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Development of a Flexible Measurement System for Offshore Wind Farms

Łukasz Hubert Kocewiak, Iván Arana, Jesper Hjerrild, Troels Sørensen, Claus Leth Bak, Joachim Hølbøll

Abstract—The development process of a flexible measurement system for multi-point, high-speed and long-term offshore data logging is described in this paper. This covers the complete design taking into account precise synchronisation, electromagnetic compatibility, software development and sensor calibration. The presented measurement set-up was tested in a rough offshore environment. Results from measurement campaigns at Avedøre and Gunfleet Sands offshore wind farms including synchronisation precision and accuracy, electromagnetic interference of power electronic devices are briefly presented.

Index Terms—GPS synchronisation, harmonic measurements, high-speed logging, long-term logging, measurement software, offshore wind farm, transient measurements.

I. INTRODUCTION

Accurate measurements of harmonic and transient voltages and currents in offshore wind farms followed by proper data analysis are essential for model creation/validation of components or subsystems. These models can be further used in simulation tools during the development of offshore wind farms.

In order to observe the harmonic and transients in the collection grid without any misleading disturbances, a great deal of effort was put into making the measurements as accurate as possible.

The measurement system developed was designed taking into account the special application, requirements and environment of offshore wind farms (OWFs). Here, the access is limited due to weather conditions and significant operational costs; hence a robust and reliable measurement system is important.

The most important requirement for development of the measurement system is that it can be used for harmonic and transient measurements. This means that for harmonic measurements the system should be reliable for long-term use and for transient measurements it should have a sufficient sampling rate. For both applications, harmonic and transient measurements, the system should be able to store large amount of data.

The recorded measurements in Avedøre Holme (AVV) and Gunfleet Sands (GFS) will form the base for system analyses in connection with two ongoing PhDs as well as future R&D projects at DONG Energy.

II. AVEDORE HOLME AND GUNFLEET SANDS WIND FARMS

AVV and GFS OWFs are two OWFs partly owned by DONG Energy where the measurement system was installed. The wind turbines (WTs) used on both OWFs are Siemens Wind Turbine SWT-3.6.

A. Wind farms description

AVV OWF in the south of Copenhagen is a shared project between DONG Energy and Hvidovre Vindmøllelaug A/S. A location so close to shore and easy accessibility to the offshore WTs via a footbridge is the basic idea behind the project. This gives DONG Energy a unique opportunity to test and try out new WT concepts, before they are implemented in large scale OWFs.

Figure 1. Simplified single line diagram of Gunfleet Sands Offshore Wind Farm, where the locations of the measurement system are shown.

GFS OWF is located on the east cost of the UK and consists of two phases, one with WTs and another with WTs. The WTs are connected in “rows” by kV submarine cables. Each pair of rows is then connected by one “root” cable and later in the substation to a MV busbar via a vacuum circuit breaker (VCB). Two park transformers (MVA, kV) are placed in the centre of the WF in the offshore substation. From the substation the electricity is transmitted to shore via a km long submarine cable which connects to the Clacton substation at Cooks Green. A simplified single line diagram of GFS with the three main measuring locations is shown in Figure 1.

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B. Wind turbine description

The wind turbines used in GFS and AVV are SWT-3.6-107 and SWT-3.6-120, respectively. These are state of the art variable-speed WTs utilising full scale frequency converters. The frequency converter system comprises two AC/DC converters and a DC-link decoupling the variable-frequency generator and the grid frequency. There is a transformer (4 MVA, 34/0.69 kV in GFS and 10/0.69 kV in AVV) to step-up the voltage on each of the WTs. The WT transformer is connected with a VCB to the MV network.

III. MEASUREMENT CAMPAIGNS

In order to test the flexible measurements system for multi-point, high-speed and long-term offshore data logging in the field, the measurement system was first installed in AVV and then in GFS, once the measurement system was proven to be reliable. The measurement system was installed in several locations of the MV grid and the LV system of the AVV and GFS wind farms.

A. Measurement campaign purposes

As mentioned before, the measurement system has been designed to measure the harmonic emission and transient overvoltages in OWFs.

To record the harmonic emission of a single WT, the measurement system was installed at selected points in the LV system of a turbine and in the MV grid in AVV and GFS. To record the harmonic emission of a group of WTs the measurement system was installed in the transformer platform substation of GFS. In both instances the measurement system was left recording continuously for more than three weeks.

To do this, appropriate voltage and current probes have been selected. The LV voltage and current probes used are commercial components, while MV voltage probes used are costume made from standard MV equipment.

B. Voltage and current probes location

In the wind turbine of AVV the LV voltage probes were installed in the auxiliary switchboard, DC/AC converter and DC-link of the wind turbine. The LV current probes were installed on the output terminals of the DC/AC converter, DC-link and LV side of the WT transformer. The MV voltage and current probes in the WTs were installed in the WT transformer side of the VCB.

The measuring locations within the collection grid of GFS were the transformer platform, the first turbine of a radial and the last turbine of the same radial. Within the WTs, the LV voltage and current probes were installed in the auxiliary switchboard. The MV voltage and current probes in the WTs were installed on the transformer side of the VCB; while in the substation the voltage and current probes were installed in the cable side of the VCB of the radial.

IV. MEASUREMENT EQUIPMENT

Since the OWFs have particular operating conditions and environmental constrains, special attention should be placed when selecting additional equipment to be installed offshore as a measurement equipment.

The test equipment consists of three National Instruments (NI) PXI-1033 chassis each comprising PXI-6682 timing and synchronisation board with Trimble Bullet III GPS antenna used to read GPS timestamp, PXI-4472 dynamic signal acquisition (DSA) board with second-order low-pass anti-aliasing filter [1] applied in case of harmonic measurements and PXI-6133 multifunctional board used for transient measurements. The main information for the three measurement set-ups is shown in Figure 2.

The chassis is connected to a portable computer via ExpressCard laptop host. Used MXI-Express remote controller achieves up to 110 MB/s sustained throughput. The measurement PC units used for measurements comprise Intel Core 2 Duo T9400 @ 2.53 GHz CPU, 4 GB @ 800 MHz RAM, Windows Vista Enterprise operating system (OS) and Seagate ST95005620AS Hybrid-HDD.

In order to avoid problems, industrial solutions were used. For example the LV voltage probes installed in the wind turbines were fitted to the terminals of the AC switchboard and in the DC/AC converter terminals through fuses and 4mm standard plugs. The MV voltage probes were built with standard cables and cable connections. The different voltage and current sensors used are:

- HIOKI 9279 – St-9001
- CW3FL – St-9002
- CW30FL – MV t-connectors

A. Equipment for harmonic measurements

The measurements were carried out in the OWFs by means of the Dynamic Signal Analyzer cards with two-pole lowpass Butterworth filter. Taking into consideration Nth-order Butterworth filter one can describe it in terms of energy spectra (squared magnitude) which has the form of Eq. (1)

$$|H(\omega_c)|^2 = \frac{1}{1 + (\omega/\omega_c)^{2N}}$$

where $\omega_c$ is −3 dB cutoff frequency. The Butterworth approximation of ideal lowpass filter has only poles (i.e. no finite zeros) and yields a maximally flat response around zero and infinity. This approximation is also called maximum flat magnitude. This feature becomes extremely important in case of harmonic measurements where each frequency within a passband has to be filtered in the same way.

B. Equipment for transient measurements

Carefully selected sensors were used for transient measurement purposes. It was expected to carry out measurements with sample rate of 2.5 MS/s/ch which requires sensors with a flat bandwidth (±3dB) of at least up
to  MHz. Since the frequency range of interest in case of harmonic measurements is much lower, the same probes were used in both cases.

Such demanding frequency range of interest creates additional problems with electromagnetic interference (EMI). It was not expected to have higher frequency components than  MHz during transient measurements, therefore no additional anti-aliasing filtering was provided. In order to deal with the EMI, EMC-proof boxes were used as well as sophisticated shielding solutions.

C. GPS synchronisation

Used for offshore measurement in AVV and GFS purposes receivers provide a pps on-time pulse. The GPS receiver is limited to using SPS, which has 50% probability that a given on-time pulse from GPS will be within  ns of UTC. The uncertainty of GPS is ns, and the uncertainty is  ns [2].

![Figure 3](image.png)

Figure 3 Variation of pulse-per-second signal synchronized with a GPS timestamp using phase-locked loop.

To reduce such uncertainties, the system had to be calibrated for receiver and antenna delays, as well as synchronisation errors. This was done with the available software from NI. The antenna was connected to the receiver and mounted outdoors where it had clear, unobstructed view of the sky. This condition can be easily fulfilled in large OWFs situated far from natural barriers and effects such as multipath propagation due to the signal reflection, and high dilution of precision, when detected satellites are close together in the sky, can be neglected. Positional accuracy was improved due to the fact that the WTs and the substation at GFS OWF are situated far from each other (see Figure 1) and naturally are far from multipath reflectors [3].

The pulse-per-second signal accuracy as measured during measurements at GFS OWF is shown in Figure 3. The accuracy is even better than provided by the manufacturer ( ns, ).

D. Current probes

In order to measure currents, Powertek CWT3LF and CWT30LF flexible Rogowski coils were used with  Hz- MHz minimum bandwidth. The cable from sensor to integrator is a fixed-length double screened RG58 type which is suitable to be used in harsh WT electromagnetic environment. The cable is relatively long ( m) and cable parasitic capacitance is compensated for to achieve flat performance within the bandwidth. Also the integrator by its low-pass filter nature is suitable to attenuate EMI.

E. Voltage probes

Si-9001 and Si-9002 differential voltage sensors with bandwidth of DC- MHz were used in the LV and in the MV capacitive voltage sensors installed as “dead-end” T-connectors with bandwidth of  Hz- MHz.

The MV T-connector is installed in the MV network as a “dead-end” and the phase-to-earth voltage is measured using an end-plug. Since the capacitive end-plug is not normally used for precision measurements, an amplifier for precision measurements with high frequency response developed by DELTA has been used.

V. MV Probes Calibration

The MV voltage probes and amplifiers were calibrated in the high voltage laboratory at The Technical University of Denmark, DTU. By means of a controlled and variable frequency voltage amplifier, the corresponding gains and offsets of each voltage probe-set were found. The high voltage amplifier used at DTU is a TREK P0621P and the voltage measurements were done with a Tektronix P6015A High Voltage Probe.

Some of the results from the calibration are shown in Figure 4; here it is possible to see that the sensor has a linear characteristic from to kV. Once the main values of the linear characteristic are known, appropriate scaling factors were programmed in the software to be used during the measurement campaigns. Only the results are Hz are shown below.

![Figure 4](image.png)

Figure 4 Input-output characteristic from one of the voltage probes.

As it can be seen in Figure 4, the coefficient of determination is almost equal which means that within the measured voltage range the regression line perfectly fits the data and a linear scale can be successfully used during measurements.

VI. Measurement Results

The measurements were carried out in two stages. Firstly, long-term harmonic measurements were performed within a period of one month. This was enough to record under all possible production levels. Typical WT power curve from the measurement period is shown in Figure 5.

![Figure 5](image.png)

Figure 5 Wind turbine power curve obtained from measurements.

Secondly high-speed measurements were carried out in order to record switching transients in the WT and the whole
from DC side of the grid-side converter, AC terminals of the power converter, and LV side of the WT transformer as well as MV side of the transformer were acquired and saved. Some examples of the results are shown below.

Figure 7 shows the current measured from both sides of the WT transformer. Additional harmonic content in both time series can be easily seen. Measurements later are subjected to data processing according to guidelines presented in [1].

VII. CONCLUSIONS AND DISCUSSION

The development process of flexible measurements system suitable for multi-point, high-speed and long-term offshore data logging is described in this paper. The complete design taking into account precise synchronisation, electromagnetic compatibility, software development, and sensors calibration is described. Some results regarding electromagnetic interference, power curve and power quality have been shown.

VIII. ACKNOWLEDGMENT

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IX. REFERENCES


X. BIOGRAPHIES

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Iván Arana was born in Mexico City in Mexico, 1983. He received the bachelor degree from ITESM, Mexico in 2005 and MSc. degree from DTU, Denmark in 2008. He is now an Industrial PhD student at the CEE in cooperation with DONG Energy and Siemens Wind Power.

Jesper Hjerrild was born in 1971. He holds an MSc and PhD degrees in electrical engineering from the Technical University of Denmark, Lyngby, in 1999 and 2002, respectively. Currently, he is employed with DONG Energy. His main technical interest is electrical power systems in general, involving a variety of technical disciplines including modeling of power systems including wind power and power system control, stability and harmonics. Furthermore, he also works with designing of the wind farm.

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Claus Leth Bak was born in Århus in Denmark, on April 13, 1965. He graduated from High School in Århus and studied at the Engineering College in Århus, where he received the BSc with honors in Electrical Power Engineering in 1992. He pursued the MSc in Electrical Power Engineering with specialization in High Voltage Engineering at the Institute of Energy Technology (IET) at Aalborg University (AAU), which he received in 1994. After his studies he worked with Electric power transmission and substations with specializations within the area of power system protection at the HV Net transmission company. In 1999 he got employed as an assistant professor at IET-AAU, where he is holding an associate professor position today. His main research areas include corona phenomena on overhead lines, power system transient simulations and power system protection. He works as a consultant engineer for electric utilities, mainly in the field of power system protection. Claus Leth Bak has supervised app. 15 MSc thesis projects, 10 BSc thesis projects and 6 PhD thesis project. Claus Leth Bak teaches and supervises at all levels of the AAU and he has a very large teaching portfolio. He is the author/coauthor of app. 56 publications. He is a member of Cigre C4.502, Cigré SC C4 and Danish Cigré National Committee. He is an IEEE senior member.

Joachim Holboell is Associate Professor at DTU with many years experience within electric power components, their properties and high frequent equivalents plus methods for condition assessment of these components. Past years focus has been on high voltage transformers and cables and, in general, insulating materials performance under AC, DC and transients. The work is now concentrated on wind turbine components, materials and high voltage research with respect to the future power grid. J. Holboell has been visiting researcher at Ontario Hydro Research, Canada, Royal Institute of Technology in Sweden and Monash University, Australia. J. Holboell is Senior Member of IEEE and secretary of Cigré Study Committee D1.