GPS Synchronized high voltage measuring system

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Abstract —This paper presents a measuring system build for documentation of voltage conditions in medium voltage (MV) systems and for verification of a high frequency simulation of transients in wind farm collection grids. The system consists of three units of measurement synchronized using GPS. Phase-earth voltages are measured using capacitive voltage sensors and phase currents using Rogowski-coils. The measurements are performed synchronously with 2.5 MHz sampling frequency in the three different measurement points in the grid. The measurement system runs on a Windows XP PC using National Instruments hardware and software developed in LabView for streaming data to an external FireWire harddisk.

Index terms — Transient measurements, wind farms, switching transients, synchronization, data sampling, and medium voltage (MV) systems.

1. Introduction

Although the wind power development is still mainly based on land sites, a number of large offshore wind farms have been developed, and there are significant plans for further offshore wind power development, e.g. in Denmark, Germany, the Netherlands and United Kingdom.

This development yields a need for accurate models of all main components in a wind farm (WF) as simulations are widely used to predict what happens in case of faults and switching operations in the grid and to verify design choices. The need for accurate simulations is major for offshore WFs as consequences of faults are more severe in terms of repair costs and lost revenue than for a land based WF. Transients from switching of circuit breakers (CB's) and fault situations in the MV collection grid can result in break down of components and therefore need to be addressed.

The result of simulations can always be questioned depending on the accuracy of the component models used in the simulation program, and validation of models and simulations with reliable measurements performed in a real large WF, makes it possible to verify and improve the simulations to give more reliable results.

Furthermore documentation of actual voltage conditions and current flow in a real WF gives useful information concerning the design parameters for the components and which level of stress they are going to have to withstand.

2. Defining the specification of the measuring system

The purpose of the measuring system is to document high frequency transients in large off-shore wind farms. The amplitude, the time derivative and the propagation time of the voltage and current transients are important and this reflects in the specifications for the measurement system. The number of measurement channels is given: Three voltages and three currents - totally six channels. The highest frequency simulated in [1] is 625 kHz, therefore the sampling frequency is selected to 2.5 MHz giving a Nyquist frequency of 1.25 MHz. The maximum amplitude of the transients in [1] is calculated to be below a maximum of 80 kV, this peak value sets the upper limit for measurement of the voltage. To be able to record propagation time of a transient in the MV collection grid, it is crucial that the measurement in the three different locations in the WF are synchronized within one sample e.g. 400 ns. To be able to record a switching transient in the WF, the measuring system then must record data continuously for up to 5 minutes, as the switching sequence has to be coordinated with the grid operator manually by phone and exact timing is not possible. To use the data, they must be stored on a harddisk and in a format that can be read and browsed at a reasonable speed.

3. Building the system

The measuring system consists of a recording system and transducers for measurement of voltage and current.

3.1. Data recording system

To meet the specification several solutions where discussed, from oscilloscopes to PXI-system, but the selected solution show in Figure 1 is based on PCI-cards and a stationary Windows PC, as this solution was the most cost efficient

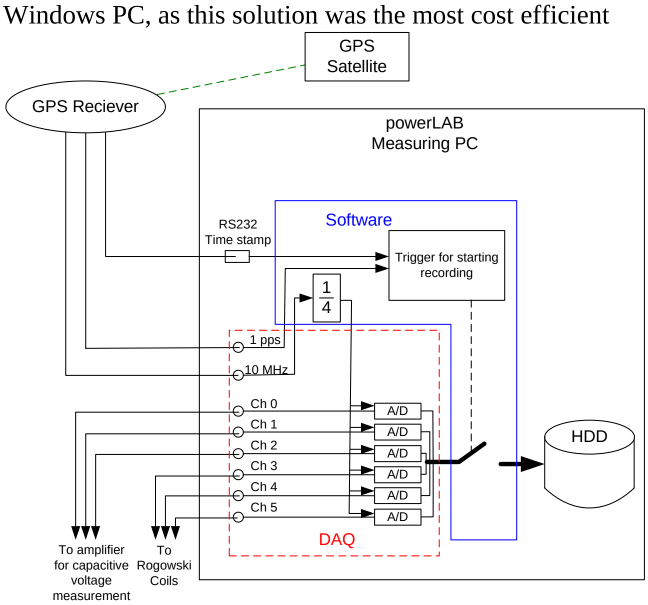

Figure 1 Principle diagram of measurement system

The system is an extension of DELTA's exciting measuring system for power quality measurements according to IEC 61400-21 [3]: powerLAB.
The data acquisition card is a PCI-card from National Instruments, it features simultaneous sampling of 8 channels at a maximum sampling rate of 2.5 MHz with a resolution of 14 bit. Saving data in LabView's TDMS-format gives 30 Mb data pr second from 6 channels. The operative system must be able to stream this amount of data to an external Firewire harddisk or an internal SATA harddisk.
The synchronization is based on a GPS timing device where one pulse per second and a 10 MHz clock signal are available together with a time stamp via serial interface. The precision of the GPS time is 100 nanoseconds. The time stamp is used for starting the measurement simultaneously in the three measuring points. The 10 MHz is divided by four to get a 2.5 MHz signal used for driving the AD-converters.
As break-out box NI suggest BNC-2110 Noise-Rejecting BNC I/O Connector Block, but test showed that the synchronization 10 MHz signal was easy disturbed in the connector block. The 10 MHz signal was disturbed by the measurement signals when switching with wind turbine and a new break out box was therefore designed, where all measuring signals and timing signals has a good ground reference. The new break-out box is also grounded together with the rest of the system.

3.2. Transducers

Measurement of high voltage at the transformer of a wind turbine involves some safety issues that have to be addressed, and furthermore connecting laboratory test equipment on a WT is generally not possible, therefore a capacitive voltage sensor system has been developed which utilizes standard high voltage equipement, thereby resolving the safety issues.
A standard high voltage T-connector is connected to the transformer as a "dead-end" and the phase to earth voltage is measured using a capacitive end-plug. The capacitive end-plug is normally used for control measurement only and not for precision measurement. The T-connector with capacitive end plug is shown in Figure 2. DELTA has developed and builds an amplifier for precision measuring with high frequency response on the end-plug. As the capacitance is very small, the measuring system is very sensitive to electrical fields and an efficient shielding is necessary to get a useful measurement. As the capacitive end-plug is not produced for precision measurements each end-plug / T-connector /amplifier combination has been calibrated with a known voltage signal before use.
The voltage measurement system consists of a standard T-connector with a capacitive end plug and an amplifier.
The specification of the system are: 20 nF input capacitance, giving a voltage ratio of 8500 : 1 depending on the end-plug, maximum input voltage of 85 kVpeak, output voltage ± 10 V, LF (3 dB) fL = 1 Hz and HF (3 dB) fH= 10 MHz.

Currents are measured with a Rogowski-coil sensor from Powertek. The flexible Rogowski-coils were chosen because the installation is very easy and it is always possible to get the coil around the cables. The specification is: 10 mV/A, peak current 600A, LF (3 dB) f_L = 0.55 Hz and HF (3 dB) f_H= 3.0 MHz.

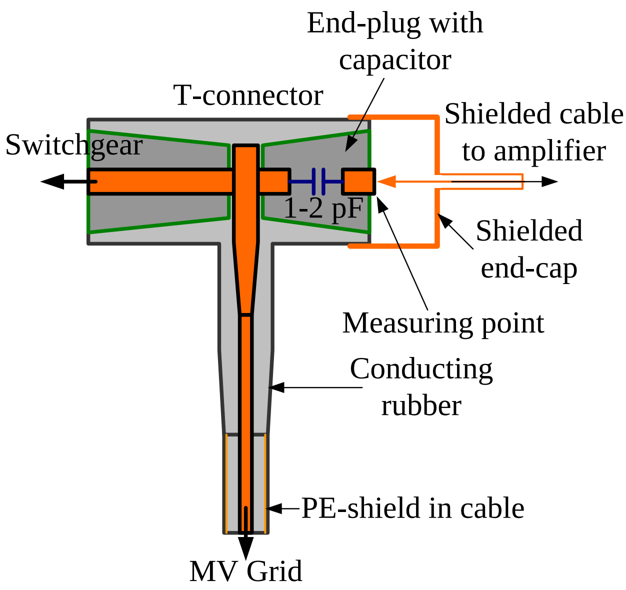

Figure 2 Capacitive measuring end-plug in standard T-connector.

3.3. Test of the system

Test of the system showed, that saving with 30 Mb/s is close to the limit of what can be possible on a Windows PC. To make the system continuously running, it was necessary to completely reinstall the PC and only have the must critical processes running. After this the data-recording runs continuously until the hard disk is full.
Synchronization was tested by setting up the three systems together and measuring the same signal. The three GPS receivers were placed on each side of the building, so the GPS receivers did not find the same satellites. After 5 minutes of recording the synchronization was still within one sample (400 ns) between the three systems.

The voltage sensor system is calibrated in the laboratory, and frequency response, temperature dependency and voltage linearity is documented.
Frequency response is tested using a network analyzer and the result shows that the system is linear up to 10 MHz (1 dB). In the high voltage laboratory the voltage linearity of the system is tested. The voltage ratio (input divided by output voltage) is linear up to 20 kV within 1 %. To determine the relation between temperature and the voltage ratio the system was cooled down to – 25°C and heated to +55°C. This showed the voltage ratio of the system is within 1 % in a temperature range from +10°C to +40°C and has a temperature coefficient on the voltage ratio -650 ppm with 20°C as reference temperature.

The data stored on the hard disk is easy to read and display using a standard LabView TDMS reader.

4. Measurement results

Measurements where made on Nysted Offshore Wind Farm, Denmark. The 72 off-shore wind turbines are placed in a parallelogram consisting of eight rows of nine wind turbines each. The wind turbines are delivered by the Danish wind turbine manufacturer Siemens Wind Power (BONUS). The tower is 69 m and the rotor has a diameter of 82 m. Each wind turbine has a max. production of 2.3 MW. The total output of the off-shore wind farm is 165.6 MW.
Measuring points were chosen to be (see Figure 3):

- At the transformer platform after the circuit breaker for radial A (the radial on the west side of the farm).
- At wind turbine A01, the first turbine in the radial A.
- At wind turbine A09, the last turbine in the radial A.

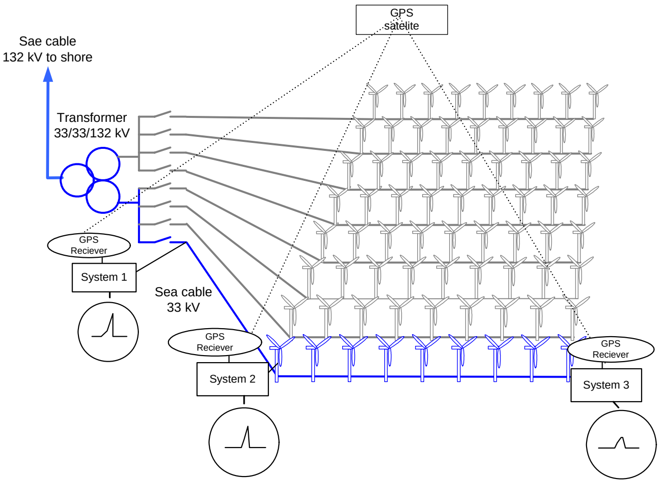

Figure 3 Measuring points at Nysted Offshore Wind Farm

Several switching transients where generated and recorded by switching the line breaker for the radial A and the load breaking switch in turbine A09.

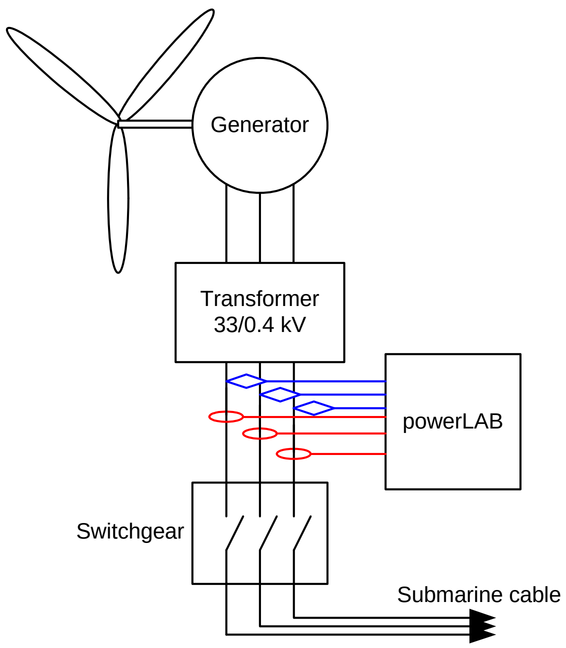

Figure 4 Measuring points in the wind turbine

4.1. Closing of line breaker radial A

The line breaker for the first row of wind turbines (radial A) was switched off and on to record the energisation of the radial cable and the magnetisation of the transformers in the nine wind turbines connected to the radial.
The opening of the breaker is not shown here. For the closing of the line breaker the voltages are shown Figure 5 and the currents in Figure 6. Time /div is 20 ms.
The voltages measured at the three locations are very similar at the ms time scale, and except for the first few milliseconds immediately following the energization the voltages appear not to be distorted (i.e. the short circuit power level is high enough to sustain the voltage during energization of a radial without significant distortion).

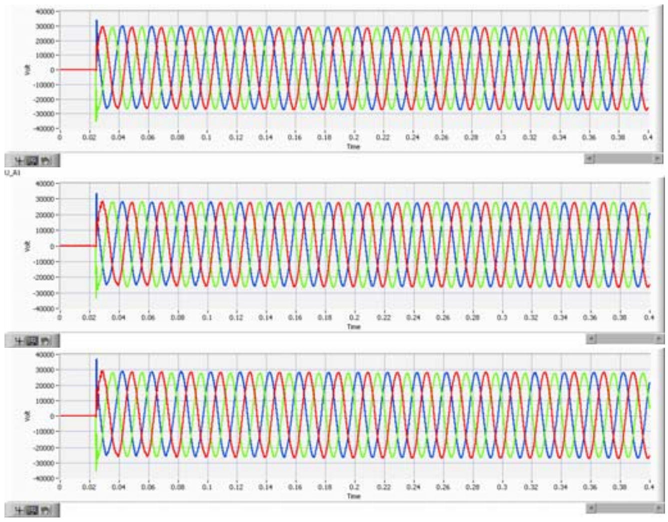

Figure 5 Voltage measurements at three locations during closing of the line breaker. Top: Transform platform, Middle: Turbine A01, Bottom: Turbine A09. Time: 20ms/div

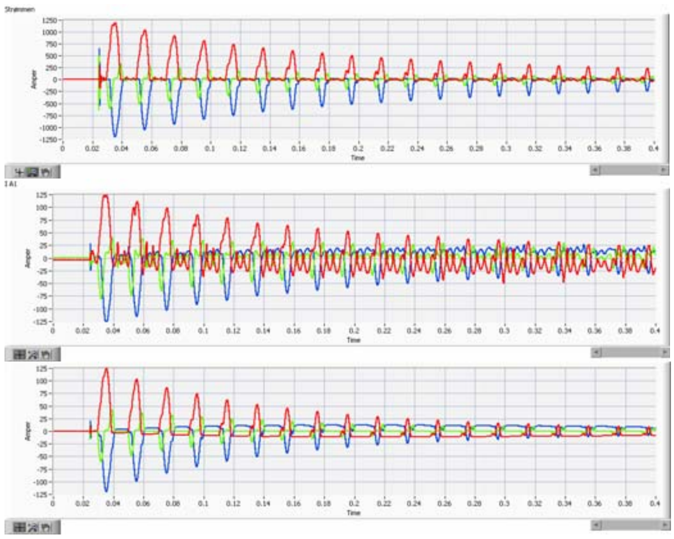

Figure 6 Current measurements at three locations during closing of the line breaker. Top: Transform platform, Middle: Turbine A01, Bottom: Turbine A09. Time: 20ms/div.

The currents measurements clearly show the effects of the saturation of the wind turbine transformers which results in very asymmetrical currents. In the wind turbines peak currents reach 125 A (i.e 2.2 p.u.) in the first period and decrease to under 1 p.u. after 10 periods. Although the wind turbines are identical is the current more distorted in turbine A01 than in turbine A09.

On the transformer platform the measured current peaks at 1190 A (i.e. 2.3 p.u.)

With a 50µs/div resolution is it possible to see the voltage wave traveling from the transformer platform to turbine A01 and to A09 during the period after closing of the breaker. The closing of the breaker does not happen simultaneously for the three phases: there is a delay from phase 2 (green) is closed to phase 1 (red) of 227 µs and from phase 2 (red) to phase 3 (blue) another 140 µs. It can be noted that the energization of an individual phase doesn't affect the voltage of the other phases. This is because the phase cables are shielded and grounded individually, and therefore there is no appreciable capacitive coupling of the phases.

The amplitude of the voltage at the transformer platform is 18.3 kV and the front of the wave is very sharp.

It takes the wave 21 µs to travel from the platform to A01, where the front of the wave is rounded due to damping in the cable. The amplitude is of the front is 15.5 kV. It takes the wave 25 µs to travel from A01 to A09.

At A09 the wave meets an open end and the voltage is doubled to 27 kV and the front is rounded.

The wave travels back to A01 in 25 µs and from A01 to the transformer in 21 µs.

The corresponding current measurements, shown in Figure 8 show the primarily capacitive current charging the submarine cable of radial A measured at the platform reaching 600 A peak, and narrow 15 A to 30 A current peaks less than one microsecond wide measured at wind turbine A01 and A09 due to the charging the capacitances of the MV transformers in the wind turbines.

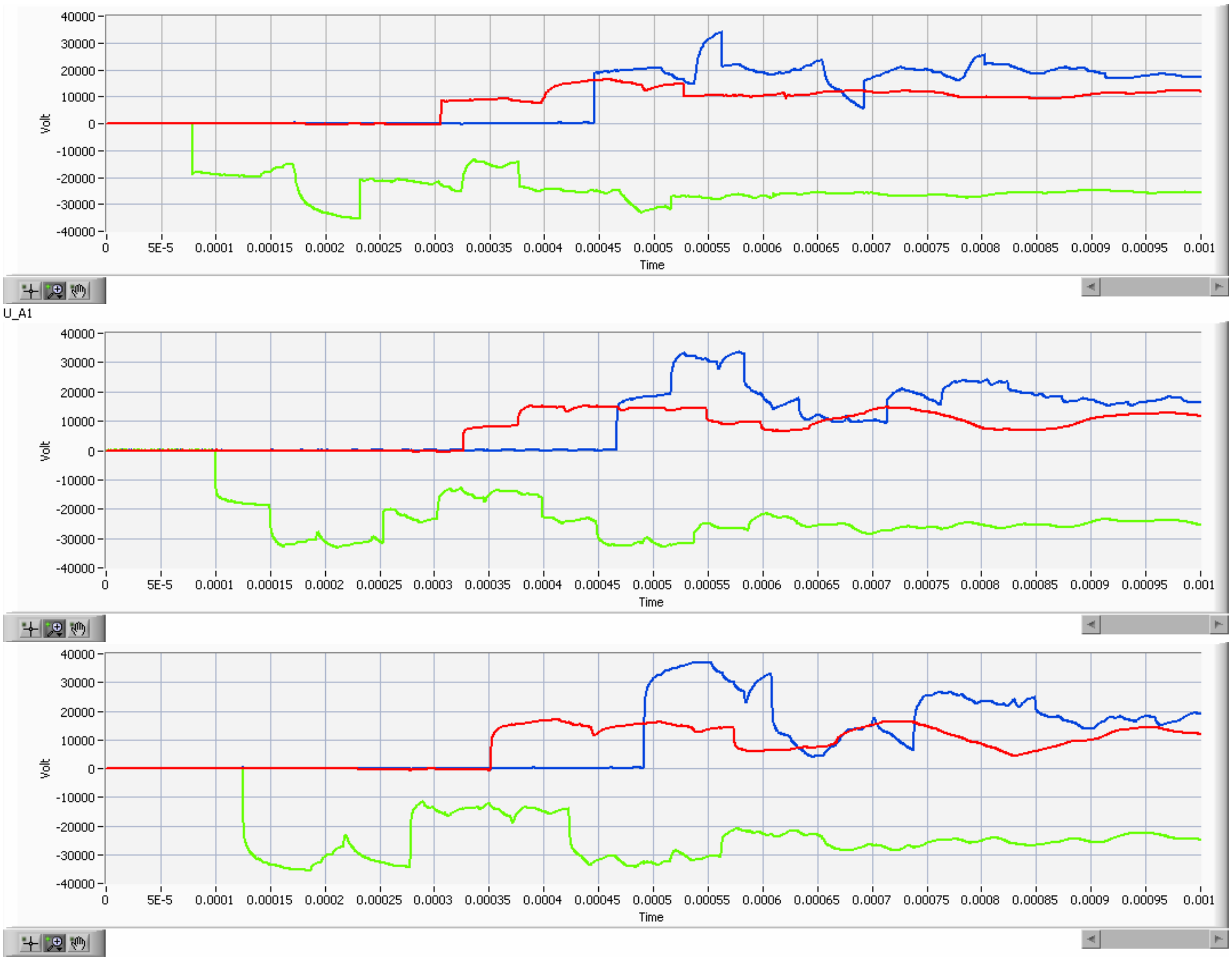

Figure 7 Voltage measurements at three locations during closing of the line breaker. Top: Transform platform, Middle: Turbine A01, Bottom: Turbine A09. Time: 50µs/div.

Figure 8 Current measurements at three locations during closing of the line breaker. Top: Transform platform, Middle: Turbine A01, Bottom: Turbine A09. Time: 50μs/div.

4.2. Closing of the load breaking switch in wind turbine A09

Opening and closing of the high voltage switch in a wind turbine is a normal operation that can happen many times during the life time of the offshore wind farm. It is therefore important to investigate if this practice produces any transients that can affect the wind turbine transformer or even the other turbines in the wind farm.

Figure 9 shows the voltage and Figure 10 shows the current in the three measuring points during closing of the switch in wind turbine A09. The other wind turbines of radial A including A01 were stopped during this test. There is no sign of any voltage transients from the switching on neither A01 nor at the transformer platform, as the short circuit power in the wind farm is high enough to hold the voltage during magnetization of the transformer of A09. The measurement in A09 show the current drawn for magnetization of the wind turbine transformer, which peaks above 125 A (the current probes saturates at 125 A) which is significantly higher than what was measured when switching with the line breaker for radial A. At wind turbine A09 the saturation of the transformers result in a very asymmetrical currents and peak currents above 125 A (i.e. 2.2 p.u.) in the first six periods. After 18 periods the peak current has fallen to below 1 p.u. The measurements performed in wind turbine A01, which was connected but not operating, show some distortion of the no load currents.

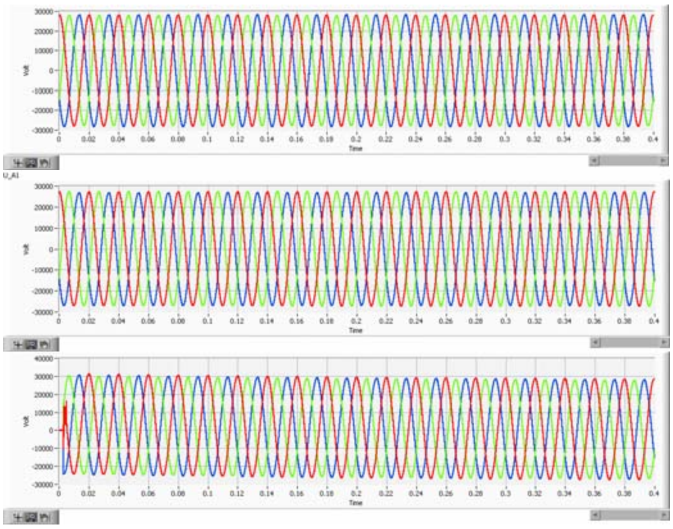

Figure 9 Voltage measurements at three locations during closing of switch in the wind turbine A09. Top: Transform platform, Middle: Turbine A01, Bottom: Turbine A09. Time: 20ms/div.

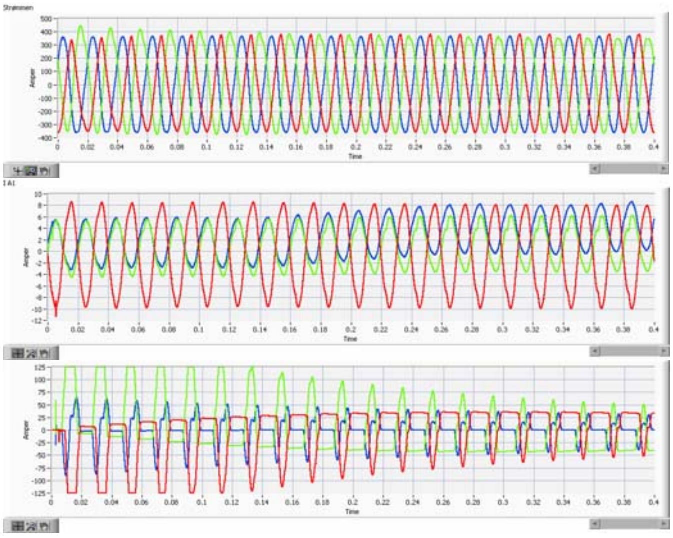

Figure 10 Current measurements at three locations during closing of switch in the wind turbine A09. Top: Transform platform, Middle: Turbine A01, Bottom: Turbine A09. Time: 20ms/div.

5. Conclusion

Three GPS synchronized measuring systems have been built and used for simultaneous measurement at three different locations in a large off-shore wind farm. The precision of the synchronisation is better than or equal to one sample (i.e. 400 ns). The sampling frequency has been set to 2.5 MHz and simultaneous recording of six channels at 14 bit resolution totally producing 32 Mb of data per second is recorded onto a harddisk. A voltage measuring system for medium voltage based on standard T-connectors with a capacitive end-plug and an amplifier has been developed for the measurements. The voltage measuring system has a linear frequency response up to 10 MHz, the voltage ratio is also linear up to 20 kV.

Measurements have been made with the three systems at Nysted Offshore Wind Farm, Denmark and measuring results has been presented.

The measurement results will be used for verification of simulation models of the wind farm thereby making it possible to have a more accurate determination of transient voltage conditions in a wind farm during faults and switching events.

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