A NOVEL CENTRALISED WIND FARM CONTROLLER UTILISING VOLTAGE CONTROL CAPABILITY OF WIND TURBINES

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Abstract – As many other European countries, Germany is now going to install large wind farms off shore. The turbines used in such farms are variable speed wind turbines, either doubly-fed induction generators or synchronous generators with full size converter. These turbines offer the capability of decoupled active and reactive power control. Modern onshore and offshore wind farms must provide reactive power or voltage control at the point of common coupling (PCC) on demand of the system operators. But fast changes in active power as a result of changing wind speeds can lead to fast changes in the voltage at the PCC. In this paper, a new wind farm control system will be presented which makes use of local voltage controller at each turbine using voltage reference settings from the wind farm controller. The controller is characterized by a hierarchical system structure with a high degree of autonomous local control capability. The proposed approach is demonstrated by simulation results conducted for a wind farm, currently under planning in Germany.

Keywords: wind turbines, grid code, continuous voltage control, farm controller

1 INTRODUCTION

In the next few years, large offshore wind farms will be installed in Germany. Following a study of the German Energy Agency[1], there will be up to 52.3 GW wind power in the German grid in 2020, 20.4 GW of which installed offshore. In contrast, the guaranteed power plant capacity in Germany today adds up to 86.2 GW [2]. Following these figures, wind power is no longer negligible in any respect.

These factors lead to the conclusion that large wind farm have to be operated like conventional power plants. In Germany and other European countries TSOs published special requirements which all newly installed wind farms have to fulfill. But offshore wind farms as well as new onshore wind farms are spread over a smaller area (per MW) than older and smaller wind farms. As a result, changes of wind speed lead to faster changes of active power production than before, they do not average out as much any more. These rapid changes of active power can lead to considerable changes in the reactive power demand and as a result in the grid voltage - a new challenge that did not exist with conventional power plants with rather constant power output. In order to limit voltage changes in the grid and to minimize resulting costs for limiting voltage deviations like grid reinforcements or reactive power regulators in the grid improved control schemes for wind farms are required.

To provide such a performance, a new wind farm control scheme was developed, which provides improved control capabilities at the point of common coupling (PCC). This farm controller gives voltage references to each wind turbine. In the wind turbines themselves, a local voltage controller is installed. An exemplary application of such a wind farm controller for a wind farm of wind turbines with a doubly fed induction generator (DFIG) system was simulated and the results are presented in this paper.

2 GENERAL LAYOUT OF A WIND FARM WITH DFIG WIND TURBINES

Common centralized wind farm controllers give set points of reactive power to the wind turbines. These set points depend on the requirements of the transmission system operator (TSO) and are calculated by the farm controller based on the measured values of voltage, active and reactive power.

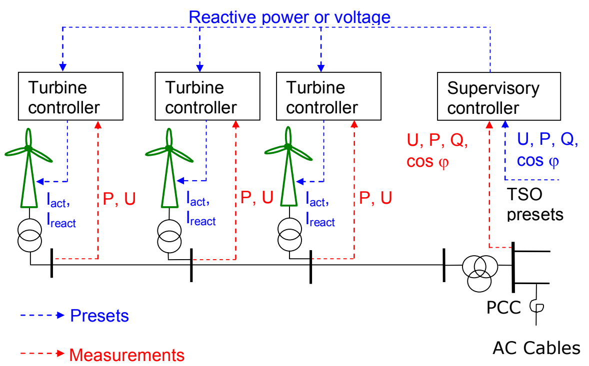

Figure 1: Basic layout of a wind farm and its controllers

The DFIG is the most commonly used device for power generation in wind turbines at the moment. The basic layout of a wind turbine with DFIG is shown in Figure 2. The wind drives the blades of the turbine, which are coupled to a slip-ring induction generator through a gear box. The doubly fed induction generator is coupled to the grid with the stator windings. The rotor windings are connected to the grid via a 4 quadrant voltage source inverter.

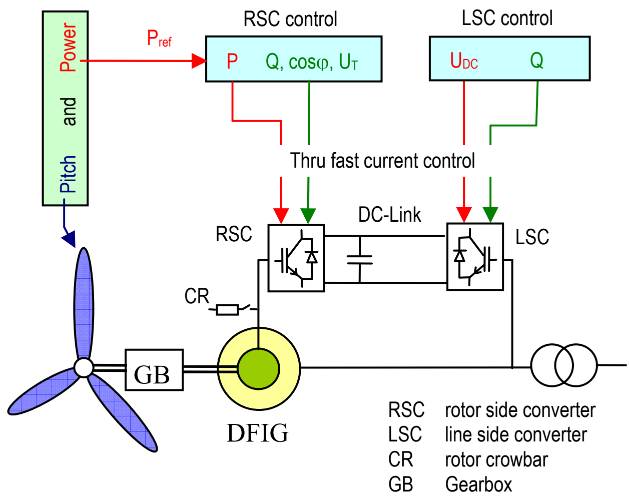

Figure 2: Basic Layout of a DFIG wind turbine

Mathematically, a DFIG can be described by five basic equations, two describing the voltage of rotor and stator respectively, two for flux linkages and one for the mechanical part. Here, all values are given in per unit, and the reference system is defined in such a way that consumed active power and inductive reactive power is positive.

Voltage terms:

$$\underline{u}_S^{\angle K} = r_S \underline{i}_S^{\angle K} + \frac{d\underline{\psi}_S^{\angle K}}{dt} + j\omega_K \underline{\psi}_S^{\angle K} \quad (1)$$

$$\underline{u}_R^{\angle K} = r_R \underline{i}_R^{\angle K} + \frac{d\underline{\psi}_R^{\angle K}}{dt} + j(\omega_K - \omega_R)\underline{\psi}_R^{\angle K} \quad (2)$$

The superscript $\angle K$ denotes the rotating reference frame. ω_K is a freely chosen speed related to this reference frame.

Flux linkages:

$$\underline{\psi}_S^{\angle K} = l_S \underline{i}_S^{\angle K} + l_h \underline{i}_R^{\angle K} \quad (3)$$

$$\underline{\psi}_R^{\angle K} = l_h \underline{i}_S^{\angle K} + l_R \underline{i}_R^{\angle K} \quad (4)$$

with $l_S = l_h + l_{\sigma S}$ and $l_R = l_h + l_{\sigma R}$.

Finally, the equation of motion can be derived as:

$$\frac{d\omega_R}{dt} = \frac{1}{\theta_m}\left(\psi_{Sd}^{\angle K} i_{Sq}^{\angle K} - \psi_{Sq}^{\angle K} i_{Sd}^{\angle K} + t_m\right) \quad (5)$$

where:

$$t_{el} = \psi_{Sd}^{\angle} i_{Sq}^{\angle} - \psi_{Sq}^{\angle} i_{Sd}^{\angle} \quad (6)$$

The doubly-fed induction machine is controlled from the rotor side via its converters. Therefore, reference values for the rotor current have to be calculated, which requires knowledge of the steady state relationship between rotor and stator currents.

To calculate active and reactive currents, the derivative terms in (1) and (2) will be neglected and the d-axis will be oriented along the stator voltage. It then follows from eq. (1):

$$\underline{u}_S = r_S \underline{i}_S + j\omega_0 \underline{\psi}_S \quad (7)$$

in the synchronously rotating reference frame. (7) can be rewritten as

$$\underline{u}_{SR} = \underline{u}_S - r_S \underline{i}_S = j\omega_0 \underline{\psi}_S \quad (8)$$

where the stator flux linkage lags π/2 behind $\underline{u}_{SR}$. Using this reference frame for (6), it follows

$$t_{el} = \left|\underline{\psi}_S\right| i_{Sd}^{\angle u_{SR}} \quad (9)$$

since

$$\psi_{Sd}^{\angle u_{SR}} = \left|\underline{\psi}_S\right| \quad (10) \quad \text{and} \quad \psi_{Sq}^{\angle u_{SR}} = 0 \quad (11).$$

Due to the lagging of the flux-linkage, $i_{Sq}^{\angle}$ in (6) becomes $i_{Sd}^{\angle u_{SR}}$ if u_{SR} is oriented along the d-axis.

$i_{Sd}^{\angle u_{SR}}$ corresponds to active current and $i_{Sq}^{\angle u_{SR}}$ to the negative of the reactive current.

For large machines, it can be assumed that $\underline{u}_{SR} \approx \underline{u}_S$, i.e. the stator voltage can be used as the reference system.

To control the DFIG from the rotor side, the rotor currents have to be derived. Using (1) and (3) in stator voltage reference frame and again neglecting derivative terms and r_s, it follows

$$i_{Rd}^{\angle u_S} = -\frac{x_S}{x_h} i_{Sd}^{\angle u_S} \quad (12) \qquad i_{Rq}^{\angle u_S} = -\frac{x_S}{x_h} i_{Sq}^{\angle u_S} - \frac{\left|\underline{u}_S\right|}{x_h} \quad (13)$$

Here, the active power is given by the speed controller of the turbine and reactive power outputs are given from the supervisory controller.

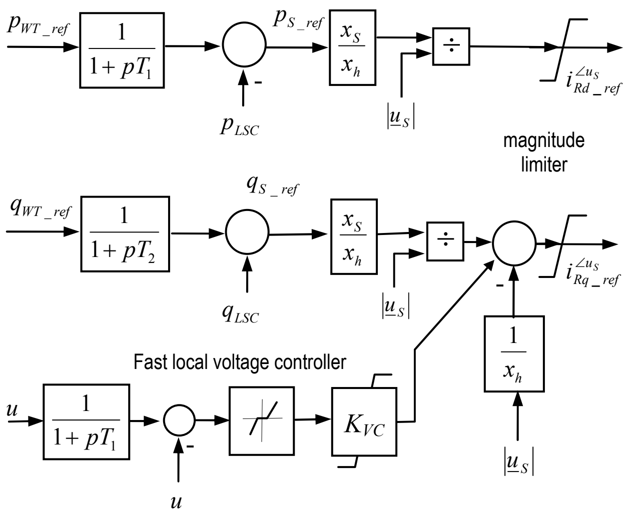

Figure 3: DFIG Control structure using reactive power control at the wind turbine

Hence, the reference values for the rotor currents can be denoted as:

$$i_{Rd\_ref}^{\angle u_S} = -\frac{p_{S\_ref}}{\left|\underline{u}_S\right|}\frac{x_S}{x_h} \quad (14)$$

$$i_{Rq\_ref}^{\angle u_S} = \frac{q_{S\_ref}}{|\underline{u}_S|}\frac{x_S}{x_h} - \frac{|\underline{u}_S|}{x_h} \qquad (15)$$

$|\underline{u}_S|/x_h$ is the magnetization current of the induction machine. This current has to be provided by the rotor side. Figure 3 gives a short overview of the control structure which corresponds with eq. (12) and (13). The delay introduced considers communication delays. The magnitude limiter considers the maximum permissible rotor current, i.e. the current magnitude. A fast acting local voltage controller is included for transient situations. This controller is only active outside the normal voltage operating range; it commonly uses a proportional gain to meet the requirements of the TSO. A more detailed explanation of the machine model used and of the wind turbine controller can be found in [8].

The calculation of the rotor voltages from the rotor reference currents is shown in Figure 4. Again disregarding the derivative terms and assuming r_s to be negligible, it can be derived from eq. (1)-(4):

$$\underline{u}_R = r_R\underline{i}_R + js\left(x_h\frac{\underline{u}_S - jx_h\underline{i}_R}{jx_S} + x_R\underline{i}_R\right) \qquad (16)$$

Converting into stator voltage reference frames gives

$$u_{Rd}^{\angle u_S} = r_R i_{Rd}^{\angle u_S} + s\left(\frac{x_h}{x_S}|\underline{u}_S| - i_{Rq}^{\angle u_S}\,\sigma\,x_R\right) \qquad (17)$$

$$u_{Rq}^{\angle u_S} = r_R i_{Rq}^{\angle u_S} + s\,i_{Rd}^{\angle u_S}\,\sigma\,x_R \qquad (18)$$

where $\sigma = \left(1 - x_h^2 / x_R x_S\right)$, the leakage coefficient, is introduced. The second summands in eq. (17) and (18) are called cross-coupling terms. They have to be added to the output of the current controller.

3 GRID CODE WIND FARM REQUIREMENTS FOR REACTIVE POWER

In the initial stages of wind power generation in Germany, wind turbines were treated similar to normal power consumers, as a 'negative load'. Each turbine was required to provide reactive power in order to remain within a power factor of unity to 0.95 lagging [3].

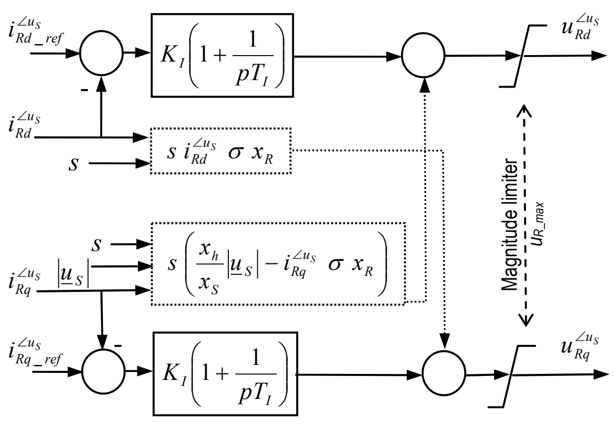

Figure 4: Rotor current control structure

As a result, in respect to reactive power generation, wind turbines only had a more or less 'passive' role in the grid.

The increasing number of wind turbines led to a major change in the connection requirements, starting in Germany with the E.ON-Netz Grid Codes of 2001 and 2003 ([4],[5]). In order not to endanger the stability of the grid, it was regarded as necessary that wind farms should play a more 'active' role in the grid.

3.1 Steady State reactive power requirements

The main new requirements for the reactive power supply at steady state in these Grid Codes are:

- supply of reactive power at the point of common coupling (PCC) of a wind farm instead of at the turbine
- capability of a wind farm to change the reactive power setpoint on external request

Modern grid codes in Germany ([6],[7]) now usually require the possibility to control the reactive power contribution of a wind farm using either (1) a power factor setpoint (2) a reactive power setpoint or (3) a voltage setpoint at the PCC of the wind farm in the same way they are required by conventional power plants.

3.2 Transient reactive power requirements

In addition to a steady state reactive power contribution, a reactive current contribution to the grid during grid faults is now also part of many grid codes. The aim is to support the grid during faults and to improve the voltage recovery after grid faults. The E.ON requirements (see Figure 5) demand capacitive reactive current if the voltage drops below 90% rated voltage to increase the grid voltage in the case of grid faults. If the voltage increases above 110% rated voltage, an inductive reactive current contribution is demanded to reduce the grid voltage.

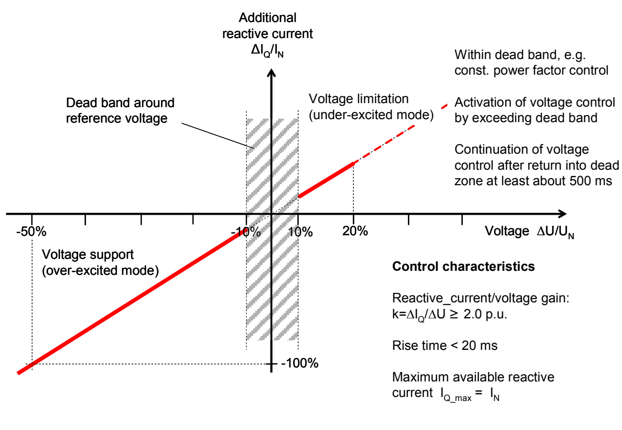

Figure 5: Reactive power demand according to E.ON [7]

This reactive current is supposed to be available within 20 ms of fault detection. It is supposed to be added to the actual reactive current resulting from the steady state operation.

4 STATE OF THE ART REACTIVE POWER CONTROL STRATEGIES

Grid codes usually offer several possibilities to control the reactive power of a wind farm.

4.1 Control strategies at the PCC

A possible control structure for a wind farm controller is shown in Figure 6. Possible setpoints from the system operator are (1) power factor, (2) reactive power or (3) voltage. The actual power factor, reactive power or voltage can be measured or estimated. The difference between setpoint and measurement can then be used as an input to a PI-controller that sends setpoints to the individual wind turbines.

4.1.1 Power factor control at the PCC

Power Factor control is still used in most cases, as it can provide a certain 'passive' contribution to the reactive power requirements of the grid. This means, the power factor control can provide an increased reactive power contribution to the grid as soon as there is an increase of active power supply.

A disadvantage of power factor control is that changes in active power production at the turbine lead to a change in the power factor at the PCC as a result of the cable and transformer inductance. Even though there is a certain smoothing effect of large wind farms, changes in wind speed lead to a rather fast change of active power. As a result, the wind farm controller continuously needs to provide changing reactive power setpoints to the wind turbines, requiring aggressive controller settings and fast wind farm communication hardware to provide adequate control action and to avoid power factor oscillations as a result of wind farm communication delays.

4.1.2 Reactive power control at the PCC

A reactive power setpoint is more common with large synchronous power generators. It has disadvantages if the power output changes fast. As mentioned above, different to large conventional power plants, the power output of wind turbines depends on the wind

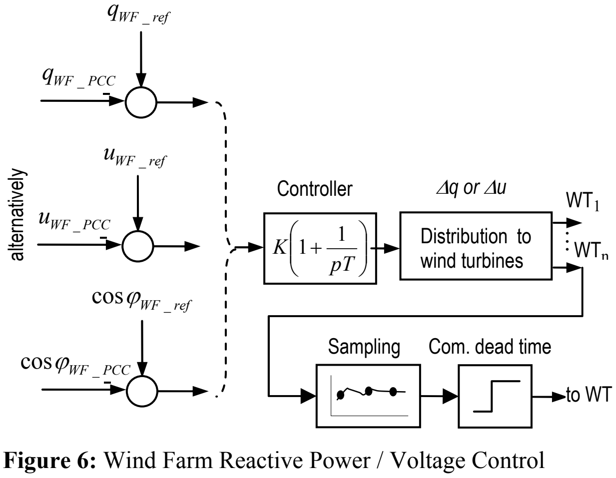

Figure 6: Wind Farm Reactive Power / Voltage Control

speed. For wind speeds above rated, a constant power output is available, but at normal sites above rated wind speed is only available during 20% to 30% of the time. A reactive power setpoint would require a fast control of the setpoint by the system operator to avoid undesired impacts on the voltage.

4.1.3 Voltage control at the PCC

Wind farm voltage control offers a possibility to reduce the effect of changing active power supply by the wind farm without the need to rapidly change the setpoints of the wind farm by the system operator. But due to communication delays within the wind farm, a certain amount of voltage changes at the grid connection point can not be avoided.

4.2 Control strategies at the wind turbine

Independently from the setpoint for the wind farm, the reactive power demand for each wind turbine is usually in the form of a reactive power setpoint.

4.2.1 Reactive power setpoints from the wind farm controller

A possible control structure for the reactive current of a wind turbine with DFIG is shown in Figure 3. The turbine receives reactive power setpoints from the wind farm as an input. The wind farm controller input can be either power factor, reactive power or a voltage setpoint controller (Figure 6).

At the wind turbine, two input values can influence the reactive power output. One is the reactive power setpoint from the wind farm controller. The second input is the measured voltage in case of a grid fault.

As a result, the operation mode during grid faults is basically switched from reactive power control to voltage control.

5 IMPROVED WIND FARM CONTROL STRATEGY

The proposed new control strategy is based on a fast continuous voltage control at the wind turbine level combined with a relatively slow setpoint control at wind farm level. The wind farm controller sends voltage setpoints to the wind turbine controller instead of reactive power setpoints as it had been common so far.

The voltage setpoint at the turbine is compared to the measured value, and the difference is the input to a P or PI voltage controller. The continuous voltage control remains active both during normal operation and during grid faults (see Figure 7). The steady state limitation enables higher currents in case of grid faults but limits the reactive current during normal operation.

The wind farm controller is acting slow in order to avoid undesired control actions and to provide a smooth change of reactive power or voltage as a result of setpoint changes at wind farm level from the system operator. The local controller is acting fast. It is designed to reduce undesired voltage changes during normal operation. In case of a sudden voltage change, a reactive power controller would need commands from the wind farm controller to react. The proposed voltage controller instead does not need to wait for such an

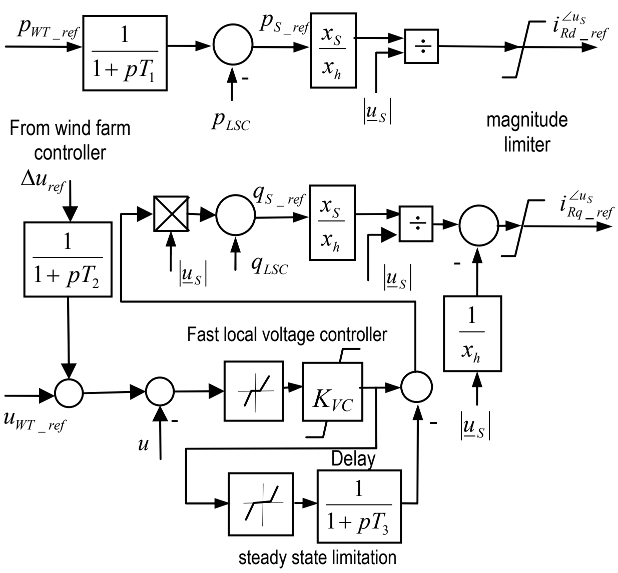

Figure 7: Wind turbine control structure with local voltage control

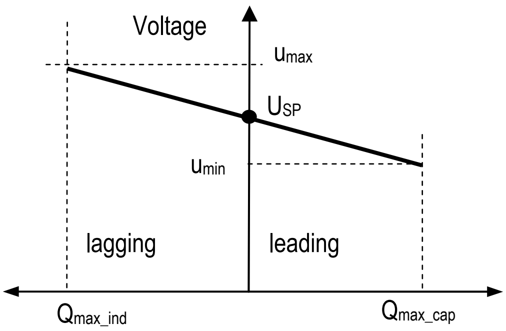

Figure 8: Voltage / Reactive Power Characteristic

input, it can react immediately. As a result, it can be considerably faster in controlling grid voltage changes than a conventional reactive power controller, thus mitigating voltage flicker in the grid.

An additional advantage of the local voltage control is its inherent capability to reduce voltage differences between wind turbines within a wind farm. Voltage deviations within a wind farm can become a problem in wind farms located along a long distribution line. Using a reactive power controller at the turbine and identical reactive power setpoints for all turbines, the voltage would increase along the line with each turbine. In case of high grid voltages or high capacitive reactive power requirements, a risk of high voltages at the turbine at the end of the line arises. This could lead to an undesired shutdown of turbines.

Using voltage control, all turbines can receive the optimum voltage setpoint; it can be made sure all turbines in the wind farm remain within safe voltage operating limits. In the event of grid faults, the fast voltage controller is able to supply high reactive currents within very short time in order to support the grid as long as the voltage is below its nominal value.

The gain of the proportional voltage control can be calculated as

$$K_{VC} = \frac{\Delta Q}{\Delta U} = \frac{Q_{max\_cap} - Q_{max\_ind}}{U_{max} - U_{min}} \qquad (19)$$

Q_{max_cap} and Q_{max_ind} are the maximum capacitive and inductive operation limits at the PCC, U_{max} and U_{min} the voltage limits for normal operation. This results in a voltage / reactive power characteristic as shown in Figure 8. Using voltage limits of 0.95 and 1.05 for normal operation and a power factor of 0.95 (0.33 p.u.), the gain results in 6.6 p.u.

The control strategy of the wind farm controller is not influenced by the selection of the local control mode of the turbine. As it is shown in Figure 6, the input to the wind farm controller can be power factor, reactive power or a voltage setpoint. But independently of the system operator command, the setpoint that is sent to the turbines is a voltage setpoint.

5.1 Local Voltage control with reactive power setpoints from the system operator.

Depending on the requirements of the system operator, either reactive power setpoints or voltage control setpoints at wind farm level will be preferred. If the grid operator provides a stable controller at the PCC, reactive power setpoints may be preferred.

On wind farm level, the controller has a slow control loop in order to avoid undesired overshooting of reactive power or voltage at changes of the setpoint. At the same time, the fast voltage controller on wind turbine level is able to reduce voltage changes in the grid both during grid faults as during normal operation.

5.2 Local Voltage control with voltage setpoints from the system operator.

In case of remote wind farms or the lack of a fast control system at operator level, a wind farm voltage control combined with local voltage control at the turbine will be the best solution. The voltage control on wind farm level can keep the grid voltage at a constant level, independently of wind farm production or system load. The fast voltage controller at turbine level on the other side is able to reduce fast voltage changes in the grid that could result from changes of wind farm active power, but also from load changes in the grid.

5.3 Robustness aspects of the proposed control strategy

The good inherent response of the local voltage control system enables a wind farm design that is limited mainly to trim control. Additionally, the voltage support during grid faults is completely implemented in the turbines, the farm controller is not required to react on fast voltage changes. As a result, the demands on the communication speed in the wind farm are rather low. Therefore, the design of the wind farm controller and communication hardware can be focused on fail safety and reliability rather than on speed.

To increase fault tolerance even more, it is possible not to give actual set points to the turbines but deviations of a local preset. In such a case, each turbine generates its local set point of voltage while the farm controller only propagates deviations based on this general set point. Even if communication or the wind farm controller itself fails, the turbines can keep generating but will fall back to a fixed operating point.

This offers also the possibility of installing a load flow optimizer, which gives the results of the optimization to the turbines as local preset. In case of an error, the turbines then fall back to a precalculated optimal operating point.

6 SIMULATION RESULTS

For the comparison of different wind farm controller strategies, four configurations were selected: Reactive Power control and voltage control at turbine level, each with power factor control and voltage control at farm level.

ID	Wind farm setpoint	Wind turbine control
a	power factor	reactive power
b	voltage	reactive power
c	power factor	voltage
d	voltage	voltage

Table 1: Overview of control structures compared during the simulation.

The layout of the wind farm is shown in Figure 9. The turbines are located offshore and are connected to the high voltage grid of the TSO using a 110 kV cable.

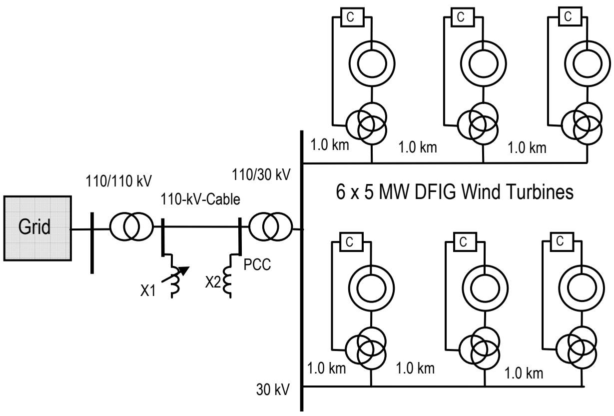

Figure 9: Layout of the wind farm analyzed during simulation.

6.1 Set-Point-Change

A setpoint change at wind farm level can be seen in Figure 10. A power factor reference step and a voltage reference step at wind farm level have been simulated. There are only minor differences between local reactive power control [(a),(c)] and local voltage control [(b),(d)] strategies for both setpoint changes. The same smooth response to setpoint changes can be implemented for local reactive power control and local voltage control.

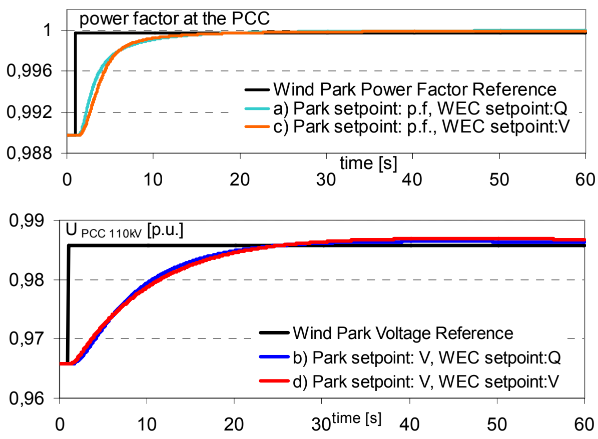

Figure 10: Step response to 0.1 power factor reference step and 0.2 p.u. PCC voltage reference step in WF controller for the selected control strategies.

6.2 Grid Fault

Fast changes in the voltage as a result of a grid fault are shown in Figure 11. Both a local reactive power control and the local voltage control offer voltage control capabilities for voltages outside the normal turbine operating range. The E.ON Netz and VDN - requirements ([6],[7]) of a reactive current contribution within 20 ms of grid fault detection can be met by both strategies. As a result of the reactive power fed into the grid during the voltage dip at the turbine, the voltage at the turbine increases compared to the voltage at the PCC.

The voltage control strategy leads to an improved grid support because a higher gain than required by the grid codes ([6],[7]) can be used. The reactive current is limited to 1 p.u.

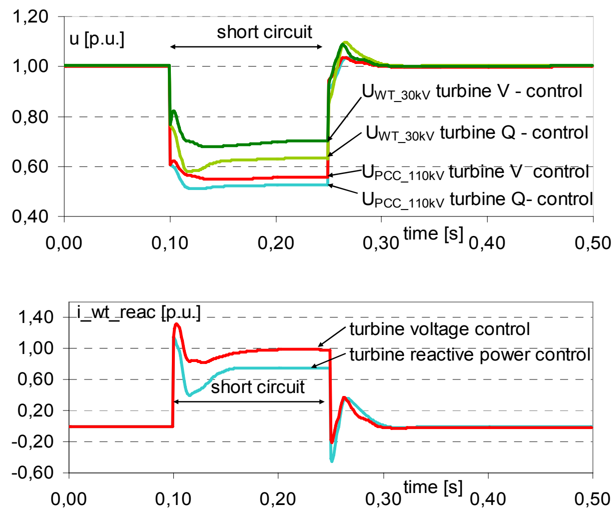

Figure 11: Voltage and reactive current at the wind turbine during a short circuit close to the PCC

6.3 *Load Variation Wind Farm operation*

The effect of the different control strategies during changes of wind speed is shown in Figure 12 and Figure 13. At wind farm level both strategies, power factor control [(a), (c)] and voltage control [(b), (d)] are able to limit voltage changes at the PCC (Δu= 0.15%) compared to the voltage at the turbine (Δu= 0.3%). But only voltage control is able to keep the voltage at the PCC at a constant level in average.

When comparing the control strategies at turbine level, the advantages of the proposed local voltage control can be seen. The voltage deviation as a result of wind speed changes (i.e. active power changes) are considerably lower for local voltage control compared to local reactive power control. In the simulated interval, the voltage deviation for local voltage control is more than 50% lower (see Figure 13) than during local reactive power control.

The simulation results are based on a relatively slow (500 ms) communication cycle within the wind park; as a result there are only limited demands on the required communication hardware. These low demands on communication hardware are a great advantage for the use of the local voltage control in existing wind farms, or for the extension of existing wind farms. Using the proposed control structure, local voltage control can be used for the entire wind park without the need to change the existing communication infrastructure hardware.

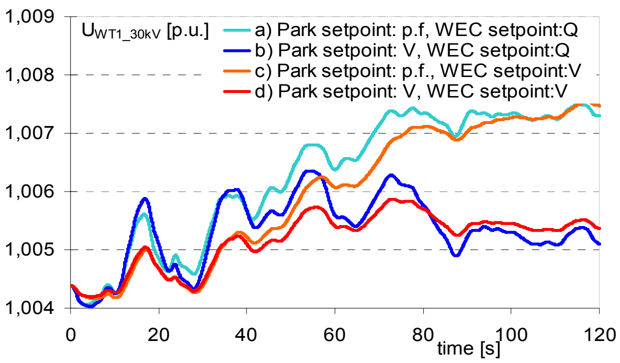

Figure 12: Voltage at turbine 1 for fluctuating wind using different control strategies

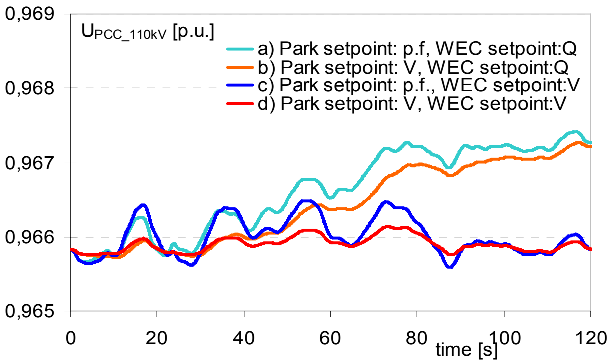

Figure 13: Voltage at the PCC for fluctuating wind using different control strategies

7 CONCLUSION

A novel control structure for wind farms is presented. The proposed voltage control strategy is able to provide the same response to park setpoint changes and during grid faults as common reactive power control strategies. It shows improved capabilities to limit grid voltage changes as well as undesired voltage deviations between wind turbines, thus minimizing both voltage flicker at the PCC as well as the risk of overvoltages within the wind park.

The proposed control structure has very limited requirements on the wind farm communication hardware, it allows an upgrade of existing wind farms without the need of hardware changes. The control structure is robust and provides improved voltage quality even during a possible outage of the wind farm controller. It does not require a specific parameterization for each wind turbine; all turbines can receive the same setpoint. The proposed system is therefore well suited both for new offshore installations as for the update of existing wind farms based on existing limited wind farm communication technology.

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