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General Analysis of Frequency Containment and Restoration Reserves of Wind Power Plants in Power Systems

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Abstract. **The increasing share of renewable energies, such as photovoltaics and wind power, lead to an all new situation in power systems over the past years. It changes the demand and possibilities of providing ancillary services like frequency containment (FCR) and restoration reserves (FRR). To cover the reduction of conventional generation units, which are usually used to provide those services, new possibilities have to be analysed. The aim of this paper is to show the possibilities of providing FCR and FRR by pitch-controlled wind power plants, regarding the overall dynamic system behaviour. Hence, a basic grid model with an integrated wind park, using pitch-control to adjust its power output, is being introduced and described. The simulation results of different wind situations during a power loss in the grid are then presented in order to assert the practicability of wind power plants providing FCR and FRR. As a conclusion, it is to ascertain that, pitch-control can be a way to support conventional units in providing ancillary services, but can't be a stand-alone solution.**

Keywords

Frequency Containment Reserves, Frequency Restoration Reserves, Wind Power Plants, Wind Speed Dependency, Pitch-Control, Dynamic System Behaviour.

1. Introduction

To guarantee a stable power system operation, the transmission system operators (TSOs) have to provide ancillary services [1]. This includes the categories frequency control, voltage and system control as well as system restoration [2]. The grid codes build the fundament of the design and operation of a connected power plant. Each generation unit has to meet the requirements of the grid codes. TSOs and power suppliers conclude contracts about the provision of prequalifications for all generation units taking part in providing ancillary services [1]. To ensure the ability of fulfilling the prequalifications, power plants need to meet even further technical requirements. Predominantly conventional generation units are used to provide ancillary services nowadays [2].

The growing share of renewable energies leads to changes in the profile of requirements for the operational management of the supplying system [2]. Alternating power flows and the rising distances of electrical supply are just two consequences of the shift in share [2]. Furthermore, because of the ongoing shutdown of conventional power plants, fewer of these units are available to provide ancillary services [2]. As a result, new ways of reliable service supply have to be found in the future. There are already several different projects using renewable energies to meet this need such as [3], using biomass, wind and solar power. Another investigation regards the possibilities of wind power plants providing frequency containment reserve [4].

To show the possibilities of using wind power plants for frequency containment and restoration, this paper does a general investigation and different practical basic simulations. In contrast to previous publications it focusses on the overall dynamic system behaviour. For this purpose the basics of wind power generation and the options of power control are getting recaptured, with a following analysis of one of the methods in different situations.

2. Basics of wind power generation and possibilities to provide FCR an FRR

The following paragraphs describe the general relations of wind power generation and the basics of frequency containment and restoration reserve. Moreover it is described how a wind turbine can provide these ancillary services. Similar possibilities are also described in [5].

A. Basics of wind power generation

Most wind turbines, with the purpose to provide electrical energy, use the lifting force of the blowing wind to generate a mechanical torque at the rotor [6].

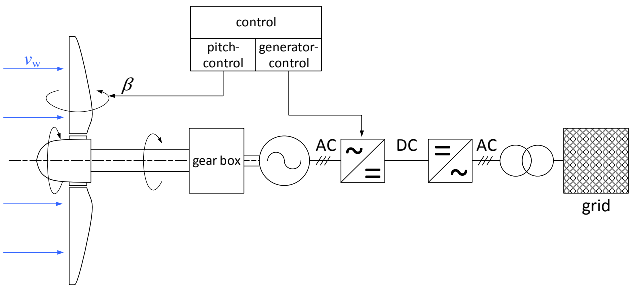

Figure 1: Simplified scheme of the energy conversion at a type 4 wind turbine connected to the grid

By transferring this torque over a drive train to the generator (as shown in Figure 1), a part of the wind energy in (1) can be transformed to electrical power [7].

$$E_{\text{kin}} = \frac{1}{2} m v_{\text{wind}}^2 \quad (1)$$

In some wind turbines there is an additional gearbox to adjust the speed ratio between the rotor and the generator [6]. The derivate of the kinetic wind energy describes the available wind power [7].

$$P_{\text{w}} = \frac{\text{d}E}{\text{d}t} = \frac{1}{2}\frac{\text{d}m}{dt} v_{\text{wind}}^2 = \frac{1}{2}\rho\frac{\text{d}V}{\text{d}t} v_{\text{wind}}^2 = \frac{1}{2}\rho A \frac{\text{d}x}{\text{d}t} v_{\text{wind}}^2 = \frac{1}{2}\rho A v_{\text{wind}}^3 \quad (2)$$

The extractable mechanical power is determined by the difference between the wind speed in front (v_1) and behind (v_2) the rotor [7]. To gain maximum power, the ratio between v_1 and v_2 has to be 1/3 [7]. This correlation is summed up in Betz' law defining a power coefficient c_{p} with it's maximum value of 0.593 [7]. The resulting equation for the extractable power is given with [7]:

$$P = P_{\text{w}} c_{\text{p}} = \frac{1}{2}\rho A v_{\text{wind}}^3 c_{\text{p}} \quad (3)$$

The power coefficient is thereby dependent on the tip speed ratio λ, the pitch angle β and the aerodynamic constants c_i $(i = 1 \ldots 6)$, developed by numerical approximations depending on the wind turbine [6]:

$$c_{\text{p}} = c_1 \left(\frac{c_2}{\lambda_{\text{i}}} - c_3\,\beta - c_4\right) e^{\left(-\frac{c_5}{\lambda_{\text{i}}}\right)+c_6\,\lambda} \quad (4)$$

$$\lambda = \frac{u}{v_{\text{wind}}} \quad (5)$$

$$\frac{1}{\lambda_{\text{i}}} = \frac{1}{\lambda + 0.08\,\beta} - \frac{0.035}{\beta^3 + 1} \quad (6)$$

The blue graphs in Figure 2 show a typical λ-c_{p}-curve for a wind turbine with the maximal c_{p} at 0° as the result of these correlations.

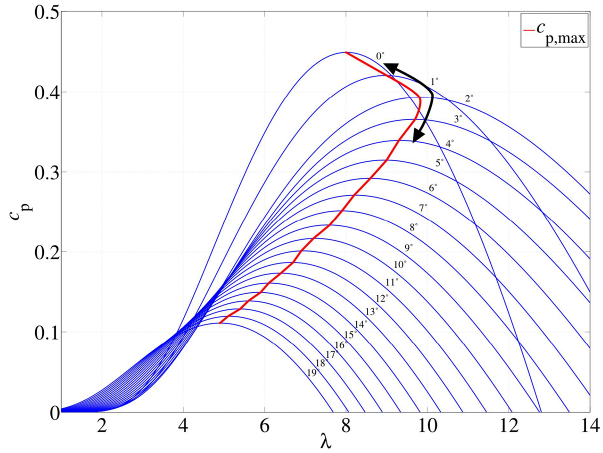

Figure 2: Power coefficient to lambda for different pitch angles

B. Possibilities to provide frequency containment and restoration reserves using wind power plants

The frequency is based on the speed of all rotating machines directly connected to the grid. For stable operation, the frequency has to be held in a certain bandwidth around its nominal value. Based on the equation for the difference between mechanical and electrical torque of a generator (7), the change of frequency can be expressed as the balance between generation and load (8), linearized for nominal operation:

$$J\frac{\text{d}\omega}{\text{d}t} = M_{\text{m}} - M_{\text{e}} \quad (7)$$

$$\frac{\text{d}f}{\text{d}t} = \frac{f_{\text{n}}}{T_{\text{A}} P_{\text{n}}}\left(P_{\text{gen}} - P_{\text{load}}\right) \quad (8)$$

If there is an imbalance between consumption and supply, generators adjust their power output to compensate the frequency deviation. The first step is to stop the change in frequency and regain a stable operation point. This is accomplished by frequency containment reserve using a speed governor to balance the difference in power [8]. Restoring the reference frequency is the task of frequency restoration reserve of the affected area, executed by power-exchange- or power-frequency-control [8]. Therefore a generation unit participating in providing the ancillary services frequency containment and restoration reserves has to be able to control its power output. Additionally, to provide positive reserves, the unit has to be able to operate at a power-reduced point below nominal power.

Power control of wind turbines can be realised in different ways. The most common applications are stall- and pitch-control. Stall-control represents a passive way of power control especially used to prevent damage of the turbine at high wind speeds [6]. A selective control of the power output below nominal operation is not quite applicable with stall-control [6]. In contrast to that, pitch-control offers the possibility to actively control the wind turbines power, by adjusting the pitch angle of the rotor blades [9]. Thereby it's also possible to operate at reduced power and offer positive and negative reserves. That makes pitch-control the suitable solution for the application of frequency control and is therefore implemented in the further described model.

Figure 3 displays the forces at a rotor blade in consequence of the pitch angle (β) and the wind speed (v_{w}). The rotation of the rotor blade is caused by the tangential component of the lifting force [6].

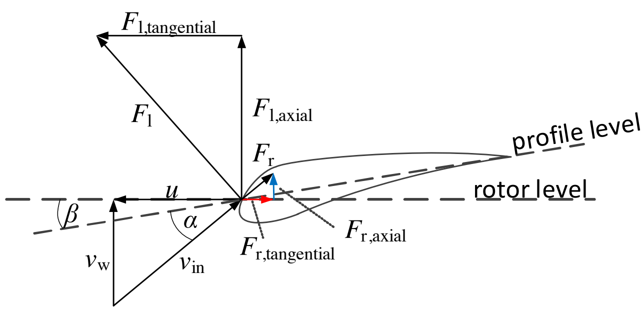

Figure 3: Speeds, forces and angles at a rotor blade

3. Introduction of a testing environment

A. Implementation of a test grid

To analyse the possibilities of providing frequency control by wind power plants, a test grid consisting of two connected areas was modelled (Figure 4). The connection is implemented as a 100 km long 400 kV transmission line with a reactance of 0.3 Ohm/km [10] without real power losses. The voltages at the busbars is constantly held at V_n whereas the exchanged power is calculated with [11]:

$$P_{\mathrm{ex},ij} = \frac{V_\mathrm{n}^2}{X}\sin(\delta_i - \delta_j) \tag{9}$$

Each area contains an aggregated frequency dependent load and an aggregated generation unit modelled with the steam turbine model IEEEG1 from [12]. The generation units provide FCR according to their speed droop coefficient, as well as FRR through a proportional-integral controller. The mechanical power output of the steam turbine model is considered to be directly the electrical power output. The initial load is adjusted to equal the offered generated power. Additionally the damping behaviour of the generators is reproduced by using the average speed ω_COI of the generators and a damping factor D.

$$P_{\mathrm{D},i} = (\omega_i - \omega_\mathrm{COI})D \tag{10}$$

$$\omega_\mathrm{COI} = \frac{\sum_{i=1}^{2} P_{\mathrm{n}i}\omega_i}{\sum_{i=1}^{2} P_{\mathrm{n}i}} \tag{11}$$

To determine the actual frequency, the power balance between generation, load and exchange is calculated.

$$\Delta P_i = P_{\mathrm{gen},i} - P_{\mathrm{load},i} - P_{\mathrm{D},i} + P_{ji} \tag{12}$$

To get the current frequency, the power imbalance gets integrated over time:

$$f_i = \int k_\mathrm{m}\,\Delta P_i\,\mathrm{d}t + f_0 \tag{13}$$

with:

$$k_\mathrm{m} = \frac{f_\mathrm{n}}{T_\mathrm{A} P_\mathrm{n}} \tag{14}$$

The phase angle δ_i is determined by equation (15). To simulate a default exchange unequal to zero, the default angle of area one in the load flow is set to zero whereas the angle of area two is calculated with equation (16).

$$\delta_i = \int 2\pi(f - f_\mathrm{n})\mathrm{d}t + \delta_{0,i} \tag{15}$$

$$\delta_{0,2} = \arcsin\left(-\frac{P_{\mathrm{exstat},12}}{V_\mathrm{n}^2}X\right) \tag{16}$$

To identify the cause of a power imbalance, each area also contains a calculation for the area control error (ACE) (17). The ACE is zero if the difference between the set value of exchange and the actual exchange is zero and the frequency deviation is zero at the same time. If the power exchange difference and the product of frequency change and frequency bias factor Λ_i balance each other, the ACE is also equal to zero and the source of the imbalance lies in the other area.

$$ACE_i = \Delta P_{\mathrm{ex},i} + \Lambda_i \Delta f \tag{17}$$

B. Implementation of a test wind park

To analyse the potential of wind turbines providing frequency reserves, a wind park of 48 identical wind turbines is implemented in the first area, leading to the overall test grid shown in Figure 4. The wake effects and wind time delays are neglected in this study.

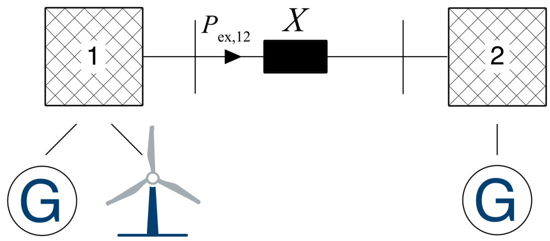

Figure 4: Scheme of the overall test grid

To provide FCR and FRR in case of a power imbalance, the wind turbines initially operate at reduced power, using the pitch angle. Thus the whole wind park has positive reserves of 20 MW at initial conditions.

Table I - Basic test wind park parameters

	Value	Description
$P_{\mathrm{WP,n}}$	120 MW	Total wind park rated power
$P_{\mathrm{WP,0}}$	100 MW	Initial wind park real power
β_0	2.7°	Initial pitch angle

The input of the wind park control model is the initially requested respectively available power, the currently generated wind power, the actual frequency and the area control error. The frequency is the input value for primary control, whereas the ACE is crucial for secondary control. Primary control is executed as a proportional gain with a droop of 5% and a first order lag element (T_FD = 9.6 s) before, to filter the input signal allowing a smooth pitch-control. Secondary control uses the ACE as input and a proportional-integral controller with the same parameters as the generation units to pass the required power change in order to restore the nominal frequency. The difference between the sum of initial power, primary power change, secondary power change and the currently delivered power forms the input for the main wind park controller.

This wind park controller transfers the requested power of the wind park over a proportional-integral controller (Table II) to the wind turbines.

Table II - Parameters of the main wind park controller

	K_WPR	T_WPR	$\mathrm{d}P/\mathrm{d}t$
Value	0.9	2.6316 s	0.01%/s

The new reference value is then getting compared to the currently provided power of the wind turbine, the difference being the input signal for the pitch-control shown in Figure 5.

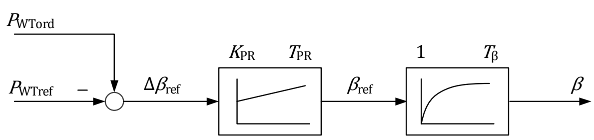

Figure 5: Pitch-control of the wind turbine

A proportional-integral controller and a first order lag element with the time constant T_β model the pitch-control process (parameters in Table III).

Table III - Parameters of the pitch-control process

	K_{PR}	T_{PR}	T_β	$d\beta/dt$
Value	0.1087	2.7586 s	0.3 s	8°/s

As already described, the power factor and therefore the extractable power of the wind turbine are dependent on the tip speed ratio and the pitch angle. For a given wind speed, the rotational speed u of the rotor is the crucial factor. The rotational speed of the wind turbine model is controlled so as to always get the maximum power coefficient at the current pitch angle as shown in Figure 2. Operation is therefore always kept on the red curve ensuring ideal speed control.

4. Analysis of the FCR and FRR capability

In this chapter, three different scenarios as shown in Table IV are presented to analyse the ability of wind power plants to provide FCR and FRR and to investigate the dynamic test system behaviour.

Table IV - Analyzed scenarios

Scenario 1	Scenario 2	Scenario 3
Constant wind speed	Increasing wind speed	Decreasing wind speed
$\frac{dv}{dt} = 0$	$\frac{dv}{dt} = +0.001\frac{m}{s^2}$	$\frac{dv}{dt} = -0.001\frac{m}{s^2}$

In all scenarios, a step of 2% of the total nominal power of the test grid represents the trip of a generation unit in area one. The wind speed is varied within the scenarios from being constant to linear increasing and decreasing. The following tables show general simulation environment parameters as well as the controller parameters.

Table V – Simulation environment parameters

	Value	Description
T_A	14 s	Time constant of generation units
f_n	50 Hz	Nominal frequency
V_n	400 kV	Transmission voltage
X'	0.3 Ohm/km	Reactance of the transmission line
l	100 km	Length of the transmission line
D	$0.1 P_{gen,i,n}$	Damping factor
$P_{load,1,0}$	600 MW	Initial load of area one
$P_{load,2,0}$	500 MW	Initial load of area two
k_{pf}	2	Load coefficient
$P_{gen,i,n}$	600 MW	Total generator rated power
$P_{gen,i,0}$	500 MW	Initial generator power
$P_{ex,12,0}$	0 MW	Initial exchange power
ΔP	$-0.02 P_{n,ges} = -26.4$ MW	Real power step
t_{step}	5 s	Time at power step
$v_{wind,0}$	10.4932 m/s	Initial wind speed

Table VI - Used time constants in IEEEG1 steam turbine model

	T_1	T_2	T_3	T_4	T_5	T_6	T_7
Value in s	0.5	1	1	0.4	8	4	3

Table VII - Used gain constants in IEEEG1 steam turbine model

	K	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
Value	20	0.15	0.15	0.2	0.2	0.1	0.1	0.05	0.05

Table VIII - Parameters of secondary control for the generation units and the wind park

	K_{SR}	T_{SR}
Value	0.008	200 s

Table IX - Constants for the calculation of c_p

	c_1	c_2	c_3	c_4	c_5	c_6
Value	0.5176	116	0.4	5	21	0.0068

A. *Trip of a generation unit at constant wind*

The first scenario investigates the behaviour at a constant wind speed. Because of the sudden power imbalance at t_{step} in area one, the frequency starts to decrease rapidly throughout the whole system (Figure 6).

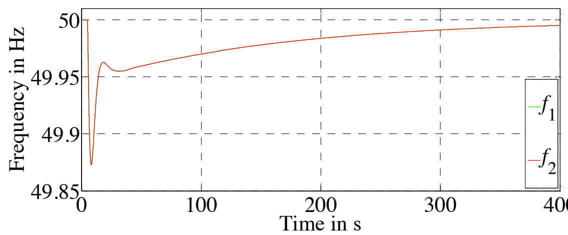

Figure 6: Frequency in area one and two

All generation units, no matter which area they belong to, take part in frequency containment to balance supply and demand (Figure 7, Figure 8). At $f \approx 49.95$ Hz a new stationary operating point is reached. Restoring nominal frequency in the following is the task of the frequency restoration reserves. As mentioned before, only generation units in area one are responsible for FRR. Therefore the aggregated generation unit one and the wind park increase their power output for FRR, while the generation unit of area two restores the reserves by returning to its nominal power output. The activation of the FRR of the generation units is 30 seconds delayed due to facilities starting times. In contrast, the wind turbines pitch-control is not affected, allowing the FRR to start immediately.

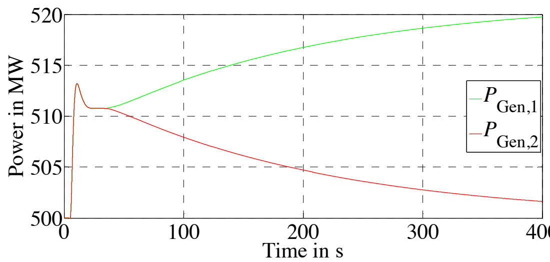

Figure 7: Power of generation units in area one and two

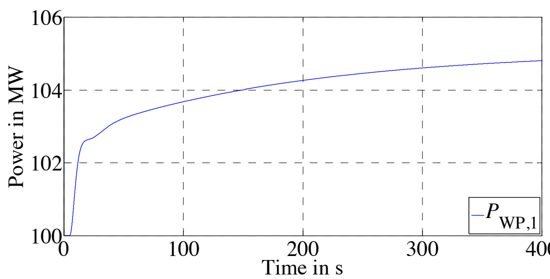

Figure 8: Wind park power in scenario one

Area two delivers its power change directly to area one, which can be seen in Figure 9.

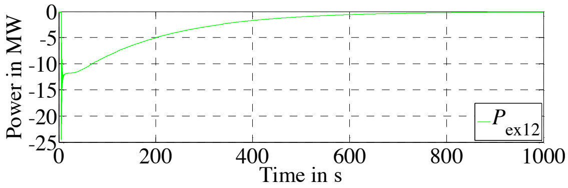

Figure 9: Power exchange between area one and two

At $t = 5$ s the frequency containment reserves and the frequency restoration reserves of the wind park get activated (see Figure 10).

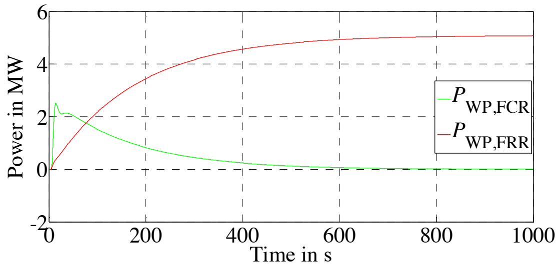

Figure 10: Wind park FCR and FRR

Figure 11 shows the pitch-reduction of the wind turbines, resulting in the total power output of the wind park in Figure 8. During the first 30 seconds the pitch angle is getting reduced from 2.7 to 2.3 degree.

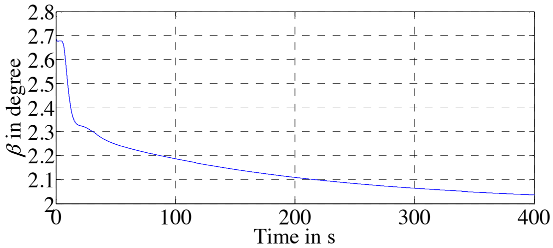

Figure 11: Pitch-control due to FCR and FRR

During this time, the FCR predominates, until it gets replaced by FRR, for which the pitch angle has to be further reduced to a final value of 2 degree.

Figure 12 shows the change of power supply by all units in relation to each areas maximum power. Due to the integration of the wind park, the generation units in area one don't have to provide the complete FCR and FRR.

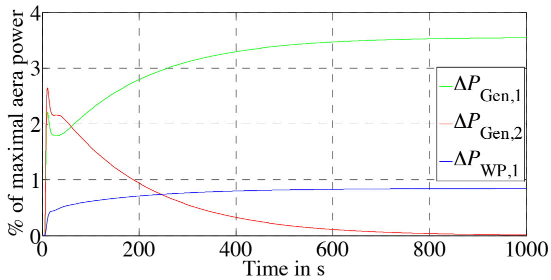

Figure 12: Power change in % of each areas maximum power

As seen, by operating at reduced power, the wind park can provide the necessary reserves to support the generation units in containing and restoring a stable operation point, assuming the wind is sufficiently and constantly blowing.

B. Trip of a generation unit at increasing wind speed

Scenario two illustrates the consequences of increasing wind. Therefore a wind speed increase is simulated at the same time as the power step occurs. With a linear slope of 0.001 m/s^2 the speed rises up to 11.3864 m/s at $t \approx 900$ s.

The power output of the wind park increases the same way as in scenario one (Figure 8), with the result that the behaviour of the generation units is also not affected by the change of wind speed, leaving the frequency unchanged compared to scenario one.

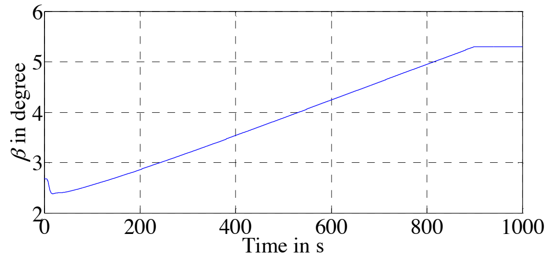

Figure 13: Pitch-control at increasing wind speed

Figure 13 thereby shows the difference in achieving the power change of the wind park in contrast to the first scenario. At the moment of imbalance the wind speed is still too low to cover the necessary power change without further action, leading to a reduction of the pitch angle. With the continuously increasing wind speed, the wind turbines then even have to increase their pitch angle, to prevent a power overshoot.

C. Trip of a generation unit at decreasing wind speed

Another interesting case with respect to the ability of wind power plants providing FCR and FRR is scenario three, which analyses the behaviour at decreasing wind.

The slope and the height of the speed change equates scenario two. Starting at $v_{wind,0}$ the wind slows linearly down to 9.6 m/s.

During the first 460 seconds after the power step, there is no difference between this scenario and the ones before regarding the frequency deviation (Figure 14). After that, the frequency starts to decrease again before it's getting stabilized and returned to its nominal value.

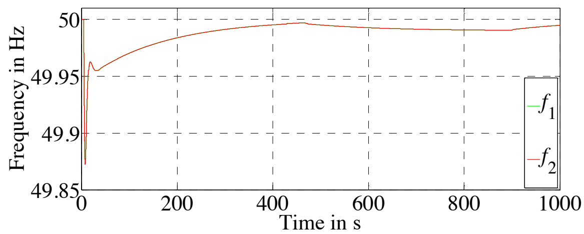

Figure 14: Frequency in scenario three

This is due to the decreasing power delivered by the wind park from $t = 465$ s on, shown in Figure 15. With the stop in wind change at $t = 900$ s the power output of the wind turbines becomes constant.

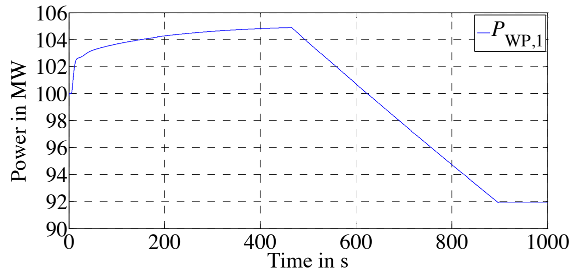

Figure 15: Wind power in scenario three

The pitch angle change in Figure 16 shows the reason of the wind power gradient. Until $t = 465$ s the wind turbines are able to compensate the decreasing wind speed and provide frequency reserves at the same time by gradually decreasing their pitch angle.

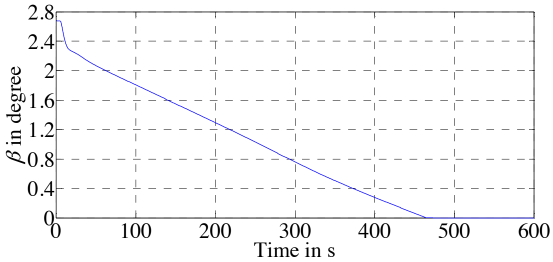

Figure 16: Pitch-control at decreasing wind speed

After that, the pitch angle is at 0° and hence the wind park at its maximum operation point. The persistent decrease in wind speed can't be counterbalanced anymore, leading to the on-going decrease of wind power (Figure 15). As soon as the wind speed change stops, the wind parks power is constant again, providing as much power as possible with the available wind.

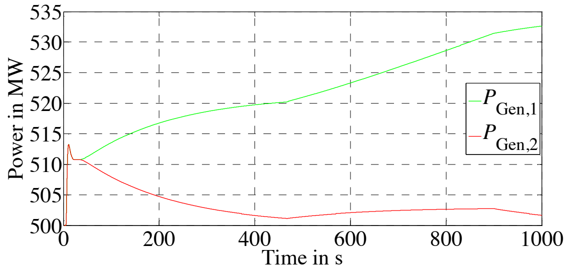

Figure 17: Generation units power of both areas

Because of the limited wind power, the generation units have to take over the amount of missing power to stabilize and restore nominal frequency. Therefore, a part of the FCR of both turbines has to be activated again, as shown in Figure 17. The complete FRR has to be covered by the generation unit of area one, while area two is returning to its nominal output (Figure 17).

This way, nominal frequency can be restored within acceptable limits, even though this scenario shows how dependent the frequency stability is on a sufficient assured capacity.

5. Conclusion and Outlook

This paper analyses the possibility of providing the ancillary services frequency control and restoration reserve by wind power plants with regard to the dynamic system behaviour.
On the basis of a simple test grid model with aggregated generation units and wind turbines it's shown that, wind power plants theoretically can provide power reserves by adjusting their pitch angle. Given that sufficient wind is available, a wind park could thereby support conventional generation units providing frequency control and restoration reserves.
The challenges clearly arise in case of the wind speed being not high enough or lowering down while a power imbalance is occurring. The wind parks then can't provide enough reserves to fulfil their intended amount of power change and therefore conventional generation units have to take over.
Other challenges of this concept to be investigated in the future are fluctuating wind speeds leading to variably available wind park power and therefore more difficult control-processes.
This means that, even though the share of wind parks is growing and the possibility of providing FCR and FRR is given, sufficient capacity has to be installed in the power system to assure frequency stability.

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