CONTRIBUTION OF A WIND FARM TO VOLTAGE AND SYSTEM STABILITY: RESULTS OF A MEASUREMENT CAMPAIGN

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ABSTRACT

The rising percentage of inverter-based generation poses new challenges to the grid. Approaching a majority share of inverter-based generation, technical issues in grid operation and the contribution to grid stability have to be analysed. A measurement campaign in a wind farm has been carried out in order to investigate the performance of a wind farm and its interaction with the grid. Due to a long feeder, the short circuit power at the connection point of the wind farm was low. The results are used to recognize technical challenges and to find adequate solutions. The main objective of this paper is an evaluation of the wind farm performance and a comprehensive comparison with requirements of grid codes and guidelines to contribute to reactive power balance and system stability.

INTRODUCTION

A measurement campaign has been conducted in a wind farm, which is connected to the medium voltage grid. At the point of connection (POC) the grid has a relatively low short circuit power (S_k'') due to the long distance to the high voltage substation. The wind farm consists of six turbines. The measurement campaign included an active and a passive part. The active tests were conducted during two weeks, whereas the passive measurements lasted almost two months. The tests included performance checks, which exceed today's requirements. As the wind speed in the second week of the active measurement campaign was very low (active power always below 20% P_r), the test series could not be completed.

ACTIVE TESTS

The active tests are divided into three sections; frequency control, voltage control and reactive power setpoints.

If the mains frequency surpasses the threshold (settable between 50.2 Hz and 50.5 Hz), the generation unit has to reduce its power according to the ENTSO-E Network Code on Requirements for Grid Connection Applicable to all Generators (RfG). Non-synchronously connected power-generating units have to reduce the actual active power with droop settings in the range 16.6 % and 100 % P_{actual} / Hz [1]. For the determination of P_{actual}, the active power is frozen in the moment, when the mains frequency surpasses the threshold of the frequency. Each ENTSO-E member can implement different settings.

In order to participate in the voltage regulation, the wind farm controller is equipped with closed loop $Q(U)$-control. The wind farm controller allows to export or import reactive power as a function of the measured voltage. The $Q(U)$-curve and the points of intersection can be calculated as predetermined and then implemented in the wind farm controller. It has to be noted that the absolute influence of the wind farm on the voltage depends to a large degree on the grid impedance at the POC.

For the interaction with the grid it is important, that the wind farm is capable of adapting its reactive power according to the grid requirements. This can be either tan φ control or setpoints.

MEASUREMENT SETUP

The wind farm consists of 6 type 4 turbines (full converter) and has a total rated power P_r of 12 MW. The farm is connected to a HV/MV substation via a 23.5 km MV cable. Measurements have been performed using nine GPS synchronized IEC 61000-4-30 class. A power quality analyzers (PQA) with a frequency up to 10 kHz. In addition, four transient recorders (TR) with a sampling rate up to 1 MS/s have been installed for acquiring raw waveform data during the short-term measurements. The general wind farm layout and position of the measurement devices is presented in Fig. 1.

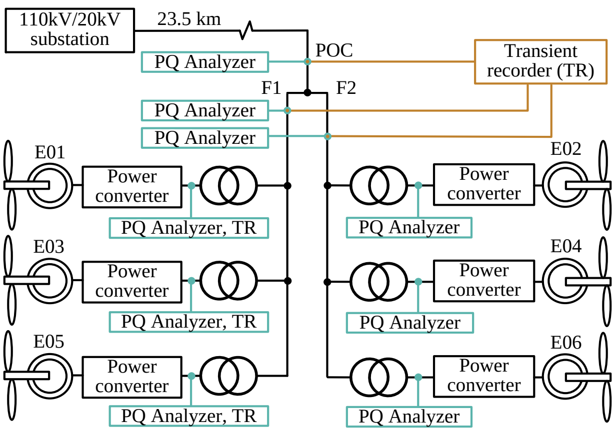

Fig. 1: Layout of the wind farm and measurement locations

DATA ANALYSIS AND MEASUREMENT ACCURACY

The network frequency is calculated by averaging over ten periods of the fundamental. The rms-voltage is arithmetically averaged across the three single phases. The estimation of reactive power can be performed either using cos φ (based on fundamentals) or power factor PF (considering fundamentals and harmonics) [2].

Substantial differences are expected only during low power infeed. However, the measurement uncertainty is more significant in this range. This paper is using cos φ derived from TR and PQA measurements. The farm controller uses the value taken from the measurement devices of the wind farm (MD_WF). Based on the values at the working point (WP) and the maximum measuring range (MMR), Table 1 shows the range of uncertainty of the existing MD_WF and TR resp. PQA, which have been installed for the tests.

Table 1: Range of measurement uncertainty (caused by device and converter uncertainties)

	MD_WF	PQA	TR
WP	18.2 kVA	4.6 kVA	4.6 kVA
MMR	128.9 kVA	32.3 kVA	32.3 kVA

MEASUREMENT CAMPAIGN

P(f)-control

Preliminary considerations and constraints

The constraints of the frequency dependent active power control are given by the local grid operator today (standard settings shown in Table 2). The *P*(*f*)-control works according to Fig. 2 and begins to reduce the active power output at frequency f_1 going down to zero power output at frequency f_2. A preliminary statistical analysis has shown that the threshold frequency of 50.2 Hz is rarely exceeded. Therefore, the settings have been adjusted for the test period (cf. Table 2) in order to record a sufficient number of events.

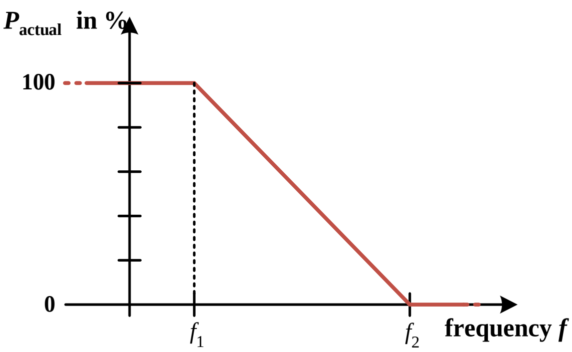

Fig. 2: Frequency dependent reduction of active power

P(*f*)-control can be either implemented for each single turbine or for the whole wind farm. In our case it was implemented in each turbine. The active power and frequency were recorded on the LV-side of the transformer.

Table 2: Setting of frequency limits

	Local Standard	Test 1	Test 2
f_1 in Hz	50.5	50.01	50.03
f_2 in Hz	52.0	50.11	50.13

Measurement and results

The *P(f)*-control was set up for 4.5 hours during one day. The time curve of the measured frequency and the sum of the active power (WTG 2-6) are shown in Fig. 3. In WTG1 *P(f)*-control was not activated, as it was intended to be used as reference. However, wind speed variations across the turbines did not allow the comparison.

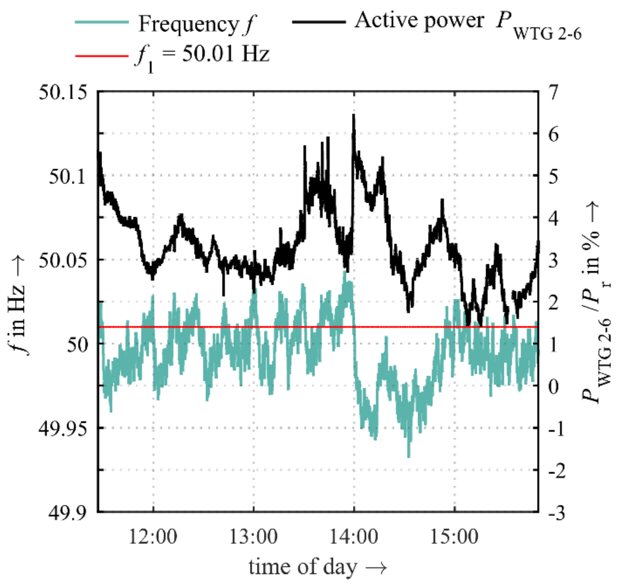

Fig. 3: Frequency and active power with threshold frequency f_1 (Test 1)

During the observed period, the set threshold frequency has been exceeded several times. Fig. 4 shows an excerpt of ten minutes from the test period. The threshold frequency was set to 50.01 Hz. Active power reduction can be observed at a threshold exceeding 50.02 Hz according to the calculation method used. This deviation is within the accuracy of all measurement devices of ± 10 mHz. Today there is no standard for determining the frequency and each manufacturer has own measurement algorithms.

Besides the course of the frequency and the measured active power an uncertainty band for frequency measurement framed by red dotted lines is shown in Fig. 4. Furthermore, the expected active power P_{exp} (dotdashed line) is calculated based on the *P(f)*-characteristic and the measured frequency taking into account the uncertainty band. For frequencies below f_1 the expected power equals the actual power of the turbine. For frequencies above the limit, P_{exp} represents the reduced active power set by the controller due to over-frequency. The calculation is based on the frozen reference value of active power, which is shifted to the lower and upper boundary of the frequency uncertainty band, respectively, to generate an expected active power band.

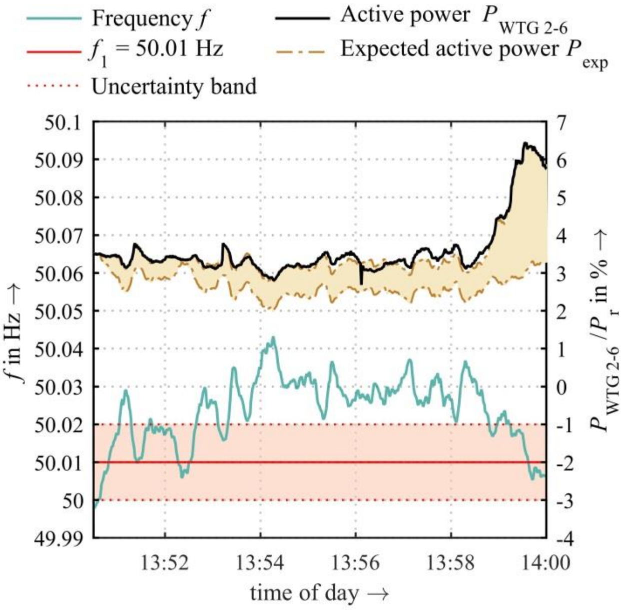

Fig. 4: Comparison of measured and expected active power acc. to frequency considering measurement uncertainty

The measured active power nearly equals the calculated values based on the frequency $f_1 = (50.01 + 0.01)$ Hz of the upper uncertainty band. The same behavior was observed during a 16-hour test over night with the second parameter set (Test 2). The performance of *P(f)*-control meets the expectations.

Q(U)-control

Preliminary considerations and constraints

The characteristic of the *Q(U)*-control is defined by the grid operator. This includes the dead band and the slope $\mathrm{d}Q_{\text{POC}}/\mathrm{d}U_{\text{POC}}$ to the maximum reactive power export and import requested. Furthermore, the grid operator defines the response time.

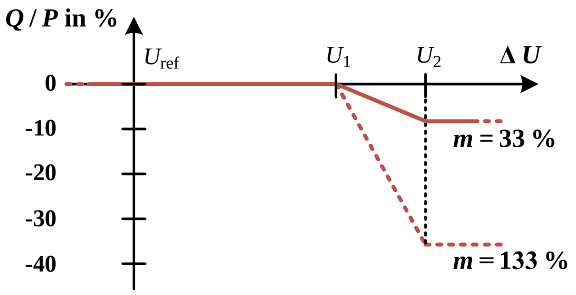

Fig. 5: *Q(U)*-diagram of reactive power consumption

Fig. 5 shows the *Q(U)*-diagram with different slopes. The diagram only shows reactive power consumption. As the voltage level at the POC does not allow it, reactive power infeed could not be included in the tests. The dead band of reactive power consumption ranges from U_{ref} to U_1. The width of the dead band is fixed according to the regulations of each country. The reasons for a dead band include, that Type 3 turbines are otherwise mechanically stressed and additional losses in grid and in the wind farm can occur.

The wind farm controller has to operate according to these requirements. Three factors determine the stability of the closed loop control of the wind farm:

- slope of implemented *Q(U)*-characteristic
- dynamic of farm controller
- measurement and communication delays

Additionally, the short circuit power at the POC has to be considered, as it determines the voltage sensitivity, which is defined by the voltage alteration based on changes in the reactive power.

Up to now the wind farm controller of the manufacturer used operates in standard grids with sufficient short circuit power (typically 200 MVA).

Measurement and results

The wind farm under consideration operates with tan φ-control in normal operation. As the short circuit power at the POC is low, *Q(U)*-control is not permitted. For the measurement campaign, *Q(U)*-control was permitted on an exceptional basis within a fixed PQ diagram.

First tests have shown that the voltage reacts very sensitively to changes of the reactive power under these special conditions. The given *PQ*-curve with high slope leads to an unusual behavior of the controller as the value of the voltage at POC U_{POC} was systematically surpassed due to the inadequate slope $\mathrm{d}Q/\mathrm{d}U$. Fig. 6 and Fig. 7 show an overview and a detailed view on the voltage and reactive power at the POC during this special *Q(U)*-control test. It has to be noted, however, that EN 50160 has always been respected.

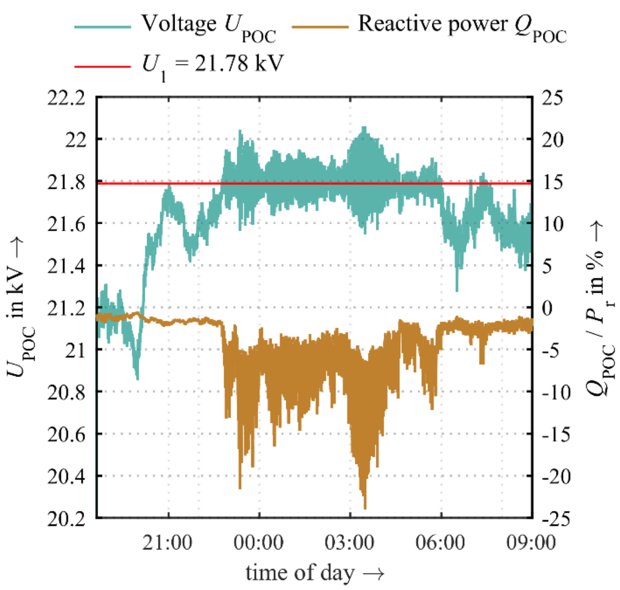

Fig. 6: *Q(U)*-control measurement (high controller slope)

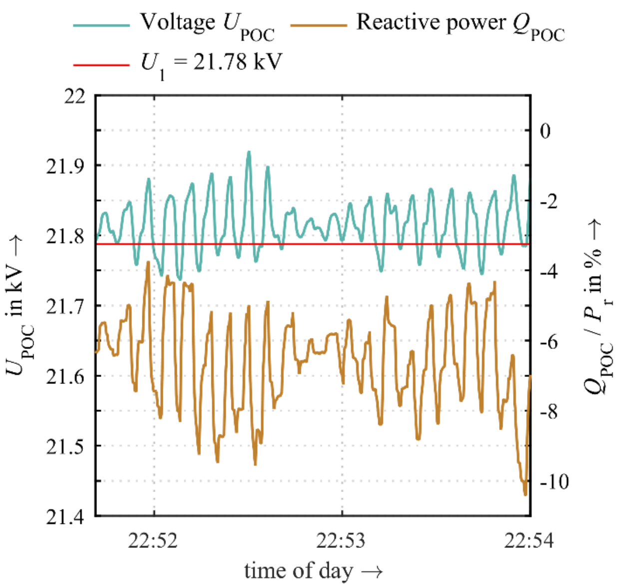

Fig. 7: Detailed view on the *Q(U)*-control measurement

The analysis of the active tests has shown, that the wind farm controller could not provide a stable voltage at a POC with a very low S_k'' and an inadequately high slope setting of the controller. Therefore, an in-depth analysis of the local grid has been performed.

The set up for the simulation was adjusted regarding S_k'' at the POC, which is below 70 MVA. This configuration leads to a voltage sensitivity

$$\frac{\mathrm{d}U_{\mathrm{POC}}}{\mathrm{d}Q_{\mathrm{POC}}} \approx 0.25 \, \frac{\mathrm{kV}}{\mathrm{Mvar}}.$$

For the simulation an adjusted generic wind farm model according to IEC 61400-27-1 [3] type 4A was used in PowerFactory® from DIgSILENT. The parameters were adjusted to the values in the investigated farm.

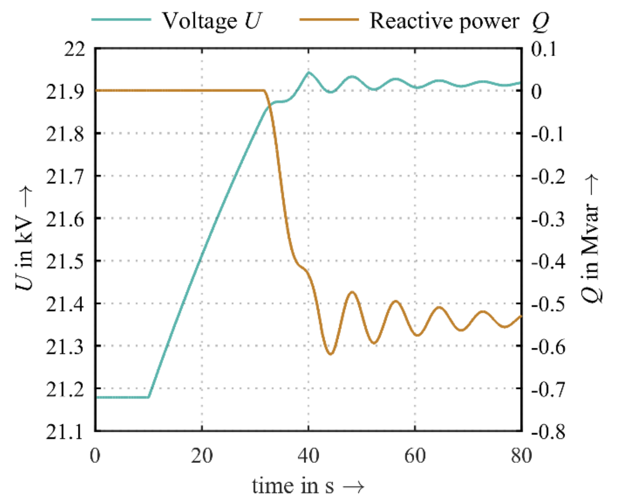

Fig. 8: *Q(U)*-simulation with recommended slope *m* = 33 %

Due to the delay of the wind farm controller and the given sensitivity at the POC a maximum slope *m* of 33 % can be recommended (Fig. 8).

The manufacturer has also replicated the behavior by simulation. The controller was then modified and the behavior was simulated again. The results of the simulation show, that the controller can now cope with steeper slopes also at points in the grid with low S_k''. However, the updated version of the wind farm controller could not yet be tested in the field.

Q(U)-control for active power infeed below 20 %

In the second week of the active tests the wind conditions did not permit to produce an active power above 20%. Below 20 % P_r no requirements exist according the functionality of the *Q(U)*-control. Therefore, no relevant *Q(U)*-tests could be performed at this low wind speed.

The analysis of the active power of the wind farm shows the importance of defining requirements for *Q(U)*-control for wind farms for low wind speeds. An analysis for a period of 24 month has shown, that during almost 40 % of the time the active power is below 20 % P_r (Fig. 9).

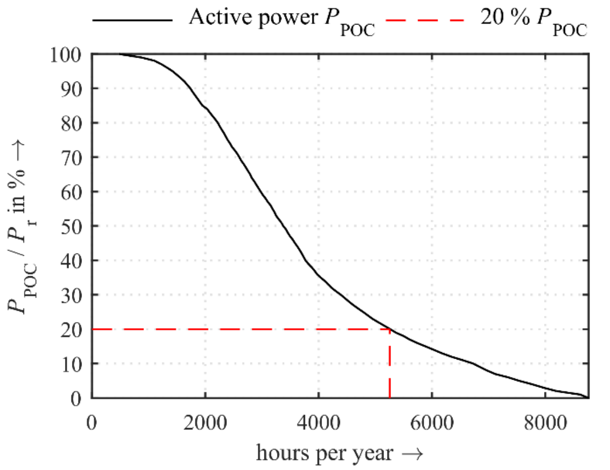

Fig. 9: Duration curve of the active power P_{POC} over 8760 h

CONCLUSION

As the share of inverter based capacity is continuously rising, the contribution of wind farms to grid stability will become crucial. During the tests, which exceeded the normal range of operation of the wind farm, EN 50160 was respected at all time.

This paper has shown, that a inverter based wind farm is capable of providing compliant *P(f)*-control. This way it can contribute to frequency stability of the system.

The capability to provide *Q(U)*-control could not be conclusively shown for a POC with low S_k'' during the tests. From the experience gained it can be concluded, that *Q(U)*-specifications need to be adjusted to the grid situation. Therefore, measurements of the wind farm behavior for different wind and grid situations are highly recommended before its commissioning. The measurement unit should be able to measure mean values, power quality and include a transient event recorder. *Q(U)*-requirements do not exist for operation at $P < 20\,\%\,P_r$. As wind farms operate very often in this range, it will become increasingly important to fill this gap.

During the campaign the testing of different *Q*-setpoint schemes could not be completed. It is planned to conduct these tests in a complementary measurement campaign.

In order to prove the capability of inverter based wind farms to contribute to voltage stability in grids with low short circuit power, further tests of *Q(U)*-control are planned as well in the course of this campaign.

REFERENCES

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