW wind turbines. Maximising $C_p(\lambda,\theta)$ per realisable $C_t(\lambda,\theta)$ resulted in figure 2.2.

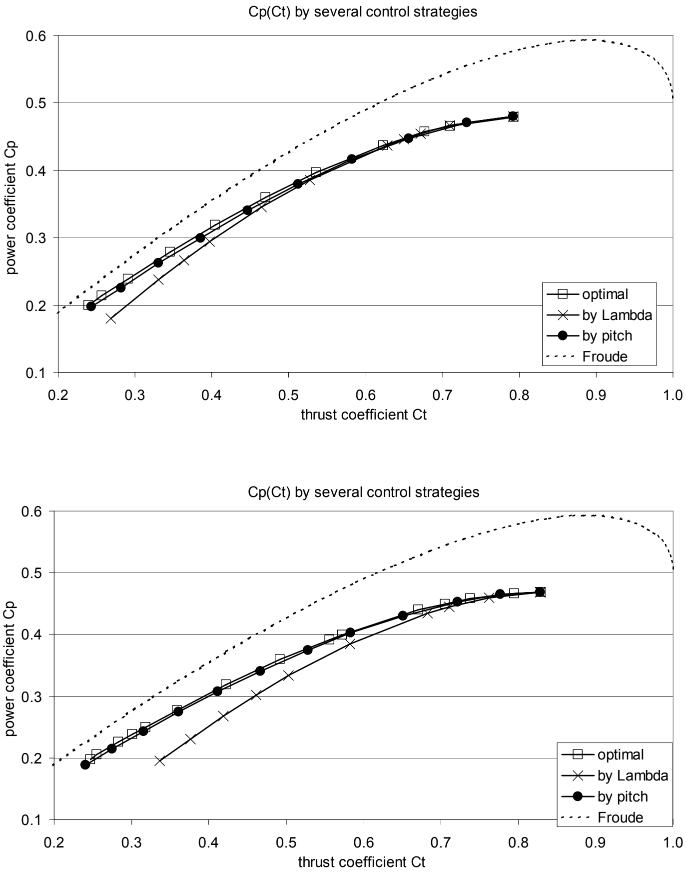

Figure 2.2: *Combinations of C_p and C_t for 2 typical multi-MW wind turbines by different control strategies.*

The dotted lines follow from the $C_p = 4a(1\text{-}a)^2$ and $C_t = 4a(1\text{-}a)$ derived by Lanchester [13] and Betz [14] for the actuator disc as introduced by Froude [15], in which a is the induction factor. Controlling both λ and θ alternatively shows the optimal achievable performance. Controlling only θ alternatively, a turbine would perform slightly less. Controlling only λ alternatively, a turbine could perform significantly less. For reasons of simplicity and thus reliability it is advisable to abandon the minuscule profit by optimal control above control by θ. This choice will slightly decrease the (already slight) increase in net farm production. The decrease of axial forces and turbulence reduction will be completely insignificant. We conclude that Heat & Flux turbine control is realised best by applying alternative blade angle settings for certain combinations of the wind speed and direction, but always remaining conventional torque control.

A conventional controller as well as a Heat & Flux controller has to deal with the operational restriction of maximum rotor speed. To limit the rotor speed for higher turbine production levels the generator torque must be set above the settings that would follow from aiming at the optimal C_p and, in case of Heat & Flux, C_t. This implies a decrease of the tip speed ratio. For the smaller pitch angles of the studied typical blade characteristics this results in a more or less significant change of C_p and C_t. To illustrate the presumed effect, figure 2.3 shows the change in C_p and C_t for the 2 turbines during the limitation of the rotor speed by raising the torque.

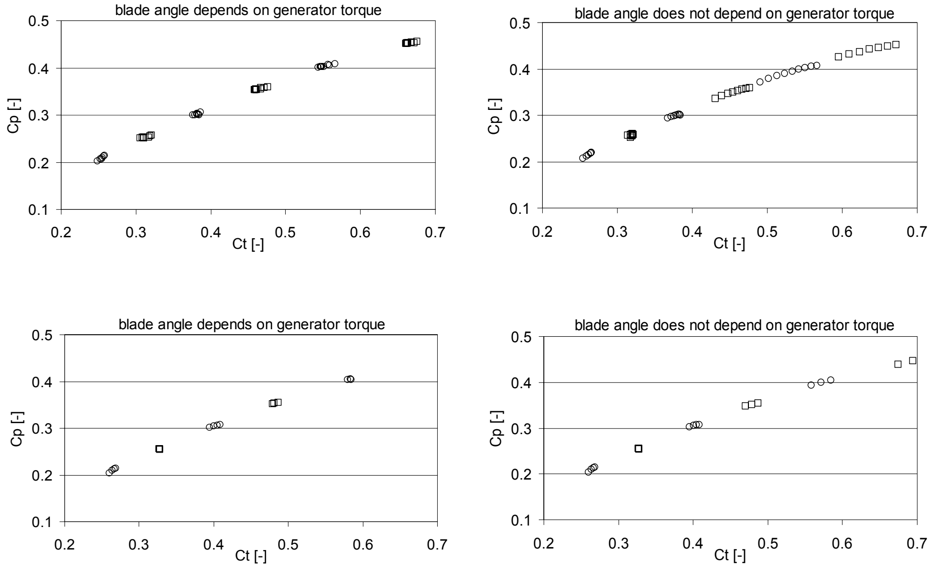

Figure 2.3: *Combinations of C_p and C_t for 2 typical multi-MW wind turbines while the rotor speed is limited by the torque settings. Strings of circles or squares are supposed to coincide 1 (C_p,C_t) point.*

The upper plots of figure 2.3 belong to the turbine of the upper plot of figure 2.2, the lower plots to the turbine of the lower plot of figure 2.2. The left plots show per string of circles or squares the relation $C_p(C_t)$ when the blade angle is decreased to compensate for the raising torque. The strings do not exactly coincide 1 point in the (C_p,C_t) area, because the blade angles are digitalised to 0.25°. The right plots of figure 2.3 show the relation $C_p(C_t)$ when the blade angle remains constant while the torque is increased. The figures show that at the designing of a Heat & Flux turbine controller pitching to feather should be reduced at higher torque settings and smaller blade angles.

In a wind farm Heat & Flux control can be realised as follows:

- A farm controller demands the desired turbine transparency on the basis of measurements.
- The demanded transparency is translated into turbine control demands by a turbine specific procedure.
- The turbine controller effectuates the demanded control signals.

Most obviously, a farm controller demands turbine transparency via induction factor a, since that is the determinative property for turbine transparency. The induction factor is defined by the decrease of wind speed at the rotor: $U_{\text{rotor}} = (1\text{-}a)\cdot U_{\text{ambient}}$. In the case of Froude's actuator disc model this results in $C_p = 4a(1\text{-}a)^2$ and $C_t = 4a(1\text{-}a)$ and thus $a = 1\text{-}C_p/C_t$. Real-life turbines do not fulfil $a = 1\text{-}C_p/C_t$ (remark that the C_p concerns the transfer of aerodynamic into useful energy). Nevertheless we still like to optimise the farm performance by tuning turbine transparencies via the determinative induction factor a. $C_t = 4a(1\text{-}a)$ justifies the induction factor a to fulfil:

$$a = \tfrac{1}{2} - \tfrac{1}{2}\sqrt{1 - C_t} \tag{2.1}$$

Turbine controllers aim to realise a blade angle and generator torque on the basis of measurements. This approach will not be changed. The Heat & Flux farm controller only leads to other demands. Optional code to identify the relations $C_p(\lambda,\theta)$ and $C_t(\lambda,\theta)$ should neither be incorporated in the turbine control code nor in the farm control code. If applicable such code can be used to change the control strategy and thus change the parameters used by the controllers.

3. Design

In chapter 2 we determined that a Heat & Flux wind turbine controller is designed by deriving the relation between the blade angle θ and the best combination of C_p and C_t, while the torque T is being controlled conventionally, i.e. as a function of rotor speed Ω. For clear communication about turbine transparencies, θ shall be tuneable by the induction factor a that accompanies the best combination of C_p and C_t. On the one hand the conventional torque control blocks the most simple design approach since λ cannot be tuned by T now (The most simple design approach would be to define the relevant range of C_t values; determine the largest $C_\mathrm{p}(\lambda,\theta)$ value per value of C_t; determine the accompanying blade angle θ and tip speed ratio λ). On the other hand this similarity to conventional control helps us to design the Heat & Flux turbine controller.

Using the index 'c' for conventional control and 'HF' for Heat & Flux control, the delivered turbine power P is respectively:

$$P_\mathrm{c} = \tfrac{1}{2}\eta\rho A C_\mathrm{p,c} U_\mathrm{c}^3 \tag{3.1}$$

$$P_\mathrm{HF} = \tfrac{1}{2}\eta\rho A C_\mathrm{p,HF} U_\mathrm{HF}^3 \tag{3.2}$$

In which:

η = efficiency factor concerning electro-mechanical power transfer
ρ = air density
A = swept rotor area
U = ambient wind speed

The key for deriving the Heat & Flux turbine settings follows by being conscious of the feature that the same (T,Ω) working points are applicable for both conventional and Heat & Flux control. After hitting on this idea, it even becomes surprisingly simple to derive the Heat & Flux turbine settings. The power is the product of torque T and rotor speed Ω, so for similar (T,Ω) working points $P_\mathrm{c} = P_\mathrm{HF}$. Further the fact of equal (T,Ω) working points allows us to replace the wind speeds in 3.1 and 3.2 by using the following formulas for tip speed ratios:

$$\lambda_\mathrm{c} = \frac{\Omega R}{U_\mathrm{c}} \tag{3.3}$$

$$\lambda_\mathrm{HF} = \frac{\Omega R}{U_\mathrm{HF}} \tag{3.4}$$

In which R is the rotor radius. Equating 3.1 and 3.2 and filling in 3.3 en 3.4, it follows that:

$$C_\mathrm{p,HF} = C_\mathrm{p,c}\left(\frac{\lambda_\mathrm{HF}}{\lambda_\mathrm{c}}\right)^3 \tag{3.5}$$

So given (Ω,T), a λ_c value can only be realised by one θ_{HF} value, which leaded to the $C_{p,HF}$ of formula 3.5. Using this we determine the appropriate blade angle θ_{HF} for Heat & Flux control per (Ω,T) working point by:

- calculate $C_{p,HF}$ by formula 3.5 for all applicable values of λ_{HF}.
- look up θ for all applicable values of λ_{HF} and accompanying calculated $C_{p,HF}$ in the table $C_p(\lambda,\theta)$
- look up $C_{t,HF}$ for all applicable values of λ_{HF} and accompanying looked up θ in the table $C_t(\lambda,\theta)$
- calculate a from $C_t(\lambda,\theta)$ by formula 2.1: $a = {}^1/_2 - {}^1/_2\sqrt{(1-C_t)}$

This should be done for 2 classes of (Ω,T) working points:

- on the "optimum Lambda-curve" where conversion of aerodynamic power is maximised ($\lambda_c = \lambda_{opt}$);
- on the nominal working point where power, torque and rotor speed are nominal; for this working point the situation of importance is when it is reached from partial load (below nominal), so the wind speed is nominal as well.

For turbine operation during the transition from optimum Lambda to nominal the Heat & Flux settings will be interpolated.

4. Integration in ECN's Control Tool

The design method of chapter 3 has been automated and implemented in ECN's Control Tool for designing wind turbine controllers. Besides implementing this method to calculate the appropriate Heat & Flux settings, the Control Tool has been extended by a transition mechanism between Heat & Flux and conventional operation, a wind direction signal, a yaw control algorithm and a simple Heat & Flux farm controller. Herewith it became possible to verify the controller design by simulations, including the wind direction dependent behaviour. Before the design of rotor speed control and power control of wind turbines did not depend on the direction of the wind.

4.1 Tool Development

Farm controller design comprises the derivation of the appropriate induction factor per turbine yaw angle. This derivation can either be implemented on-line (adaptive) or off-line. In both cases the turbine controller must be provided with the desired induction factor per yaw angle to enable Heat & Flux control. For that we implemented a control table in the turbine controller on the basis of farm performance calculations by FluxFarm [16]. The design of the farm controller itself is no part of this research.

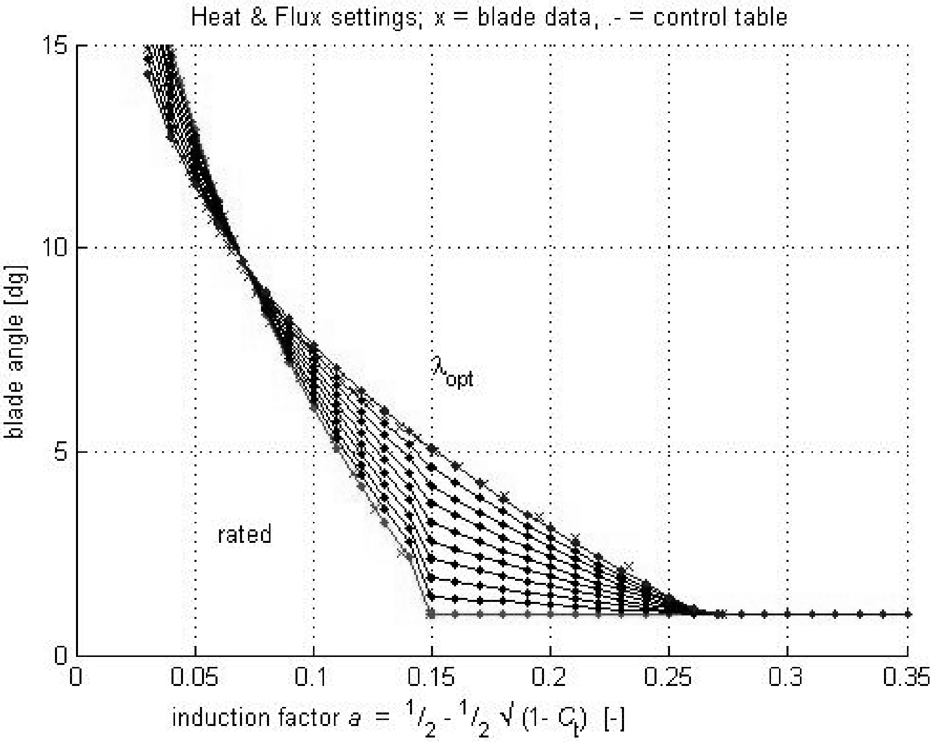

Figure 4.1: *Heat & Flux turbine control design plot.*

The Control Tool code that comprises the automated design method of chapter 3 have been appended in appendix A. Running this code results in the design plot of figure 4.1, which gives the blade angle as a function of the desired induction factor *a* per turbine state (each curve represents a (T,Ω) working point between optimum Lambda and rated).

After the design has been finished the turbine controller comprises:

- an empty table of variable length, suited to comprise desired induction factors *a* versus yaw angles; this table must be filled on the basis of the farm controller design;
- an algorithm that sets the appropriate blade angle on the basis of the desired induction factor, using the characteristics of figure 4.1; the applicable curve follows from the torque settings (in our particular case we use the unambiguously related rotor speed for that).

Figure 4.2 shows the resulting control scheme. Transitions between conventional and different Heat & Flux settings are realised by the conventional partial load pitch servo controller. The Heat & Flux controller only desires a different partial load blade angle. Introducing the modes "Conventional" and "Heat & Flux" appeared to fulfil all the needs. Switching between partial load and full load or between different Heat & Flux modes turned out to require no additional control modes.

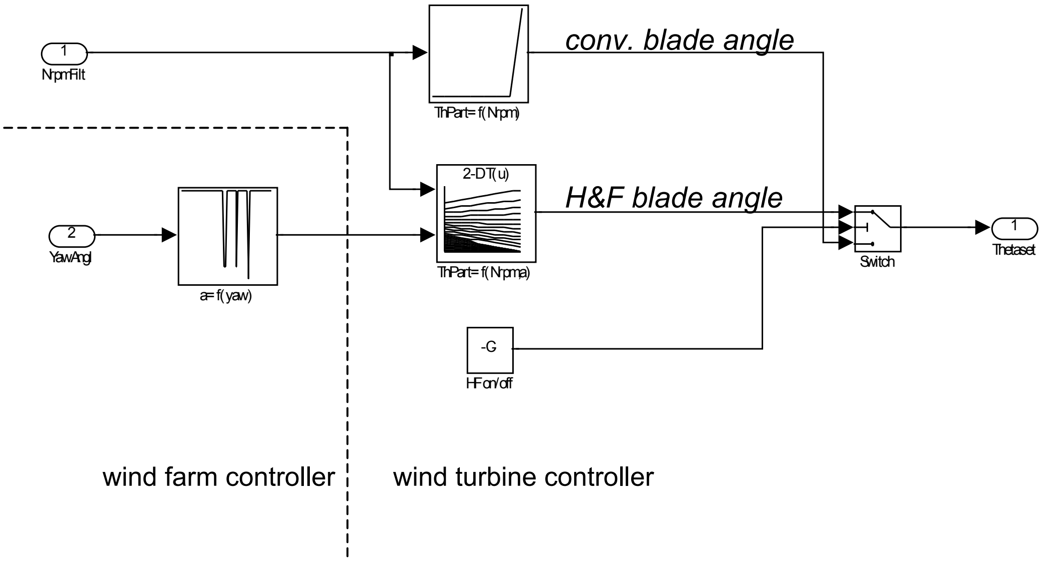

Figure 4.2: *Heat & Flux control scheme.*

For the control of power and rotor speed, the yaw angle is an input value. A yaw control algorithm sets the yaw angle. To facilitate realistic yawing signals we introduced a yaw control algorithm into the Control Tool. To verify this yaw control algorithm and simulate realistic circumstances for Heat & Flux operation, we also introduced a wind direction signal for simulation purposes into the Control Tool. The wind direction has been modelled by a pre-defined sequence of angles plus additional white noise. The yaw control algorithm and wind direction model have been appended in appendix C.

4.2 Simulations

Using ECN's Control Tool we designed a Heat & Flux wind turbine controller for a typical offshore multi-MW wind turbine being part of a farm laid out as the Horns Rev wind farm [17]. Figure 4.2 shows the layout of this farm. Each circle represents a wind turbine position. The turbines are separated by 7 rotor diameters in both the east-west and the more or less north-south direction.

We designed a Heat & Flux wind turbine controller for the typical turbine on the position of the filled circle of figure 4.3. For this configuration figure 4.4 shows the desired induction factor per yaw angle as it has been determined using FluxFarm [16][1]. Remark that $a \approx 0.27$ for the conventionally controlled turbine, which is already significantly below the Lanchester-Betz optimum of $a = {}^{1}/_{3}$. However, the blades had been designed such that the maximum of the $C_p(a)$ -curve is just above $a = {}^{1}/_{2} - {}^{1}/_{2}\sqrt{(1\text{-}C_t)} = 0.27$ (not precisely fulfilling the rotor-disc model).

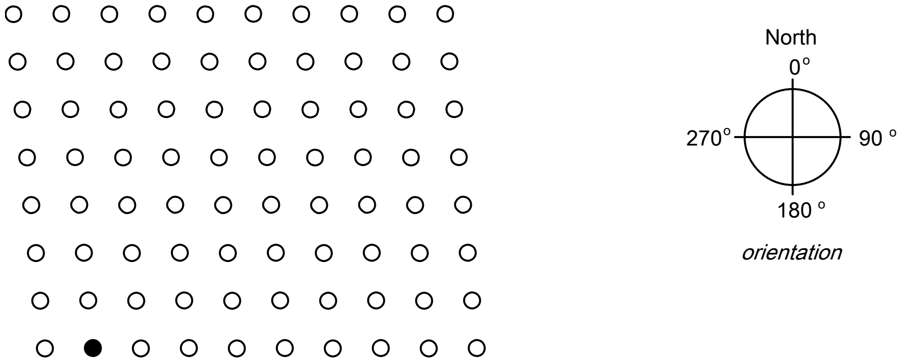

Figure 4.3: Lay out of the Horns Rev offshore wind farm (turbine spacing is 7 rotor diameters). The filled circle marks the position of the simulated wind turbine.

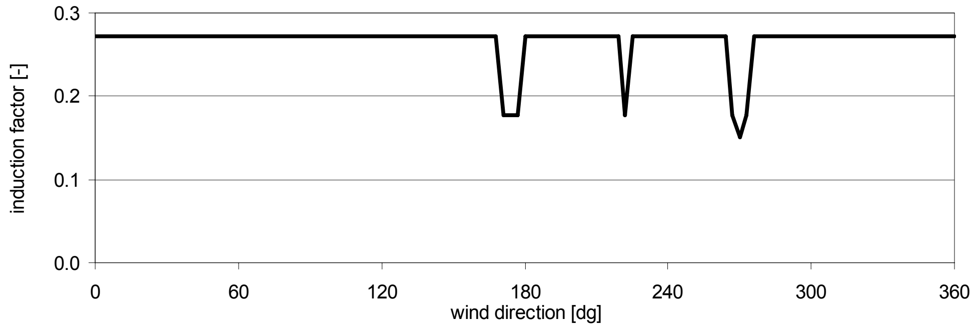

Figure 4.4: *Desired induction factor* $a = {}^{1}/_{2} - {}^{1}/_{2}\sqrt{(1\text{-}C_t)}$ *per yaw angle on the basis of farm performance calculations using FluxFarm [16]* [1].

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[1] The current version of FluxFarm assumes turbine wakes like in an undisturbed ambient flow. Though in real-life the wind speed in the wakes of turbines that are hindered by an upwind turbine will recover faster and downwind in the farm the ambient flow will decay. Because of the faster recovery in real-life we expect FluxFarm to overestimate wake effects in the case of wind directions parallel to turbine rows. Therefore the smallest induction factors for the sake of Heat & Flux are expected to be applicable in larger or denser wind farms than calculated for by FluxFarm. Because of the decay of the ambient flow we expect FluxFarm to under-estimate wake effects in the case of wind directions not parallel to turbine rows, particularly since the 3 or 4 most upwind rows decelerate the more or less undisturbed flow farm-wide then. Therefore we expect Heat & Flux settings to be suitable over a wider range of wind directions in real-life. Those barely identified deviations between real-life and FluxFarm are unimportant for verifying our design of the wind turbine controller. For more information about the flow through and behind HornsRev one could consult [18,19].

The following simulations have been executed for the typical turbine with the designed controller by the Control Tool:

- Wind speed from 0.5 times up to 2 times nominal wind speed, covering the modes "optimum Lambda", "transition" (from optimum Lambda to full load) and "full load". Both conventional control (wind direction = 0°) and Heat & Flux control (wind direction = 270°, so $a \approx 0.15$) have been applied.
- Constant wind speed of 0.7 times nominal wind speed; wind direction from 200° up to 300°.
- Realistic fluctuating wind speed around 0.7 times nominal wind speed [6-10]; wind direction from 200° up to 300°.

The relevant results have been plotted in respectively figure 4.5 to 4.7. Per figure the following signals have been plotted from above:

- rotor effective ambient wind speed
- wind direction (filtered wind vane output)
- yaw angle
- pitch angle
- axial force
- power (electrical generator output)
- rotor speed

The figures show the pitching to feather, i.e. the increase of the blade angle, for those combinations of yaw angle and wind speed that Heat & Flux is applicable. This results in decreasing axial forces at the cost of some production losses as expected, most clearly shown by figure 4.5 (where the nearly constant wind direction signal results in 'Heat & Flux' all the time that the wind speed is below nominal). The wind direction dependent behaviour of the Heat & Flux controller is shown by especially figure 4.6 and also by figure 4.7. For those 2 figures the wind speed has been below nominal all the time and the wind direction and thus yawing signal lead to 'Heat & Flux' settings around *time* = 215 s and 470 s. A more detailed discussion about the behaviour of the Heat & Flux wind turbine controller follows in the next chapter, where Phatas simulations are dealt with.

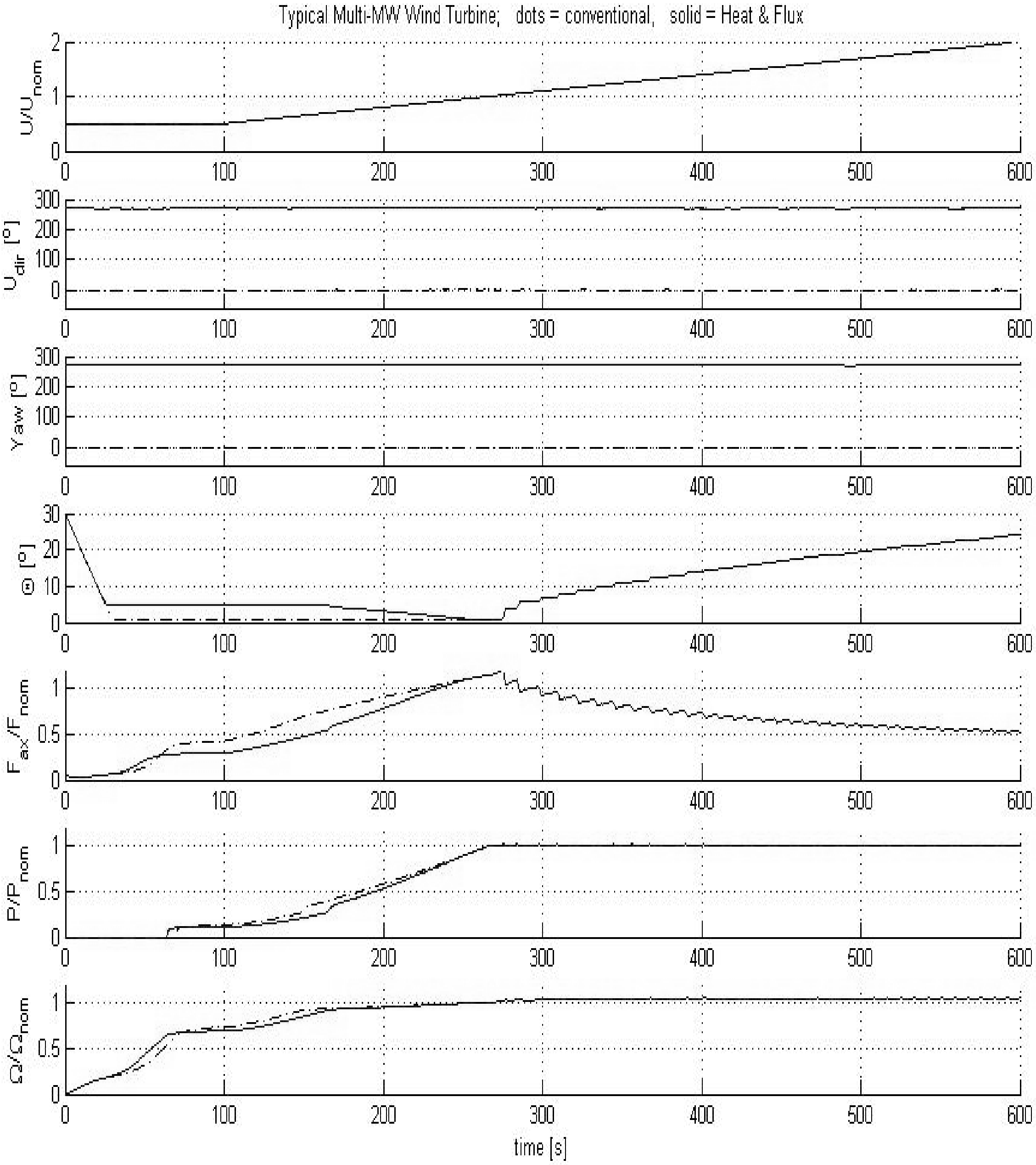

Figure 4.5: Control Tool simulation results for a typical Multi-MW wind turbine model. Once the model has been equipped by a conventional controller and once by a Heat & Flux wind turbine controller. Both controllers have been designed using the Control Tool.

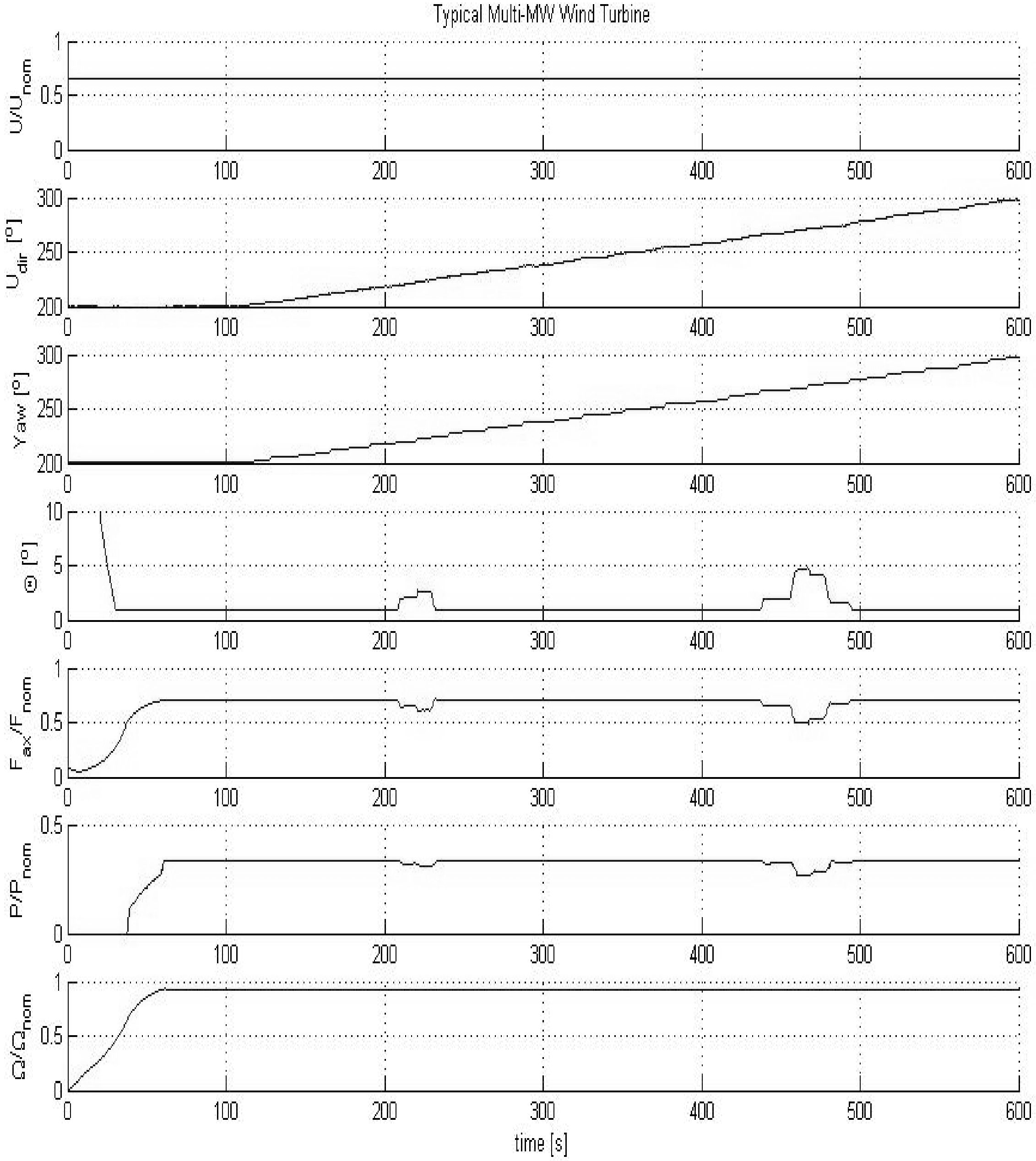

Figure 4.6: *Control Tool simulation results for a typical Multi-MW wind turbine model equipped with a Heat & Flux wind turbine controller that has been designed using the Control Tool. The simulated wind speed has been 0.7 times nominal constantly.*

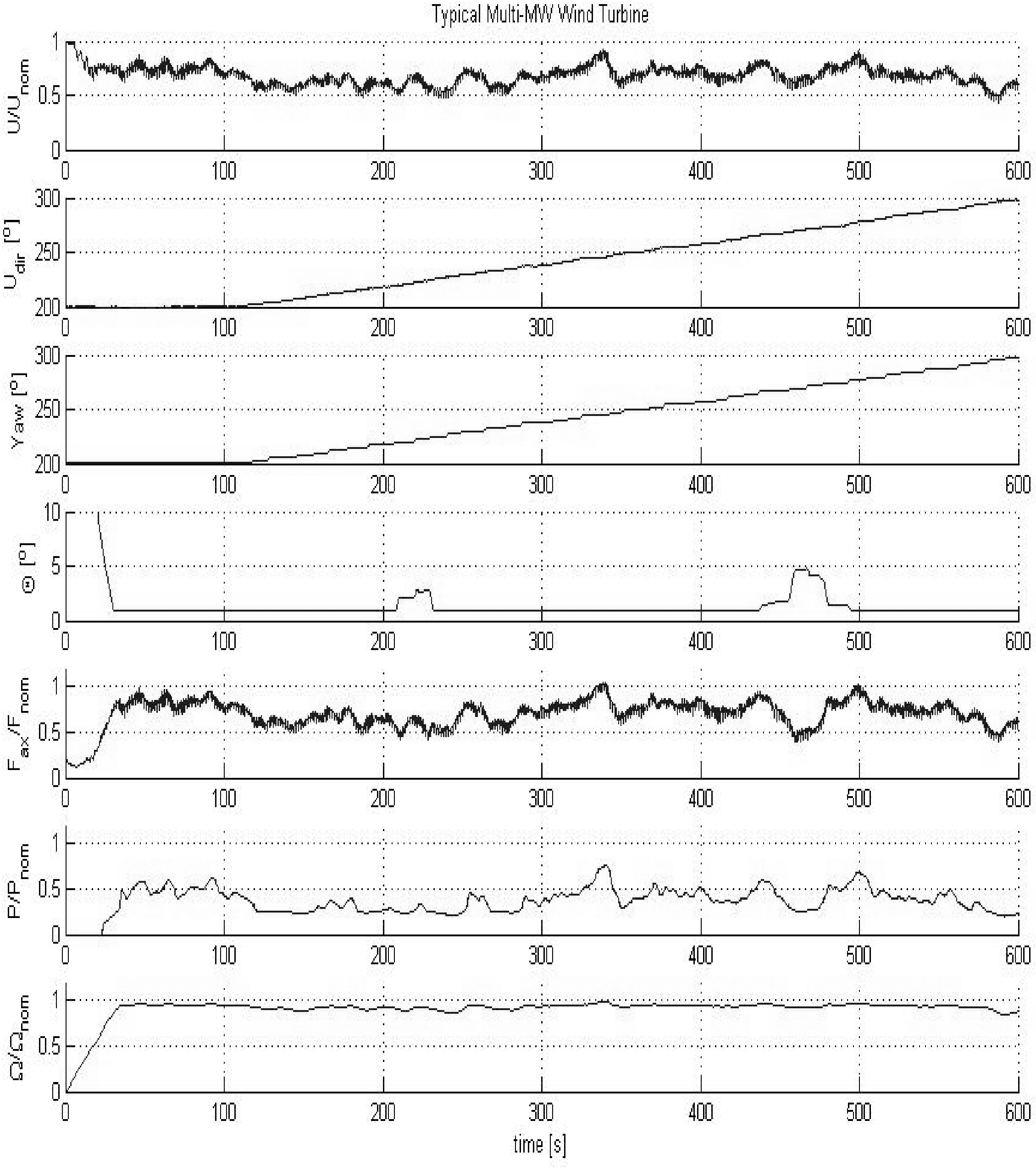

Figure 4.7: *Control Tool simulation results for a typical Multi-MW wind turbine model equipped with a Heat & Flux wind turbine controller that has been designed using the Control Tool. The simulated wind speed has been fluctuating in a realistic way [6-10].*

5. Verification by Phatas

We verified the performance of Heat & Flux wind turbine control by the authorised aero-elastic wind turbine code Phatas [12]. A Phatas model of the typical turbine has been exposed to an increasing simulated wind speed from 4 upto 15 m/s twice. During the first simulation run the typical model has been controlled conventionally, i.e. aiming at maximum individual turbine production. During the second run the model has been controlled by a Heat & Flux farm optimisation aim of $a = 0.14$. At both simulations the controller has been limited by an upper rotor speed and upper production level. Figure 5.1 shows the simulation results. The dotted line represents the conventional turbine, the solid line the Heat & Flux turbine.

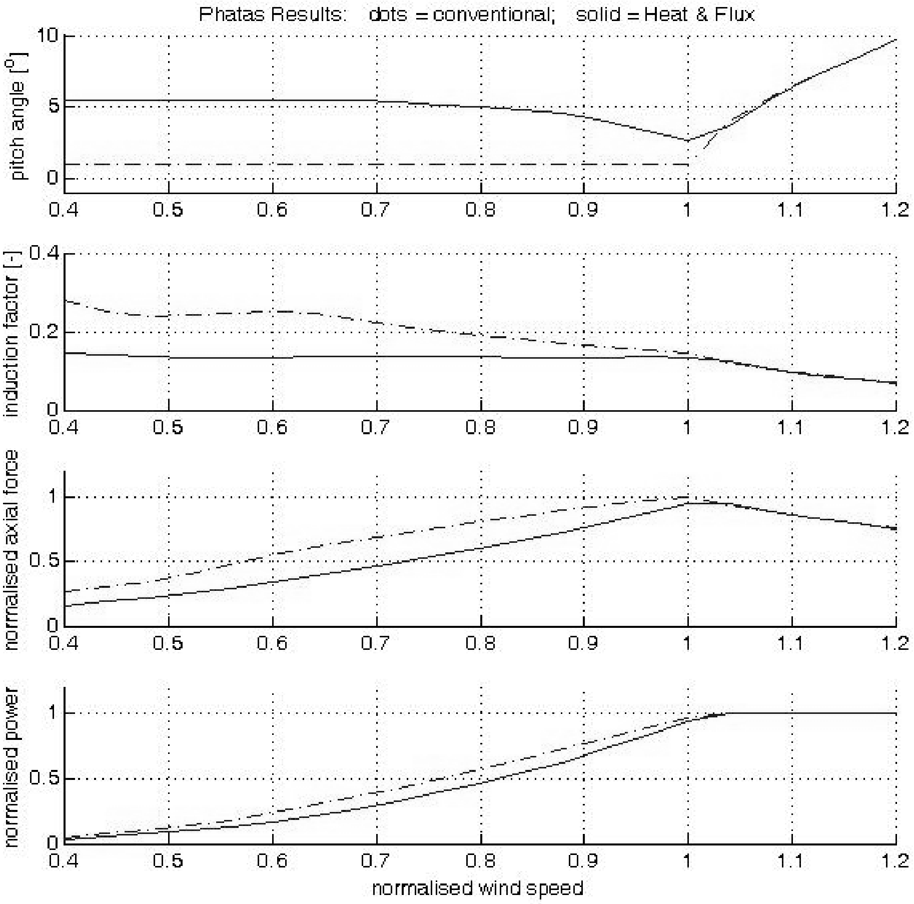

Figure 5.1: Phatas simulations for a typical multi-MW wind turbine model . Once the model has been equipped by a conventional controller and once by a Heat & Flux contoller.

Turbine operation can be split up in three areas with respect to the normalised wind speed U_n:

- $U_n < 0.7$: optimum λ
- $0.7 \leq U_n < 1$: transition (between optimum λ and above rated)
- $1 \leq U_n$: above rated

The transition is a consequence of the upper rotor speed limitation. Therefore the torque increases above the optimum λ settings, when the power in the wind increases above "maximum rotor speed times optimum λ torque".

The upper plot of figure 5.1 shows that Heat & Flux settings have been realised by pitching the blade to feather in the partial load operational area: optimum λ and the transition. The resulting induction factor $a = {}^1/_2 - {}^1/_2\sqrt{(1-C_t)}$ is showed by the second plot. During conventional control a already decreases somewhat when optimum λ is left and the transition is entered. The Heat & Flux controller then keeps a constant a by reducing the additional pitching to feather. Above $U_n = 1$ the conventional controlled turbine pitches to limit production. Above $U_n \approx 1.04$ the conventional controller aims at the same a as the Heat & Flux already aims at during partial load and from then on both controllers behave identical.

The third plot from above shows that our aim to realise a lower axial force than conventionally has been realised by the Heat & Flux controller. As foreseen the bottom plot shows some production losses when pitching to feather. Maximum production, i.e. normalised power = 1, occurs just above $U_n = 1$ because the plot shows electrical power, while wind speed and power are normalised on the basis of reaching the normalisation power value before mechanical losses.

No risks have been identified with respect to applying suitable Heat & Flux wind turbine controllers. The maximal axial loading force of Heat & Flux turbines will reduce and turbulence in the farm will reduce as well. Only positive effects concerning the risks involved.

The only thinkable safety risk of applying Heat & Flux wind turbine control would follow by human failure while adapting the control mechanism. Even this risk has been minimised by limiting Heat & Flux control to pitching to feather on the basis of yaw angles and abandoning minor improvements by tuning the generator torque.

Another "risk", not concerning safety, is bad use of the foreseen control mechanism. Ultimately the farm control strategy determines the profits obtained. The potential profits of Heat & Flux could be missed by an erroneous farm control strategy, but still no new risks will be introduced then. The turbine still will be loaded as much as conventionally or less. Only some production could be lacked then.

6. Conclusions and Recommendations

We found a general method to derive the relation between turbine transparency and blade pitch angle, while remaining conventional torque control (and thus changing the tip speed ratio). Analysis learned that raising the generator torque above usual levels could realise only minor improvements to the Heat & Flux objectives. Alternative torque control has been abandoned for reasons of simplicity and thus reliability.

Now we are able to calculate the Heat & Flux control parameters straight forward from the parameters already used for conventional control. The resulting method to design a Heat & Flux wind turbine controller has been implemented in ECN's Control Tool for designing wind turbine control algorithms. This method has been summarised in appendix D.

Further a transition mechanism between Heat & Flux and conventional operation, a wind direction signal, a yaw control algorithm and a simple Heat & Flux farm controller have been developed and implemented in the Control Tool. Herewith it became possible to verify the controller design by simulations within the Control Tool, including the wind direction dependent behaviour.

Using ECN's Control Tool we designed a Heat & Flux wind turbine controller for a typical offshore multi-MW wind turbine. FluxFarm has been used to determine the parameters of the simple farm controller for the case that the turbine would stand in the Horns Rev wind farm. The resulting Heat & Flux wind turbine control algorithm has been verified by the authorised aeroelastic wind turbine code Phatas.

The risks of applying suitable Heat & Flux turbine control appeared to be limited to some lack of production, occurring if the farm controller would misuse the introduced turbine control options. The only thinkable safety risk would follow by human failure while adapting the control code, although the code adaptations are very straightforward.

Simulations confirmed the decrease of both turbine production and turbine loading by applying Heat & Flux turbine control. Concerning the situation behind the turbine, we still expect a net raise of farm production and a lowering of turbulence by applying Heat & Flux in wind farms. With reservation of full-scale farm and turbine experiments, we propose to implement Heat & Flux turbine control algorithms in wind turbines intended for wind farms. Applying Heat & Flux wind turbine control we advise to verify the extent of correspondence between real-life aerodynamics and the rotor characteristics presumed during controller design.

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Appendix A Heat & Flux Turbine Control Design Code

Heat & Flux wind turbine control design code, implemented as a part of the partial load control design file ecnpartctrl.m in ECN's Control Tool for wind turbine control algorithms:

```
%---------------------------------------------------------------------------------------
--
% 2. Determination of Heat & Flux settings

    % figure settings
    FigNo = 1;
    figure(FigNo);
    clf;
    title('Heat & Flux settings; x = blade data, .- = control table');
    xlab = 'induction factor {\ita}  =  ^1/_2 - ^1/_2 \surd (1- {\itC}_t)  [-]';
    xlabel(xlab);
    ylabel('blade angle [dg]');
    axis([0 0.35 0 15]);
    grid on;
    hold on;

    % determination of Heat & Flux settings: Theta as function of a = 0.5-0.5*sqrt(1-Ct)
    [HFtbOpt] = ecnHFsettings(CpMax,LbOpt,'b');   % optimum Lambda conditions
    [HFtbRat] = ecnHFsettings(CpLbRat,LbRat,'r'); % rated conditions

    % equalize a = 0.5-0.5*sqrt(1-Ct) grids to enable 2D interpolation
    gpCo2r = HFtbOpt(find( rem(HFtbOpt(:,1), ... % a = 0.5-0.5*sqrt(1-Ct) grid point
       round(1000*(HFtbOpt(2,1)-HFtbOpt(1,1)))/1000) ~= 0),1);
    gpCr2o = HFtbRat(find( rem(HFtbRat(:,1), ... % a = 0.5-0.5*sqrt(1-Ct) grid point
       round(1000*(HFtbRat(2,1)-HFtbRat(1,1)))/1000) ~= 0),1);
    if isempty(gpCo2r) == 0,
       gpT     = interp1(HFtbRat(:,1), HFtbRat(:,2), gpCo2r); % Th grid point
       HFtbRat = sortrows( [HFtbRat; gpCo2r, gpT] );
       clear gpT;
    end
    if isempty(gpCr2o) == 0,
       gpT     = interp1(HFtbOpt(:,1), HFtbOpt(:,2), gpCr2o); % Th grid point
       HFtbOpt = sortrows( [HFtbOpt; gpCr2o, gpT] );
       clear gpT;
    end
    nOmega     = 10; % Nr of Nrpm grid points (cut off by minimal Th requires large nr)
    OmegaStep  = (RpmRat-RpmOptout)/(nOmega-1);
    OmegaGrid  = RpmOptout:OmegaStep:RpmRat; % grid of rotor speeds
    aLowBothIx = find( HFtbOpt(:,1) == max( HFtbOpt(1,1), HFtbRat(1,1) ) );
    HFtbTh = interp2( HFtbOpt(aLowBothIx:end,1), [RpmOptout, RpmRat], ...
                [ HFtbOpt(aLowBothIx:end,2), ...
                  HFtbRat( find(HFtbRat(:,1) == HFtbOpt(aLowBothIx,1) ):end,2) ]', ...
                HFtbOpt(aLowBothIx:end,1), OmegaGrid );
             % blade angles on 2D grid of a = 0.5-0.5*sqrt(1-Ct) and rotor speed
    plot(HFtbOpt(aLowBothIx:end,1),HFtbTh(nOmega,:),'r.-');
    for i = nOmega-1:-1:2,
       plot(HFtbOpt(aLowBothIx:end,1),HFtbTh(i,:),'k.-');
    end
    plot(HFtbOpt(aLowBothIx:end,1),HFtbTh(1,:),'b.-');
    HFa     = HFtbOpt(aLowBothIx:end,1); % a = 0.5-0.5*sqrt(1-Ct) grid for HF control
    HFnRpm  = OmegaGrid;                 % rotor speed grid for HF control
    HFtheta = HFtbTh';                   % Accompanying Theta values for HF control

    % figure settings
    text(0.15, 7 , '\lambda_{opt}');
    text(0.06, 3 , 'rated');

    % (re)save figures as postscript
    PsFileName = [PATHName.ps,'HFsettings'];
    xlabel(ecnaddfiles(xlab,PsFileName,10,1,1));
    eval(sprintf('%s -dps %s;','print',PsFileName));
    ecnfprintf(FunOpt.logging,'Figure %d saved as %s\n',FigNo,PsFileName);
```

```
% Store Heat & Flux settings in ascii format
DatFileName = sprintf('%sHFset%s',PATHName.dat,TURBINEIdf);
eval(sprintf('save %s.dat HFa HFnRpm HFtheta -ascii;',DatFileName));
ecnfprintf(FunOpt.logging,...
    'Heat & Flux settings in ascii format stored in %s.dat\n', DatFileName);

% Store Heat & Flux settings in mat-file
MatFileName = sprintf('%sHFset%s',PATHName.mat,TURBINEIdf);
varlist = {'HFa','HFnRpm','HFtheta'};
eval(sprintf('save %s %s;',MatFileName, ecncell2str(varlist)));
ecnfprintf(FunOpt.logging,...
    'Heat & Flux settings stored in .MAT-file %s.mat\n',MatFileName);

hold off;
pauseon=ecnpausefun(pauseon);
```

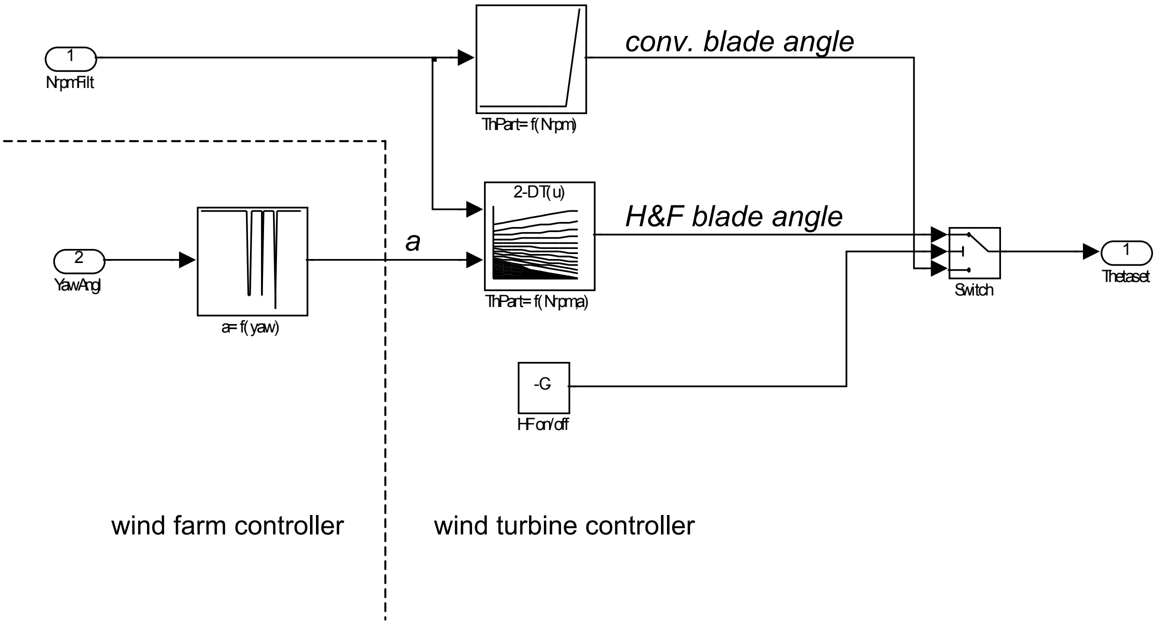
Core function in the design of Heat & Flux wind turbine control, called twice by ecnpartctrl.m:

```
function[HFtb]=ecnHFsettings(CpConv,LbConv,pltclr,FunOptLoc);
% ecnHFsettings: determination Heat and Flux settings
%
% CALL: [HFtb] = ecnHFsettings(CpConv,LbConv,pltclr,FunOptLoc);
%
% LOG: Feb,  2006: First version of ecnHFsettings; PS
%
% INPUT:
%   All required parameters (except input parameters) are retrieved by ecnDataGet()
%   from the global 'ParActList' into the local workspace of ecnHFsettings(). The
%   following (previous defined) parameters are mandatory required:
%
%      ecngenchar         <-- parameter definition
%      ------------------------------------------------------------
%      CprTb   [-]        <-- rotMod.CprTb       : Fine grid Cp-table
%      CtrTb   [-]        <-- rotMod.CtrTb       : Fine grid Ct-table
%      LbrTb   [-]        <-- rotMod.LbrTb       : Fine grid Lb-column
%      ThrTb   [dg]       <-- rotMod.ThrTb       : Fine grid Th-row
%
%   CpConv [-] : conventionally applied Cp value                             [mandatory]
%   LbConv [-] : accompanying tip speed ratio                                [mandatory]
%   pltclr     : color for plotting                                          [mandatory]
%   FunOptLoc  : Local settings for function navigation (1x5 numeric array)
%                                                                       [-1,-1,-1,-1,-1]
%
% OUTPUT:
%   HFtb : table to control the blade angle Th on the basis of desired
%      a = 0.5-0.5*sqrt(1-Ct) values, applicable for the conventional partial
%      load generator curve HFtb(:,1) = a = 0.5-0.5*sqrt(1-Ct) and HFtb(:,2) = Th.
%
%   Datafiles in PATHNAME.dat:  -
%
%   Datavariables in gencv<TURBINEIdf>.mat (PATHNAME.mat): -
%
%   Figures to postscript format to PATHName.ps: -
%
% GLOBAL:
%   PATHName:   Set op pathnames of current design (struct)
%   TURBINEIdf: Turbine identifier of current design version (char)
%   ParActList: Cell array of structs of previous parameter definitions
%
% ECN M-FUNCTION:
%   ecnmfiledir():  Return dir & name of calling M-func OR dir of specified M-func
%   ecnfprintf():   Message/Warning/Error handling to screen, file or both
%   ecnsetfunopt(): set function navigation options to final value for use
%   ecnDataGet():   Supplies validated previous param definitions to (local) workspace
%
% DESCRIPTION:
%   ecnHFsettings determines the table to control blade angle Th on the
%   basis of desired a = 0.5-0.5*sqrt(1-Ct) values. The determination is
%   based on the inputs CpConv and LbConv. Those inputs are supposed to be
%   a conventionally applicable combination of Cp and Lambda values. The
%   output HFtb gives the blade angles to realise the desired a =
%   0.5-0.5*sqrt(1-Ct) values for all combinations of torque and rotor
%   speed that conventionnaly leaded to CpConv and LbConv.
%
%   Content:
%     0. Retrieval and check of required input parameters
%     1. Determine relation between a = 0.5-0.5*sqrt(1-Ct) and Theta for H&F
%     2. Determine table to control Theta by the desired a = a = 0.5-0.5*sqrt(1-Ct)

%--------------------------------------------------------------------------------------
% 0. Retrieval and check of required input parameters

FunName=ecnmfiledir;

global PATHName TURBINEIdf ParActList
if isempty(TURBINEIdf) | isempty(PATHName) | isempty(ParActList)
    % Error and abort
    ecnfprintf(42,'Bad definition of required global(s) in %s\n',FunName.f);
end
```

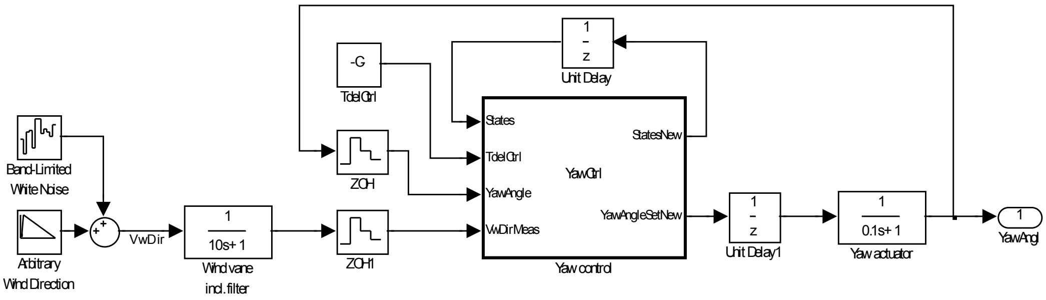
```
% Check on data class and size
if nargin<3 | ~isnumeric(CpConv)  | ~isnumeric(LbConv) | isempty(pltclr),
    % Error and abort
    ecnfprintf(42,'Bad function call %s\n',FunName.f);
end

if nargin<4 | isempty(FunOptLoc), FunOptLoc= -1*ones(1,5); end

% Set function options
FunOpt=ecnsetfunopt(FunOptLoc);
pauseon  = FunOpt.pause;

ecnfprintf(FunOpt.logging,'\nBegin of: %s (%s)\n',FunName.f,FunName.d);

% Retrieve required parameters only
datagetList= {'rotMod.CprTb', 'rotMod.CtrTb','rotMod.LbrTb', 'rotMod.ThrTb'};
ecnDataGet;
clear datagetList

%Assign inputs to local quantities
CprTb     = rotMod.CprTb;
CtrTb     = rotMod.CtrTb;
Lbr       = rotMod.LbrTb;
Thr       = rotMod.ThrTb;

clear rotMod

% 1. Determine relation between a = 0.5-0.5*sqrt(1-Ct) and Theta for H&F relevant condi-
tions
jLb = 0; HitLbConv = 0; % initialize while loop
while ( HitLbConv == 0 ) && ( jLb < length(Lbr) ), % while previous Lambda < conven-
tional
   jLb = jLb+1; % next Lambda
   jTh=find(max(CprTb)==max(max(CprTb))); % index of conventional theta;
                                          % lower theta's are irrelevant
   % find CpHF, ie. the unique Cp given Lbr(jLb) and the conventional gen.curve
   CpHF   = min( max(CpConv)*(Lbr(jLb)/LbConv)^3, max(CpConv) );
   if CpHF == max(CpConv), % if Lambda = conventional (larger values are irrelevant)
      HitLbConv = 1;
   else
      HitCpHF = 0; % initialize while loop
      % find Theta leading to Lbr(jLb) and thus CpHF
      while ( HitCpHF == 0 ) && ( jTh < length(Thr)-1 ),
         jTh = jTh+1;
         if ( (CprTb(jLb,jTh-1) <= CpHF) && (CprTb(jLb,jTh) >= CpHF) ) ||...
               ( (CprTb(jLb,jTh-1) >= CpHF) && (CprTb(jLb,jTh) <= CpHF) ),
            HitCpHF = 1;
            % determine closest grid point
            if abs( CpHF-CprTb(jLb,jTh-1) ) < abs( CpHF-CprTb(jLb,jTh) ),
               jTh = jTh-1;
            end
         end
      end
      % add point to [a, Th]-table for conventional gen.curve (a = 0.5-0.5*sqrt(1-Ct))
      HFtbTmp(jLb,:) = [0.5 - 0.5*sqrt( 1 - CtrTb(jLb,jTh) ), Thr(jTh)];
   end
end
% jLbRng ignores largest blade angles of non-unique [a,Th]-curve (a=0.5-0.5*sqrt(1-Ct))
jLbRng = find( HFtbTmp(:,1)==min(HFtbTmp(:,1)) ) : length(HFtbTmp(:,1));
plot(HFtbTmp(jLbRng,1),HFtbTmp(jLbRng,2), [pltclr 'x']);
plot(0.5 - 0.5*sqrt( 1 - CtrTb(jLb,jTh) ), Thr(jTh), [pltclr 'x']);
                                                            % Lb and Th conventional

% 2. Determine table to control Theta on the basis of desired a = 0.5-0.5*sqrt(1-Ct)
gsT = 0.1; % grid step size Theta
HFpol = polyfit( HFtbTmp(jLbRng,2), HFtbTmp(jLbRng,1), 3);
HFtbInv(:,2) = -10:gsT:20; % grid of blade angles
HFtbInv(:,1) = HFpol(1)*HFtbInv(:,2).^3 + HFpol(2)*HFtbInv(:,2).^2 + ...
   HFpol(3)*HFtbInv(:,2) + HFpol(4); % a = 0.5-0.5*sqrt(1-Ct) values
gsC = 0.01; % grid step size a = 0.5-0.5*sqrt(1-Ct)
aMin = min(HFtbInv(:,1)); % to prevent for ambiguity in HFtb
iMin = find( HFtbInv(:,1) == aMin ); % to eliminate ambiguity from HFtbInv
HFtb(:,1) = ceil(aMin/gsC)*gsC:gsC:0.5; % grid of a = 0.5-0.5*sqrt(1-Ct) values
HFtb(:,2) = interp1(HFtbInv(1:iMin,1),HFtbInv(1:iMin,2),HFtb(:,1));
```

```
aConv     = 0.5 - 0.5*sqrt( 1 - CtrTb(jLb,jTh) ); % conventional point
if rem(aConv, gsC) ~= 0,
   HFtb = sortrows( [aConv, Thr(jTh); HFtb] );      % add conventional point
   HFtb( find( HFtb(:,1) > aConv ), 2 ) = Thr(jTh); % a > aConv => ThConv
end
HFtb(:,2) = max( HFtb(:,2), Thr(jTh) );          % all Th >= ThConv

ecnfprintf(FunOpt.logging,'End of: %s (%s)\n\n',FunName.f,FunName.d);
```

Appendix B Heat & Flux Control Scheme



Appendix C Yaw Control Scheme and Code



```
function [StatesNew, YawAngleSetNew] = YawCtrl(States, TdelCtrl, ...
    YawAngle, VwDirMeas)
%
% PS 2005/11: introduction of simple yaw control, the controller time
% step (ctrp.p.v.samplCfg.TdelCtrp) is copied from the pitch controller

StatesNew = States; % initialisation required by Matlab

% input states
YawState     = States(1);
YawAngleSet  = States(2);

% control parameters
StartYawError  = 2;  % offset to the measured wind dir to start yawing [dg]
StopYawError   = 0;  % offset to the measured wind dir to stop yawing [dg]

YawStateNew = YawState;
switch YawState,
    case 0, % no yawing
        if YawAngle - VwDirMeas > StartYawError,
            YawStateNew = 1;
        elseif VwDirMeas - YawAngle > StartYawError,
            YawStateNew = 2;
        end
    case 1, % yawing in negative direction
        if YawAngle - VwDirMeas < StopYawError,
            YawStateNew = 0;
        end
    case 2, % yawing in positive direction
        if VwDirMeas - YawAngle < StopYawError,
            YawStateNew = 0;
        end
end

switch YawStateNew,
    case {1,2} % yawing
        YawAngleSetNew = max(min(VwDirMeas,YawAngleSet+0.2),YawAngleSet-0.2);
    otherwise, % no yawing
        YawAngleSetNew = YawAngleSet;
end

% output states
StatesNew(1) = YawStateNew;
StatesNew(2) = YawAngleSetNew;
```

Appendix D Method to Enable Turbines to Aim at Heat & Flux[1]

Nomenclature

a	rotor induction factor, determinative for rotor transparency
C_p	rotor power coefficient
C_t	rotor thrust coefficient
λ	blade tip wind speed ratio
θ	blade angle

With subscript 'c' indicating conventional control and 'HF' indicating Heat & Flux control.

Design Method

- Calculate:

  $$C_{p,HF} = C_{p,c}\left(\frac{\lambda_{HF}}{\lambda_c}\right)^3 \qquad \text{for the interval } 0 < \lambda_{HF} < \lambda_c \qquad \text{(D.1)}$$

  once with λ_c as realised by "optimum λ control" and once as realised at nominal wind speed

- Look up θ_{HF} that accompanies found combinations of λ_{HF} and $C_{p,HF}$
- Look up $C_{t,HF}$ that accompanies found combinations of λ_{HF} and θ_{HF}
- Calculate:

  $$a_{HF} = \tfrac{1}{2} - \tfrac{1}{2}\sqrt{1 - C_{t,HF}} \qquad \text{for all } C_{t,HF} \qquad \text{(D.2)}$$

- Fill the Heat & Flux turbine control table that prescribes θ on the basis of the additional controller input a by accompanying a_{HF} and θ_{HF}. (A farm controller must provide a).
- Interpolate (a_{HF},θ_{HF}) for λ_c between the ones realised by "optimum λ control" and realised at nominal wind speed.

Boundary conditions

- Verifying the rotor characteristics presumed during controller design by real-life aerodynamics is recommended.
- The risks of applying a suitable Heat & Flux wind turbine controller is limited to some lack of production, occurring if the farm controller would misuse the introduced turbine control options. The only thinkable safety risk would follow by human failure while adapting the control code, although the code adaptations are very straightforward.
- Introducing alternative torque control in addition to the above proposed blade angle control $\theta_{HF}(a)$ could slightly increase the already slight increase in net farm production. For reasons of simplicity and thus reliability it is recommended to abandon alternative torque control.

---

[1] Corten, G.P., Schaak, P., *Heat and Flux*, Patent Number WO2004111446, 2003