Substation monitoring and control

Part 1.

Capacitive voltage measurement

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These articles concern the subject of monitoring and controlling substations, primarily in the medium voltage power grid.
The articles investigate measurement techniques and remote control options.
Part 1 touches upon the subject of voltage measurement, while Part 2 covers the subject of current measurement. Part 3 describes remote control and substation control strategies.

Precision requirements for monitoring

While the requirements for measurement on delivered power are rather strict, the precision related to generalized monitoring are less so. Often an error margin of up to 5% on the absolute measurements is acceptable. The measurements may provide vital information supporting decisions on service needs and grid control.
The lower requirement level enables new measurement methods and uncalibrated installations.

Phase measurement

If one wants to measure the direction of the energy flow between two points in a power grid, the phase of the current compared to the phase of the voltage must be known. The energy direction is of special interest in case of short circuits in a decentralized power grid. A directional short circuit indication can point towards the direction of failure immediately.

The measurement of reactive power also requires concurrent voltage and current phase information.
The reactive power may be found using:

$$Q = U_{RMS} \cdot I_{RMS} \cdot \sin(\alpha)$$

where α is the angle between the current and the voltage (see Figure 1).

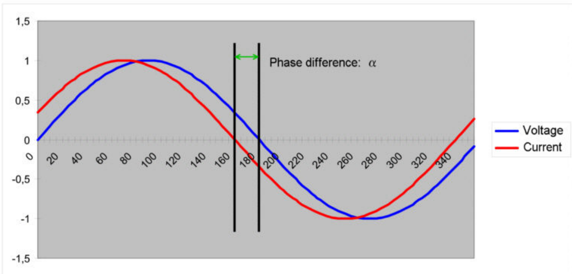

Figure 1

Therefore, it is important to ensure correspondence between the voltage and current phase measurements.
Voltage is traditionally measured using voltage transformers. In this context, however, another principle and implementation will be described. The principle is based on capacitive voltage division.

Capacitive voltage measurement

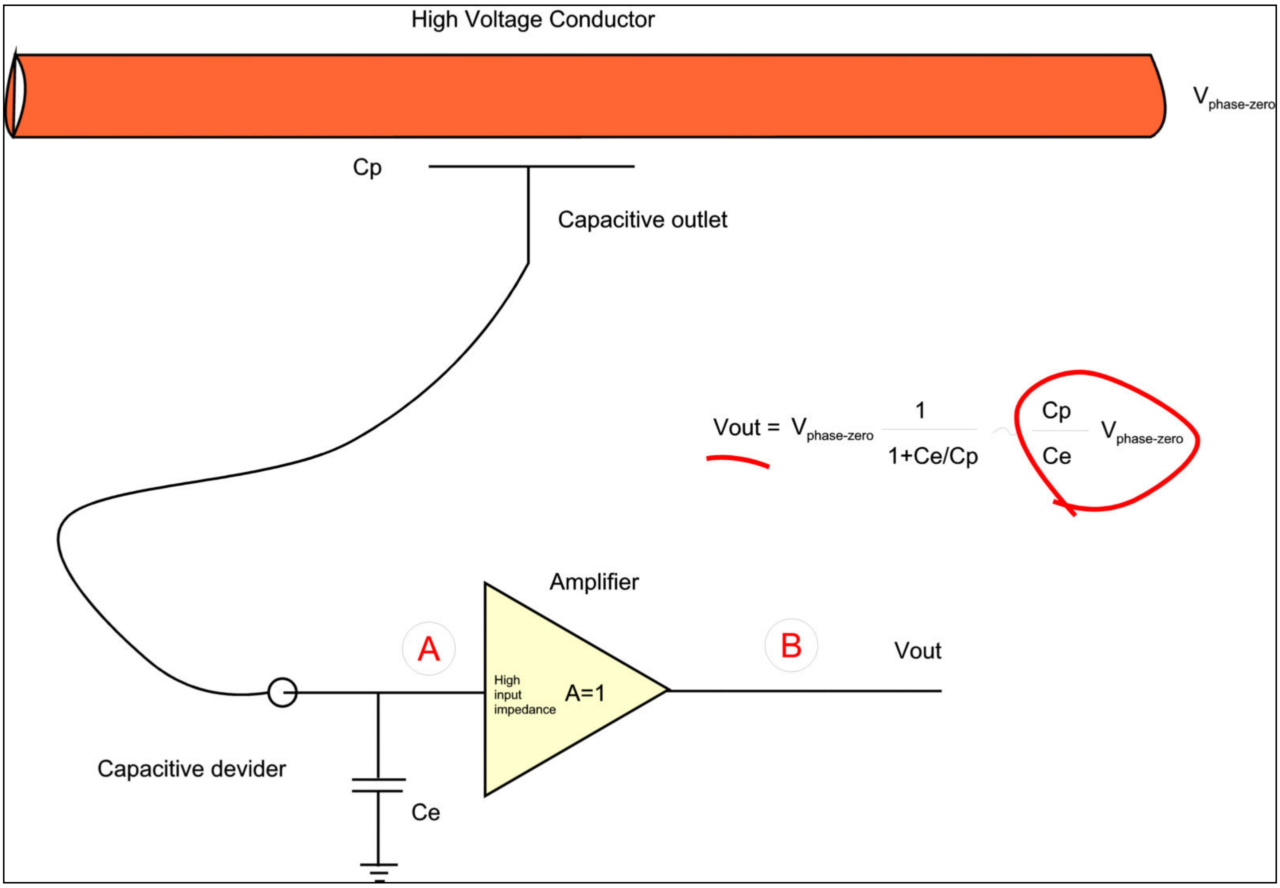

Figure 2

An isolated metal sheet placed near a high voltage conductor will experience a voltage level determined by the conductor. It will act as a capacitor, where one side is the high voltage conductor and the other side is the metal sheet. If this 'capacitor' is connected to a traditional capacitor which is related to earth potential, the configuration can be represented by the circuit of Figure 3.

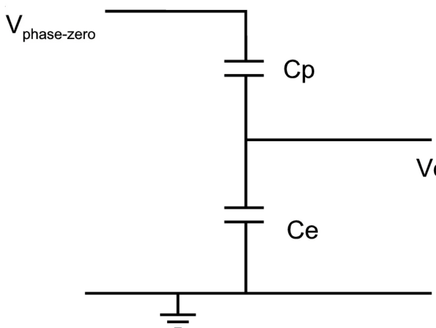

Figure 3

A capacitor is an impedance. The magnitude of the impedance is frequency dependent, and may be expressed by the equation:

$$Z_C = \frac{1}{2\pi \cdot f \cdot C}$$

where f is the frequency and C is the capacity.

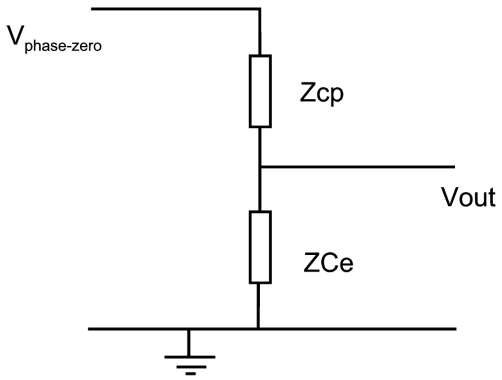

Figure 4

Figure 4 is a representation of Figure 3 using lumped elements. Here, it is apparent that the setup is a voltage divider.
The voltage divider has an output voltage of:

$$V_{out} = \frac{1}{1 + Z_{cp} / Z_{ce}}$$

By inserting the expression for the impedances, and using the fact that $C_{ce} >> C_{cp}$, the following relation can be found:

$$V_{out} = V_{phase-zero} \frac{1}{1 + C_e / C_p} \approx V_{phase-zero} \frac{C_p}{C_e}$$

As a remark there is no frequency dependence in the produced output, V_{out} .

The frequency
It is often assumed that the fundamental frequency in the power grid, that being either 50 or 60 Hz, is all important in measuring setups. However this is often not the case when we are looking at error situations or coupling situations in the network. Whenever fast intentional or unintentional changes in a power grid occurs the voltage and current may exhibit high frequency behavior in the form of sudden jumps and oscillations. From a measurement point of view these jumps may be crucial to detect correctly. In terms of voltage information these details can be easily measured using the capacitive voltage division principle, as it is measures linearly (correctly) over a large frequency span. A traditional measurement transformer or the secondary side of a high voltage distribution transformer tends to eliminate the higher frequencies from the measurement.

The phase
Another important parameter to appreciate, when using the capacitive voltage divider, is the phase. Using an ideal capacitive division there will be no phase delay or distortion of any kind of the fundamental grid frequency, nor of any other frequencies. In practice an upper and lower bound applies however, ranging from approximately 1 Hz up to the MHz range, due to small resistive and inductive components.
The capacitive voltage divider is thus technically far superior compared to the transformers, while being price competitive and relatively easy to install.

Practical capacities
The voltage in the distribution network of 10-36kV give rise to certain isolation requirements. A number of different options exist for practical capacitive outlets. A straight forward type is the outlet on the elbow connectors. Their original purpose was simple voltage testing.

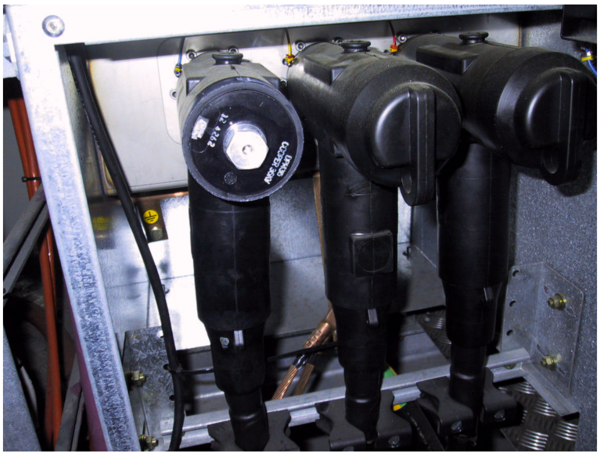

Figure 5

The capacitive outlet is typically made of two pieces of copper as shown in Figure 6. One may calculate the capacity using the approximation:

$$C = \varepsilon \frac{A}{d}$$

Where ε is the permittivity of the insulating material, A is the area of the piece and d is the distance between the pieces.

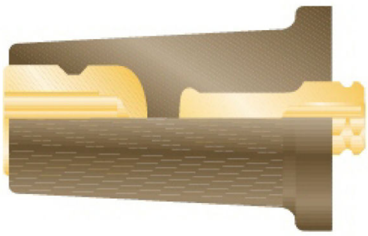

Figure 6

The typical capacity for the elbow connectors is 2.0 pF. This is a very small capacity, but if we earth this capacity with a 2nF capacity we will get a voltage division of approx. 1000.
A phase-to-ground conductor voltage of 10 kV peak will thus produce an output of approximately 10 V. This voltage is easy to handle in measurement PLCs.

Safety considerations

A capacity of 2 pF can contain a very small electrical charge Q (= C ∗ U). This electrical charge is of no risk for the operating personnel at any realistic voltage level. Nevertheless, since an unconnected capacitive outlet will obtain high voltage levels, it is important to ensure appropriate containment and earthing of such outlets, since unwanted electrical discharges may otherwise occur.

Electrical fields

Some vendors of elbow connectors accept that earthing of the capacitive outlet is done without having the original earthing encapsulation, while other vendors are more reluctant. A shielded connection should therefore always be used as show in Figure 7.

Figure 7

Integrated capacity in the bushing

Another excellent place for the capacitive coupling to the high voltage conductor is in the bushing (see Figure 8).

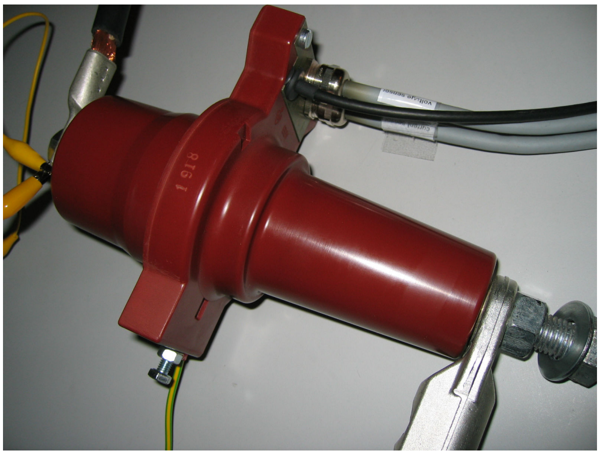

Figure 8, Bushing with integrated capacitor (Fab. ABB) photo from lab. test

Capacitive isolators

In some cases it is not possible to get access to elbow connectors. Instead one may use isolators with an integrated capacitor. These isolators may be connected directly to an open phase conductor or directly to the high voltage side of the distribution transformer.

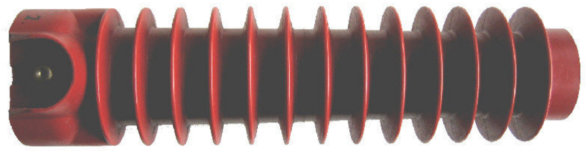

Figure 9

The capacity in these isolators are often much higher than the elbow connectors, in the area of 50-100pF.
This implies a higher charge to handle, but an additional earthing ensuring the safety makes this alternative quite useful.
The capacitive isolators are often made of a ceramic capacity which can exhibit some un-linearity. For ordinary control purposes this is without significance.

New measurement options
The capacitive measurement method gives new options for measuring the harmonics i.e. up to the 50th which is at 2500Hz. Using adequate calibration a very high precision is obtainable.
When measuring partial discharge (PD), capacitive voltage division is very useful as the signals of interest have frequencies in the MHz range.

Figure 10, Measuring amplifiers for measurement at very high frequencies

The next article will detail a method on performing accurate current measurements.

Substation monitoring and control

Part 2.

Current measurement

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The reactive power may be found using:

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where α is the angle between the current and the voltage, see Figure 11.

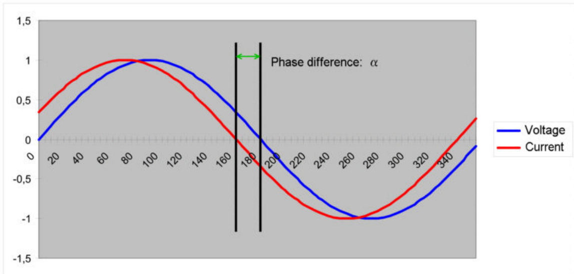

Figure 11

It is therefore important to ensure correspondence between the voltage and current phase measurements.
Current is traditionally measured using current transformers. In this context, however, another principle and implementation will be described.

Measurement methods

Using a traditional current measurement transformer (i.e. having a conversion of 100A:1A or 1000A:1A) gives a precise measurement of the current amplitude at 50 Hz. The measurement of phase is a vital issue, as this is subject to phase delay variation at 50 Hz and other frequencies when using a transformer.

Current measurement transformers

A number of good measurement transformers are available, where the high voltage conductor is the primary winding, and the

secondary winding is a Rogowski coil. These measurement transformers display a reasonably flat frequency characteristic up to several kHz. Unfortunately it is usually not possible to get data about such characteristics from the vendors for frequencies other than 50/60 Hz. Through detailed tests of some of these transformers, it is found that the result is heavily influenced by how the conductor is placed with respect to the centre of the coil. Additionally the frequency characteristic is found to vary depending on the load impedance. The frequency characteristic is of interest, as it is of major importance when measuring current transients. The transients typically contain a broad spectrum of frequencies.
If the sensitivity of the transformer increases at higher frequencies, which is often the case, there is a risk that it will indicate a current higher than a certain short circuit level, introducing a risk of producing false alarms.

An example of an integrated current transformer is shown in the bushing in Figure. 12 (Fab. ABB).

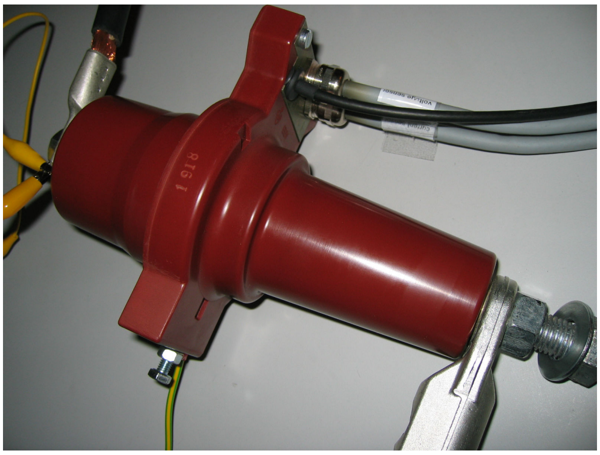

Figure 12, Combisensor with outlets for voltage and current, Lab. photo.

New current measurement methods
All current measurement transformers have a certain size and must be in series with the conducting cable or placed around the conducting cable. This might be expensive and not very practical for a number of reasons. It is worth considering the use of magnetic field sensors to measure the current of cables.

H-field measurements
A current carrying conductor will always give rise to a magnetic field as shown in Figure 13.

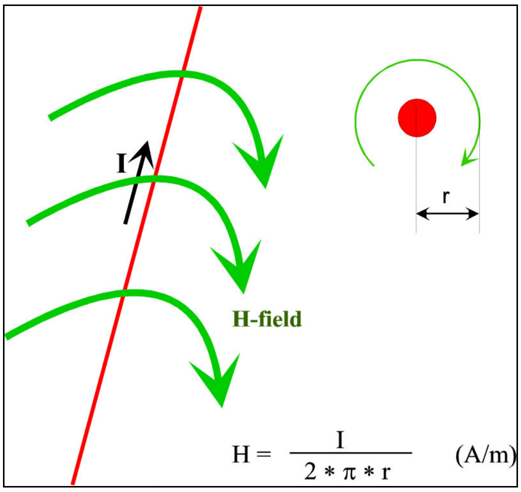

Figure 13

As can be seen in the formula of Figure 13, the H-field in a certain distance from the center of the conductor is proportional to the current in the conductor. This proportionality implies that the output of a magnetic field measurement can be directly related to the current using an appropriate scaling. H-fields can be measured by semiconductor components. Another alternative is using optical sensors, but these are prone to sensitivity drifts due to vibration, have isolation issues due to conducting moisture depositing on the optical fibers, and actual setups often need calibration for each installation. Semiconductor sensors can measure the magnetic field strength with a high resolution and can therefore be placed at relatively large distances from the high voltage conductor.
In principle the semiconductor sensors have a potential close to earth potential, meaning that they must be placed at a decent isolation distance.

H-fields cannot be blocked, however they may be slightly dampened in cases where circulating currents are induced in conducting materials (eddy currents). This leads to the requirement that sensor systems must be calibrated on a type basis. Note that this is a one-time calibration, which applies to all future installations on a given type of equipment.

Shielded cables

Whether measurements are performed on shielded or unshielded cables is in general of no significance, however, in case of a short circuit between shield and conductor, the current running through the shield will be of equal magnitude but opposite direction of the current of the conductor. This results in no magnetic field outside the cable, giving rise to unwanted sensor readings. Therefore it should always be evaluated if an additional earthing should be established or if other arrangements are necessary.

3-phase measurements

In many cases cables are placed with all three phase conductors in close proximity of one another. This implies that the H-fields from the individual conductors are superimposed (mixed) on one another, see Figure 14.

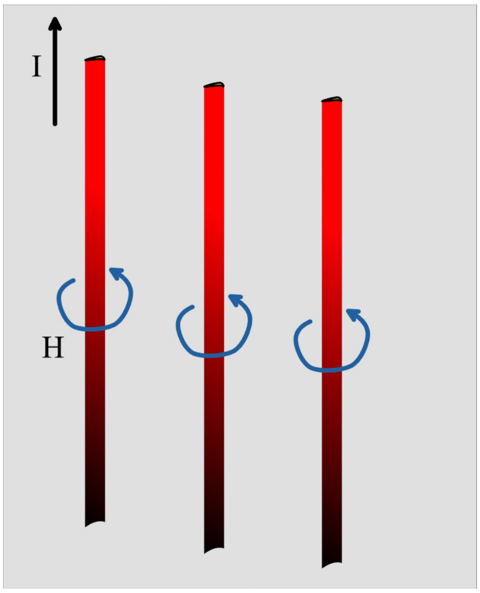

Figure 14, H-field from 3 phase conductors

Reyroll

The old Reyroll equipment is a good example of a type of system, where only semiconductor based sensors are suitable to measure the currents in the individual conductors, because the cable ending is enclosed in a big encapsulation containing isolating fat and therefore not accessible. From outside the casing it is possible to measure the H-fields that the individual conductors generate. The fields are mixed and to some extent also skewed phase-wise due to very high iron content in the casing. Using appropriate type calibration and signal processing, it is possible to filter the measured signals, such that the current of the individual conductors can be found. The precision for this type of sensors is 3-5% for the absolute magnitude, which is adequate for controlling purposes. It should be noted that higher accuracies are usually obtained when there is less iron in the equipment.

Figure 15, Reyroll having a current sensor

Installation requirements

Industry feedback and experience reveals that it is essential for sensor systems to be (1) easy to mount/install, (2) require no site-based setup in terms of calibration, and (3) should not in terms of the location of equipment interfere with other potential service needs, i.e. the system should preferably not encircle the conductors.

Especially in compact switchgear, there is not much room for measuring equipment, but using the presented technique the solution is straightforward – a semiconductor based sensor placed behind the cables and at a distance that meet all isolation requirements.

The ultimate sensor system

A sensor system which covers both advanced and basic monitoring needs in the medium voltage grid must be capable of reporting the following parameters: Current, voltage, power, var (reactive power), and direction of energy flow, and give an alarm, including directional indication, in case of short circuits. Finally it must all be reported home to the controlling SCADA system.

Such a system has been developed. The companies ABB in Norway and Eaton/Holec in Holland have been very cooperative in supplying equipment for type calibration and tests of such a sensor system. The resulting product is highly adaptable to various physical measurement setups, and has been shown to produce robust results with a precision of 1-3% in normal operation (up to 5% in special cases) on individual current measurements, with a phase precision of 1-2 degrees.

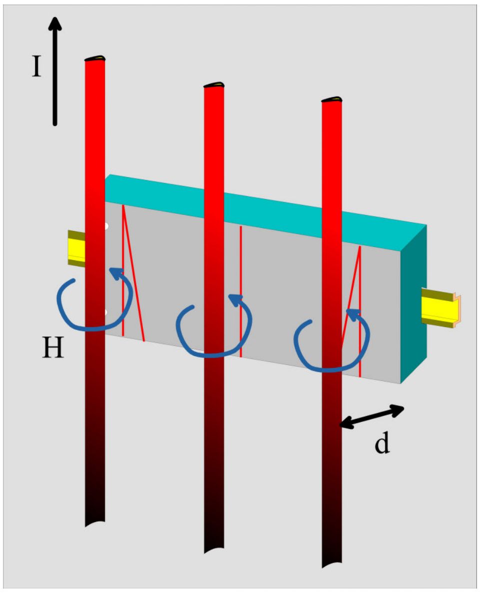

Figure 16

Focusing on compact switchgear, it is indicated in Figure 16 that the distance between the vertically mounted cables and the back side of the compartment is fixed, which allows for a high accuracy without the need for calibration.

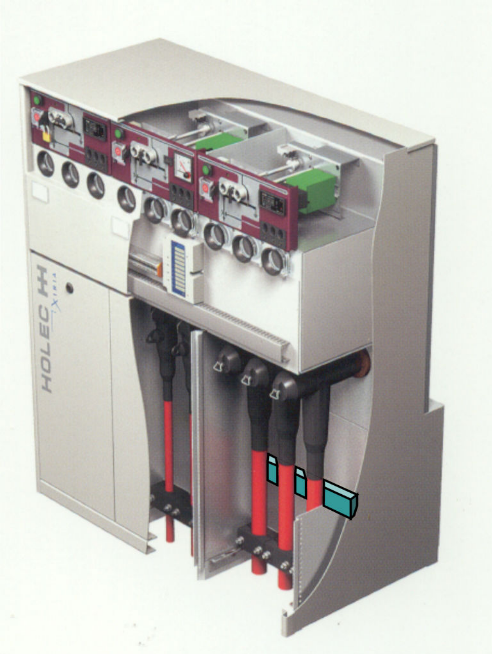

Figure 17, Xiria switch gear with the sensor system indicated by a green box in the lower right corner

Sensor data processing

The rest of the job is a matter of only computer calculations – maybe not the most simple mathematics – but this is no problem as long as it all functions and the measuring system is stable towards all thinkable and non thinkable situations.

The stability when encountering short circuit situations is very important. It has been decided that a short circuit less than two 50Hz periods should not produce an alarm. This simple definition prevents alarms in case of intentional couplings in the power grid.

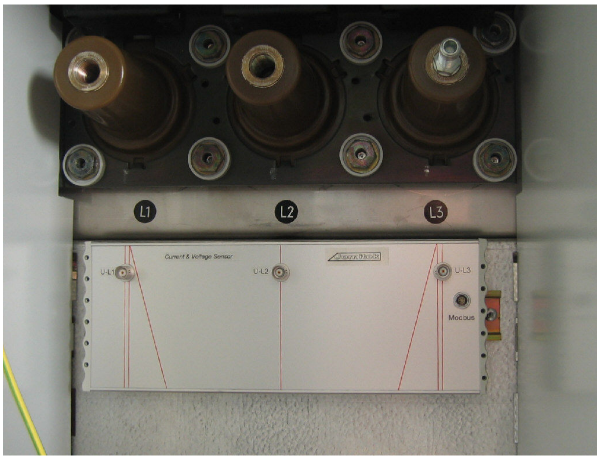

Figure18, Sensorbox in an ABB SafePlus section

In the last article in this series, the focus will be on how the digital signals are handled, how to communicate locally, as well as with a central SCADA system.

About the author:
Peter Johansen is the founder of the 10 year old company Jomitek in Denmark. Jomitek specializes in measuring electrical and magnetic fields. More information is available at www.jomitek.dk