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Analysis of the short-term overproduction capability of variable speed wind turbines

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Abstract:
Emphasis in this article is on variable speed wind turbines (VSWTs) capability to provide short-term overproduction and better understanding of VSWTs' mechanical and electrical limits to deliver such support. VSWTs' short-term overproduction capability is of primary concern for the transmission system operators (TSOs) in the process of restoring critical situations during large frequency excursions in power systems with high wind power penetration.
This study is conducted on a simplified generic model for VSWTs with full scale power converter (Type IV), which includes several adjustments and extensions of the Type IV standard wind turbine model proposed by the IEC Committee in IEC 61400-27-1. This modified standard model is able to account for dynamic features relevant for integrating active power ancillary services in wind power plants, such as frequency support capabilities.
The performance of VSWTs during short-term overproduction is assessed and discussed by means of simulations for different wind speed levels, overproduction percentages and durations. The results show that the capability of VSWTs providing short-term overproduction to the grid strongly depends on the initial pre-overproduction conditions.

Keywords: active power, overproduction, inertial response, variable speed wind turbine, standard model;

I. INTRODUCTION

High wind power penetration levels into power systems have posed serious concerns regarding security of supply. They have led to a growing interest in the wind turbines' potential to provide the ancillary services delivered by conventional generations up to now [1], [2]. Even though wind turbines do not inherently provide these services, they can stipulate them through suitable additional control actions. In particular, the impact of large amounts of wind power on the power system frequency stability is of primary concern for TSOs [3-4].

Frequency stability is a challenging technical issue, which has initiated both an intensification of the research on VSWTs' frequency support capability and a continuous revision by TSOs of the grid requirements for large wind farms [5]. The frequency support terminology includes both the inertial response and the primary frequency control [6]. The inertial response of a wind turbine (WT) refers to the short-term additional active power contribution that can be temporarily released by a WT equipped with an appropriate control, by exploiting the stored kinetic energy in the rotating mass of the turbine. This action is also called short-term overproduction [7] and it is activated during grid frequency excursions until the primary frequency control reserve of the power system is released [8] or some operational limit in the VSWT is reached during this action.

A comprehensive state of the art review, regarding the frequency response capability of wind turbines, is conducted in [4]. According to [4], TSOs in some countries, i.e. Germany, Spain, Canada and United Kingdom recognize the importance of the wind power inertial response for the system reliability, and stipulate therefore that wind power must provide frequency support and spinning reserve, as conventional power stations do. The TSOs of Ireland and Denmark are in different stages of implementing inertial response requirements in their operations. Recent studies [9] made in the UK have led to the conclusion that “inertia should be provided by ancillary services market and not by a Grid Code requirement (either as an obligation or as a capability)”.

Several studies regarding the inertial response contribution from VSWTs [10-12] have as goal to enhance their capability to actively support the power system. However, as indicated in [7], [13], it is important to assess both the capability of VSWTs of injecting short-term additional active power into the grid and its limiting factors (i.e. rotational speed, stress in the mechanical and electrical components). Nevertheless, further studies for a better understanding and extensive quantification of the wind turbines capability to provide short-term active power overproduction are still necessary in order to enhance the reliability of modern wind turbines’ frequency support capabilities. This capability, as is limiting the frequency excursions, might be especially beneficial in power systems with reduced inertia, i.e. in non-interconnected power systems, island power systems [14] or in power systems with weak interconnections and high wind power penetration.

The objective of this article is to analyze and quantify the capability of providing short-term active power overproduction by VSWTs. The article does not focus on the impact of this capability on a power system frequency profile, as this has been addressed in many relevant publications [6], [12-14] over the years. Rather, focus is on explaining features of VSWTs capability to provide short-term overproduction and on a better understanding of the WT limitations to deliver such support.

The WT model used in this study has as starting point the generic approach proposed by the IEC Committee in Part 1 of IEC 61400-27 [15] for VSWTs. Nevertheless it is extended to include the dynamic features relevant for active power and grid frequency control capability studies. The IEC standard models [15] are not directly suitable for the type of study presented in this article, as their range of applicability focuses on the short-term stability of the power system.

The article is organized as follows. Section II briefly presents the WT modeling. Section III focuses on the behavior of the proposed WT model during short-term overproduction. Simulation and analysis results, illustrating the short-term overproduction capability of VSWT, are described in Section IV. The main parameters characteristic for the turbine behavior during overproduction operation are assessed and analyzed for different wind speed and overproduction conditions. Finally, conclusive remarks are reported.

II. MODEL DESCRIPTION AND CHARACTERISTICS

A simulation model for a VSWT with full scale power converter is illustrated in Figure 1.

Figure 1: Type IV wind turbine model structure.

The model aims to reflect the dynamics caused by changing the active power references of the WT. In addition to the IEC standard Type IV model [15], this model includes information on the aerodinamical behavior of the rotor and on wind speed variability, as this is of high relevance whenever study of new control functionalities, like short-term active power overproduction, inertial response and primary frequency control are in focus [16].

As illustrated in Figure 1, the model mainly consists of an aerodynamic model, a mechanical model, a pitch control model and models of the generator system and the electrical control system. The coupling between the aerodynamic and mechanical model contains information about WT’s limitations to provide short-term active power overproduction.

A simplified aerodynamic model, based on a two-dimensional aerodynamic torque coefficient *Cq(θ, λ)* table, is used to illustrate the effect of the speed and pitch angle changes on the aerodynamic power. A 2-mass mechanical model is used in order to reflect the torsional shaft oscillations whenever there is a sudden torque imbalance in the mechanical system [17]. The block diagrams of the pitch control and the active power control are illustrated in Figure 2. The pitch control system is realized by a PI controller with anti-reset windup, using a servo-mechanism model with limitations on both the pitch angle and its rate of change, while the active power controller uses the error signal between the measured power and the power reference as input.

Figure 2: Block diagrams of the pitch and active power control.

Even though the control, illustrated in Figure 1, both includes active and reactive power controllers, the attention in this investigation is only on the active power control loop. A frequency control block could be also implemented, as suggested in [6], but how or why the overproduction decision is taken is out of the scope of this study.

Besides component and control blocks, the WT model also contains blocks for wind speed, available power, maximum power point tracking (MPPT) and selection mode. A constant wind speed model is considered. This investigation, as is focusing on wind turbine level only, is performed based on the assumption of a perfect estimation of the available power.

Figure 3 depicts the power reference selection block between optimal production and overproduction mode. The actual active power reference P_{ref}^{wt} is generated based on:

- active power from MPPT
- imposed active power reference $P_{imposed}^{wt}$
- rotational speed.

The power reference selection block includes a protection mode of the WT in case that its rotational speed becomes lower than its allowed minimum rotational speed $\omega_{\min}$. This means that during an overproduction regime, if the WT's rotational speed becomes lower than its allowed minimum value, the active power reference is directly calculated based on the MPPT look-up table.

Figure 3: Control switching logic between optimal production and overproduction mode, including the protection logic for rotational speeds lower than the allowed minimum value.

Figure 1 also depicts the interface signals between the WT model and the wind farm controller (WFC). In a general control topology the WT model receives the active and reactive power setpoints from WFC, while the WT model provides the generated and the available active power to WFC. However, in the present investigation, it is assumed that the power setpoint of the WT model ($P_{imposed}^{wt}$) is directly set to a predefined value, being stepped up and down in order to study the dynamic behavior of the WT during different overproduction levels and wind speed levels. The power that is injected into the grid from the WT is thus temporarily increased above its pre-overproduction value.

III. MODEL BEHAVIOR DURING OVERPRODUCTION

The behavior of VSWTs differs for low and high wind speeds during normal operation and short-term overproduction, as well.

Figure 4 illustrates the mechanical and the electrical power versus generator speed for different wind speeds and pitch angle zero. It depicts the static relation between the rotational speed and the mechanical and electrical power at different wind speeds (i.e. from 0.4pu to 1.02pu).

Figure 5 illustrates the power-speed trajectory during a short-term overproduction at wind speeds lower than the rated wind speed. The electrical and mechanical powers versus rotational speed are shown as follows:

- the mechanical power versus rotational speed is illustrated at a fixed pitch angle ($\theta=0$) and at two wind speeds lower than the rated wind speed, i.e. at 0.6pu and 0.93pu.
- the electrical power versus rotational speed, corresponds to the normal production characteristic (i.e. MPPT curve). On the MPPT curve, the turbine runs with an optimal aerodynamic efficiency as long as the wind speed is lower than its rated value, while for wind speeds higher than the rated value the WT runs at the rated power, keeping constant the turbine's rotational speed by the pitch controller.

Figure 4: Mechanical and electrical power versus generator speed for different wind speeds.

In Figure 5 two short-term overproduction cases are depicted by the static trajectories ABCD and by A'B'C'D'E' for the 0.6pu and 0.93pu wind speed, respectively. For example, as long as the WT is running in normal operation at a 0.6pu wind speed, it is operating at point A, which corresponds to the crossing point between the mechanical power and the optimal electrical power. When an overproduction is initiated, the speed of the turbine does not change instantaneously due to its inertia. However, as illustrated in Figure 5, there is an instantaneous step in the electrical power of the turbine, i.e. the electrical power is increased from point A to point B.

Figure 5: Power-speed trajectory for short-term overproduction for wind speeds lower than 1pu (pitch angle zero).

In this situation, the turbine starts to decelerate due to the imbalance between the electrical and mechanical power. This rotor deceleration continues as long as the overproduction lasts, namely from point B to point C.

As expected, for constant wind speeds lower than the rated wind speed, the mechanical power is also reduced during overproduction due to its dependency on the rotational speed. The power imbalance is thus increasing even more during the overproduction, due to the decrease in mechanical power, while electrical power is kept constant to its increased setpoint value (i.e. trajectory from point B to point C). Note that, during the overproduction at wind speeds lower than the rated value, it is not possible to increase the mechanical power and thus to reduce the power imbalance by pitching the blades, as the WT is already running with its maximum possible production (i.e. with optimal pitch angle).

As soon as the requested overproduction is completed, the turbine moves from point C to point D, where the WT returns to operate on the normal production MPPT curve, however with a short-term non-optimal rotor speed. As a result of the movement from point C to point D, the electrical power is reduced to a non-optimal level, lower than the one before the start of the overproduction operation. The fact that the mechanical power is higher now than the electrical power initiates instantaneously an acceleration of the turbine, due to the change in sign in the power imbalance. The rotor accelerates as long as the power imbalance exists, namely from point D to point A, which corresponds to the initial normal operation (where mechanical power equals the electrical power for 0.6pu wind speed). The period DA is referred as the "*recovery period*" in literature.

The same analysing procedure can also be applied for the overproduction trajectory A'B'C'D'E', corresponding to 0.93pu wind speed. However, in this case, different values for recovery powers and periods are experienced.

As depicted in Figure 5, the change in mechanical power depends on the wind speed as well as on the overproduction duration. Moreover, the recovery trajectory differs for the two illustrated cases. At low wind speeds the recovery process can be very slow, as the turbine is following the “flat” part of the optimal MPPT curve, while at wind speeds just below the rated wind speed, the recovery process is relatively faster, as the turbine is recovering back to its pre-overproduction operation through A'B'C'D'E', namely by spending first short time on the “flat” part of the optimal curve (i.e. D'E') and then continuing on the ramp part of the optimal curve (i.e. E'A'), which shortens the process significantly.

Figure 5 also shows the critical situation, when the turbine might decelerate and reach its minimum rotational speed, due to a long overproduction duration. This case is depicted i.e. for the 0.6pu wind speed, by point S, corresponding to the minimum rotational speed $\omega_{\min}$. If the rotational speed decreases below this minimum speed limit, the WT stops, if no protection mode, as i.e. indicated in Figure 3, is implemented.

Figure 6 exemplifies the overproduction trajectory ABCD, described in Figure 5, in the time domain. It illustrates the dynamic behavior of the active power, the rotational speed and the shaft torque of the turbine before, during and after the overproduction. The main characteristics associated with the overproduction process are defined as following:

- ΔP is the deviation in the active power during overproduction, namely $\Delta P = \Delta P_{ov} + \Delta P_{rec}$, where:
  - ΔP_{ov} is the active power overproduction step, which is the amount of additional active power on top of the initial power production P_0.
  - ΔP_{rec} is the amount of the power that is decreasing below the initial power production after the overproduction period.
- $\Delta\omega$ is the speed deviation during overproduction
- T_{ov} is the overproduction period
- T_{rec} is the recovery period, i.e. the time duration which it takes the turbine to accelerate back to initial operating point after the overproduction is completed.

Figure 6: Dynamic behavior during short-term overproduction and partial load operation.

As shown in Figure 6, the rotational speed is decreasing while the WT is generating additional power during the overproduction period. Note also that if T_{ov} is increasing, there is a risk of reaching the minimum rotational speed value $\omega_{\min}$ (i.e. point S). For lower wind speed the possible overproduction period gets shorter, as the operation point on MPPT curve is closer to the minimum rotational speed.

Note also that, the shaft torque increases, when applying an overproduction step in the active power, and decreases to a lower value than its initial operation value T_{shaft0}, when the overproduction is completed. During the recovery period, the shaft torque is increasing back to its initial operation value.

The behavior of the WT during overproduction for wind speeds higher than the rated value is difficult to be illustrated using a steady-state characteristic, as the pitch controller is active in this operating zone. The pitch controller changes now the pitch angle in order to limit turbine's power by controlling the generator speed at its nominal value. Figure 7 depicts the power-speed trajectory for short-term overproduction at wind speeds higher than the rated wind speed. The turbine is operating at point A as long as it is in normal operation, where the mechanical power equals the rated electrical power at a pitch angle higher than the optimal pitch angle. When the overproduction is initiated by making a step in the electrical power, the turbine starts to decelerate, this being however not as significant as in the case of overproduction performed at low wind speeds. This is due to the fact that the power imbalance can now be actively reduced by the pitch controller, which can decrease the pitch angle to increase the mechanical power.

Figure 7: Power-speed trajectory for short-term overproduction at high wind speeds.

During overproduction the turbine decreases its pitch angle and as a result the mechanical power increases towards a new steady-state point, which corresponds to the short-term overproduction setpoint. The speed increases until it returns back to its initial rated value. As soon as the overproduction is completed, the electrical power steps down to its initial value. Note that the pitch angle cannot be changed as quickly as the step in electrical power, and therefore the mechanical power is larger than the electrical power for a short period. As a result, the rotor accelerates until mechanical power equals the electrical power in the steady-state value that corresponds to the rated operation. During the acceleration of the rotor, the pitch controller reacts by increasing the pitch angle leading to a decrease in the mechanical power. Depending on how large the overproduction power is the power reduction when overproduction stops can be before or after the rated speed. The dynamic of the speed after the overproduction period, can present an overshoot before the normal steady-state is reached again. However, the total speed deviation during the overproduction is significant lower than the overproduction case during low wind speeds. Note also that the recovery (underproduction) period after overproduction at high wind speeds is not typically significant, as long as the electrical power steps down to its initial value before the overproduction event. This might however not be the case for a long overproduction period or a high overproduction power.

IV. OVERPRODUCTION PROCESS - RESULTS

In this section, two sets of studies are presented in order to illustrate and analyze the capability of VSWTs' while providing short-term active power overproduction. The first set illustrates through dynamic simulations how the proposed WT model handles any request of overproduction in both partial and full load operation. The second set focuses on a sensitivity analysis of the WT performance during short-term overproduction. This analysis is performed for different constant wind speeds, overproduction power values and overproduction periods.

A. *Dynamic simulations*

The performance of the presented VSWT model during a short-term overproduction is exemplified in the following. The way of assessing the WT's capability for providing short-term overproduction is by applying a step in the active power setpoint during a certain period of time. Three wind speeds corresponding to three different WT operational levels (i.e. a low wind speed, a wind speed just below the rated wind speed and a high wind speed), three different overproduction steps (i.e. 5%, 10% and 20%) and a fixed overproduction period of 10 sec have been considered. These cases address representative and challengeable conditions for studying the WT behavior during imposed overproductions. They provide information on the WTs' limitations to support the grid during frequency dips. In all cases the illustrated signals are the electrical power, the rotor speed, the shaft torque, the aerodynamic power, the generator-rotor swings (i.e. the difference between the generator and rotor speed) and the pitch angle.

Figure 8 shows the dynamic simulation result of the overproduction process, when the WT is running at a 0.6pu wind speed. In accordance to Figure 5, the rotational speed is decreasing, as result of the overproduction power, and is increasing back to its initial value, when the overproduction is completed.

Figure 8: Wind speed 0.6pu, overproduction period 10 sec and different overproduction power (5%, 10% and 20%).

As expected, the higher the overproduction power, the deeper the drop in the rotational speed. This also means that at low wind speeds for a higher overproduction power or for a longer overproduction period, there is a higher risk for stopping the turbine, by decelerating it beyond its minimum rotational speed, if no special protection actions are implemented. Note that the higher the overproduction request, the deeper the drop in electrical power after the overproduction and the longer the recovery period. The shaft torque and the generator-rotor swings are increased when applying higher overproduction steps. For a 20% overproduction the shaft torque is increased up to 25% during overproduction. Moreover, it can be seen that the generator-rotor swings are reflected in the oscillations of the shaft torque.

As previously mentioned, at low wind speeds the pitch controller is inactive and therefore the WT is running with a constant zero pitch angle. For low wind speeds, the aerodynamic power of the turbine is almost constant or slightly decreasing during overproduction, as result of the small decreases in the rotational speed and of the constant pitch angle.

Figure 9 illustrates the WT response during a short-term overproduction for a 0.93pu wind speed, i.e. just below the rated wind speed. The simulation results are similar to the previous case. However, as expected, it is seen that the deviations in all the signals, except the pitch angle, due to the overproduction request, are larger this time. The reason is that, at this wind speed, overproduction power conveys larger deviations in the rotational speed and in the recovery power, as before the overproduction event, the turbine is running on the steep ramp of the MPPT curve (i.e. in point A' in Figure 5). During a 20% overproduction, the power deviation can get up to 50% of the nominal turbine's power.

Moreover, in case of the 20% overproduction power, the shaft torque increases to a 56% higher value than its corresponding value in the normal operation.

Figure 9: Wind speed 0.93pu, overproduction period 10 sec and different overproduction power (5%, 10% and 20%).

This might generate very high mechanical loads on the turbine. Note also that the shaft torque does not reach a steady-state at the end of the 10 sec overproduction. This implies that a longer overproduction period could bring the turbine in a critical situation, as its mechanical stress could get very high. The high values in the shaft torque above admissible limits are noticeable not only during overproduction but also when the overproduction is completed, as the deviation in the shaft torque gets higher than 1pu. Additionally, there is also a risk of the shaft torque crossing through zero as well. This aspect as well as the higher amplitude of the generator-rotor swings during overproduction is indicating a higher mechanical stress of the drive train during overproduction at wind speeds just but below the rated wind speed. Another reason for the increased mechanical stress at wind speeds just below 1pu is that the pitch control is inactive and therefore there it is not possible to reduce actively the power imbalance.

In Figure 9, the recovery period is drastically reduced compared to the case illustrated in Figure 8. The reason for the shorter recovery period at wind speeds just below the rated wind speed, is that the overproduction trajectory curve (A'B'C'D'E') depicted in Figure 5, has a knee point (i.e. E'). The turbine is thus following the D'E'A' curve to recover back to its initial operating point. The presence of the knee point on the trajectory changes the dynamic of the turbine during the turbine's recovery. The turbine is thus running on the ramp part (i.e. E'A') of the MPPT curve, and as a result its recovery is faster. Moreover, for a high wind power penetration case in this wind speed range, the power system stability might be seriously challenged by the large power drop during recovery, unless a smart recovery period control is implemented in the turbine for reducing it.

Figure 10 illustrates the WT response during a short-term overproduction for a wind speed of 1.1pu, i.e. higher than the rated wind speed. Similar to the simulation results illustrated in Figure 8 and Figure 9, the turbine decelerates during an overproduction also at wind speeds higher than 1pu. However, this deceleration is not as significant as in the cases for wind speeds lower than 1pu. The reason is that the turbine now has the possibility to decrease its pitch angle in order to reduce the power imbalance during overproduction. Note that the higher the overproduction, the deeper the drop in the pitch angle and in the generator speed. The effect of the pitch angle is visible in the aerodynamic power and in the shaft torque. Contrary to the cases illustrated in Figure 8 and Figure 9, the aerodynamic power is increased during overproduction period in this case, and this is due to the reduction in the pitch angle. Similarly, the higher the overproduction power, the higher the shaft torque. However, the shaft torque does not increase as significant as in Figure 9 and this due to the active pitch controller. The shaft torque during the 20% overproduction reaches a steady-state level 20% higher than that corresponding to initial operation. This implies that for a higher overproduction power than 20%, the shaft torque can increase to even higher levels, as the pitch angle cannot be further reduced. Contrary to the case of partial load operation, the rotor speed starts accelerating already before the overproduction is completed, due to the pitch control activity (see also Figure 7). Depending on how large the overproduction power is the rotational speed can either reach its rated value or not before the overproduction is completed. For instance, as shown in Figure 10, the rotor speed is already back to the rated value during the 5% and the 10% overproduction, while this is not the case for the 20% overproduction. As already depicted in Figure 7, the rotor speed can also present an overshoot at higher overproduction steps. The recovery period of the WT after overproduction at high wind speeds is almost negligible, as the electrical power returns directly to its rated value when the overproduction is completed.

Figure 10: Wind speed 1.1pu, overproduction period 10 sec and different overproduction power (5%, 10% and 20%).

B. Sensitivity Analysis

A sensitivity analysis is presented to determine the impact of independent variables, such as wind speed, overproduction power and overproduction duration, on characteristics like the recovery period T_{rec}, the power deviation ΔP and the speed deviation $\Delta\omega$, defined in Figure 6. The sensitivity analysis provides a generalized view of the conclusions depicted in the results of the previous dynamic simulations.

A set of simulations has been carried out for different wind speeds, overproduction power values and overproduction durations (i.e. 2sec, 10sec, 20sec). In the following, the sensitivity analysis is presented with focus on the 5% overproduction step only, since the impact of different overproduction steps during a certain constant overproduction period (i.e. 10sec) has been previously addressed through dynamic simulations.

Figure 11 shows the recovery period T_{rec}, the power deviation ΔP and speed deviation $\Delta\omega$ versus the overproduction period T_{ov} for a 5% overproduction power and different wind speeds.

As depicted in the previous figures, Figure 11 illustrates that T_{rec} strongly depends on the WT operation as well as on wind speed conditions during an overproduction. Figure 11 shows two distinct groups of curves for the recovery period: one for low wind speeds (i.e. 0.5pu and 0.6pu) and one for higher wind speeds (i.e. 0.68pu to 1.27pu). This separate alignment of the curves is in accordance with Figure 4, which illustrates how, the WT is operating on the optimal part of MPPT curve (namely before the knee point) for wind speeds lower than 0.65pu. At higher wind speeds, the turbine is operating on the steep ramp of the curve (namely, after the knee point), which results in a significant reduction of T_{rec}.

For low wind speeds T_{rec} is significantly higher compared to that at high wind speeds. Note that, for wind speeds lower than 0.65pu, T_{rec} is about 15 sec at an overproduction period of only 2 sec, while it is increasing up to about 50 sec, when the overproduction period is 20 sec. Moreover, as shown in Figure 8, the higher the overproduction power, the longer the recovery period. For example, during an overproduction power step of 20%, T_{rec} for wind speeds lower than 0.65pu can reach the level of 80 sec for a 20 sec overproduction period. Furthermore, the higher the high wind speeds, the shorter the recovery period. The recovery period, drastically reduced as a consequence of the active pitch actuation at high wind speed, is almost constant no matter the overproduction period.

Note also that, the power deviation ΔP is lower than 0.1pu. It is slowly increasing with overproduction period T_{ov} as long as the WT is operating at wind speeds lower than 0.65pu or at wind speeds higher than 1pu. Instead, as expected, the power deviation ΔP is higher and is increasing with T_{ov} for the wind speeds where the WT is operating on the steep ramp of the MPPT curve (i.e. see Figure 4). For example, for 0.93pu wind speed, the power deviation during a 5% overproduction power and a 20 sec overproduction period can get up to 64% of the nominal turbine's power, which causes significant mechanical stress in the turbine.

As shown in Figure 11, the speed variation $\Delta\omega$ is increasing with the wind speed and T_{ov} as long as the WT is operating at wind speeds lower than the rated wind speed. For example, for 0.6pu wind speed the speed deviation during the 5% overproduction is 2% of the nominal speed, while for 0.93pu wind speed, it is about 10% of the nominal speed for a 20 sec overproduction period. As expected, larger speed deviations during overproductions occur on the steep ramp of MPPT curve, where the wind speeds get higher and the pitch control is inactive. Instead, the speed deviations during overproduction are significantly reduced for wind speeds higher than the rated wind speed, where the pitch angle is active.

Figure 11: T_{rec}, ΔP and $\Delta\omega$ versus T_{ov} for an overproduction step of 5% and for different wind speeds.

V. CONCLUSIONS AND OUTLOOKS

The capability of VSWTs for providing short-term overproduction is assessed through a set of simulations, which reflects the dynamic features of the WT response during normal and overproduction operation. The study is performed using a generic Type IV WT model, which is including the mechanical, aerodynamical and electrical dynamics relevant to active power control studies and which can easily be adjusted with respect to specific real WT implementation.

The results of the investigations have shown that the capability of VSWTs for providing short-term overproduction to the system strongly depends on the initial pre-overproduction conditions, i.e. wind speed conditions, limits of the mechanical/electrical components and control strategies. The higher the wind speed, the shorter the recovery period. Long overproduction periods intended for grid frequency support can create large active power underproduction from wind turbines, which can impose significant mechanical stress on the power system. Especially in wind speeds just below the rated, the underproduction can be considerable, unless advanced control actions are applied. At low wind speeds there is a risk of stopping the WT during overproduction, if the imposed overproduction period is so long that the turbine decelerates below the minimum rotational speed limit. The higher the overproduction power or the larger the overproduction period, the higher the speed and power deviations are. At wind speeds just below the rated, an imposed overproduction can stress the mechanical shaft drastically.

It is obvious that the turbine short-term overproduction capability varies significantly with the WT's operational mode, and therefore the design of a reliable frequency support scheme needs to take this into account in order to ensure satisfactory results in all ranges of operation and for various levels of overproduction requirement. A trade-off between the mechanical stress imposed on the WT and the desired frequency support from VSWTs during large frequency excursions in the power system with high wind power penetration has to be considered in the definition of the frequency control requirements set by TSOs.

The results of this work can be used as a starting point in the design of frequency control functionalities, corresponding to ancillary services, which may be required for future WTs.

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