A process for providing positive primary control power by wind turbines

V Marschner[1], J Michael[2] and J Liersch[2]

[1]Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany
[2]Key Wind Energy GmbH, Cicerostraße 37, 10709 Berlin, Germany

E-mail: v.marschner@keywind.de, j.michael@keywind.de, j.liersch@keywind.de

Abstract. Due to the increasing share of wind energy in electricity generation, wind turbines have to fulfil additional requirements in the context of grid integration. The paper examines to which extent wind turbines can provide positive control power following the related grid code. The additional power has to be obtained from the rotating flywheel mass of the wind turbine's rotor. A simple physical model is developed that allows to draw conclusions about appropriate concepts by means of a dynamic simulation of the variables rotational speed, torque, power output and rotor power. The paper discusses scenarios to provide control power. The supply of control power at partial load is examined in detail using simulations. Under partial load conditions control power can be fed into the grid for a short time. Thereby the rotational speed drops so that aerodynamic efficiency decreases and feed-in power is below the initial value after the control process. In this way an unfavourable situation for the grid control is produced, therefore the paper proposes a modified partial load condition with a higher rotational speed. By providing primary control power the rotor is delayed to the optimum rotational speed so that more rotational energy can be fed in and fed-in power can be increased persistently. However, as the rotor does not operate at optimum speed, a small amount of the energy yield is lost. Finally, the paper shows that a wind farm can combine these two concepts: A part of the wind turbines work under modified partial load conditions can compensate the decrease of power of the wind turbines working under partial load conditions. Therefore the requested control power is provided and afterwards the original value of power is maintained.

1. Introduction

Wind energy covers a significant part of the demand for electricity in many countries, especially in Denmark (34 percent of the electricity consumption in the year 2013, cf. [1]), Portugal (25 percent), Spain (21 percent) and Germany (8 percent). The increasing proportion of the wind energy requires to involve wind turbines in the grid control and grid balancing. The expansion of renewable energies leads to a displacement of classical controllable thermal power plants. In addition, many renewable energy sources require a very powerful grid control due to fluctuating input.

By the reason of the limited storability of electrical energy (cf. Erdmann, Zweifel [2], p. 294) is the central task of grid control in maintaining the balance of electricity generation and demand. Imbalances are equalized with control power. This paper examines the extent to which wind turbines can provide positive control power.

The grid load is changing constantly subjected by connecting, disconnecting and controlling of electrical consumers. In power plants, which generate electrical energy by driving a generator

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causes a change in the grid load a different counter torque on the generator. Due to the change in torque arises a new rotational speed. A stationary frequency deviation results because the speed is proportional to the grid frequency. So, an oversupply of power generation leads in an increase of the grid frequency. An active power deficit causes a frequency reduction. Therefore the drive power is controlled, since even small changes in the grid load lead to unacceptable changes in the grid frequency (cf. Heuck, Dettmann [3], p. 62 - 71).

For the exact balancing of the grid frequency is used a further control loop. These one eliminates the steady-state error of the rotational speed control. In this case the grid frequency is used as a control variable instead of the rotational speed. The grid frequency is a result of the generator speed and is a secondary value. Consequently this control loop is called a secondary control. In this way the speed control is called primary control. The concept of internal – speed controller – and external controller – frequency controller – is a classical cascade control (cf. figure 1). These models represent the simplest case and are valid for stand alone grids with one power plant. In interconnected power grids set the secondary control the power plant output.

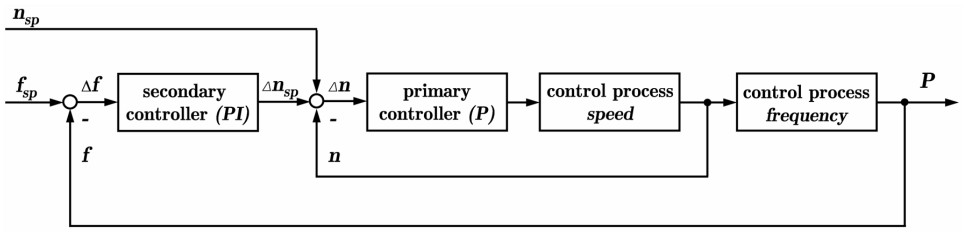

Figure 1. Control of the grid frequency

The frequency control in the power supply is performed by the controlled feeding of primary control power (cf. [4]). Conventional power plants achieve the power increase by increasing the fuel supply. This approach is not possible for wind turbines because the plants utilize the entire potential of the wind. The concepts developed in this work rely substantially on the inertia of the rotating components of the wind turbine.

The flywheel mass of the turbogenerator also plays an important role in classical power plants. In distinction to modern wind turbines the speed of the turbogenerator in power plants is proportional to the grid frequency. The grid-supporting effect of this inertia is assigned to spinning reserve (cf. [5]).

The profitability is not considered in this paper. The provision of primary control reserve of renewable energies would get paid the same way as the provision of primary control reserve of conventional power plants.

2. Operation concepts of wind turbines for providing primary control power

2.1. Providing primary control power at partial load operation

At partial load operation, wind turbines mostly work at this operation point, the entire energy supplied by the wind is converted into electrical energy, considering the efficiency of the wind turbine. Variable-speed turbines equalize the drive train loads by storing wind energy from wind fluctuations as rotational energy. To increase the feed-in capacity, it is possible to take advantage of the kinetic energy of the rotating parts in the opposite process. By imposing additional power from the generator, the output torque of the generator shaft is increased. The rotor experiences a higher counter torque and the rotational speed decreases. The stresses of the modules remain within the allowed range because the rated power is not exceeded. The following cases can be distinguished:

(i) The output power is increased by a certain value, while the rotational speed must not be less than the specified value. Afterwards the rotor accelerates according to the prevailing wind conditions.

(ii) The output power is increased and provided without considering the rotational speed. A superior device informs the control system of the wind turbine about the end of the process. The following situations can occur:
   (a) The required control power can be delivered completely. At the end of the process the rotor has a residual speed and accelerates to operating speed.
   (b) The required control power can not be provided completely, since the total kinetic energy of the rotor was converted. The rotor stops.

2.2. Providing primary control power at modified partial load operation

In partial load operation a reduction in rotor speed results in a lower power output, assuming previously the wind turbine was at the maximum power point. After an acceleration phase the rotor reaches the initial rotational speed and the initial power. Thus, the power output collapses after the control operation. Therefore we suggest a modified operation process for the partial load range, that prevents power losses at the end of the procedure. To obtain this desirable property, the partial load speed will be increased. This has two advantages and one disadvantage:

+ The rotor has a higher rotational energy due to the higher rotational speed. There is a bigger amount of energy stored, which can be used for the delivery of control power.
+ Because the rotor is operating at a higher rotational speed than the optimal speed, the power coefficient decreases. While the delivery of control power, the rotor speed returns to the optimum speed. The power coefficient increases – even the higher power output can be maintained.
– The previous fact implies directly the disadvantage: In this mode, the rotor does not work optimal, and loses some energy yield. On the other hand, the system obtains the desired primary control capability.

The modified operation leads to the scenario:

(iii) In the modified partial load operation primary control power is delivered as long as the optimum speed is reached.

3. Modelling

The different concepts are evaluated using simulations based on a physical model of the wind turbine. The following assumptions are made for modelling:

- Bearings, gearbox, generator and inverter have no losses.
- During the control process there is a constant wind speed.
- Generator and inverter can handle all speeds.
- The rotor blades are the result of an ideal design by Schmitz (Gasch, Twele [6], p. 202).

Under these assumptions, the model leads to the ideal case – it calculates the maximum control power that can be delivered.

3.1. Setting up the model equations

A wind turbine is the basis for the power conversion considerations. The focus is on the modelling of the rotor dynamics. A dynamic energy balance is expedient.

$$\frac{dE}{dt} = P_{in} - P_{out} \tag{1}$$

The storage term $\frac{dE}{dt}$ describes the system's energy change over time. Especially the energy of the rotating components of the wind turbine will be investigated. The balancing is done over the change of rotational energy $\frac{dE_{ROT}}{dt}$. The input power P_{in} is the power extracted from the wind – the rotor power. The output power P_{out} is the electric power produced by the generator – the generator power.

$$\frac{dE_{ROT}}{dt} = P_{rotor} - P_{gen} \tag{2}$$

The wind turbine's rotor is capable of converting a part of the winds energy. This energy conversion depends on the rotor design and the rotor angular velocity ω. The generator power can also be expressed as a rotation against a torque M with the angular velocity ω.

$$\frac{dE_{ROT}}{dt} = P_{rotor}(\omega) - M_{gen}\,\omega \tag{3}$$

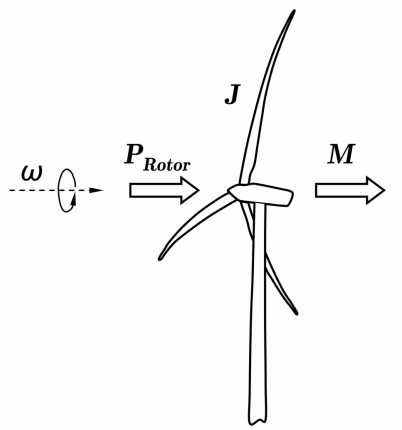

Figure 2. Model for rotor dynamics

The rotational energy of the rotor of the wind turbine is determined by its moment of inertia J and its angular velocity ω.

$$E_{ROT} = \frac{1}{2}J\omega^2 \tag{4}$$

These reflections lead to a differential-algebraic system of equations (DAE). It consists of a differential equation – equation 5 – and an algebraic constraint – equation 6.

$$\boxed{\begin{aligned} \dot{E}_{ROT} &= P_{rotor}(\omega) - M_{gen}\,\omega && (5)\\ E_{ROT} &= \frac{1}{2}J\omega^2 && (6) \end{aligned}}$$

3.2. Solution of the model equations
The model equations are solved with the explicit Euler method. The discretisation turns the differential quotient of the rotational energy into a difference quotient:

$$\dot{E}_{ROT} \approx \frac{E_{ROT}(k+1) - E_{ROT}(k)}{\triangle t} \tag{7}$$

The numerical solution of the system can be obtained by repeatedly performing the following two equations.

$$\boxed{\begin{aligned} &E_{ROT}(k+1) = E_{ROT}(k) + (P_{rotor}(\omega, k) - M_{gen}(k)\,\omega(k))\,\triangle t && (8)\\ &\omega(k+1) = \sqrt{\frac{2E_{ROT}(k+1)}{J}} && (9)\end{aligned}}$$

For step $k = 0$ the rotational energy is calculated with the angular velocity at the initial step $\omega(k = 0)$:

$$E_{ROT}(0) = \frac{1}{2} J\omega(0)^2 \tag{10}$$

All following steps $k \geq 1$ are calculated with the equations 8 and 9 . In this way the results for the discrete-time functions of the rotational energy $E_{ROT}(k)$ and the angular velocity $\omega(k)$ can be calculated:

$$E_{ROT}(1) = E_{ROT}(0) + (P_{rotor}(\omega, 0) - M_{gen}(0)\,\omega(0))\,\triangle t \tag{11}$$

$$\omega(1) = \sqrt{\frac{2E_{ROT}(1)}{J}} \tag{12}$$

$$E_{ROT}(2) = E_{ROT}(1) + (P_{rotor}(\omega, 1) - M_{gen}(1)\,\omega(1))\,\triangle t \tag{13}$$

$$\omega(2) = \sqrt{\frac{2E_{ROT}(2)}{J}} \tag{14}$$

$$\ldots$$

The simulation variables – the rotational energy and the angular velocity – have been calculated for the discrete steps $k = 0, 1, 2, \ldots$. The shift to time-related variables is done via the step size $\triangle t$:

$$t = k\,\triangle t \tag{15}$$

3.3. Calculation of the rotor power
The rotor power $P_{rotor}(\omega)$ includes the aerodynamic aspect in the equation of the rotational energy. It represents the power obtained by the rotor depending on the respective rotor speed:

$$P_{rotor}(\omega) = c_P(\omega)\,P_{wind} \tag{16}$$

The power coefficient c_P is usually expressed over the tip speed ratio λ for a wind turbine. The exact graph of this function is determined by the profile type of the rotor blades. The tip speed ratio is obtained directly from the angular velocity, assuming constant wind speed.

Variable-speed wind turbines are always working with the maximum power coefficient in the partial load range. Upon delivery of primary control power, the speed drops off and the rotor operates at a lower power coefficient $c_{P,\,control}$. By pitching the rotor blades, it is possible to return to a higher power coefficient $c_{P,\,control,\,pitch}$.

$$c_{P,\,control} < c_{P,\,control,\,pitch} < c_{P,\,max} \tag{17}$$

Besides rotational speed, the rotor power also depends on the pitch angle. In a characteristic diagram several c_P-λ-curves for different pitch angles are listed (cf. figure 3).

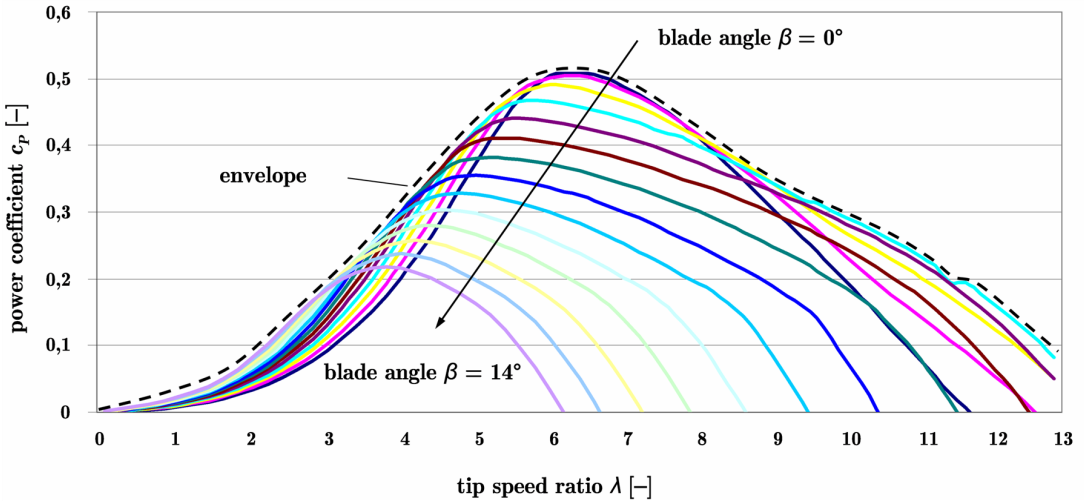

Figure 3. c_P-λ-characteristic diagram for different pitch angles β.

To maintain the characteristic diagram in figure 3 a rotor was designed according to Schmitz. Then c_P-λ-curves for different pitch angles were determined using the blade element method. The execution of the two methods, design and rotor blade element method, was performed according to Gasch, Twele ([6], p. 205 - 221).

The blade element method returns the desired characteristic diagram in the form of a table (cf. table 1). In each simulation step, the tip speed ratio is determined for the present rotational speed by the calculation algorithm, which searches in the corresponding row of the characteristic diagram for the highest c_P. The column returns the corresponding pitch angle β.

	$\beta = 0°$	$\beta = 1°$	$\dots$	
λ_1	$c_P(\lambda_1,\, 0°)$	$c_P(\lambda_1,\, 1°)$	$c_P(\lambda_1,\, \dots)$	$\dots$
λ_2	$c_P(\lambda_2,\, 0°)$	$c_P(\lambda_2,\, 1°)$	$c_P(\lambda_2,\, \dots)$	$\dots$
$\vdots$	$c_P(\dots,\, 0°)$	$c_P(\dots,\, 1°)$	$c_P(\dots,\, \dots)$	$\dots$
	$\vdots$	$\vdots$	$\vdots$	$\ddots$

Table 1. Characteristic diagram of the power coefficient c_P.

4. Evaluation of selected scenarios for the primary control capability of wind turbines

Based on the introduced model the possible contribution of wind turbines in grid control will be examined. The model parameters are adapted to a wind turbine of 2 MW class. For the following simulations the wind speed, unless otherwise stated, is set to $8\,\mathrm{m\,s^{-1}}$.

4.1. Simulation of primary control capability at partial load

An increase in the power output of wind turbines is possible at partial load only by reclaiming energy of rotation, if the turbine were did not operated throttled previously. The induced drop in rotational speed shifts the operating range of the rotor to unfavourable power coefficients. To return to the optimal operating point, the rotational speed is returned to the initial value after the delivery of the additional energy. This is accomplished by the opposite process. The generator output power is reduced below the currently available rotor power ($P < P_{rotor}$). Under this condition, the rotor accelerates and thereby increases its rotational energy. It is not possible to skip with the phase with reduced power after the delivery of the additional power P_A and continue to operate the turbine at the initial power P_0. The output power could only be provided at the expense of rotational energy. Finally, the system would stop.

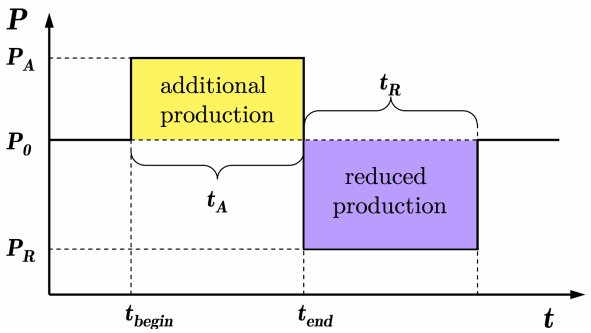

Figure 4. Additional power and reduced power at partial load

In figure 4 the profile of the output power at partial load is shown. The bold solid line shows a possible profile. At the time t_{begin} the infeed power increases from P_0 to P_A. The energy that is delivered additionally in the power grid is just the yellow coloured area under the power curve. At the end of increased output at time t_{end} follows a phase with reduced infeed power P_R. Compared to normal operation, the infeed of energy that results from the difference between violet and yellow area is eliminated.

In figure 5 the amount of additional power P_A is varied. The duration of the additional power is 10 seconds. The subsequent reduction in performance is at 10 % of the initial power P_0. The duration of the power reduction is variable. Once the initial speed n_0 is reached, it is switched back to their initial power P_0.

The rotational energy (figure 5 a) is converted directly into additional grid infeed power (figure 5 d) which is the requirement (cf. figure 4). The rotational speed (figure 5 b) drops significantly with increasing additional energy. Also the rotor power wanes (figure 5 c).

With the help of the torque profile (figure 5 e) the drive train load can be detected. The loads are not investigated in detail. Some scope to the rated loads does exist in the partial load operation. Power changes of 50 percent of the rated power are possible in 1 to 2 seconds in practice (cf. Heier [9], p. 314).

The pitch angle (figure 5 f) is gained from the characteristic map. The higher the additional power, the more pitch usage is required.

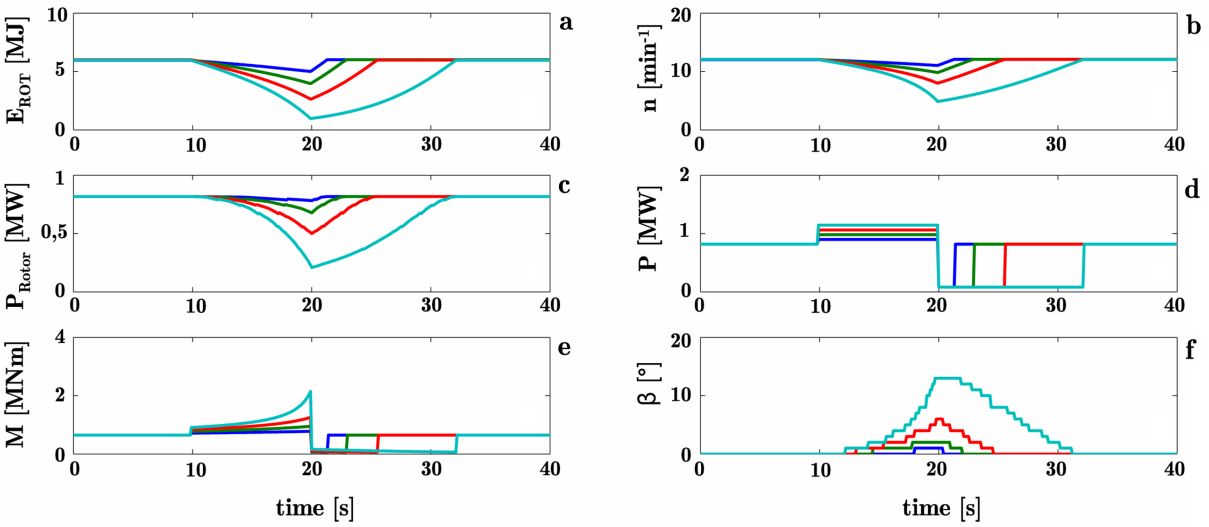

Figure 5. Simulation for different additional powers: +10 % (blue), +20 % (green), +30 % (red) and +40 % (cyan)

The quantity of electricity, which is lost during the rotor acceleration phase, is always greater than the amount that is obtained while the rotor deceleration. Once the rotor leaves the optimum speed range due to the deceleration, the aerodynamic efficiency decreases. Even with the assumed constant wind speed, the energy conversion of the rotor is reduced by a smaller power coefficient c_P. Thus, in the acceleration phase, there is initially a lower rotor power that gradually increases with increasing speed. Upon reaching the optimum rotor speed, the rotor power corresponds with the power at the initial time.

This simple approach is also proposed in the previous paper (cf. [7], p. 433-434). If the allowed grid frequency range is deceeded, the wind turbines will increase their infeed power at the expense of their rotational speed. There is no yield loss in normal operation. In the examined case a wind farm does provide frequency support during a short term failure. The drop of grid frequency is limited by the control reserve of the wind farm. The acceleration phase of the wind turbines, characterized by lower infeed power, takes place when the full generating capacity is available again. In this particular case, it is shown that even the simple approach can be valuable for the grid balancing.

Another approach proposes the throttling by a pitch angle (cf. [8]). If the grid balance requires positive control reserve, the pitch angle may reduce and the infeed power increases. Of course this approach leads to a continuously loss of energy yield.

4.2. Simulation of primary control capability at modified partial load

The modified operation mode at partial load consists, as explained, of an increase in the rotor speed $n > n_{opt}$. The progress of the infeed power of the wind turbine during delivering control power is shown in figure 6. While the rotor is delayed to the optimum angular velocity $\omega_{opt} = \lambda_{opt}\, v/r$ the generator releases the rotational energy stored in the speed difference $E_{ROT} = {}^1\!/_2\, J\,(2\,\pi)^2(n^2 - n_{opt}^2)$. This amount of energy is called additional energy II. During deceleration to the optimum speed increases the aerodynamic efficiency of the rotor, the feed-in can be increased durably. The infeed amount obtained by this procedure is called additional energy I. Hence this energy is abandoned in favour of true primary control properties during normal operation.

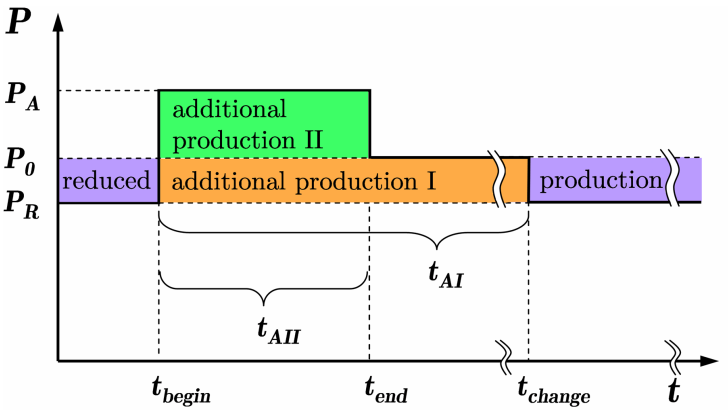

Figure 6. Additional power and reduced power at modified partial load

The operating points above the optimum speed are in the c_P-λ-characteristic diagram right side of the maximum power coefficient. The power coefficient decreases further with increasing speed enhancement and with increasing tip speed ratio. Due to the increased rotational speed more rotational energy is available. In consequence of the discrepancy to the maximum power coefficient, the feed-in can be raised permanently. Figure 7 shows the time characteristics of simulation variables for different speed increases. The advantageous properties increase with speed enhancement. However, the permanent yield loss increases further.

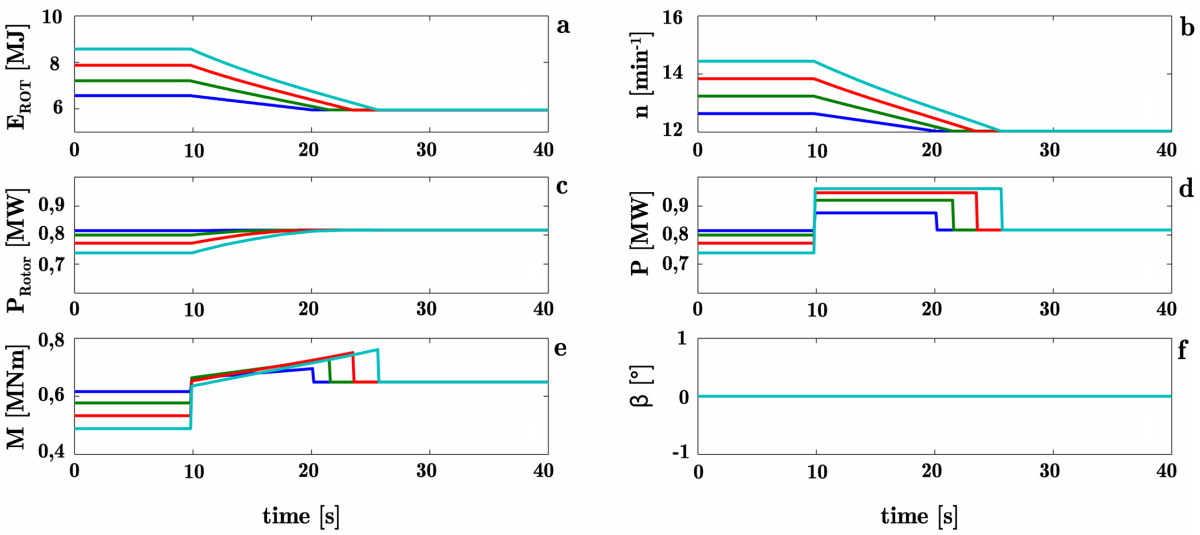

Figure 7. Speed enhancements of : +5 % (blue), +10 % (green), +15 % (red) and +20 % (cyan)

The stored rotational energy (figure 7 a) increases with the speed-raising. During the delivery of the control power, the speed is decelerated to the optimum speed (figure 7 b). The rotor power leaves the throttled level and reaches the optimal value (figure 7 c). After the delivery of the additional energy I and II the grid infeed power hits the unthrottled level (figure 7 d).

4.3. Combining both concepts in a wind farm

In a wind farm, the two mentioned concepts can be combined so that the disadvantages are weakened, and a maximum of the benefits remain. The idea is to operate only a part of the

wind turbines of a wind farm at the modified partial load (mpl). The other part continues to work in the normal partial load (pl) without yield losses. When control power is requested all plants provide rotational energy as grid feed. The modified operated wind turbines then have higher power output, because the operating point is now in the optimum. For the remaining wind turbines it is necessary to reduce the power output below the initial level to prevent a further drop in speed. The configuration should be based on the premise that the increased power of the turbines in the modified operation compensates the reduced performance of the other turbines. As a result, there is a total power output (t), that can provide control power and then maintaining the initial level (figure 8).

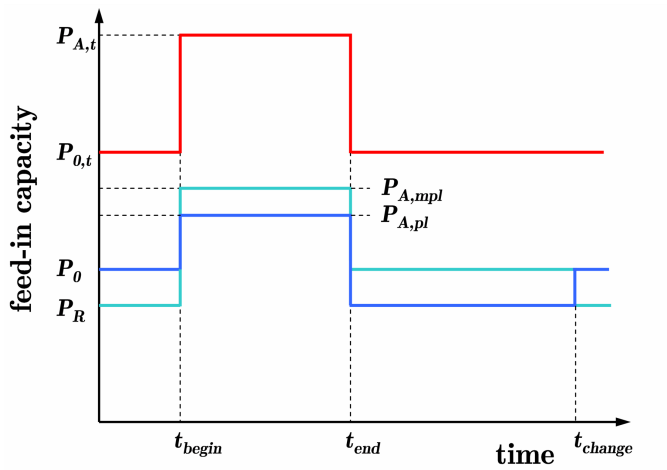

Figure 8. Infeed power of a wind farm at the request of control power

Table 2 shows an example design for two wind turbines: One turbine operates at partial load and another one at modified partial load. If 1 % energy yield loss is tolerated, the wind farm can be provided with a primary control capability. The primary control makes it possible to raise the infeed power for 20 seconds to 105.5 %. The example is for a wind speed of 7 $\mathrm{m\,s^{-1}}$. The speed of the modified operated turbine is increased by 9.5 percent. It may not be ignored that the values were determined with the idealized model. There are also losses and restrictions in practice, which have negative effect on the absolute values. Nevertheless the suggested approach achieves the goal – providing control power.

	normal mode		control process 20s		balancing 57s		normal mode	
	[kW]	[%]	[kW]	[%]	[kW]	[%]	[kW]	[%]
WT pl	547	100	564	103	537	98	547	100
WT mpl	537	98	591	108	547	100	537	98
total	**1084**	99	**1155**	105.5	**1084**	99	**1084**	99

Table 2. Control process in a wind farm, $v = 7\,\mathrm{m\,s^{-1}}$

In the example the balancing process is finished after 57 seconds – the turbine operating at partial load is accelerated back to the optimum speed. It should be considered that the table 2 is valid for a fixed wind speed. At the time t_{change} (figure 8) both groups change to intended normal operation. Afterwards control power can be delivered again. The control capability can be be used extensively because it is free of charge.

5. Conclusion

Wind turbines can stabilize the grid frequency with short-term, but instantaneously available control power. If the frequency difference requires a long-term use of control power, wind turbines bridge the time left until the complete activation of the classical primary control power. In both cases, wind turbines make an important contribution to grid stability.

The support of other controllable power plants is necessary in the simple approach. The benefits for the grid control can be reached on two different ways: (1) The total infeed power can be equalized using the inertia of the wind turbines. In case of short term power system failures the wind turbines support the grid frequency by converting moderately rotational energy into additional infeed power. (2) If the classical control power is available, wind turbines can raise aggressively the infeed power to counteract the drop of grid frequency. The classical power plants increase the power output additionally in the context of primary control to compensate the reduced infeed power of wind turbines in the rotor acceleration phase.

The modified version is conditionally capable to participate in the grid control. The available control power depends on the load of the wind turbines. Thus, the wind turbines have a control reserve which is gaining in importance at a high share of wind energy in the energy mix.

Figure 9 (cf. Heier [9], p. 337) shows the control structure of a variable speed and grid connected wind turbine. At high wind speed the power limiting and controlling of the rotational speed is achieved by the pitch system. At partial load operation the speed is controlled by the inverter. During normal operation a balance between delivered power by the rotor and the taken power by the generator is always set. If control power has to be delivered, this equilibrium condition is temporarily suspended by a special controller. In figure 9 the new controller is illustrated by dashed blocks and connections. This controller is also connected to the pitch system. As shown, the pitch control improves the aerodynamic behaviour during decreasing speed. If the grid frequency or the gradient of the grid frequency leaves the allowed range, the operation management enables the control power.

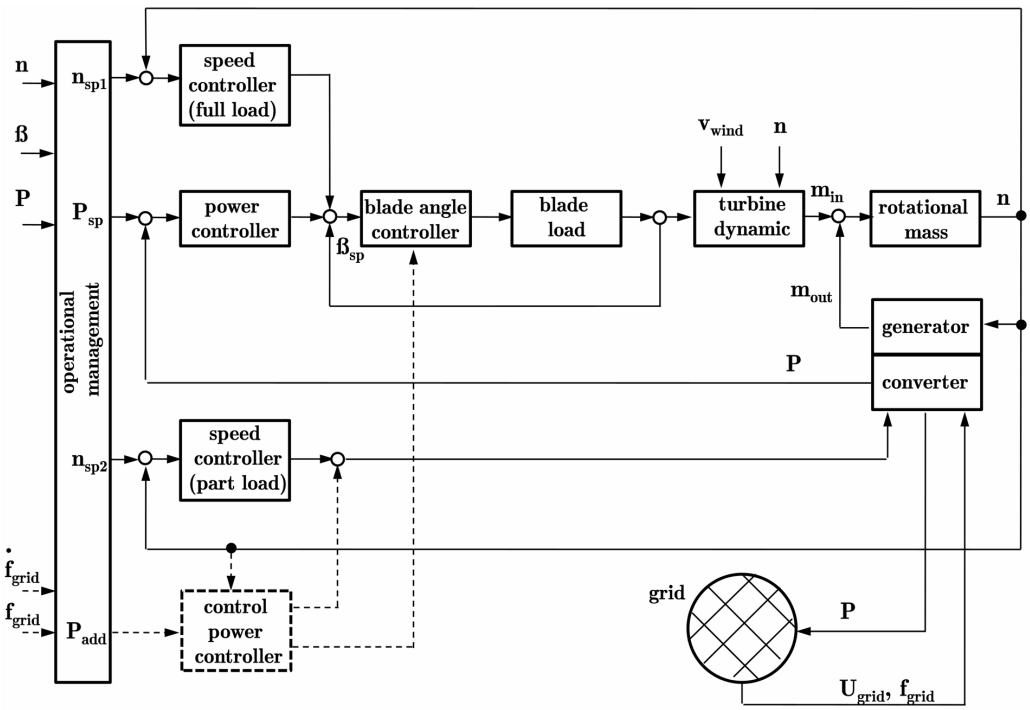

Figure 9. Advanced control structure for wind turbines

This paper shows how wind turbines can effectively participate in primary control of the electrical power grid. The quality of the control power from wind turbines is particularly high. In contrast to thermal power plants, the control power can be activated instantaneously (cf. Kurth, Kallina [10]). Thus grid frequency dips can be eliminated at their appearance. The implementation can be done with a powerful control algorithm and would be a further important step for the integration of renewable energy into the power system.

6. Future tasks

To obtain the control capability of wind turbines at partial load operation, only minor or no constructional changes are necessary. A great task consists in the determination of legal framework conditions for the participation of wind energy in the primary control (cf. [11]). Furthermore the consideration of the occurring dynamic loads is required as part of the type approval.

The primary control capability can be acquired with a powerful control software. The model predictive control (MPC) is considered as a particularly suitable method. The mechanical and aerodynamic model of the wind turbine rotor is the basis for the MPC to predict the future behaviour. The power conversion of the rotor is a highly non-linear process. Furthermore, during the increase in power output constraints need to be considered. For example, the available control power can be maximized. For both requirements, the handling of a non-linear processes and consideration of constraints, the MPC is suitable.

Especially the response to the varying wind speed requires a high-performance control algorithm. So far, disturbance variables were not considered. A decrease in wind speed during the control process implies another challenge for future work. For reasons of grid stability wind turbine downtime has to be minimized.

In addition to the control task of an individual wind turbine, the coordination of all plants of a wind farm will be another objective. Especially in large wind farms many possible variations of providing control power exist, due to the large number of wind turbines. For example, for true primary control capability the wind park can be divided into several subsets (cf. figure 8 and table 2). One subset supplies control power, while the other subsets are in the balancing phase. In general, the objective of the largest possible available control power at the lowest possible yield loss faces an optimization problem. To balance and control the amount of control power kept available at a certain prevailing wind speed should be the focus of upcoming research work.

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