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GPS synchronisation of harmonic and transient measurements in offshore wind farms

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Abstract

The GPS synchronization challenges during the development, construction and installation of a measurement system for multi-point, high-speed and long-term data logging is described in this paper. The presented measurement system was tested in a rough offshore environment at Avedøre Holme and Gunfleet Sands Offshore wind farms.
The paper will describe the application of GPS technology in synchronised measurements carried out at Avedøre Holme and Gunfleet Sands wind farms. Different aspects of software development and hardware configuration in order to optimise measurement system reliability during offshore measurements will be presented. Also real-life examples of results from both offshore measurement campaigns will be described. Some limitations and improvements of the measurement system will be explained based on measurements from both harmonic and transient measurements.

Keywords: GPS; measurements synchronisation; harmonic measurements; offshore wind farm; transient measurements.

1. Introduction

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

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

The measurement system developed here 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 trustful measurement system is important.

The synchronization of measurement systems in different locations is one important aspect taken into account in the development process of a flexible measurements system for harmonic and transient measurements in OWFs.

The recorded measurements in Avedøre Holme (AVV) and Gunfleet Sands (GFS) will be used for two ongoing PHD's as well as future R&D projects at DONG Energy.

2. Synchronisation in offshore wind farms

If during measurements the transfer of electromagnetic energy from source (emitter) equipment, which in a WT is the main power circuit, through a coupling path to a receptor (receiver), which is the measurement equipment, an EMI occurs.

The most likely scenario for incompatibility occurs when a relatively high power circuit (i.e. power converter) is located near a very sensitive receptor (e.g. sensors, cables, measuring head unit) [1], [2]. Switch-mode high power density converters commonly used in nowadays wind turbines are potential generators of EMI due to the switching action of the converter The switching action generates a spectrum of the switching frequency and its harmonics. The main noise sources of switching frequency harmonics are the switched currents and the commutating diode. This noise is a combination of the switching frequency and its associated rise time (approximately 100 ns) and turn on spikes caused by the diode recovery current. This recovery current spike occurs at the end of a diode conduction cycle when reverse voltage is just applied by the transistor [1].

2.1. Wind farms description

Avedøre Holme and Gunfleet Sands offshore wind farms are two OWFs partly owned and owned by Dong Energy where the measurements system was installed. The WTs used on both OWFs are Siemens Wind Turbine SWT-3.6.

2.2. Avedøre Holme

Avedøre Holme offshore WF in the south of Copenhagen is a shared project between DONG Energy and Hvidovre Vindmøllelaug A/S. The two wind turbines are located less than 10 meters from shore in a water depth of 0.5-2 metres. A location so close to shore and easy accessibility to the offshore wind turbines via a footbridge is the basic idea behind the project. This gives DONG Energy a unique opportunity to test and try out new wind turbine concepts, before they are implemented in large scale in OWFs.

Due to the simple access to the turbine in Avedøre the measurement system was installed in several locations of the MV and LV of the wind turbine. Sensors for harmonic measurement were installed in four different locations in the same WT and in total twenty channels were logged simultaneously. Electrical quantities from DC side of the grid-side converter, ac terminals of the power converter, LV side of the WT transformer as well as HV side of the transformer were acquired and saved.

2.3. Gunfleet Sands

Gunfleet Sands OWF is located on the east cost of the UK (see Fig. 1) and consists of two phases, one with 30 wts and another with 18 turbines. The WTs are connected in “rows” by 36 kV submarine cables. Each pair of rows is then connected to the platform by one “root” cable. Two park transformers (120 MVA, 132/33 kV) are placed in the centre of the WF in the offshore substation. Each root cable is connected in the substation to a MV busbar via a vacuum circuit breaker (VCB). From the substation the electricity is transmitted to shore via a 8.5 km long submarine cable which comes ashore at Holland Haven and connects to the Clacton substation at Cooks Green.

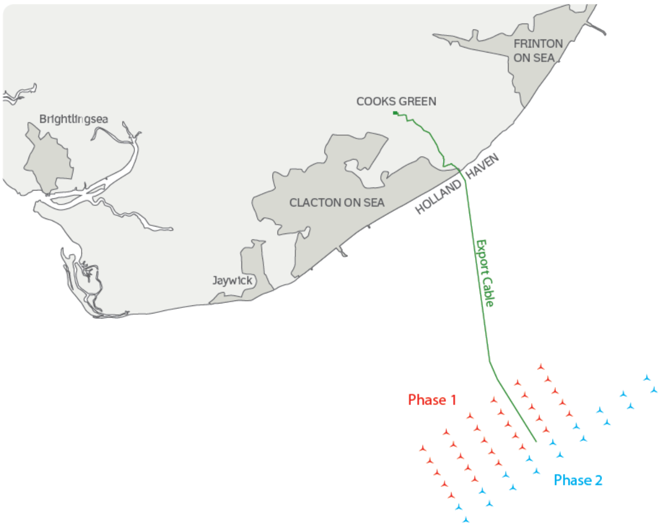

Fig. 1 Gunfleet Sands Offshore Wind Farm located on the east cost of the UK close to Clacton on Sea.

Once the measurement system was proven to be reliable under offshore conditions for short term and long term measurements, the system was installed in Gunfleet Sands.

The measuring locations within the collection grid of Gunfleet Sands were the transformer platform, the first turbine of radial and the last turbine of 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 in 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.

One of the most important requirements for the measurement system in Avedøre and Gunfleet Sands was that the installation of the chassis, antennas and probes should not disturb the normal operation of the service technicians that require doing some maintenance work in the turbines and transformer platform.

3. Methods

3.1. Synchronisation board

Specially designed EMC-proof boxes were equipped with cooling system in order to keep constant ambient temperature. If the ambient temperature differs from the calibration temperature by more than ±5°C the temperature compensated crystal oscillator (TCXO) will be affected by drift and introduce additional synchronization uncertainties.

3.2. Software development

In software development it is of special importance to implement synchronization support in the easiest way as possible. In case of transient measurements synchronization delays affected by the software layer can affect the whole measurement process. It was decided that the measurement software will start according to the time reference obtained from timing and synchronization board. A time reference is an external source of timestamp that provides periodic time updates. It is possible to provide time reference from GPS satellites, IEEE 1588 masters, or IRIG-B sources. As mentioned earlier each of the sources provides periodic time updates. In case of GPS satellites broadcast the current time once per second, on the second's boundary. The synchronization board has the oscillator (clock) accuracy of 1ppm which provides accurate time reference every second (PPS).

In order to configure the driver on the software layer in the simplest and most efficient way a linear structure was used. It was done in the following way:

- Initialize driver: initializes a session to the timing and synchronization board, which is the first required step before any I/O operation (e.g. digital triggering on the hardware level) can be performed.

- Enable trigger: the timing and synchronization board is ready to start time stamping on the specified input terminal (i.e. triggering on the hardware level). Any trigger that occurs on the specified input terminal with the specified active edge is time stamped.

- Read trigger timestamp: the oldest, non-read time stamp associated with the specified terminal is returned.

- Disable timestamp trigger: disables time stamping on the specified terminal.

- Close driver: stops all ongoing operations associated with the session and all the resources can be used later is needed.

3.3. Synchronisation uncertainties

Used for offshore measurement purposes receivers provide a 1 pps on-time pulse. The GPS receiver is limited to using SPS the uncertainty is defined by the top row in Table 1. It shows that there is a 50 % probability that a given on-time pulse from GPS will be within ±115 ns of UTC. The 1σ uncertainty of GPS (~68 % probability) is ±170 ns, and the 2σ uncertainty (95 %) is ±340 ns [3], [4].

Table 1 Timing uncertainty of GPS in One-Way Mode.

Service	Uncertainty (ns) 50^{th} percentile	Uncertainty (ns) 1σ	Uncertainty (ns) 2σ
SPS	±115	±170	±340
PPS	±68	±100	±200

To achieve uncertainties presented in Table 1 one has to calibrate receiver and antenna delays, and estimate synchronization errors. The antenna providing reliable performance in harsh radio frequency (RF) jamming environments was connected to the receiver and mounted outdoors where it had clear, unobstructed view of the sky. This condition can be easily satisfied in large OWFs situated far from natural barriers and effects such as multipath propagation [5] due to the signal reflection, and high dilution of precision (DOP) 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 and naturally are far from multipath reflectors (see [6]).

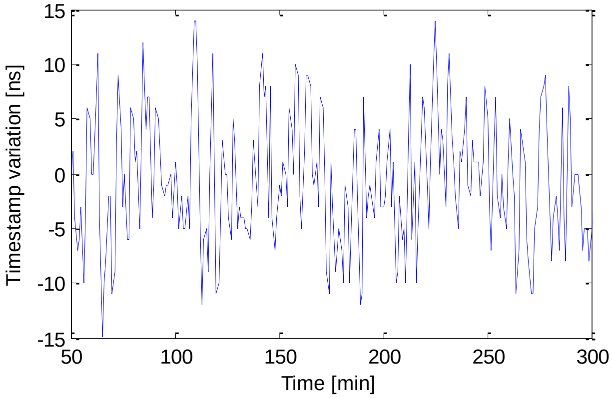

Fig. 2 Variation of pulse-per-second signal synchronized with a GPS timestamp using phase-locked loop.

It is important to mention that in all location data were acquired using the same DAQs with the same sampling rate, so phenomena such as filter delay does not affect the synchronization effectiveness. Also RG59/U coaxial cables with the same length of 30 m were used to connect the active GPS antenna with the timing and synchronization board, which means the propagation delays were the same.

Pulse-per-second signal accuracy measured during measurement campaign at Gunfleet Sands OWF is shown in Fig. 2. The accuracy is even better than provided by the manufacturer (15 ns, 1σ).

3.4. Installation considerations

The measurement equipment in the wind turbines in Avedøre and Gunfleet Sands was installed in the basement of the wind turbine, where the service technicians do not require going often. In the transformer platform the measurement equipment was installed in the 33kV switchgear room, close to the voltage and current probes.

It is important to mention, that the installation of the GPS antennas in Avedøre and Gunfleet Sands had to be done in open space outside the wind turbines and the transformer platform, in order to receive the best signal from the satellites. Nevertheless, the measurement equipment should be installed indoor, in a controlled environment. These two opposite requirements for the entire measurement system had to be fulfilled.

This was solved in the wind turbines in Avedøre and Gunfleet Sands, by installing the GPS antennas outside the turbine tower in the service stairs to enter the wind turbine, with the coaxial cable though a service opening in the turbine tower. This is shown in Fig. 3.

The GPS antenna in the transformer platform was installed in the platform upper level, close to the helipad, to reduce the possibility of interference with high structures. Then, the coaxial cable was lowered though the transformer hall, until the flexible cable sealing system that connects the transformer hall with the 33kV switchgear room. This is shown in Fig. 4.

Fig. 3 GPS antenna installed on the service stairs of a wind turbine in Gunfleet Sands.

Fig. 4 GPS antenna installed on the platform upper level in Gunfleet Sands.

4. Results

The some of the transient measurement results are shown in this section, first from Avedøre and then from Gunfleet Sands.

4.1. Transient measurements synchronization in AVV

Some of the transient measurements during the switching in of the VCB in the AVV wind turbine are shown in Fig. 5. In this figure the voltage and current on the MV side of the transformer are shown, as well as the LV side voltage. It is possible to see in this figure the high frequency voltage oscillation caused by the pre-strike in the VCB that is transfer to the LV side as well as the inrush current of the transformer.

The VCB model validation, as well as the wind turbine transformer and external grid validation has been reported in [7].

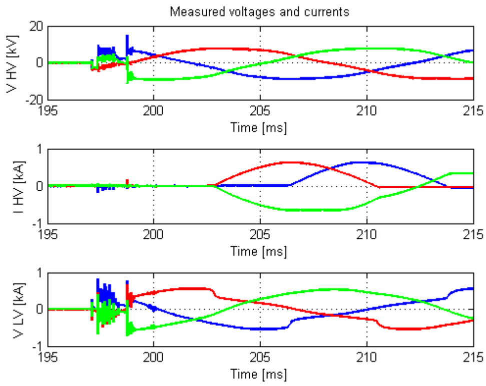

Fig. 5 Measured three-phase voltages and currents, during the closing operation of the MV VCB in the wind turbine of AVV from 195 to 215ms. The voltage on the primary side of the transformer is shown in the top, the current on the primary side of the transformer is shown in the middle and in the bottom Fig. the voltage on the secondary side of the transformer.

4.2. Transient measurements synchronization in GFS

Due to maintenance, in large offshore wind farms the MV VCB in the offshore substation could be operated several times a year. These normal switching operations would cause transient overvoltages in the collection grid that will move along the energized radials. Such transient overvoltages were measured in GFS during the measurement campaign.

The measured voltages in the offshore substation (OS) and the last turbine in a radial (F9), during the energization of a cable connected parallel to the measured radial is shown in Fig. 6. Here it is possible to see how a voltage dip and a small voltage transient are measured in the three phases and both locations. The voltage dip is caused after the cable connection (left subplot); while the small voltage transient on top of the voltage dip (right subplot) is caused by the VCB operation in the offshore wind farm substation. This small voltage transient appears first in the offshore substation at 60ms, and then travels for 22µs to the last turbine in the radial (F9) and finally back to the offshore substation. The 22µs corresponds to the travelling time the voltage wave would take to travel from the offshore substation to wind turbine F9 based on the different cables' parameters and lengths.

The measured travelling speed of the voltage wave, corresponds half the speed of light, reported previously by similar switching operations recorded in Nysted offshore wind farms [8].

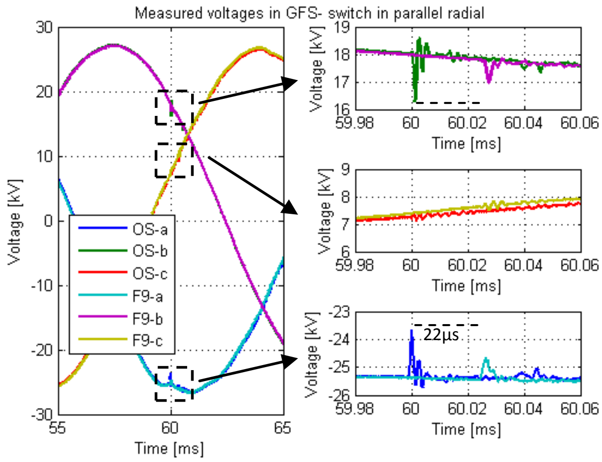

Fig. 6 Measured three-phase voltages, during the energization of a parallel cable in GFS from 55 to 65ms. The three-phase voltages on the offshore substation (OS) and the last wind turbine in the radial (F9) are shown in the left subplot, while a zoom in on each individual phase is shown in the three right subplots.

5. Discussion

During the removal of the measurement equipment in GFS, after 8 months of measurements, it was noticed that one of the GPS antennas was damaged. The antenna presented high level of corrosion in the metallic lower part of the antenna. Only the antenna in one of the wind turbines presented this corrosion.

Due to this deterioration, the coaxial cable connected to the antenna, was also damaged, and had to be repaired afterwards. The metallic part of the antenna was simply cleaned.

The damage in the antenna clearly shows the harsh environment to which the offshore wind turbines are subjected. In practice, this is solved by carefully isolating the equipment inside the turbine tower from the offshore environment.

6. Acknowledgment

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