SUBSTATION AUTOMATION

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ABSTRACT

A practical implementation of simple and phase-correct measurements of current and voltage in substations and how to derive power, energy direction and short circuit direction. Digital I/O and communication is included.

INTRODUCTION

This article concern the subject of monitoring and controlling substations, primarily in the medium voltage power grid.

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 un-calibrated 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.

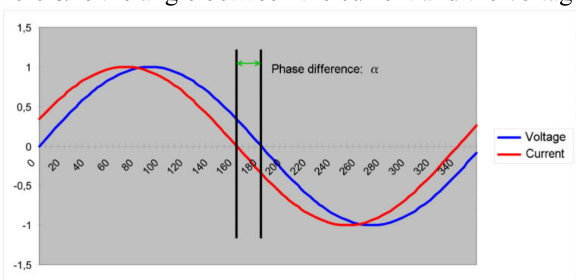


Figure 1

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

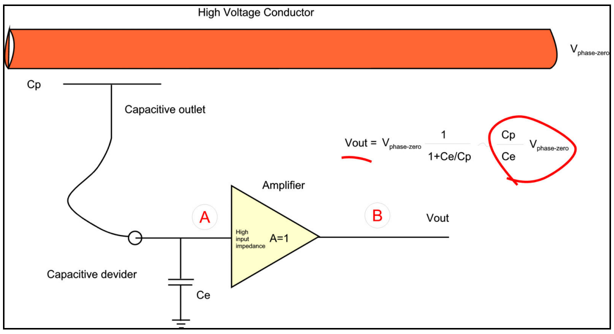


Figure 2

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 a traditional voltage devider.

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.

Figure 3

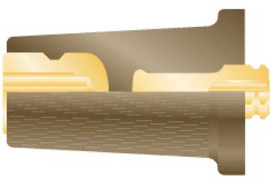


Figure 4

The capacitive outlet is typically made of two pieces of copper as shown in Figure 4. One may calculate the capacity using the approximation: $C= \varepsilon\ (A/d)$
Where ε is the permittivity of the insulating material, A is the area of the piece and d is the distance between the pieces.
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.

Electrical fields

To control the electrical field and to reduce interference from outside,a shielded connection should be used as show in Figure 5.

Figure 5, Capacitive shielding and connection

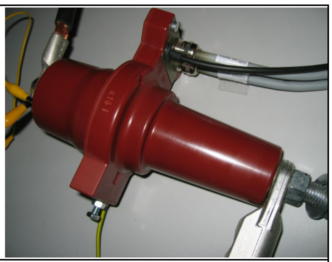


Figure 6, Bushing with integrated capacitor (Fab. ABB) photo from lab. test

Integrated capacity in the bushing

Another excellent place for the capacitive coupling to the high voltage conductor is in the bushing (see Figure 6).

Capacitive insulators

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

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.

PART 2.
CURRENT MEASUREMENT

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 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

Curent measurement transformers display a reasonably flat frequency characteristic up to several kHz. 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. 6.

New current measurement methods

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

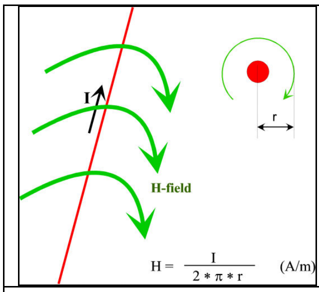


Figure , H-field along a conductor.

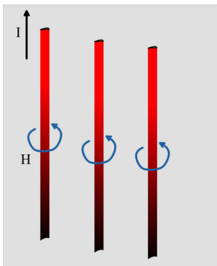


Figure 8, H-field from 3 phase conductors

As can be seen in the formula of Figure 7, 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.
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.

The ultimate sensor system

Focusing on compact switchgear, 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. 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.

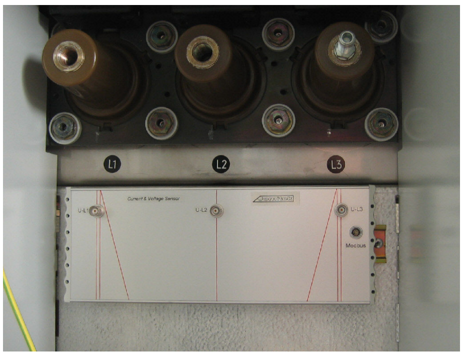


Figure 9, Compact Sensor in ABB SafePlus section

PART 3.
SUBSTATION AUTOMATION

To complete the substation automation the analogue measures are integrated with the digital control and the communicating towards the central remote control system.

The typical substation

The typical substation intended for automation could be a station having 3 cable sections and one transformer section. To get full advantage of automation, the switch gear must be controlled by motors.
The Substation must have a low voltage supply, making sure that a 12-24VDC is available. Often a battery backup is attached to the 24V supply.

The analogue signals

For each section the following analogue signals are relevant: Voltage, Current (amplitude and phase). From those analogue signals some interesting signals may be derived: Power, Reactive power, Energy direction, Short Circuit Direction.

Digital outputs

The digital relay outputs have to control the motor relays for the breakers. It might be somewhat different from one equipment to another, but it usually fits with 2 outputs per section: Breaker in & Breaker out. In a 4-section switchgear the requirement is in total 8 digital outputs.

Digital inputs

For each section it must be possible to read the breaker position. This is implemented in different ways from the suppliers of switchgear. In general 4 digital inputs are needed per section: Breaker in, Breaker out, Earth in and Earth out / Control ready.. For the complete switchgear this becomes 4x4 + 8 extra in total 24 digital inputs.

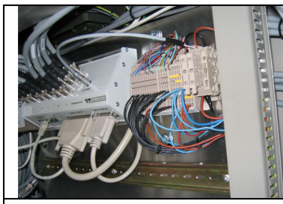


Figure 10, CombisensorPLC

Figure 11, RTU using cage clamp I/O conections.

One substation – one address

To make the installation process and management easy and reliable, all communication lines must be combined through just one box. This box will have just one address

for the communication. The remote control will see the complete substation as one unit.
A local sensor can be the one shown in figure 13.

Communication

A number of communication options are available: Direct cable connection, Radio Modem, GPRS, Optical fibre. The protocols used are Modbus, IEC 60870-101/104.

Local control

During installation and maintenance of automation equipment, it is important to have the option for a local control in the station. This tool must be able to give full control and give 'live' readouts as if it was communication to the SCADA system or even better.
An example of a local control is the Windows program shown in figure 12. This program contains all the functions needed for a local control. The program consist of just a single .exe-file that might be used on a laptop PC brought into the substation by the technician.

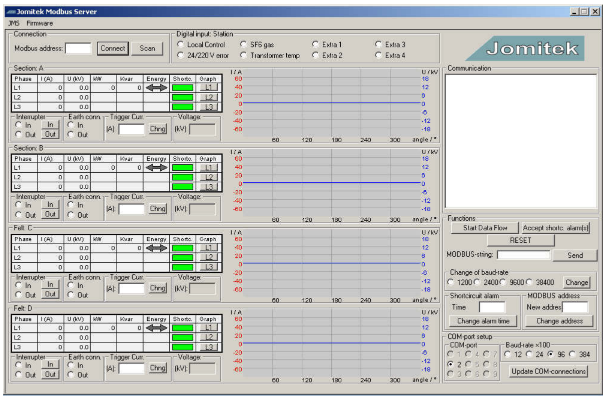


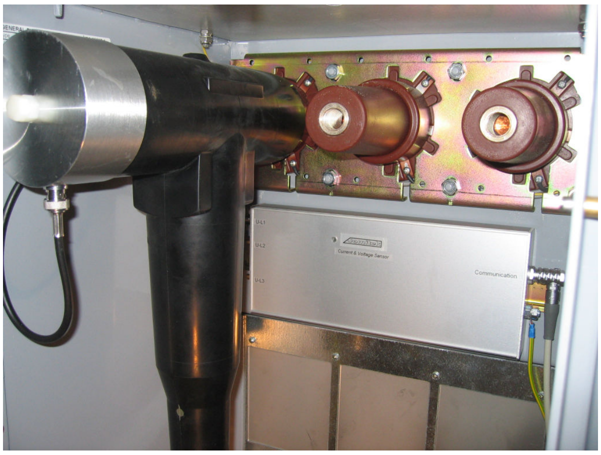
Figure 12, Software for local installation and control of substation.

Practical implementation

Sensors

For new switchgears it is possible to use the ABB c*ombisensor*, where the Jomitek C*ompaktsensor* may be used in both new and old switchgears and only require a very simple installation.

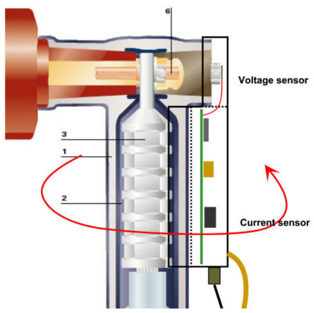
The *Combisensor* is placed inside the bushing and therefore this requires to be mounted in the factory. ABB delivers RTU equipment giving up to 9 analogue channels for this sensor. For this type of sensor Jomitek delivers a *CombisensorPLC*, having in total 18 analogue inputs. The Jomitek box can interface in total 3 sections having each 3 current sensors and 3 voltage sensors, giving 18 analogue inputs.
The *CompactSensor* from Jomitek is an integrated sensor and PLC unit, having a simple interface. It includes a small measurement box which through a thin cable communicates directly to either the communication modem or into the box having the digital I/Os. The *CompactSensor* is available for a number of switchgear types.



Figur 13, The CompaktSensor in a Xiria switchgear. The capacitive voltage is measured at phase R.

The ultimate sensor

The ultimate sensor is a sensor which is integrated into the elbow connector. Tyco/Raychem is the first vendor that will be able to offer such a connector. It will be based on the new shielded and silicone isolated elbow connector RSTI-58 and the connector RSES. The output signal from this connector-sensor will be the same as the output signal from the other sensors mentioned in this article. It will be a serial communication giving data for current, voltage, energy direction, short circuit direction, power and reactive power. If required it will also have the option for frequency analysis.



Figur 14, The new intelligent connector from Tyco-Raychem.