# Application of Non Conventional Voltage and Currents Sensors in High Voltage Transmission and Distribution Systems

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**Abstract: This paper investigates the use of new technologies for current and voltage measurement especially in high voltage equipment. It is focused to the principle of low power current transformers with voltage output and to the resistive-capacitive dividers for voltage measurement. The principles of these devices are explained and their advantages and new features in comparison to known inductive and capacitive principles are discussed. An important step into the world of smart grid is the integration of these sensor principles into the new digital communication. A digital interface, realised with a merging unit, is proposed. With this digital interface the values of current and voltage can be distributed to the secondary measurement and protection equipment.**

*Keywords: current transformers, low power current transformers, voltage transformers, RC dividers, digital interface, merging unit*

## I. New Technologies for the Measurement of Current

### *A. Current measurement with low power current transformers*

Conventional current transformers are built to provide at their secondary terminals not only an accurate image of the primary current with small errors due to the magnetization losses in the core; they are also designed to provide the necessary output power to drive the electromechanical relays and to cope with the burden of the connection wires. The principle of this conventional current transformer is an iron core with a secondary winding (see *Fig.1*). The secondary current represents the primary current and can be calculated with the turns ratio between primary and secondary windings. Because of the non linear magnetization characteristic of the iron core, the accuracy of the conventional instrument transformer depends on the burden range and the range of the primary current.

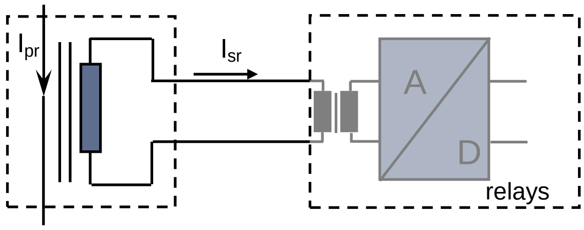



***Fig.1:*** **Principle of current measurement with conventional current transformer**

Modern secondary equipment based on microprocessor technology does not require power that is provided by the current transformer. For this application new designs and technologies for current measuring can be used.

The low power current transformer described in this paper is still using an iron core with primary and secondary winding. The secondary winding of this low power current transformer is short circuited with a shunt resistor. This shunt resistor is part of the secondary winding. The output signal of this device is the voltage across the shunt resistor. (see *Fig.2*)

This output voltage is direct proportional to the primary current and can be calculated to

$$u_s = R_{Sh} \cdot N_1 / N_2 \cdot i_p \,. \qquad (1)$$

The burden to the low power current transformer is mainly the burden or the shunt resistor and the internal burden of the resistance of the secondary winding. This very low burden compared to conventional current transformers is changing the accuracy behavior. The range of linearity is much larger and high accuracy can be achieved in a big range of primary current. In addition the size of the core can be much smaller which reduces the costs and the weight.

![TRENCH logo]

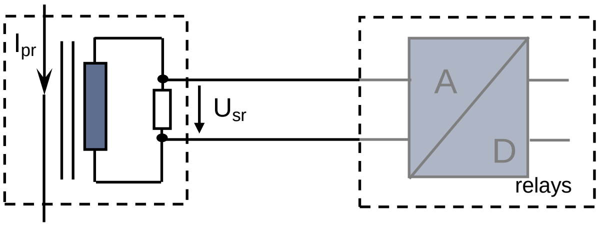



*Fig.2:* **Principle of current measurement with low power current transformer**

These low power current transformers are defined in the IEC standard 60044-8 [1]. The output value is a secondary voltage proportional to the primary current. Typical values are 22.5 mV for a primary current of 50 A, but also other values could be achieved in complete system solutions. Such a low power current transformer can be used to measure primary current up to 2500 A or higher with a very good accuracy range of 0.1%. The same low power current transformer can also fulfill the requirements for protection cores (e.g. 5P according to IEC 60044-1 [2]) up to the short circuit current. In addition it can be used for measuring the transient short time current as defined in the IEC 60044-6 [3] as TPY core. IEC 60044-8 defines such a current transformer as multi purpose current transformer (see *Fig.3*).

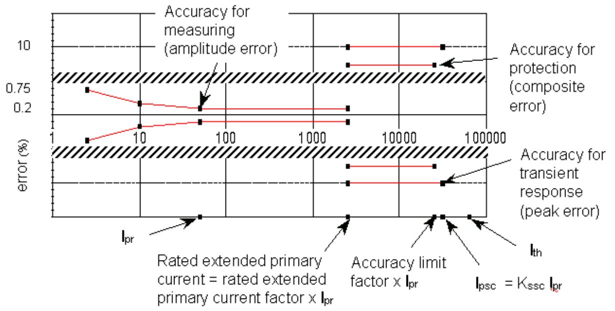



*Fig.3:* **Accuracy limits of multi purpose current transformer according to IEC 60044-8 [1]**

An example of such a low power current transformer is shown in *Fig.4* with accuracy or 0.1 % in the current range of 50 A to 5000 A and accuracy at a short circuit current of 63 kA below 3 %. *Fig.5* shows the measured accuracy of this device.

*Fig 4:* **Low Power Current Transformer for medium voltage systems for rated primary current range between 50 and 5000 A**

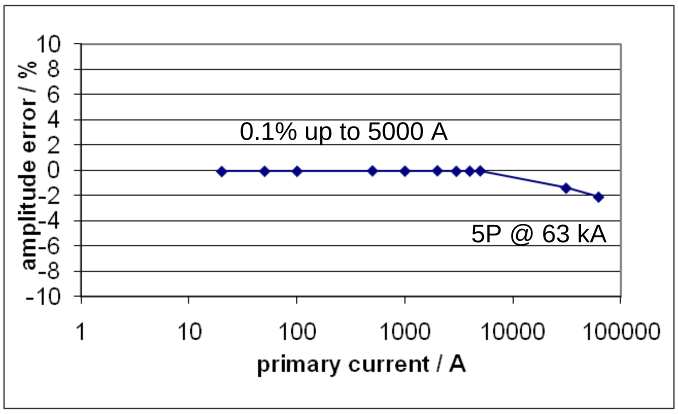



*Fig 5:* **Measured accuracy for the Low Power Current Transformer shown in *Fig.4***

The definition in IEC 60044-8 defines the burden of the low power current transformer as the input impedance of the connected secondary equipment. As example a burden of 20 kOhm means, that any input impedance higher than 20 kOhm is not influencing the accuracy of the low power current transformer.

Using this low power principle allows to standardize the current transformer. The same physical device can be used for a wide range of primary current and for a wide range of applications such as metering and protection. The huge number of different current transformer cores, all calculated for a specific application can be reduced to a small number of different core sizes.

## *B. Current measurement with air core coils*

The second solution for a current transformer with voltage output is based on an air core coil also known as Rogowski Coil. The secondary winding is wound on a non-magnetic core (air core). This current transformer does not show saturation effects and is applied to measure high currents. The Rogowski coil has a secondary output voltage proportional to the time derivative of the primary current. For sinusoidal current this implements a phase deviation of 90°. The signal has to be integrated to get a true picture of the primary current. The secondary voltage of the air core coil is proportional to the dimensions of the winding. For rectangular windings it can be calculated with the following formula [4]:

$$u_2(t) = \mu_0 \frac{Nh}{2\pi} \ln \frac{d_a}{d_i} \cdot \frac{\partial i_p(t)}{\partial t} \tag{2}$$

With
N: number of turns
h: height of the non magnetic core
$d_a$: outside diameter of the non magnetic core
$d_i$: inside diameter of the non magnetic core

The cross section of the non magnetic core has to be very accurate and independent of influences like temperature. This is for most practical solutions limiting the application of air core coils to protection. For revenue metering with high accuracy of 0.1 % or 0.2 % the air core coil is not suitable.

### C. *Current Measurement using optical Faraday Effect sensors*

Beside the passive devices described before, current sensors using the magneto-optic Faraday Effect are known since many years. These sensors are using an optical fibre or a glass ring as sensing element. A linear polarised light wave is travelling through this sensing element and the direction of the polarisation will be changed if there is a magnetic field available. The primary current is generating this magnetic field and so the current can be measured. An opto-electronic unit is then analysing the polarisation state of the light and can provide an output signal representing the value of the primary current.

The Faraday Effect sensor shows no saturation effect and is linear with the current. But the electronic unit and the analyses of the light wave do have some limitations, so that the range of measuring the primary current is not unlimited. In many cases two sensors are necessary to cover the metering range with high accuracy and the protection range up to high short time currents.

The interface between the optical part and the electronic part of the Faraday Effect sensor in many cases need complicated adjustments. This can make the commissioning of these current measuring systems more complicated.

## II. NEW TECHNOLOGIES FOR THE MEASUREMENT OF VOLTAGE

Voltage Transformers are required to provide outputs to measuring and protection devices used in transmission and distribution networks. They transform the high voltage signal into measurable values and insulate this signal from the high voltage potential of the line.

Different voltage measurement principles are in use such as:

- Capacitive Voltage Transformers (CVTs)
- Magnetic Voltage Transformers (MVTs)
- Non-conventional Voltage Transformers such as Resistor Dividers, Capacitor Dividers and RC Dividers

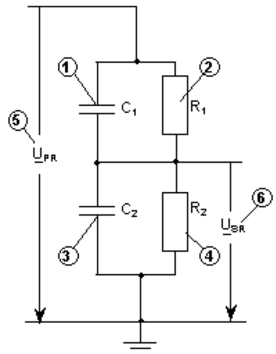
The conventional technologies of CVT and MVT are used since many years for the voltage measurement in transmission and distribution networks. These voltage transformers are designed to measure the voltage of industrial frequency 50 Hz or 60 Hz. Their accuracy for higher frequency is very limited and they are only partly suitable to measure harmonics or transients.

These conventional voltage transformers are providing output power up to several 100 VA. Modern secondary equipment do not need this high output power, therefore other technologies as dividers can be used to measure the voltage .

### A. *Voltage measurement with RC dividers*

Different solutions of non-conventional voltage transformers have been developed, such as high resistive or capacitive dividers. Resistive dividers could achieve a high accuracy measurement results but have poor frequency performance due to the strong influence of the stray capacitance on the bandwidth.

Capacitive dividers have a ratio and phase angle, which changes depending on the burden. A combination of Resistor and Capacitor Dividers results in a Resistor-Capacitor Divider (RC divider), figure 6, which has parallel resistance and capacitance elements. Such a device can be designed to give a frequency independent transformation ratio and phase angle over a frequency range up to at least 1 MHz.




1 Primary Capacitor $C_1$
2 Primary Resistor $R_1$
3 Secondary Capacitor $C_2$
4 Secondary Resistor $R_2$
5 Primary Voltage $U_{PR}$
6 Secondary Voltage $U_{SR}$

*Fig. 6:* **Simplified equivalent circuit of a RC divider**

The following equation describes the transfer function of the above-simplified equivalent circuit.

$$\frac{\underline{U}_{SR}}{\underline{U}_{PR}} = \frac{R_2}{R_2 + R_1 \dfrac{1 + R_2\, j\omega C_2}{1 + R_1\, j\omega C_1}} = \frac{C_1}{C_1 + C_2 \dfrac{1 + 1/\, j\omega C_2 R_2}{1 + 1/\, j\omega C_1 R_1}} \quad (3)$$

The condition for the frequency independence of the transfer function is fulfilled when:

$$R_1 \cdot C_1 = R_2 \cdot C_2 \quad (4)$$

If this condition is met, the frequency response of the RC divider is linear over the entire frequency range. *Fig.7* shows the measured frequency response (accuracy and phase) of a 420 kV RC divider.

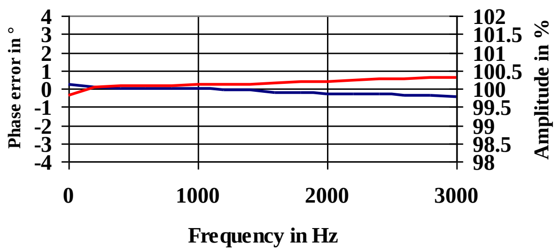



*Fig. 7:* **Accuracy versus frequency of a 420 kV RC divider**

The RC divider is a universal device for measuring voltages. Beside the application for measuring the fundamental frequency as well the harmonics, it can be applied for D.C. measurement. In fact conventional voltage transformers using magnetic principles are not able to measure direct voltages. The RC divider is the only device that can be applied to measure the voltage in HVDC systems.

*B. Frequency behaviour of different voltage transformers*

The capacitive voltage transformer (CVT) has a capacitive divider and a secondary transformer to provide the output signals. To compensate the load depending ratio and phase shift of the capacitive divider, a compensation coil is connected between the divider output and the secondary transformer. With this solution the CVT is tuned to the fundamental frequency 50 Hz or 60 Hz. For other frequencies the ratio error as well as the phase deviation is shifting. This is shown in measured results in *Fig.8*.

Magnetic voltage transformers (MVT) are using the transformer principle. The primary winding is realised as layer windings. The inductive and capacitive elements of the winding are having several resonances depending on the design of the MVT and the system voltage they are designed for [5].

Figure 8 is comparing the frequency behaviour of MVT, CVT and RC divider designed for 420 kV.

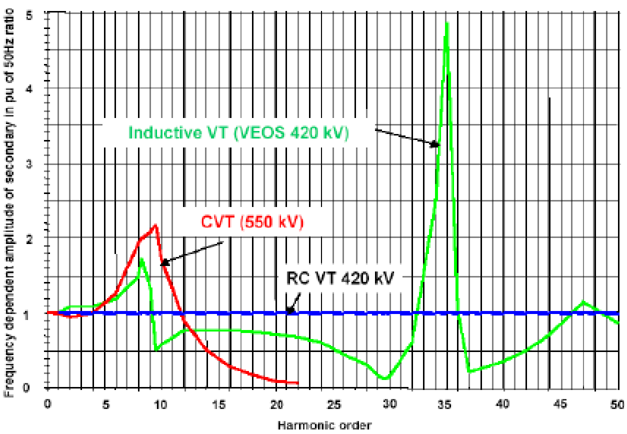


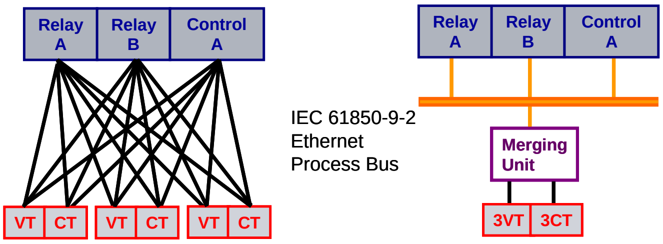

*Fig.8:* **Accuracy versus frequency for different voltage transformers for a 420 kV system**

## III. Digital Interface of Instrument Transformers

In IEC standards 3 types of interfaces for instrument transformers are defined. First the conventional interface with 1 or 5 A output value for current transformers and 100/√3 or 110/√3 V output for voltage transformers. Both types have to provide an output power up to several hundred of VA. Second the low power interface with output values up to 10 V for both current and voltage transformers and very low output power ( < 1VA). And third the digital interface is defined, which is getting more and more important.

When applying the conventional interface of instrument transformers, every single current transformer core and every single voltage transformer winding needs to be connected to the secondary equipment by copper wires. This means that many parallel copper wires are used to make these connections.

The IEC standard IEC 61850 [6], describes the communication in substations. In the part 9-2 of this standard a digital interface for sampled values such as current or voltage measurements is defined. This interface is based on industrial Ethernet. One optical fiber can replace many parallel copper wires between the instrument transformers and the secondary equipment (see figure 9). If the digitalization is done near the instrument transformer the losses in the connecting wires of conventional instrument transformers do not have to be taken into consideration when designing the instrument transformer. More or less powerless sensors can be designed and developed which allow especially in GIS application a much smaller footprint.




a. b.

*Fig.9:* **Connection between instrument transformers and secondary equipment**
**a. conventional interface using parallel copper wires**
**b. digital interface using process bus**

To connect the new low power instrument transformers to the digital process bus according to IEC 61850-9-2 an electronic device called merging unit has to be introduced. The output signals from all current and voltage transformers in one substation bay are connected to one merging unit. The merging unit performs the digitalization and the time synchronization; it merges the current and voltage data from all three phases and sends them with the protocol defined in the IEC 61850 to the process bus.

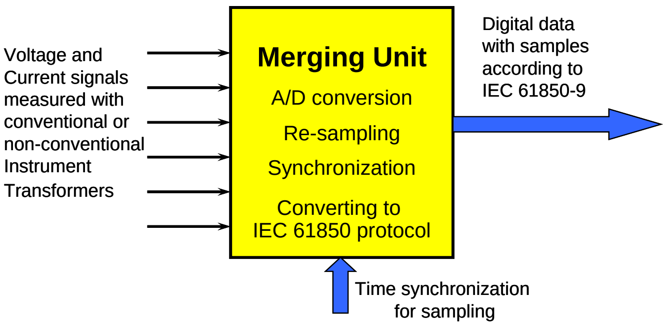



*Fig. 10:* **The merging unit to connect the instrument transformers to the digital process bus.**

The merging unit can be part of the instrument transformer electronics. This is the case in some solutions of non conventional instrument transformers which include electronic parts. But the merging unit can also be a separate device with input channels for instrument transformers and the standardized digital output channel. Such a standalone merging unit [7] can be used to connect all kinds of instrument transformers to the digital process bus. This gives a huge opportunity to integrate also existing current and voltage transformers into modern smart grid solutions.

## IV. Conclusions

Low power current transformers with voltage output and resistive-capacitive voltage dividers are non conventional instrument transformers with well known measuring principles. These devices can be very well combined with a stand alone merging unit, which is providing a digital interface according to the communication standard IEC 61850.

This system is avoiding the parallel copper wires to connect the instrument transformers to the secondary equipment.

Low power instrument transformers have a wide linearity and need smaller cross section of the cores. Using the low power current transformers avoids having high numbers of different current transformer core designs. One design can be applied for metering as well as for protection purposes.

R-C voltage dividers can be used in a wide field of applications. Besides the fundamental frequency, they can measure signals with higher frequencies. Additionally they can also be used for measuring DC.

## V. X- References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