A PROCESS TO ENABLE WIND TURBINES TO PROVIDE CONTROL RESERVE AT MINIMUM LOSS OF ENERGY YIELD

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Summary

This paper examines to which extent wind turbines can provide positive control reserve. The additional power has to be obtained from the kinetic energy of the wind turbine's rotor. A simple physical model is developed that allows drawing conclusions about appropriate concepts by means of a dynamic simulation of the variables rotational speed, torque, feed-in power and rotor power. Under partial load 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 with a higher rotational speed. By providing primary control reserve the rotor is delayed to the optimum rotational speed so that more rotational energy can be fed in and feed-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 working under modified partial load can compensate the decrease of power of the wind turbines working under partial load. Therefore the requested control reserve is provided and afterwards the original value of power is maintained.

1. Wind turbines for load balancing

Wind energy covers a significant part of the demand for electricity in many countries, especially in Denmark (34 % of the electricity consumption in the year 2013, cf. [1]), Portugal (25 %), Spain (21 %) and Germany (8 %).

The grid load is changing constantly subjected by connecting, disconnecting and controlling of electrical devices. Since the storability of electrical energy is strongly limited (cf. Erdmann, Zweifel [2] p. 294), the central task of grid control is maintaining the balance of electricity generation and demand. Imbalances are equalised by control reserve.
The increasing wind power capacity requires effective use of new control strategies.

2. Modelling

The developed concepts are evaluated using simulations based on a physical model of a 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 [3], p. 202).

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

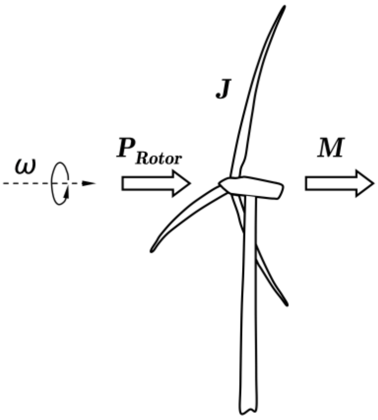

Fig. 1 Model of the rotor dynamics

The focus is on the modelling of the rotor dynamics (Figure 1). A system of discrete-time equations, developed from a differential-algebraic system (DAE) is expedient.

$$E_{ROT}(k+1) = E_{ROT}(k) \quad (1)$$
$$+\left(P_{rotor}(\omega,k) - M_{gen}(k)\cdot\omega(k)\right)\Delta t$$
$$\omega(k+1) = \sqrt{\frac{2E_{ROT}(k+1)}{J}} \quad (2)$$

Equation (1) is the result of a dynamic energy balance. The balancing is done over the change of rotational energy $\dot{E}_{ROT}$. The input power is the power extracted from the wind – the rotor power P_{rotor}. The output power is the electric power produced by the generator – the generator power $P_{gen} = M_{gen}\cdot\omega$. Equation (2) is rearranged from the rotational energy of the rotor. The angular speed ω of the rotor is determined by its moment of inertia J and its rotational energy.

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 ω and on the respective pitch angle β:

$$P_{rotor}(\omega) = c_P(\beta,\omega)\cdot P_{wind} \quad (3)$$

3. Primary control capability of wind turbines

Based on the introduced model the possible contribution of wind turbines in grid control will be examined.

3.1 Providing control reserve at partial load

If operating reserve has to be delivered, the equilibrium condition of the power train – the balance between delivered power by the rotor and the taken power by the generator – is temporarily suspended. By imposing additional power from the generator (Figure 2), the output torque of the generator shaft increases. The rotor experiences a higher counter torque and the rotational speed decreases. The induced drop in rotational speed shifts the operating point of the rotor to unfavourable power coefficients. The return to the initial operating point is accomplished by the opposite process. The generator output power is reduced below the currently available rotor power (Figure 2). Under this condition, the rotor accelerates and thereby increases its rotational energy. Compared to normal operation, the in-feed of energy that results from the difference between violet and yellow area is lost.

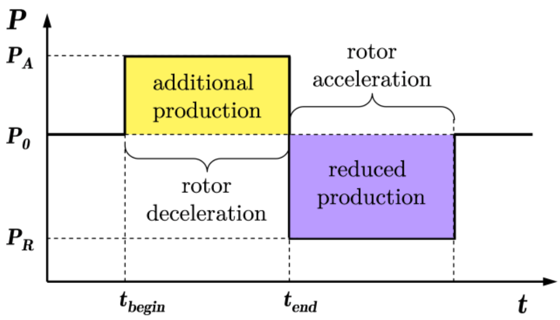

Fig. 2 Additional power and reduced power at partial load

This approach allows wind turbines to equalise drops of the grid frequency (cf. [4]). It is achieved by recovering kinetic energy stored in the inertia.

3.2 Providing control reserve at modified partial load

We suggest a modified operation process for the partial load range, that prevents power output collapses after the control operation. To obtain this desirable property, the partial load speed has to be increased.

This derating of the output power caused by a higher rotational speed increases the amount of stored kinetic energy. In previous work the derating is induced by a pitch angle (cf. [5]).

The progress of the in-feed power of the wind turbine during delivering control power is shown in Figure 3. While the rotor is delayed to the optimum angular velocity $\omega_{opt} = \lambda_{opt} \cdot v/r$, the generator releases the rotational energy saved in the speed difference $E_{ROT} = 1/2\ J(2\pi)^2 \left(n^2 - n_{opt}^2\right)$. This amount of energy is called additional energy II. During deceleration to the optimum speed the aerodynamic efficiency of the rotor increases. As a result the feed-in can be increased durably. The feed-in 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.

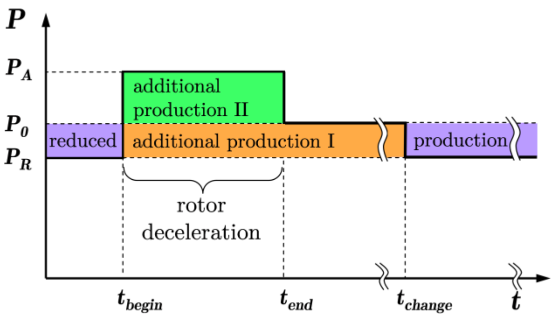

Fig. 3 Additional power and reduced power at modified partial load

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.

3.3 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. The other part continues to work in the normal partial load without yield losses. When control power is requested all plants provide rotational energy as grid in-feed (t_{begin} to t_{end}, Figure 2 and 3). The modified operating wind turbines generate a higher power output due to their ideal operating point (past t_{end}, Figure 3).
For the remaining wind turbines it is necessary to reduce the power output below the initial level to prevent a further drop in speed (past t_{end}, Figure 2). The configuration should be based on the assumption 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 that can provide control reserve and maintain the initial level (Figure 4).

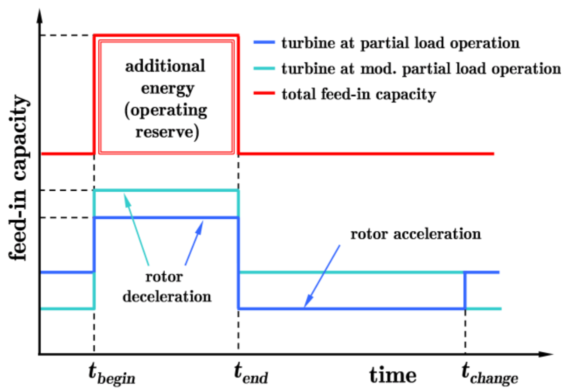

Fig. 4 Idealised process of providing control reserve

Table 1 shows an example design for two wind turbines: One turbine operates at partial load (pl) and another one at modified partial load (mpl). 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 in-feed power for 20 seconds to 105.5 %. The example is for a wind speed of 7 ms^{-1}. The model parameters are adapted to a wind turbine of 2 MW class. The speed of the modified operated turbine is increased by 9.5 %.

	normal mode		control process 20s		balancing 57s	
	[kW]	[%]	[kW]	[%]	[kW]	[%]
WT pl	547	100	564	103	537	98
WT mpl	537	98	591	108	547	100
total	**1084**	99	**1155**	105,5	**1084**	99

Table 1 Control process in a wind farm, $v = 7\,ms^{-1}$

In the example the balancing process is finished after 57 seconds – the turbine operating at partial load is accelerated back to the optimum speed. Afterwards control power can be delivered again. The control capability can be used extensively because it is free of charge.

4. Conclusion

Wind turbines can stabilize the grid frequency with short-term, but immediately available control power. In contrast to thermal power plants, the control reserve of wind turbines can be activated instantaneously (cf. Kurth, Kallina [6]). 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 reserve (cf. [7] and [8]). In both cases, wind turbines make an important contribution to grid stability.

The modified version is conditionally capable to participate in the grid control. The available control reserve 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.
The premise of the modified operation is an allowed overspeed. The further implementation can be done with a powerful control algorithm and would be a more important step for the integration of renewable energy into the power system.

Further research should focus on the determination of legal framework conditions for the participation of wind energy in the primary control (cf. [9]). Additionally the consideration of the occurring dynamic loads is required as part of the type approval. In addition to the control task of an individual wind turbine, the coordination of all plants of a wind farm at an arbitrary prevailing wind speed should be the focus of upcoming research work.

5. References

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