Causes of Harmonics and Interharmonics in Wind Energy Converters

Christoph Saniter E-mail: saniter@iee.tu-berlin.de
Detlef Schulz E-mail: schulz@iee.tu-berlin.de
Rolf Hanitsch E-mail: hanitsch@iee.tu-berlin.de
Technical University of Berlin, Germany, Institute of Energy and Automation Technology
TU Berlin, Sekr. EM 4
Einsteinufer 11, 10587 Berlin, Germany
Tel: + 49 – 30 – 314 245 39
Fax: + 49 – 30 – 314 211 33

Alan Wood E-mail: alan.wood@canterbury.ac.nz
University of Canterbury in Christchurch, New Zealand
University of Canterbury
Private Bag 4800, Christchurch, New Zealand
Tel: + 64 – 3 – 3642 406 6406
Fax: + 64 – 3 – 3642 761

Abstract

The number of grid connected Wind Energy Converters (WECs) with power ratings of up to 5 MW is continuously increasing all over the world and in particular in Europe [1]. WECs are a well known source of harmonic distortions in power transmission networks. This paper describes results from measurements carried out on eight different 1.5 and 1.8 MW wind energy converters from different manufacturers in large wind parks. The current and voltage harmonics were evaluated according to IEC 1000-3-4 [2] and are the basis for a comprehensive description of the causes for harmonics and interharmonics. The frequency resolution was 50 Hz for harmonics and 6.25 Hz for interharmonics. A power analyser with a maximum sampling rate of 25.6 kHz was used.

Keywords: power quality, harmonics, interharmonics, grid distortion, wind power

1. Distortion in power networks, definitions

Power quality is a term that embraces all aspects associated with amplitude, phase and frequency of the voltage and current waveforms existing in a power circuit. Electric utilities have the objective to deliver a sinusoidal voltage at a fairly constant magnitude and frequency throughout their system.
Power system distortions are defined as effects that alter the voltage amplitude, the voltage waveform or the power system frequency and thus degrade the power quality. This degradation in power quality may result from transient conditions in power circuits or the installation of non-linear loads drawing non-sinusoidal currents.
These currents flow through the power network and cause non-sinusoidal voltage drops across the system impedance which in turn may disturb other consumers that are connected to the power network. This situation is depicted in Fig. 1. It is important to notice that the term

"load" in this context is not restricted to loads in the true sense of the word but could be a generation unit with non-linear behaviour, too.

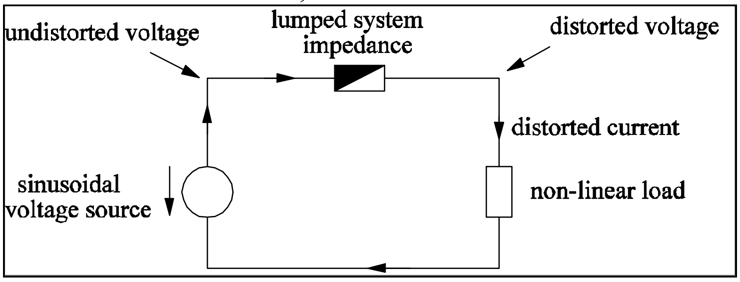


Fig. 1 Distribution system distortion due to non-linear loads

Some years ago, apart from power factor and flicker concerns, power quality problems were confined almost entirely to public utilities. However, nowadays power quality issues gain more interest due to loads that are increasingly sensitive to power quality issues and due to loads that are adversely affecting the quality of power supply. Problems associated with harmonic currents include

- equipment heating
- equipment malfunction
- equipment failure
- communication interference
- fuse and breaker mis-operation
- torque pulsation in drive systems
- conductor heating
- light flickering

The main parameters that determine the degree of distortion are the magnitude of the harmonic currents and the system impedance. If the system impedance is low, then the distortion would be low. A critical situation arises when resonances occur and the voltage increases dramatically. Power systems are able to absorb a considerable amount of current distortions without problems and the level of distortion may be well within the limits set by standards, but the collective effect of many non-linear loads taken together may impact a distribution system. Thus, it is important to identify the size and location of non-linear loads and to assess the impact of such loads when contemplating additions or changes to a system. Modern wind turbines can be considered to have a major impact on power quality issues due to their size and power ratings.

Although there is no clear definition for power quality disturbances some of the more common disturbances, which may be transient or periodic, include

- voltage and current harmonics, interharmonics and subharmonics
- voltage sags or dips and swells
- flicker
- impulses
- high frequency noise
- frequency variation

where harmonics, interharmonics and subharmonics are defined as follows:

- HARMONICS are integer multiples of a certain base frequency which is usually the power system frequency of 50 or 60 Hz.
- INTERHARMONICS are real-numbered multiples of the base frequencies. IEC-1000-2-1 defines interharmonics as follows: Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not integers of the fundamental [3].

- Interharmonics are called SUB-HARMONICS if the frequency at which they appear is below the base frequency.

The total harmonic distortion (*THD*(*X*)) of an electric quantity *X* is a useful definition to assess the degree of distortion and is defined as

$$THD(X) = \frac{\sqrt{\sum_{n=2}^{40} X_n^2}}{X_1} \tag{1}$$

where X_n is the component of *X* at the *n*'th integer multiple of the base frequency. It also may be described with a self-defined parameter, if interharmonics are included:

$$THDz(X) = \frac{\sqrt{\left(\sum_{n=1}^{400} (X_{n \cdot 0,125})^2\right) - X_1^2}}{X_1}. \tag{2}$$

2. Distortions in Variable Speed Drives and Generators

Variable speed drives and generators which are the principal component of any wind energy converter affect the power quality through many different mechanisms. Mechanical influences such as load changes, load shocks, bearing behaviour, mechanical clearance and mechanical resonances may affect the speed-torque characteristic, as depicted in Fig. 2. At the same time, electrical parameters such as inverter frequencies, smoothing elements, e.g. chokes and filters and existing distortion levels determine the drive system behaviour.

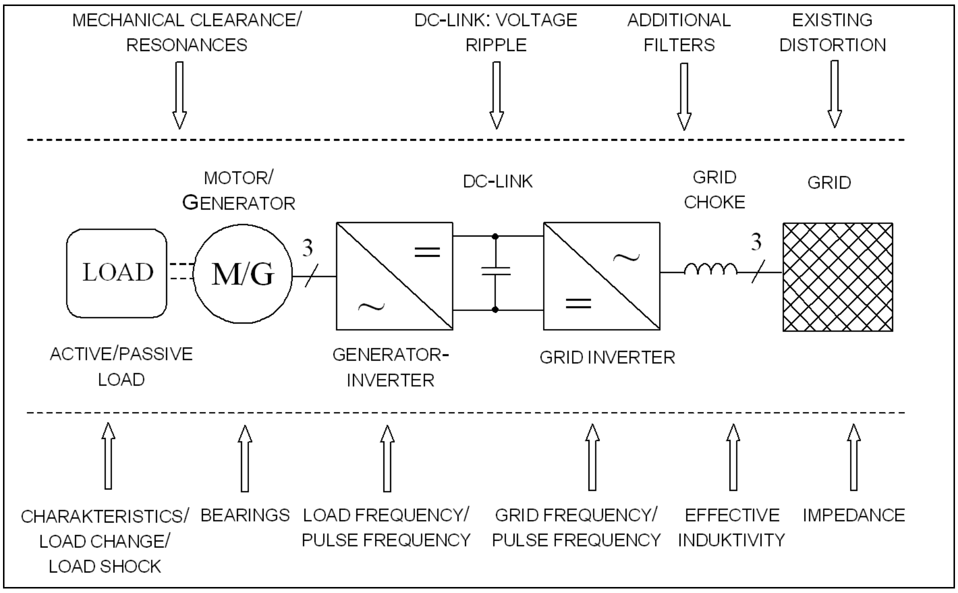
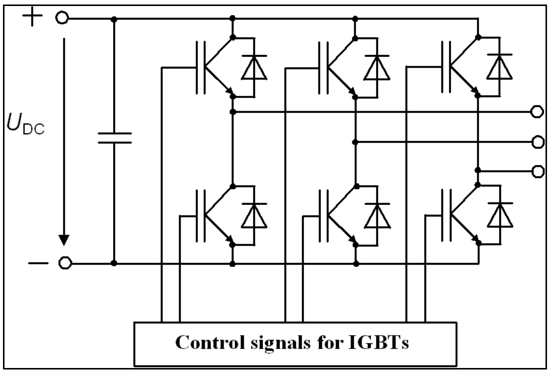


Fig. 2 Distortion influences in variable speed drive systems

Harmonic distortion mainly depends on the type of inverter and its control [4]. Three-phase, two-level converters are exclusively used in modern WECs in the MW power range. Fig. 3 shows an inverter structure with IGBT-switches (insulated gate bipolar transistors) and the three-phase output current at a pulse frequency of 1.5 kHz. The switching frequency in WECs is limited to the range of 2 kHz to 3 kHz for low-voltage converters, due to switching losses and the favoured air cooling of the inverters. Newest devices with powers up to 5 MW use medium voltage converters with pulse frequencies of only 150 Hz to 250 Hz. With decreasing pulse frequency the voltage shape deviates from the desired sinusoidal waveform and the current ripple increases.

a) 

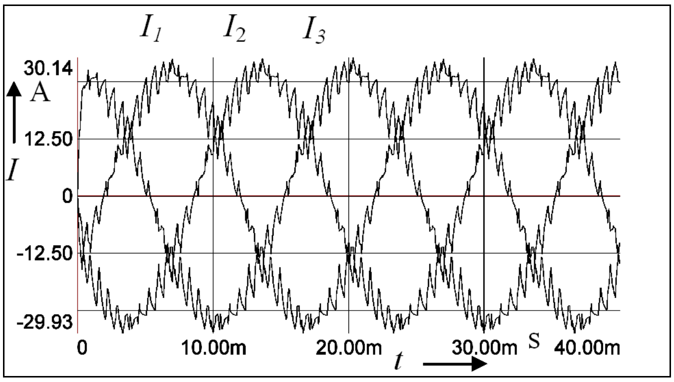
b) 

Fig. 3 a) Structure of an IGBT-inverter b) simulated output currents at a pulse frequency of 1.5 kHz

3. Distortions in Wind Energy Converters

Fig. 4 and Fig. 5 show the most common topologies for modern variable speed WECs: synchronous generators with full-size back-to-back converters, which have to transport the full apparent power over the converter and doubly-fed induction generators with two back-to-back converters in the rotor circuit that are dimensioned to handle approx. 1/3 of the turbine's total power, if the speed range is selected to ± 30 % of the nominal speed.

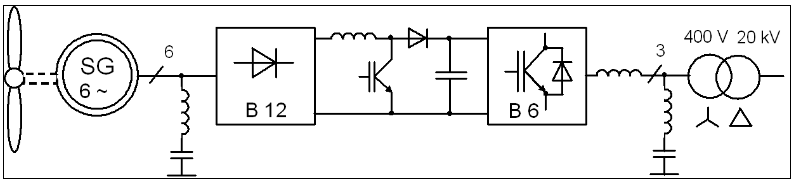


Fig. 4 Synchronous generator (SG) with full-size converter

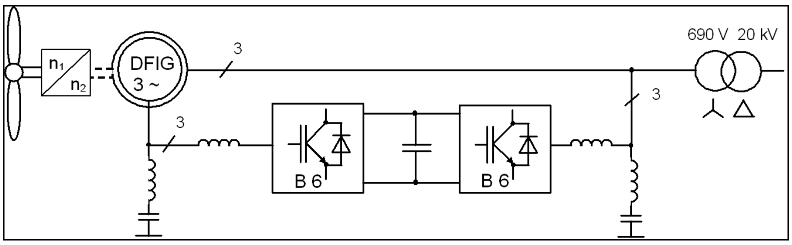


Fig. 5 Doubly-fed induction generator (DFIG)

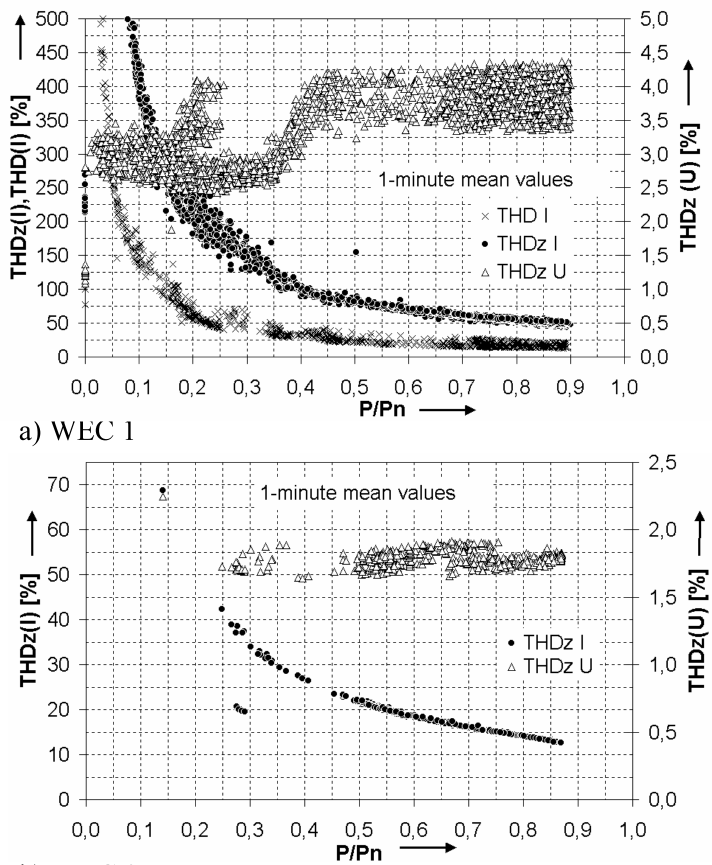
Both topologies have in common that they use power electronic converters implementing a Pulse Width Modulation (PWM) control switching strategy introduced above to allow variable speed operation and to adapt the power factor within certain limits.

However, these topologies cause harmonics and interharmonics due to non-ideal voltage shape and current ripples according to Fig. 3b which both adversely affect other consumers connected to the grid. Figs. 6a and 6b show results from measurements on two different WECs with doubly-fed induction generators. Parameters of interest are the Total Harmonic

Distortion of the current (THD_I) and voltage (THD_U) and the Total Harmonic Distortion with interharmonics of the current ($THDz_I$). These parameters are plotted against the relative power.

It is visible from Fig. 6 that all harmonic parameters decrease with increasing relative power. Furthermore, the behaviours of the two turbines differ greatly and mark the "best" and "worst" case of our measurements on doubly-fed induction and synchronous machines. The behaviour is greatly dependent on inverter types, filters or the grid impedance [6].

It can be seen in Fig. 6, that WECs cause mainly current harmonics, but do not generally affect the grid voltage significantly. This, however, is only true if the power ratio of the distributed generators to the grid short-circuit power is high enough and if the grid impedance



a) WEC 1

b) WEC 2

Figure 6 Harmonic current and voltage parameters over relative power of different WECs with doubly-fed generators

is low enough [7]. Although a strict classification is sometimes difficult, the following sources for harmonics could be identified:

- ac system impedance imbalance [8]
- transformer and / or machine saturation [5]
- converter switching action [4]
- dead time in the converter's control signal
- control signal variation [9]

Causes for interharmonics include

- the back-to-back configuration of two converters. Each converter generates harmonics which propagate through the dc link and appear as (inter-)harmonic distortion in the output spectrum of the other converter. Thus, interharmonics result

if the two converters operate at different frequencies, harmonics result if they operate at the same frequency [10]
- ac or dc system distortions [11]
- (for doubly-fed induction generators only): Harmonics are generated by the generator-side inverter and are transferred across the air gap to the stator side, where they appear as sum and difference frequencies around the slip frequency [12]

Slot harmonics are another source for harmonics, but their effect is negligible compared to other harmonic sources.

4. Conclusions

Distortion types in power network were described in order to characterise the influence of variable speed wind energy converters to the grid. Measurement results from doubly-fed WECs show that distortion levels depend on the relative power and the manufacturer and/or the point of coupling and external parameters. While the dependence on the relative power is inherent to the system and easy to describe mathematically, the dependence on the point of coupling and external parameters is much harder and cannot be qualified without additional measurements of and information on the grid impedance, filters, chokes, wind load curves, etc. However, a comprehensive overview for the main mechanisms leading to the generation of harmonics and interharmonics is given and, whenever possible, references for further reading are provided.
Investigations are ongoing for improving the WEC’s behaviour, to predict the effect of large scale wind parks on the power quality and to allow an improved power management.

References

Bundesverband Windenergie, www.wind-energie.de/informationen/informationen.htm, Foliensammlung, 2004

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

IEC 1000-2-1, 1990. Electromagnetic compability Part 2: Environment, Sect. 1: description of the environment – Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems.

G.J. Wakileh, 2001, Power system harmonics, Fundamentals, Analysis and Filter design, Springer-Verlag

D. Schulz, R. Hanitsch, T. Kompa and A. Samour, 2002. Comparative Power Quality Investigations of Variable Speed Wind Energy Converters with Doubly-fed Induction and Synchronous Generator, Proceedings of PCIM Power Quality Conference, Nürnberg, Germany, pp. 39-44

D. Schulz, 2002. Investigations of the power quality of grid connected photovoltaic- and wind energy systems (in German: Untersuchung von Netzrückwirkungen durch netzgekoppelte Photovoltaik- und Windkraftanlagen), Ph. D. dissertation, TU Berlin, VDE Verlag Berlin Offenbach

C. Saniter, A. Wood, R. Hanitsch and D. Schulz, 2003. Modelling the effects of ac side system impedance unbalance on PWM converters using frequency coupling matrices, Proceedings of IEEE PowerTech conference, Bologna, Italy, 2003

F. Jenni and D. Wüest, 1995. Steuerverfahren für selbstgeführte Stromrichter, first edition vdf Hochschulverlag; Stuttgart

C. Saniter, A.R. Wood, R. Hanitsch, 2004. Modelling the effect of control signal variation on the generation of harmonics in PWM converters, Proceedings of PCIM Power Quality Conference, Nürnberg, Germany

C. Saniter, R. Hanitsch, D. Schulz, 2003. Using small signal frequency domain modelling for predicting harmonic and interharmonic distortions generated by two back-to-back PWM converters, Proceedings of CIRED conference, Barcelona, Spain

C. Saniter, R. Hanitsch, C. Osauskas, and H. Laird, 2002. A harmonic transfer matrix model of a variable ac speed drive, Proceedings of IEEE Postgraduate Power Conference, Budapest, Hungary, pp. 51-55

D. Schulz, E. Tognon, R. Hanitsch, 2003. Investigation of the harmonic transformation properties of doubly-fed induction generators in wind energy converters, Proceedings of PCIM Power quality conference, Nürnberg, Germany, pp. 207-212