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Power Quality Monitoring for Wind Farms

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***Abstract-* With the increasing amount of wind power generation connected to the power grid, the importance of measuring the wind turbines' power characteristics and power quality characteristics is growing. By capturing this data, one can achieve improved utilization of the turbine by manipulating its control systems in accordance to power grid requirements for voltage/frequency fluctuations and fault conditions. This paper shows how this data can be used to improve power quality, system stability, and for predictive maintenance.**

Keywords: Wind farms, power quality, fault recording, predictive maintenance

I. INTRODUCTION

The current interest in renewable energy is a global trend, which will become even more important in the future due to the expected depletion/exhausting of fossil fuel based energy sources. In an effort to mitigate climate change through the reduction of emission of greenhouse gases, many countries promote renewable energy. Recent examples include the EU directive which targets a 20% contribution of renewable energy sources to the total energy consumption by 2020, and plans from the new US administration to focus more on renewable energy.

A very popular source of renewable energy is wind energy. This paper highlights how wind farm operating companies and distribution system operators (DSOs), where distributed generation (DG) like wind farms are typically connected, can benefit from monitoring wind farm power, voltage and current outputs with multifunctional monitoring equipment.

In addition to traditional power quality monitoring, modern monitoring equipment can provide other useful information, helping to assess the performance of the wind turbine, establish predictive maintenance criteria and analyze the response of the wind turbine during power system events like voltage dips/sags[1].

DSOs are now faced with the connection of large DG sources to their networks, which were not built to accept high DG penetration. Another problem is that distribution networks are not designed to accept large DG units, because their short circuit capacity is often close to the designed maximum value. Meeting the requirements for interconnection of large scale DG will imply significant increase in infrastructure investments.

II. POWER QUALITY MONITORING

There are three primary aspects to consider with regards to operation of wind farms [1]:

1. **Voltage quality of supply distribution network, impacting the performance of the wind farm.** Similarly to the influence on any other equipment, supply voltage disturbances might influence a reduction of the lifetime of wind farm equipment, erroneous tripping and damage. Unlike the normal equipment, erroneous tripping of wind farm equipment can lead to the increased safety risks, as the energy flow interruption might cause large overvoltages.
2. **Current quality of the wind farm, impacting the supply system and other connected customers**
3. **System reliability and stability**, as wind farms become a significant portion of total generation they can impact system stability when many wind farms trip offline at the same time.[2]

The first aspect is well taken care of by the wind generator manufacturers through the appropriate design, and in practice is

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[1] In US, a voltage dip is also referred to as voltage sag. These two terms are considered interchangeable; and in this paper the term voltage dip is used.

[2] There are indications that the Italian blackout from 2003 could have been prevented if distributed generation would have stayed connected to the system.

not an issue today. Conversely, the second aspect creates many concerns for DSOs before they allow operators to connect DG to their grids [2]. DSOs need to ensure that the impact of connecting wind farms on overall system power quality stays below the planning levels. The actual planning levels are set by the network operator and/or the authorities in some countries.

Typical power quality disturbances that may be influenced by wind farms are: harmonics, voltage variations, flicker, voltage dips, short interruptions, etc.

A. Measurement and assessment of power quality characteristics of grid connected wind turbines

The IEC standard [6] provides recommendations and assessment procedures for power quality characteristics of wind farms, aimed at manufacturers of wind turbines, but also purchasers (specifying), operators (verifying), planners and regulators (impact determination).

The standard gives guidance for assessing limits for both continuous operation of the wind turbine and also for intermittent operations.

DSOs and wind farm operators specifying wind generation according to this standard will get detailed information from wind turbine manufacturers on:

- *Current harmonics, interharmonics and higher frequency components*
- *Response to voltage dips*, which is important for the optimal setting of the under-voltage protection
- *Active and reactive power generation*
- *Reconnection time*

Wind farm operators and DSOs should monitor the actual impact and response from wind generators, because models and recommendations from [6] will not always reflect the field results and more accurate testing could made the certification unjustifiably expensive. For example, the test procedure for the determination of the protection levels requires testing with three-phase voltage dips (corresponding to Type III dips in [13]), while in reality most voltage dips will affect just one phase (Type I dips) or two phases (Type II dips).

The active and reactive power outputs of the wind turbine should be specified as a 600s average value, a 60s average value and a 0.2s average value according to [6].

There are many different types of wind generators in use. In general, they can be grouped into the four following types: fixed-speed (stall controlled, pitch controlled, active stall controlled) referred to as Type A, limited variable speed (Type B), variable speed with partial scale frequency converter (Type C), and variable speed with full-scale frequency converter (Type D).

B. Power quality events

In many cases where wind farms were commissioned without adjusting the under-voltage protection, an unnecessary high number of trips due to voltage dips in the supply distribution network will occur [2]. The main reason for this is that the protection settings are usually too high (i.e. protection reacts to a short dip with high residual voltage similarly to the reaction to an interruption), although the turbine could be able to continue safely with normal operation. Simple re-adjustment of undervoltage protection setting might resolve this issue.

Another phenomenon with DG is that the reduction of the fault level in the transmission system due to decreased central generation. This can lead to deeper dips when dips are caused by the transmission network.

On the other hand, there might be a reduction in experienced voltage dip magnitudes for certain locations in the network, and therefore a reduced dip frequency for customers connected close to point of common coupling (PCC). At the PCC of the DG, the fault level is higher, so customers connected there will experience less severe dips. How much the DG will help to mitigate the severity of voltage dips depends on the technology used [1]:

- Three-phase faults/dips - Type III according to [13]
  - Only synchronous machines give significant fault contribution, and thus reduce the dip severity and frequency
  - Induction machines only contribute during the initial few cycles of the fault
- Non-symmetrical faults/dips Type I and II according to [13]
  - Synchronous machines and induction machines contribute to the fault

In case of inverter-interfaced DG, power-electronic converters will contribute to a fault depending on the current limitation setting, applied control algorithm and protection settings.

Squirrel cage induction generators, which are used in fixed-speed wind turbines, draw a large amount of reactive power from the grid after the fault is cleared, what may lead to a prolonged post-fault voltage recovery [1].

C. Voltage variations

One of the main concerns of DSOs is the increase in voltage magnitude when DG is connected to their grids. Due to the variations of wind speed, and therefore variations in output power, excessive voltage variations may also occur. The variations of wind speed can be short-term (second to second) or long-term (e.g. due to changes in seasonal weather conditions).

In [2], all measured sites at low voltage (LV) showed an increase in voltage magnitude, but all values were clearly within the limit of ± 10% of nominal voltage. The local maximum limits (for Austria) for voltage variation (3% in LV and 2% in medium voltage (MV) networks) were not exceeded in any case. The local limits in different countries.

Computer simulations will show higher voltage variations, as they are usually related to the “worst case scenario”, in which maximum generation and minimum load are assumed. In cases of larger wind farms, voltage variations can exceed the local planning level, and the wind farm operator needs to integrate voltage variation control, or to increase the short circuit power at the PCC.

D. Harmonics

In [2], the measured increase of individual harmonics (up to the 50th) and THD (total harmonic distortion) was not significant during the operation of wind farms, which can be explained by the state-of-the-art performance of modern wind turbines.

It was also shown that when the wind turbines were acting as a load, the harmonic levels were higher. This was still below the planning levels, but it demonstrated that the harmonic current content in load mode is higher than in the generation mode. In order to accurately measure such impact, it is desirable to have monitoring equipment with additional measurement channels (besides 3 voltage and 3 current channels), which can be calibrated to a lower nominal current in order to accurately measure current harmonics and power consumption. Without a dedicated channel for the idle time of wind turbines, the accuracy of the measured result will be lower, as the normal current channels are optimized for a much higher current.

Technical report [4] provides applicable limits for the emission of harmonics. It contains guidance for emission limits for MV, HV and EHV power systems. It distinguishes between compatibility levels (which shall not be exceeded) and planning levels (which might be exceeded).

The compatibility level is based on the 95% probability level. The planning level is bases on 95% and 99% probability level. Both levels also distinguish:

- *Long-term related effects*
  Thermal effects on cables, transformers, motors, capacitors, etc. These are measured according to [12] with 10 min average intervals
- *Short-term related effects*
  Disturbing effects on electronic devices. These are measured according to [12] with 3 second average intervals

E. Flicker

Fast variation in generated power of the wind turbine will lead to flicker of some light sources, which is the highest when these fluctuations are around 8.8 Hz. For such frequencies, already small magnitude changes can increase the flicker level.

The three main causes of flicker due to wind turbines are [3]:

- Variation of several Hz due to the turbine dynamic, the tower resonance and the gearbox
- Periodic power pulsations at the frequency at which the blades pass the tower (caused by the wake of the tower)
- Variations due to changes of wind speed

The wake of the tower effect is particularly a problem for Type A (fixed-speed) wind turbines, as the power fluctuate each time the blade passes the tower (around 1 Hz), causing flicker. Wind speed fluctuations generally have lower frequency and thus are less critical for flicker.

Generally, Type A and B wind turbines contribute to higher flicker than Type C and D [3].

Similar to technical report [4] for harmonic distortion, technical report [5] provides applicable limits for flicker. These flicker emission limits are for MV, HV and EHV power systems, and also distinguish between compatibility and planning level.

III. PREDICTIVE MAINTENANCE

In this section, a novel practice to measure power performance of wind turbines and wind farms will be presented, and the newest IEC standards will be applied to evaluate interactions between the wind farm and power grid.

Most wind turbines use cup anemometers to measure the wind speed, which usually results in a set of raw data, obtained without any correction or calibration. The output (wind turbine?) speed data can vary due to the tower effect, different pitch settings and wake immersion of neighboring wind turbines. The most precise method of recording the wind speed is to use an independent meteorological mast located at a certain distance according to [3]. However, since these measurements need to be further applied to every type of wind turbine in the grid, we developed an economic method to calculate the wind speed with the existing cup anemometers. With this method, we also achieved better synchronization between actual active and reactive power outputs and actual wind speed.

Wind turbine performance is described by Betz's formula, which was first introduced by Albert Betz in 1919 [10]. Consider the ideal model shown in Fig. 1, where the cross sectional area swept by the turbine blade is S, the air cross section upwind from the rotor is designated as S_1 and downwind as S_2. V_1 designates the velocity (meters/second) of the wind entering the turbine, V_2 the velocity exiting the turbine, and ρ is the density of air.

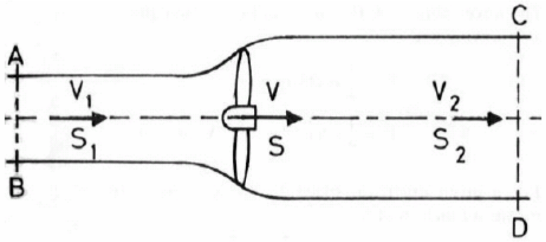

Fig. 1.

The extractable power P is:

$$P = \frac{1}{4}\rho S\left(V_1^2 - V_2^2\right)\left(V_1 + V_2\right) \tag{1}$$

After introducing the downstream velocity factor, b, as:

$$b = \frac{V_2}{V_1} \tag{2}$$

performance efficiency factor can be expressed as:

$$\begin{aligned} C_p &= \frac{P}{W} \\ &= \frac{\frac{1}{4}\rho S V_1^3 \left(1-b^2\right)\left(1+b\right)}{\frac{1}{2}\rho S V_1^3} \\ &= \frac{1}{2}\left(1-b^2\right)\left(1+b\right) \end{aligned} \tag{3}$$

Coefficient C_p is the power efficiency, i.e. the ratio of extractable power and the overall wind energy passing through the blades, W.

The above relationship can be graphically expressed as the power efficiency curve, Fig. 2.

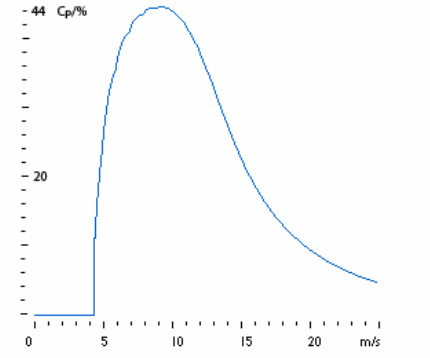

Fig. 2. Power efficiency curve.

Since we only measure the wind speed with a cup anemometer, located downwind the turbine we assume its reading is V_2. If the power efficiency curve is denoted as a function f_1, the recorded real curve can be denoted as:

$$C_{p1} = f_1\left(V_2\right) \tag{4}$$

C_{p1} is recorded power efficiency, i.e., the real data measured by the monitoring device

In order to calibrate this curve, we need to find the function F that relates C_{p1} with the real wind velocity V so that:

$$C_{p1} = F\left(V\right) \tag{5}$$

After introducing coefficient δ:

$$V_2 = \delta \cdot V \quad \left(\delta < 1\right) \tag{6}$$

Due to grid integration regulations, it is possible to get the full documentation from the turbine manufacturer, which will also have tested power efficiency curve when wind turbine is shipped to wind farm:

$$C_{p0} = f_0\left(V\right) \tag{7}$$

C_{p0} is the lab data or experimental data provided by the manufacturer.

After applying $X \leftrightarrow Y$ transformation of expressions (4) and (7) we have:

$$\begin{aligned} f_0^{-1}\left(C_{p0}\right) &= V \\ f_1^{-1}\left(C_{p1}\right) &= V_2 = \delta \cdot V \end{aligned} \tag{8}$$

where f_0 denotes the diagram or function that relates C_{p0} and wind speed, f_1 denotes the diagram or function that relates C_{p1} and wind speed.

Then we have

$$\delta = \frac{f_1^{-1}\left(C_{p1}\right)}{f_0^{-1}\left(C_{p0}\right)} \tag{9}$$

Accordingly, (4) can be rewritten as:

$$C_{p1} = f_1\left(V_2\right) = f_1\left(\delta \cdot V\right) = \left(f_1 \times \frac{f_1^{-1}\left(C_{p1}\right)}{f_0^{-1}\left(C_{p0}\right)}\right)\left(V\right) \tag{10}$$

where $F = f_1 \times \dfrac{f_1^{-1}\left(C_{p1}\right)}{f_0^{-1}\left(C_{p0}\right)}$ is desired output, i.e., the calibrated power efficiency curve, for which C_{p1} and C_{p0} are iterated under the same velocity. Since the power curve is proportional to the efficiency curve, the above calibration method also applies to the power curve as shown below:

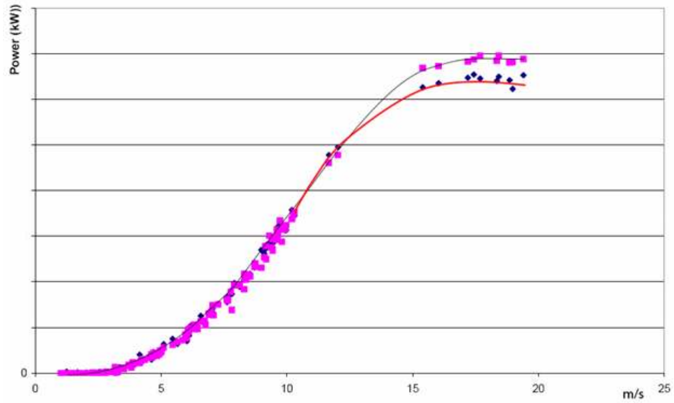

Fig. 3. Power efficiency curve.

The black curve is the original curve from the manufacturer (corresponding to V_1), the red curve is the measured curve (corresponding to V_2).

Average data of expression (4) can be calculated according to [6], but months of historical data are needed to form the basis for the comparison. However, [11] shows that precise information of power conversion could be derived from about one day data, which is based on the stochastic differential equations known as the Langevin equations of diffusive Markov processes. Accordingly, the fluctuating wind turbine power output is decomposed into two functions: (i) the relaxation, which describes the deterministic dynamic response of the wind turbine to its desired operation state, and (ii) the stochastic force (noise), which is an intrinsic feature of the system of wind power conversion.

In our case it is:

$$P_1 = P_s\left(V_2\right) + p \tag{11}$$

where $P_s\left(V_2\right)$ is the steady state power output, and p is the noise contribution.

With the algorithm introduced in [11], we reconstructed the power performance characteristic independently of the turbulence intensity of the wind, followed by aforementioned calibration. By doing so, we achieved a robust and precise estimation of wind turbines' power curves more quickly.

This power curve measurement is used not only as preliminary penetration test when a wind turbine is connected to the grid, but also as continuous monitoring tool to give DSO/TSO feedback on wind turbine performance during operation. As an example of possible applications, the Inner Mongolia TSO authorized a certified agency to monitor the 3-phase currents, 3-phase voltage and wind speeds for each model of wind turbine provided by turbine manufacturers, just as in Scotland [7]. The model's power curves are therefore constructed and stored in a database. The power output decreases for many reasons, one of which is blade decay, particularly of the highly stressed parts. Modern wind turbine blades are primarily built from carbon fiber reinforced plastics and combined with lightweight materials like wood or plastic foam. Some manufacturers use certain methods to monitor the health status of blades as referenced in [11], but many do not. As the idea of checking the blades periodically is comparatively uneconomical, it has been found to be more effective if we monitor the power curve on a regular basis to determine the need for a physical inspection.

Experiments show that decay and pollution of blades lead to around 10% decrease of the turbine's power output, as can be seen in Fig. 4.

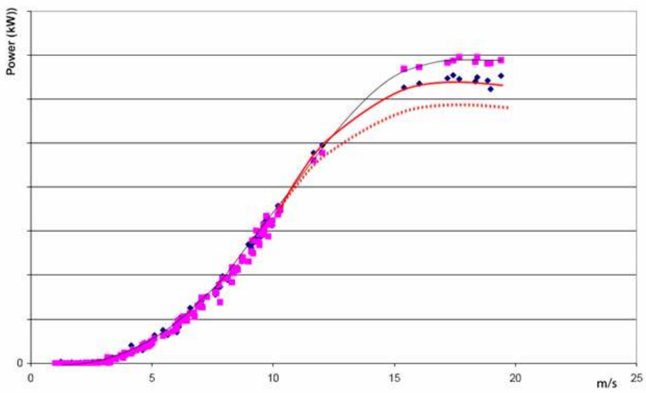

Fig. 4. Decrease in power output...

Since this analysis is based on overall power performance, the wind farm shall benefit not only by preventing the use of damaged blades, but also by identifying other indicators of potential problems, regarding the wind turbine itself, planning maintenance, avoiding unnecessary inspections and determining when retrofit is necessary. This is also a useful tool for estimating power generation during different seasons and weather conditions, after analyzing the historical power performance database.

IV. SYSTEM RELIABILTY AND STABILTY

Loss of large central generation leads to frequency swings; which are less severe in large interconnected systems. In case a low DG penetration, the tripping of that DG, in our case wind farm, due to under- and or over-frequency protection will not have big impact. However, as greater amounts of distributed generation become part of the grid, unnecessary tripping of that DG will increase the overall risk of a widespread blackout [1].

The same general concept applies when large scale conventional generation trips due to voltage dips. In both cases, finding the correct settings for over- and under-voltage and over- and under-frequency protection can avoid unnecessary tripping.

In case of low DG penetration, immunity limits (i.e. protection settings) are selected by wind farm operators, and are typically left as conservative settings based on recommendations from the turbine manufacturer. However, in case of large DG systems, the DSO will require certain settings as tripping can have adverse consequences on system operation.

It is in the best interest of both wind farm operator and DSO that the farm does not trip unnecessarily too often in this case. Conversely, if the event is severe, it is required that the DG trips to protect itself. This is to prevent islanding and allow correct operation of the short-circuit protection of the DSO. As a result, it is very important to distinguish between the immunity requirements (to avoid unnecessary tripping) and the protection requirements (required by the DSO). In practice, these settings are frequently too sensitive, causing the DG to trip unnecessarily.

For the analysis of faults and checking the protection settings, it is recommended to have a digital fault recorder combined with dynamic disturbance recording. This will allow the operator/DSO to analyze the trip in detail. The dynamic disturbance recorder provides measurement of voltage dips in rms form, so the types of voltage dips that cause the wind generator protection to trip and the types of voltage dips that do not can be determined.

Next to voltage and current rms values, modern recorders also provide information about frequency, phase angle, sequence components, active power, reactive power and apparent power. These are typically recorded as one-cycle values (refreshed every half cycle), in order to give enough details on the fault. Furthermore, with such recorders the technical performance of the wind generator according to [6] can be verified (600 s average value, a 60 s average value and a 0,2 s average value).

So far in many countries, the stability of wind generation has not been an issue due to the low penetration levels of wind generation capacity. However, this is expected to change, and therefore there will be a necessary change in philosophy in those countries regarding wind generation. DSOs and TSOs now have a growing concern about the system stability issues, and are introducing, or already have introduced, new interconnection regulations with new requirements. These requirements typically include provisions to maintain the operation of the turbine during a fault on the grid (for certain faults), to operate in a wider range of frequency, to control the active power during frequency variations, to limit the power increase to a certain rate (ramp rate control), to supply or consume reactive power, and to support voltage control. All these requirements increase the costs for wind farms and hence they are applied in cases with high wind power penetration.

V. CONCLUSION

Monitoring wind farms (power quality monitoring, dynamic disturbance recording, digital fault recording) helps to take the right decisions and actions for manufactures, wind farm operators, and network operators. This can improve the system stability, power quality, and turbine reliability. In many cases one can achieve this through simple changes to the wind turbine protection settings. In some cases external equipment needs to be installed. One important aspect for wind farm operators to remember is that monitoring can help to predict maintenance of wind turbines.

VI. ACKNOWLEDGMENT

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[1] M.H.J. Bollen, M. Häger, Power quality: interactions between distributed energy resources, the grid, and other customers, EPQU magazine

[2] H. Brunner, B. Bletterie, R. Bruendlinger, Case studies on the impact of distributed generation on power quality – Assessment results and experience in Austria, Distribution Europe,17.-19.05.2006, Barcelona, Spain

[3] T. Ackermann, Wind power in power systems, Wiley, 2005

[4] IEC 61000-3-6 : Ed 2.0, 2008. Part 3-6: Limits – Assessment of emission limits for the connection of distortinginstallations to MV, HV and EHV power systems

[5] IEC 61000-3-7 : Ed 2.0, 2008. Part 3-7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems

[6] IEC 61400-21 : Ed 2.0, 2008. Wind turbine – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines

[7] Guidance Note for the Connection of wind farm, Scottish Hydro Electric Issue 2.1.4, December 2002

[8] IEC 61400-12-1 : Ed1.0, 2005. Wind turbines – Part 12-1: Power performance measurement of electricity producing wind turbines

[9] Markovian Power Curves for Wind turbines, E. Anahua, St. Barth & J. Peinke, 2008, Wind Energy

[10] Wind Energy and its Extraction through Wind Mills, Albert Betz, 1926

[11] Sensors and Non-Destructive Testing Methods for Damage Detection in wind turbine blades, Risø National Laboratory, Roskilde, Denmark, 2002

[12] IEC 61000-4-30 : Ed 2.0, 2008. Part 4-30: Testing and measurement techniques – Power quality measurement methods

[13] M.H.J. Bollen et al., CIGRE/CIRED/UIE JWG C4.110 - Voltage Dip Immunity of Equipment in Installations – Status April 2008, Int Conf Harmonics and Quality of Power (ICHQP), September 2008, Wollongong, Australia