Electrical Power Quality and Utilisation, Journal Vol. XIII, No. 2, 2007

Wind Turbine Harmonics Caused by Unbalanced Grid Currents

Klaus-Dieter DETTMANN, Steffen SCHOSTAN, Detlef SCHULZ
Helmut-Schmidt-University, GERMANY

***Summary*: For wind turbines that feed into public grids limits for voltage and current harmonics must be assured. To verify that the actual levels are valid, measurements are necessary. Problems can occur to determine which part of these harmonics has its origin in the wind turbine. It is shown that also harmonics which originally have zero sequences can be transferred over a delta-star-transformer, if the currents of the wind turbine are asymmetric due to unbalanced loads. Measurements in an existing wind turbine configuration are discussed, which confirm the described effects.**

Key words:
AC machines
circuit analysis
current measurement
harmonic analysis
harmonic distortion
power system harmonics
power system measurements
sequences
wind energy
wind power generation

I. INTRODUCTION

Wind turbines feeding into public grids must comply with several technical standards, e.g. EN 50160 and IEC 61000 [1, 2]. In these standards limits are specified for the voltage and current harmonics. To ensure that these limits are not exceeded dimensioning calculations are not sufficient. Furthermore measurements must be performed. For an analysis of the measurement results has to be considered that harmonics are not only generated by the wind turbine but exist in the grid, too. A typical configuration is shown in Figure 1.

In this structure the wind turbine transformer is delta-star-wired with ungrounded star point. Such a transformer blocks zero sequence currents. In the following sections it is described, how harmonics of balanced and unbalanced currents split into sequences and what parameters are significant for these components.

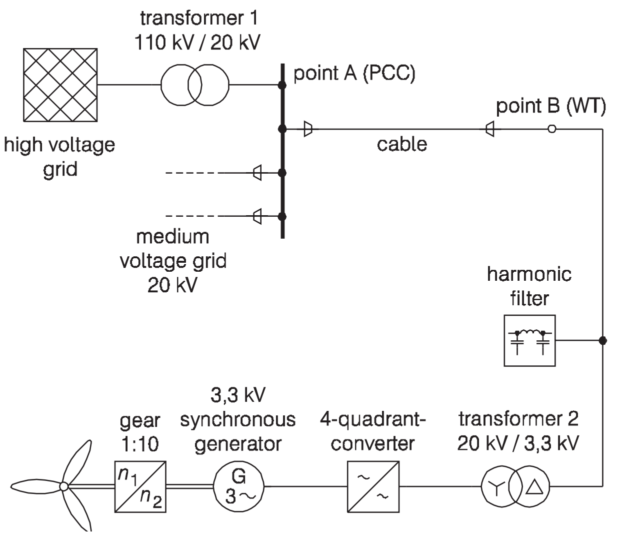

Fig. 1. Configuration of a grid-connected wind turbine

II. SEQUENCES OF HARMONIC CURRENTS

In Figure 2a a system of three-phase currents is shown, where the fundamental currents have the amplitudes $\hat{\imath}_{1,1}$, $\hat{\imath}_{2,1}$, $\hat{\imath}_{3,1}$ and phase angles φ_1, φ_2, φ_3 relative to the axis. The amplitudes of the υ-th harmonic are labeled with $\hat{\imath}_{1,\upsilon}$, $\hat{\imath}_{2,\upsilon}$ and $\hat{\imath}_{3,\upsilon}$; the harmonic's phase angles $\gamma_{1,\upsilon}$, $\gamma_{2,\upsilon}$, $\gamma_{3,\upsilon}$ are measured relative to the zero crossing of the fundamental current of the same phase, see Figure 2b. In this context e.g. $\gamma_{2,6}$ means the phase angle of the sixth harmonic in phase 2. This angle relates to the period of that harmonic, i.e. $\gamma_{2,6} = 120°$ corresponds with one third of this harmonic's full periodic time.

For more transparency we declare phase 1 as a reference and introduce the amplitude differences $\Delta\hat{\imath}_{2,\upsilon}$, $\Delta\hat{\imath}_{3,\upsilon}$ and the phase differences $\Delta\varphi_2$, $\Delta\varphi_3$, $\Delta\gamma_{2,\upsilon}$, $\Delta\gamma_{3,\upsilon}$, which describe the deviations from the balanced state in phases 2 and 3. With these definitions the time behavior of the fundamental current:

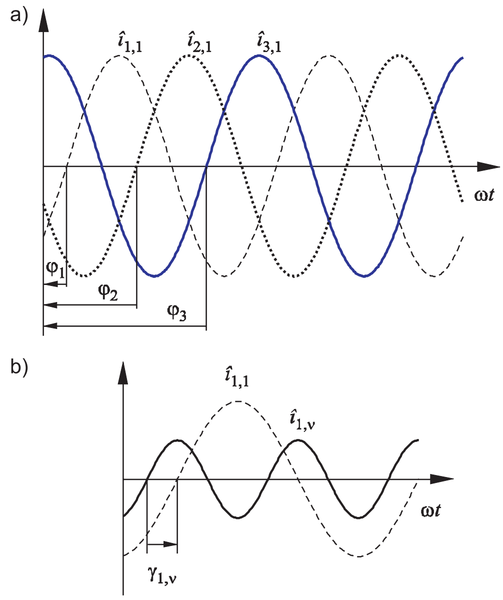

Fig. 2. Definitions, a) fundamental currents, b) ν-th harmonic and fundamental current in phase 1

$$i_{1,1}(t) = \hat{\imath}_{1,1} \cdot sin(\omega \cdot t + \varphi_1)$$

$$i_{2,1}(t) = \hat{\imath}_{2,1} \cdot sin(\omega \cdot t + \varphi_2)$$

$$i_{3,1}(t) = \hat{\imath}_{3,1} \cdot sin(\omega \cdot t + \varphi_3)$$

can be written as:

$$i_{1,1}(t) = \hat{\imath}_{1,1} \cdot sin(\omega \cdot t + \varphi_1)$$

$$i_{2,1}(t) = (\hat{\imath}_{1,1} + \Delta\hat{\imath}_{2,1}) \cdot sin(\omega \cdot t + \varphi_1 - 120° + \Delta\varphi_2) \quad (1)$$

$$i_{3,1}(t) = (\hat{\imath}_{1,1} + \Delta\hat{\imath}_{3,1}) \cdot sin(\omega \cdot t + \varphi_1 - 240° + \Delta\varphi_3)$$

and harmonics of order υ can be represented as:

$$i_{1,\nu}(t) = \hat{\imath}_{1,\nu} \cdot sin\left(\nu \cdot (\omega \cdot t + \varphi_1) + \gamma_{1,\nu}\right) \quad (2a)$$

$$i_{2,\nu}(t) = (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{2,\nu}) \cdot sin(\nu \cdot (\omega \cdot t + \varphi_1 - 120° + \Delta\varphi_2) + \\ + \gamma_{1,\nu} + \Delta\gamma_{2,\nu}) \quad (2b)$$

$$i_{3,\nu}(t) = (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{3,\nu}) \cdot sin(\nu \cdot (\omega \cdot t + \varphi_1 - 240° + \Delta\varphi_3) + \\ + \gamma_{1,\nu} + \Delta\gamma_{3,\nu}) \quad (2c)$$

The positive (+), negative (-) and zero (0) sequences of these currents can be calculated with the method of symmetrical components:

$$\begin{bmatrix} \hat{\imath}_{+,\nu} \\ \hat{\imath}_{-,\nu} \\ \hat{\imath}_{0,\nu} \end{bmatrix} = [T] \cdot \begin{bmatrix} \hat{\imath}_{1,\nu} \\ \hat{\imath}_{2,\nu} \\ \hat{\imath}_{3,\nu} \end{bmatrix} \quad (3)$$

$$\text{with} \quad [T] = \frac{1}{3} \cdot \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \quad \text{and} \quad a = \mathrm{e}^{\mathrm{j} \cdot 120°}$$

This method is a similarity transformation that does not contain the frequency in the transform matrix – in contrast to Laplace transformation and Fourier transformation. Therefore it can be applied to the harmonic currents as well.

At first the currents in (1) and (2) are reformulated with the complex calculus:

$$\underline{\hat{I}}_{1,\nu} = \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1)} \cdot \hat{\imath}_{1,\nu} \cdot \mathrm{e}^{\mathrm{j} \cdot \gamma_{1,\nu}}$$

$$\underline{\hat{I}}_{2,\nu} = \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1)} \cdot (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{2,\nu}) \cdot \\ \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_2 - \nu \cdot 120° + \gamma_{1,\nu} + \Delta\gamma_{2,\nu})}$$

$$\underline{\hat{I}}_{3,\nu} = \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1)} \cdot (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{3,\nu}) \cdot \\ \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_3 - \nu \cdot 240° + \gamma_{1,\nu} + \Delta\gamma_{3,\nu})}$$

Applying (3) to these equations we get the desired sequences:

$$\underline{\hat{I}}_{+} = \frac{1}{3} \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1)} \cdot \Big\{ \hat{\imath}_{1,\nu} \cdot \mathrm{e}^{\mathrm{j} \cdot \gamma_{1,\nu}} + \\ (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{2,\nu}) \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_2 - (\nu-1) \cdot 120° + \gamma_{1,\nu} + \Delta\gamma_{2,\nu})} + \\ (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{3,\nu}) \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_3 - (\nu-1) \cdot 240° + \gamma_{1,\nu} + \Delta\gamma_{3,\nu})} \Big\} \quad (4a)$$

$$\underline{\hat{I}}_{-} = \frac{1}{3} \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1)} \cdot \Big\{ \hat{\imath}_{1,\nu} \cdot \mathrm{e}^{\mathrm{j} \cdot \gamma_{1,\nu}} + \\ (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{2,\nu}) \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_2 - (\nu-2) \cdot 120° + \gamma_{1,\nu} + \Delta\gamma_{2,\nu})} + \\ (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{3,\nu}) \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_3 - (\nu+1) \cdot 240° + \gamma_{1,\nu} + \Delta\gamma_{3,\nu})} \Big\} \quad (4b)$$

$$\underline{\hat{I}}_{0} = \frac{1}{3} \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1)} \cdot \Big\{ \hat{\imath}_{1,\nu} \cdot \mathrm{e}^{\mathrm{j} \cdot \gamma_{1,\nu}} + \\ (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{2,\nu}) \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_2 - \nu \cdot 120° + \gamma_{1,\nu} + \Delta\gamma_{2,\nu})} + \\ (\hat{\imath}_{1,\nu} + \Delta\hat{\imath}_{3,\nu}) \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu \cdot \Delta\varphi_3 - \nu \cdot 240° + \gamma_{1,\nu} + \Delta\gamma_{3,\nu})} \Big\} \quad (4c)$$

Before the effect of asymmetries is discussed let's have a look at the results for balanced currents. And "balanced" should mean pure symmetry, in contrast to VDE 0838-2 or IEC 61000-3-2, where a device is already called symmetric, if its rated currents in the three phases do not differ more than 20 % [3, 4]. In this case we assume:

$$\Delta\hat{\imath}_{2,\nu} = \Delta\hat{\imath}_{3,\nu} = 0$$

$$\Delta\varphi_2 = \Delta\varphi_3 = 0$$

$$\Delta\gamma_{2,\nu} = \Delta\gamma_{3,\nu} = 0$$

Making use of the condition:

$$1 + \mathrm{e}^{-\mathrm{j} \cdot (120° \pm n \cdot 360°)} + \mathrm{e}^{-\mathrm{j} \cdot (240° \pm n \cdot 360°)} = 0$$

with n = 1, 2, 3,… the following sequences result:

$$\underline{\hat{I}}_{+} = \begin{cases} \hat{\imath}_{1/2} \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1 + \gamma_\nu)} & \text{for} \quad \nu = 1,4,7,\ldots \\ 0 & \text{else} \end{cases}$$

$$\underline{\hat{I}}_{-} = \begin{cases} \hat{\imath}_{\nu} \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1 + \gamma_\nu)} & \text{for} \quad \nu = 2,5,8,\ldots \\ 0 & \text{else} \end{cases}$$

$$\underline{\hat{I}}_{0} = \begin{cases} \hat{\imath}_{\nu} \cdot \mathrm{e}^{\mathrm{j} \cdot (\nu\omega t + \nu\varphi_1 + \gamma_\nu)} & \text{for} \quad \nu = 3,6,9,\ldots \\ 0 & \text{else} \end{cases}$$

Table 1. Sequences of harmonics for balanced currents

υ	1	2	3	4	5	6	7	8	9
+,-,0	+	-	0	+	-	0	+	-	0

Thus positive, negative and zero sequences alternate with increasing harmonic order, as is shown in Table 1.

Next we describe the effects of these sequences of balanced harmonics on rotating fields in electrical machines.

III. ROTATING FIELDS DUE TO HARMONICS IN THREE-PHASE MACHINES

The effect of harmonic sequences on the rotating field in the air-gap of three-phase machines is shown for a synchronous machine. At the terminals the balanced harmonic voltages:

$$u_{1,\nu}(t) = \hat{u}_\nu \cdot sin(\nu\cdot(\omega\cdot t+\varphi_1))$$

$$u_{2,\nu}(t) = \hat{u}_\nu \cdot sin(\nu\cdot(\omega\cdot t+\varphi_1) - \nu\cdot 120°) \quad (5)$$

$$u_{3,\nu}(t) = \hat{u}_\nu \cdot sin(\nu\cdot(\omega\cdot t+\varphi_1) - \nu\cdot 240°)$$

are assumed, where φ_1 is the phase shift of the first order voltage. For a machine with p pole pairs the distribution of the three phase fluxes $\Phi(\alpha)$ in the air gap is sinusoidal over the angle α, which is measured relative to the field axis of phase 1:

$$\Phi_1(\alpha) = \Phi_A(t)\cdot cos(p\cdot\alpha)$$

$$\Phi_2(\alpha) = \Phi_A(t)\cdot cos(p\cdot(\alpha - \tfrac{120°}{p})) \quad (6)$$

$$\Phi_3(\alpha) = \Phi_A(t)\cdot cos(p\cdot(\alpha - \tfrac{240°}{p}))$$

Φ_A is the flux amplitude and α has a range of 0…360°. Applying the law of induction to equations (5) and (6), the following air gap flux results:

$$\Phi_{res}(\alpha,t) = \Phi_1(\alpha,t)+\Phi_2(\alpha,t)+\Phi_3(\alpha,t) \quad (7)$$

with:

$$\Phi_1(\alpha,t) = -\frac{\hat{u}_\nu}{\nu\omega}\cdot cos(\nu\cdot(\omega\cdot t+\varphi_1))\cdot cos(p\cdot\alpha)$$

$$\Phi_2(\alpha,t) = -\frac{\hat{u}_\nu}{\nu\omega}\cdot cos(\nu\cdot(\omega\cdot t+\varphi_1-120°))\cdot \cdot cos(p\cdot(\alpha - \tfrac{120°}{p}))$$

$$\Phi_3(\alpha,t) = -\frac{\hat{u}_\nu}{\nu\omega}\cdot cos(\nu\cdot(\omega\cdot t+\varphi_1-240°))\cdot \cdot cos(p\cdot(\alpha - \tfrac{240°}{p}))$$

These equations can be transformed with the help of addition theorems for trigonometric functions. Introducing the abbreviations:

$$\xi_f = \nu\cdot(\omega\cdot t+\varphi_1) - p\cdot\alpha$$

and:

$$\xi_b = \nu\cdot(\omega\cdot t+\varphi_1) + p\cdot\alpha$$

the resultant flux (7) can be rewritten as:

$$\Phi_{res,\nu} = -\frac{\hat{u}_\nu}{2\nu\omega}\cdot\left[cos\,\xi_f\cdot\left(1+2\cdot cos\left((\nu-1)\cdot 120°\right)\right)+ +cos\,\xi_b\cdot(1+2\cdot cos(\nu+1)\cdot 120°\right] \quad (8)$$

where ξ_f and ξ_b describe one forward and one backward flux wave in the air gap. Evaluating this formula with respect to the harmonic order υ results in the following statements:

1. The air gap flux Φ_{res} represents a forward wave for harmonic orders 1, 4, 7,…, i.e. for positive sequences in Table 1,
2. Φ_{res} represents a backward wave for harmonic orders 2, 5, 8,…, i.e. for negative sequences in Table 1,
3. for harmonic orders divisible by 3 the flux Φ_{res} becomes ideally null, if leakage inductances are neglected.

The small flux for zero sequences means that the input impedance of a synchronous machine is very low for such harmonics; a connection of the machine's star point should be avoided therefore.

The angular frequency Ω_f of the forward wave can be calculated by setting ξ_f to a special value, e.g. zero:

$$0 = \nu\cdot(\omega\cdot t+\varphi_1) - p\cdot\alpha(t)$$

$$\alpha(t) = \frac{\nu}{p}\cdot\omega\cdot t+\frac{\nu}{p}\cdot\varphi_1 \Rightarrow \Omega_f = \nu\cdot\frac{\omega}{p}$$

In a machine the positive sequence harmonic fields rotate with the ν-fold velocity of the fundamental harmonic field. The same is true for negative sequence fields, but with opposite direction of rotation. Despite the higher velocity of these harmonic fields their pole pitches, i.e. their wave lengths, remain the same, however. This behavior is different to harmonic waves caused by windings that are unevenly distributed around the stator. For those waves the equation:

$$\xi_f = (\omega\cdot t+\varphi_1) - \nu\cdot p\cdot\alpha$$

is valid. Therefore if an input voltage is impressed with the fundamental frequency ω, these fields have a ν-fold pole pitch and rotate with a decreased angular frequency of $1/\nu$ times that one of the fundamental wave [5].

Due to the ν-fold velocity of the harmonic fields of harmonic voltage inputs, torque harmonics and eddy currents arise in the machine. Relative to the rotor a forward component of the air gap field has the (υ-1)-fold and the backward component a (υ+1)-fold velocity that induce currents in the damper winding.

The damper currents with (υ-1)$\cdot\omega$ have a rotor field that can again be imagined as a sum of a forward and a backward component with the same frequency and half amplitude. These rotating fields induce harmonic voltages of $\upsilon\cdot\omega$ and (υ-2)$\cdot\omega$ in the stator. So a positive sequence υ-th harmonic impressed at the stator is responded from the rotor with a υ-th and a (υ-2)-th harmonic. That means a new harmonic is created by the machine. Similarly the response of negative sequence υ-th harmonics are a υ-th and a (υ+2)-th harmonic.

IV. EFFECTS OF UNBALANCED CURRENTS ON HARMONICS

Until now the derived equations for harmonics have been discussed only for balanced currents and voltages. Next unbalanced impressed currents shall be considered. For this reason equations (4) are evaluated for different types of asymmetries.

These calculations show that the sequence pattern in Table I is only valid for balanced currents. Asymmetries cause a coupling between positive, negative and zero sequences. Thus each harmonic order can occur in every sequence. The strength of this effect is dependent on the degree of asymmetry and of its type.

At first unbalanced harmonic amplitudes $i_{1,\upsilon}$, $i_{2,\upsilon}$ and $i_{3,\upsilon}$ are assumed. If the harmonic's amplitude varies in a range of 10% ($\Delta i_{2,\upsilon}$ = -10 % and $\Delta i_{3,\upsilon}$ = +10%), an originally pure zero sequence third harmonic converts with 6% of its amplitude to a positive and with another 6% to a negative sequence. The same is true for the sixth harmonic.

Next an asymmetry in the harmonic's phase angles is considered. Deviations of $\Delta\gamma_{2,\upsilon}$ = -10° and $\Delta\gamma_{3,\upsilon}$ = +10° lead to a positive sequence of 11 % and a negative sequence of 10% both in the third and sixth harmonic. For phase differences of ±20° these values increase to 22% and 18%.

Very significant is the effect of an asymmetry in the phase angles of the fundamental current. Because of the factor φ in front of the fundamental phase deviations $\Delta\varphi_2$ and $\Delta\varphi_3$ in (4), these phase shifts are the more significant the higher the harmonic's order number is. For ±5° the transfer to the positive and negative sequences is 16% and 14% respectively for the third harmonic or 33% and 24% for the sixth harmonic. These values show that the transfer effect is much greater for order six than for order 3. It increases for ±10°, where the sixth harmonic has 67% positive and 33 % negative sequence. An extreme case occurs for ±20°; in this situation the sixth harmonic is completely converted to a pure positive sequence.

Let's have a look at the consequences of this transferring and mixing of sequences. In Figure 1 the wind turbine is connected to the grid side over a delta-star transformer. This type of transformer cannot transfer zero sequence currents from on side to the other, even if such a current is flowing in the star winding. But in the considered configuration the star point is not connected to earth. So also on the star side, i.e. in the wind turbine, there occurs no zero sequence current. This means that in the case of balanced grid currents no harmonics with an order divisible by three can develop.

Contrary to zero sequences the transformer can transfer positive and negative sequences. As a result also harmonic orders 3, 6, 9 etc. can flow from the wind turbine to the grid, if such sequences occur with these orders due to unbalanced currents. This statement is essential for the evaluation of harmonic measurements, especially if the origin of harmonics has to be found.

Unbalanced currents in medium voltage grids can be caused e.g. by single phase loads that are connected to low voltage grids fed by the medium voltage. These loads are spread over the three phases to produce a balanced load. But the result of this action is imperfect, because loads have a stochastic behavior. The positive and negative sequences of the resulting current are transferred to the medium voltage grid over the 20kV/0.4kV-transformer, which is often delta-star-connected with a grounded neutral.

If harmonic measurements are taken on the grid side of the wind turbine transformer, harmonics of the wind turbine and from the grid are measured together. To make a decision, which part comes from the wind turbine, it would be helpful to record the phase angles of the harmonics, too, if the used equipment is capable of this feature. A further way to increase transparency is measuring harmonics also at a time when the wind turbine does not feed power into the grid. It is not sufficient to look at the voltage fall of the harmonics at the medium voltage cable. As is shown in [6], e.g. a sixth harmonic is fed by the wind turbine although the voltage fall of this harmonic lies in the direction from grid to turbine. This apparent inconsistency results from resonant effects with the harmonic filter and leads to higher harmonic levels as are really created by the wind turbine. For this reason in a dimensioning of filters even such harmonics should not be neglected that cannot be transferred over the transformer under balanced conditions.

A further effect of the sequence coupling due to unbalanced currents occurs in electrical machines. If divisible-by-three harmonic orders are partly transferred to positive or negative sequences, in contrast to chapter III these currents create rotating fields, too.

In the following the described effects on the grid-connection shall be discussed with the help of measu-rements, but firstly the examined system configuration is presented.

V. DETAILS OF THE ANALYZED CONFIGURATION

Before it is shown that measurements confirm the theoretical approach, the wind turbine grid connection in Figure 1 is described more thoroughly. The wind power plant is developed for the offshore area and tested in a typical onshore grid connection.

This wind turbine prototype with a rated power of 5 MW consists of a 3.3 kV synchronous generator and a 4-quadrant-converter. The system is connected to a medium voltage transformer 20 kV / 3.3 kV, which is wired in a delta-star connection. The neutral point is not connected to earth. An integrated harmonic filter damps the fifth, seventh und eleventh current harmonics. It consists of series and parallel LC-circuits which are wired in a star-connection. Their neutral point is grounded. This fact is important in order to proof the propagation of the divisible-by-three current harmonics and is taken up later. With a medium voltage cable a connection to the 110 kV / 20 kV transformer substation is established.

VI. MEASUREMENTS

Now measurements shall substantiate the theoretical statements in the previous chapters. For that reason long-term measurements were performed in order to generate a grid quality analysis. With two network analyzers data were recorded over a time period of some weeks at both ends of the cable, points A and B, see Fiure. 1. Point A represents the PCC. At this point the wind turbine (WT) feeds in; other loads in the 20 kV grid are connected to this bus bar over cables. Point B is provided between the wind turbine transformer and its medium voltage cable. This point lies in the private grid of the wind turbine operator and thus outside the public grid. Here the limits of EN 50160 apply, which form the basis of the grid quality analysis. In this unified standards the limits of RMS-voltage, Total Harmonic Distortion (THD) of voltage, long-term flicker, harmonics etc. are specified.

The analyzers sample the voltage and current behavior and calculate offline the RMS-current, -voltage and all necessary parameters of the grid quality. These data are averaged and stored in a database on hard disc. The storage of mean average values makes possible measurements over several weeks or months. Such long periods of time are necessary to cover the whole power range of the wind turbine, because the fed power depends on the wind velocity which is varying with time.

In addition transient events can also be detected by adjustable trigger levels. More details of the measurement specifications are described in [6]. It has to be mentioned that no recording-features are included in the used equipment to detect and store the phase angles of individual current harmonics relative to the fundamental frequency. An analysis with exact phase shifts of the harmonics cannot be carried out therefore.

Positive, negative and zero sequences of the total current were measured, however. Using these parameters, statements can be made about the current unbalance. The total three phase currents are calculated and split into sequences. These calculation steps are included in the measurement software.

The ratio of negative and positive sequences as well as the ratio of zero and positive sequences of the total current is seen in Figures 3 and 4. It is shown that at both points A (PCC) and B (WT) a negative sequence of the current occurs and therefore the prerequisite of unbalanced three-phase currents is given.

The zero sequence is very low at point B and can be neglected for further considerations. Differences of the negative sequences between point A (PCC) and B (WT) result from the superposition of current sequences from the medium voltage grid and the wind turbine. A zero sequence current at the 4-quadrant converter output cannot transfer over transformer 2 to the 20 kV level, see Figure 1. But as

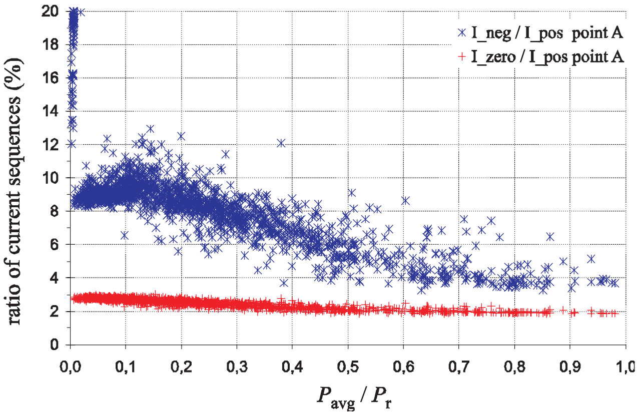

Fig. 3. Sequence ratios: negative sequences to positive sequences and zero sequences to positive sequences of total current at point A (PCC)

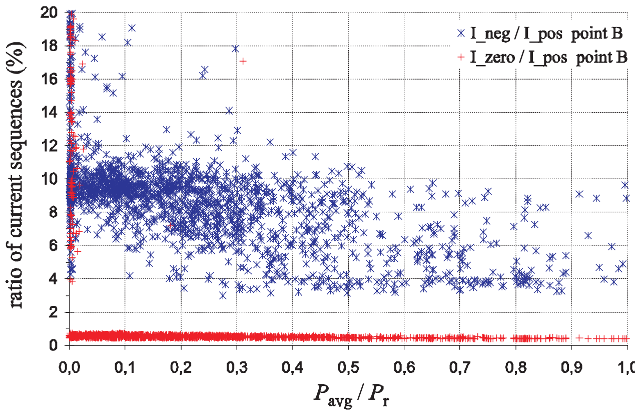

Fig. 4. Sequence ratios: negative sequences to positive sequences and zero sequences to positive sequences of total current at point B

shown before, unbalanced three-phase currents can convert zero sequence current harmonics partly into positive and negative sequences. These can propagate over the wind turbine transformer and interfere with current sequences caused by the medium voltage grid. If zero sequences on the grid side exist, they can flow through the earth-capacitances of the medium voltage cable. Therefore the zero sequence at point A (PCC) is higher than at point B. The residual current of zero sequences can flow to earth over the grounded star point of the harmonic filter.

In the next step the spectra of the current harmonics at both points A (PCC) and B (WT) are investigated. Fig. 5a and 5b show the ratios of current harmonics and the rated current, which equals to 144 A, over a time period of four weeks.

During this time domain the wind turbine feeds into the grid. The sixth current harmonic is dominating. This fact is atypical for a grid spectrum; normally the third, fifth and seventh harmonics are the dominating ones. The high level of the sixth current harmonics is caused by an undesired effect of the double tuned filter, which damps the fifth, seventh and eleventh harmonics but increases the sixth one. The proof of this measured effect is explained in detail in [6]. In our case this statement is secondary. The main focus is on the propagation of current harmonics with orders divisible by three over the medium voltage, delta-star-connected transformer with ungrounded star point. In the next step the ratio of current harmonics is investigated in

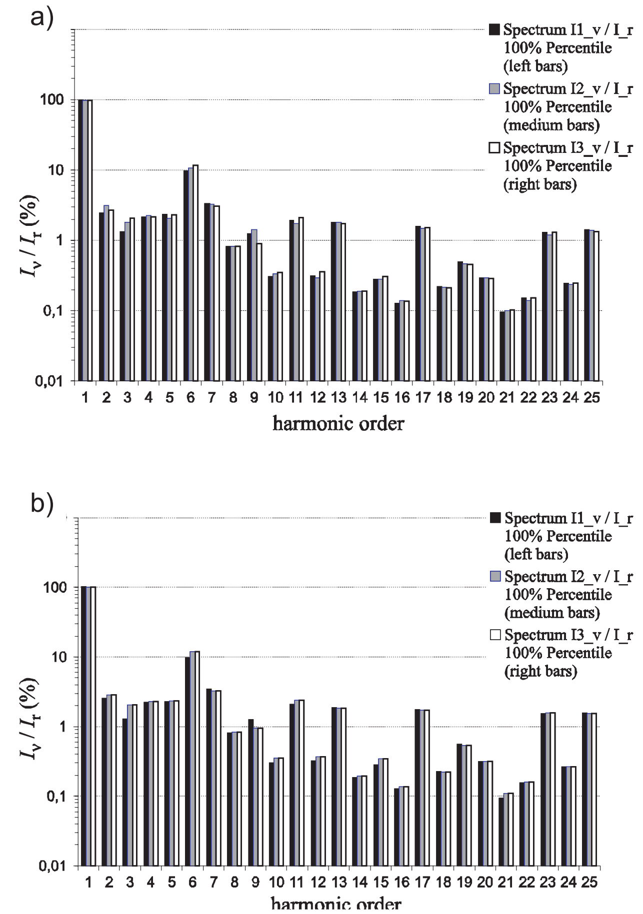

Fig. 5. Current harmonics with wind turbine feeding in a) at point A (PCC), b) at point B (wind turbine)

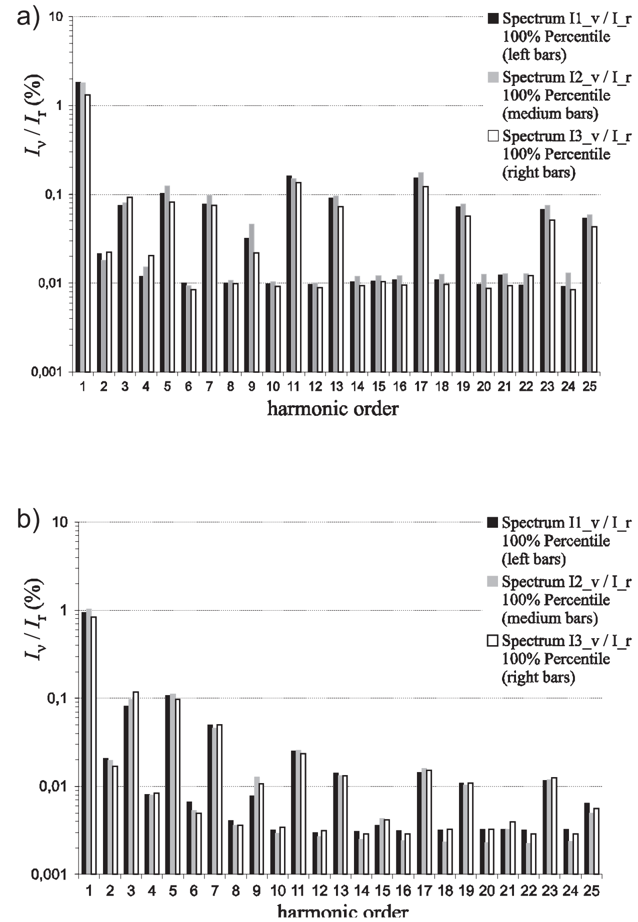

Fig. 6. Current harmonics with wind turbine switched off a) at point A (PCC), b) at point B (wind turbine)

a time period in which no power was produced by the wind turbine, see Figure 6.

The level of the sixth current harmonic is essential lower as in periods when power production of the wind turbine occurs. It is visible that a high level of third current harmonic arises. In a balanced feeding, this current builds a zero sequence which needs a way to earth. In our case these current harmonics can flow to earth potential through the double tuned filter because its neutral point is grounded.

The comparison of the spectra in Fig 5 and Fig.6 makes clear that the high sixth current harmonic levels are produced by the wind turbine configuration which consists of the wind turbine prototype, a medium voltage transformer, the double tuned filter and a medium voltage cable. A zero sequence current cannot transfer over the delta-star-connected transformer, as described before, but positive and negative sequences of the sixth harmonics, caused by unbalanced grid currents, propagate over this transformer. These harmonic currents interfere with the harmonic filter, the cable and the grid impedance so that a high level of sixth current harmonics arises during a power production of the wind turbine.

VII. CONCLUSION

In wind turbine grid-connections also harmonics with orders divisible by three can be transferred to the grid over a delta-star-wired transformer, if the loads have unbalanced currents. The asymmetries result in converting parts of zero sequence harmonics to positive and negative sequences.

For this effect phase shifts in the fundamental current that differ from balanced phase shifts are more significant than asymmetries in the harmonics. Fundamental phase deviations of ±5° lead to a transfer of 16 % of an originally pure zero sequence third harmonic to the positive and 14 % to the negative sequence. For a sixth harmonic this transfer effect is greater, the same phase deviations result in values of 33 % and 24 % respectively. With a fundamental phase deviation of ±20° the sixth harmonic converts completely from zero to positive sequence, because the correspondent phase shift in the harmonic is 6·20° = 120°, i.e. the harmonic becomes symmetric. Thus the negative and zero sequences vanish for the sixth harmonic in this special case.

With the originally zero sequence harmonics, which convert to positive and/or negative sequences, problems can arise, if harmonic filters cause resonant effects with those frequencies. Harmonic measurements have to take into account this effect, if the origin of such harmonics has to be found.

REFERENCES

1. EN 50160, Voltage Characteristics of electricity supplied by public distribution systems, March 2000
2. IEC 61000-3-4, 1998, Electromagnetic compatibility Part 3-4: Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A

3. VDE 0838-2, 2006, Elektromagnetische Verträglichkeit (EMV) Teil 3-2: Grenzwerte – Grenzwerte für Oberschwingungsströme (Geräte-Eingangsstrom ≤16 A je Leiter)
4. IEC 61000-3-2, 2005, Electromagnetic compatibility Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤16 A per phase)
5. Müller G.: *Betriebsverhalten rotierender elektrischer Maschinen*. 2nd Edition, Berlin, Offenbach: VDE-Verlag, 1990
6. Schostan S.H, Dettmann K.D. Schulz D. and Plotkin J.: I*nvestigation of an Atypical Sixth Harmonic Current Level of a 5-MW Wind Turbine Configuration*. In Proc. of IEEE Region 8 EUROCON 2007, Warsaw, Poland

Klaus-Dieter Dettmann
was born at Pinneberg, Germany, on April 20, 1954. In 1972 he got his university entry qualification from Bismarckschule at Elmhorn. He studied electrical engineering with focus on electrical power systems at the technical university in Hannover and took his diploma in 1979. His doctorate in electrical engineering he got at the Helmut-Schmidt-University in Hamburg in 1984, where he is working now as a research assistant and laboratory manager with Prof. Detlef Schulz in the area of electrical power systems. His current research focus is on grid stability and inter-area oscillations.
Address:
Electrical Power Systems
Helmut-Schmidt-University
Holstenhofweg 85, 22043 Hamburg
Germany
e-mail: kd.det@hsu-hh.de

Steffen Schostan
was born at Prenzlau, Germany, on September 01, 1978. In 1998 he got his general qualification for university entrance from Städtisches Gymnasium at Prenzlau. After his basic military service he studied electrical engineering with focus on measurement and control technology at the technical university in Berlin. In 2005 he took his diploma and changed to the Helmut-Schmidt-University in Hamburg. To date he is working there as a research assistant in the area of electrical power systems. His current research focus is on the measurement and assessment of power quality characteristics of grid connected wind turbines.
Address:
Electrical Power Systems
Helmut-Schmidt-University
Holstenhofweg 85, 22043 Hamburg
Germany
e-mail: steffen.schostan@hsu-hh.de

D. Schulz
was born in Guben, Germany, on July 28, 1967. He graduated from the German Polytechnic School, Guben. Detlef Schulz received the Diploma Engineer in 1997 from Technical University Cottbus. From 1997 to 1999 he was with ABB Industrial Automation in Cottbus. In 2002 he received the Ph.D. from the Technical University Berlin. From 2003 to 2004 he was an EU-project manager of the Technical University Berlin. The habilitation was finished at the Technical University Berlin in 2006. From 2004 to 2005 he was a professor for Electrical Engineering and Wind Energy at the University of Applied Sciences in Bremerhaven/Competence Center Wind Energy. Now he is a full professor for Electrical Power Systems of the Helmut-Schmidt-University Hamburg. His research areas are grid integration of distributed renewable energies and future power system design.
Address:
Electrical Power Systems
Helmut-Schmidt-University
Holstenhofweg 85, 22043 Hamburg
Germany
e-mail: detlef.schulz@hsu-hh.de