SENSOR TECHNOLGY – APPLICATIONS FOR MEDIUM VOLTAGE

Author & Presenter: Bo Westerholm B.Sc. – Product development engineer,
ABB Oy, Medium Voltage Technology

1. Introduction

Sensors are a new solution for measuring currents and voltages needed for protection and monitoring in medium voltage power systems.

Certain strong trends have been present during the whole period of electrical equipment manufacturing: a continuous reduction of equipment *size*, a continuous improvement of equipment *performance* and a continuously grooving need for *standardization*.

However, in some types of equipment the visible effect of those trends has, during long periods of time, been relatively small. A typical example is the transformer, including instrument transformers. The natural properties of the soft iron core, as maximal flux density and lack of linearity in the excitation curve, have set limits for the possibilities to reduce the transformer size and to use the transformer in a wider range of applications. As a consequence, most instrument transformer units have been electrically tailor-made for one certain application and a far-reaching standardization has never been realized.

This inconvenience can be defeated with the introduction of sensors based on alternative principles like the Rogowski coil and resistive or capacitive dividers for current and voltage sensing respectively.

These *principles* are far from new, they are generally as old as the principles of conventional inductive instrument transformers. However, the *utilization* of the principles has not been possible to carry out – except in special applications – due to the lack of accurate and inexpensive electronic devices required. Not until now, with the introduction of versatile electronic relays, has it been possible to make use of the advantageous properties of sensors.

This paper presents practical sensor technology solutions as it has been introduced in medium voltage applications. Characteristics and behavior of sensors in various service conditions are explained by comparing with traditional instrument transformers.

2. The principles of sensors

2.1 Various principles

Sensors for current and voltage measurement can be based on various principles. For medium voltage applications simple, compact and cost-effective solutions are needed. In the practice there are a few in commercial use:

- Current sensors:
  - Rogowski coil
  - Low Power Current Transformer
  - Hall sensor
- Voltage sensors
  - Resistive divider
  - Capacitive divider
  - RC-divider

Rogowski coil sensors and resistive/capacitive voltage divider sensors are described below.

2.2 Current sensors

The measurement of currents is based on the Rogowski coil principle. A Rogowski coil is a so-called air-core coil, a toroidal coil without an iron core placed around the primary conductor in the same way as the secondary winding in a current transformer. However, the output signal from a Rogowski coil is different:

- The output from a current transformer with its *iron core and nearly short-circuited secondary winding is a current*. This so-called secondary current is *proportional to the primary current*.
- The output signal from a sensor with *its air-core and open Rogowski coil is a voltage*. This so-called transmitted signal is proportional to *the derivative of the primary current.*

Thanks to the absence of iron in a Rogowski coil sensor, no saturation occurs. The output is therefore linear over the whole current range up to the highest currents.

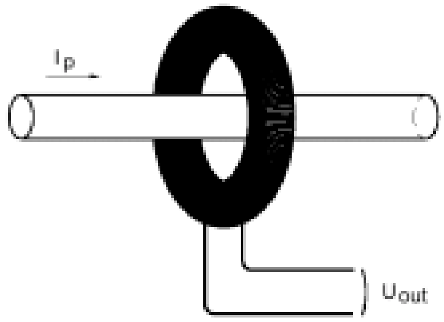

Fig. 1 Rogowski coil

Transmitted signal from a Rogowski coil

- The transmitted signal is a voltage:

$$u_{out} = M \frac{di_p}{dt}$$

- *For a sinusoidal current* under steady state conditions the voltage is:

$$\underline{U}_{out} = M \cdot j \cdot \omega \cdot \underline{I}_p$$

  The signal is a sinusoidal voltage, proportional to the current, with 90º phase shift (lead).
- *In all cases*, even if the primary current is non-sinusoidal, a signal reproducing the actual primary current waveform is obtained by integrating the transmitted signal.

2.3 Voltage sensors

The measurement of voltages is based on the use of voltage dividers, resistive or capacitive. The output is linear over the whole range. Resistive dividers are mora accurate, but capacitive ones are smaller in size.

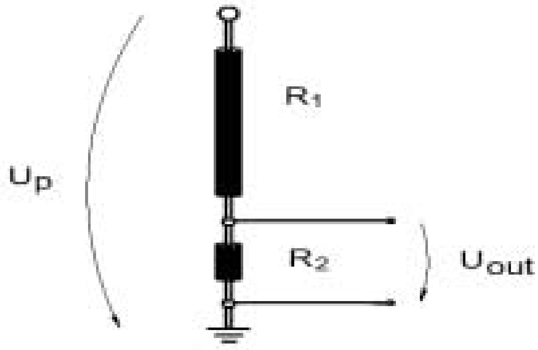

Fig. 2 Resistive voltage divider

Transmitted signal from a voltage divider

- The transmitted signal is a voltage:

from a resistive divider: $$u_{out} = \frac{R_2}{R_1 + R_2} u_p$$

from a capacitive divider: $$u_{out} = \frac{C_1}{C_1 + C_2} u_p$$

- *In all cases*, the transmitted signal reproduces the actual primary voltage waveform.

2.4 Protection and control IEDs (Intelligent Electronic Devices)

In comparison with instrument transformers the transmitted signal from a sensor is a more exact reproduction of the primary current or voltage, inclusively harmonics and high-frequency disturbances, up to the highest values such as short-circuit currents. The price one has to pay for it is a low signal level and a high output impedance. Consequently a sensor can not be connected to a traditional relay. In addition the output signal from a Rogowski coil sensor must be integrated to obtain a exact reproduction of the primary current. Even if the sensor principles has been known for a century the lack of suitable relays has until now limited the use of sensors to certain special applications.

But modern electronics has changed the situation. Relays, suitable also for sensor use are now available on the market. Thanks to them the utilization of the sensor principles is possible to carry out, even as a standard solution for medium voltage switchgear. In addition modern relays have an improved ability to perform complex calculations when accurate input data is available. Consequently more information about the operation conditions is available from the new relays, also called Protection and Control IEDs.

3. Standards

3.1 IEC standards

The following IEC-standards are published. The requirements on the primary side of the sensor is based on traditional thinking and are the same as for traditional instrument transformer. The requirements on the secondary side of the sensor are based on traditional thinking but adapted for the new technology.

- IEC 60044-7 (1999-12)
  Instrument transformers –
  Part 7: Electronic voltage transformers
- IEC 60044-8 (2002-07)
  Instrument transformers –
  Part 8: Electronic current transformers

For combined sensors there are no standard yet. The corresponding standard for instrument transformers can be used but one have to remember that the standard is old and based on old standards IEC 185 and IEC 186.

- IEC 60044-3 (1980-01)
  Instrument transformers –
  Part 3: Combined transformers

3.2 Diagrams

Below is shown a general block diagram for an electronic voltage transformer as given in IEC 600044-7. As pointed out in the standard the applied technology decides which parts are necessary for the realization.

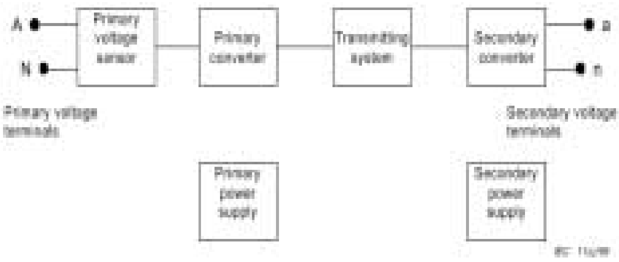

Fig 3 General block diagram according to IEC

A sensor application for medium voltage is built up of a minimal numbers of components. Below is shown a diagram for a typical installation in the practice. No active primary converter is used, and the secondary converter, if needed, is integrated in the protection and control IED.

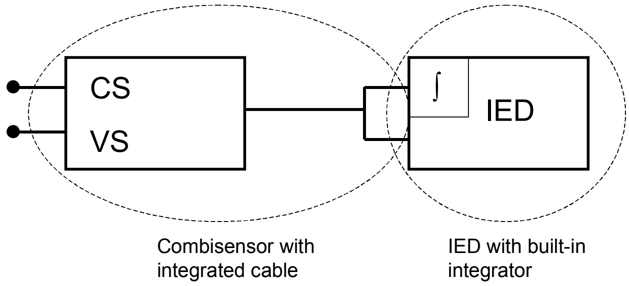

Fig 4 Medium voltage sensor application built up of only two components. CS=current sensor, VS=voltage sensor

4. Sensors v. ITs (Instrument Transformers)

4.1 Absence of iron

The characteristics of traditional instrument transformer are mostly determined by the properties of the core materials used. Because the iron core is linear only within a limited range, most instrument transformers are tailor-made to fit a certain application and can typically not be used for other applications.

Contrary, a sensor according to item 2 is built up of linear components only. The function of sensor is linear over a very vide range of currents and voltages, the limitations are often caused by other circumstances than the sensor itself.

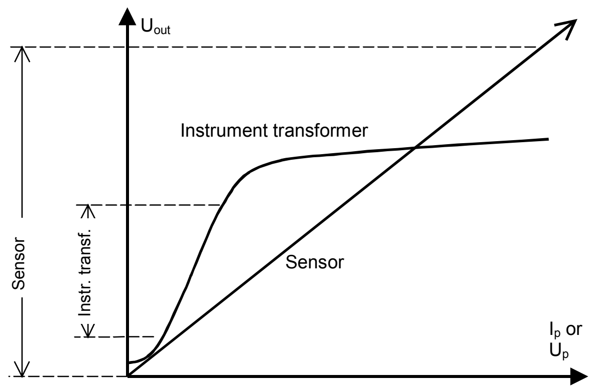

Fig. 5 Linear range for instrument transformer and sensor

4.2 A new approach to rated currents and voltages

The perhaps most important consequence of the sensor's linearity is the possible to extend the operation range far outside the limits given by the standard for a certain rated current or voltage.

In fig.6 is as an example shown the standard class limits for a current transformer or sensor with rated current 80 A. Typical accuracy curves for an CT and a Rogowski coil sensor are also shown.

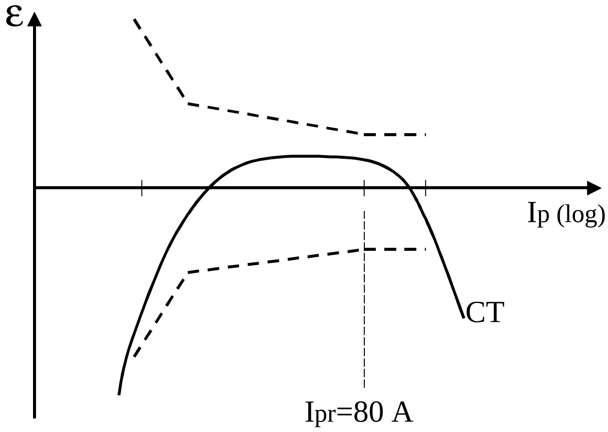

Fig. 6 Rated current, accuracy limits and accuracy curves for a current transformer (CT)

Because a current sensors is highly linear within a very wide range of currents, one and the same sensor can be used for various *switchgear* rated currents. Instead of *one sensor rated current*, a *sensor rated current range* can be defined. For every switchgear rated current within the sensor rated current range, the sensor fulfils the accuracy specification given by the standard for this particular rated current.

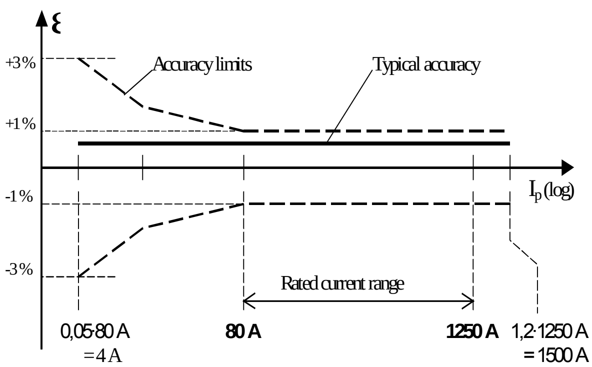

Fig 7 Rated primary current range, accuracy limits ands accuracy curv for a current sensor

The same is also valid for the rated voltage of voltage sensors

To achieve a correct function of the protection and control IED the selected rated current as well as the rated transformation ratio of the sensor must be programmed to it.

Examples of typical rated values:

<u>Current sensor:</u>
Rated primary current range: 80 – 1250 A
Rated transformation ratio: 80 A/0,150 V at 50 Hz
<u>Voltage sensor:</u>
Rated primary voltage range: 6:√3 – 22:√3 kV
Rated transformation ratio: 10 000:1

The rated current or voltage range is limited by
<u>Upper limit:</u>
- Highest voltage for equipment (voltage sensors)
- Rated continuous thermal current (current sensors)
- The highest voltage of transmitted signal which the IED can correctly process

<u>Lover limit:</u>
- The lowest value of the transmitted signal which the IED can correctly read

At higher primary currents the transmitted signal can be too big to be connected directly to the IED. In such cases a adapter shall be connected between the sensor cable and the IED. The adapter will reduce the transformation ratio to a lower value e.g. 240 A/0,150 V at 50 Hz, which value then shall be programmed to the IED. The adapter is chosen not only according to the rated current of the switchgear but also according to the specification for the IED.

4.3 Multipurpose sensors

As shown in fig. 6 the accuracy curve for an measuring current transformer is highly unlinear. Especially the fact that the (amplitude) error is big and negative at overcurrent, has been used to protect instruments from high secondary currents and voltages under fault conditions.

On the other hand a protective current transformer must have a small (composite) error particularly in the overcurrent range. That is the reason why measurement and protection have been carried out by different cores.

A Rogowski coil current sensor is linear up to the highest currents. The transmitted signal is low enough to be harmless even at the rated short-time thermal current. Consequently, in sensor applications the same core can be used for both measurement and protection. Such a sensor having double ratings for both measurement and protection is called a multipurpose sensor.

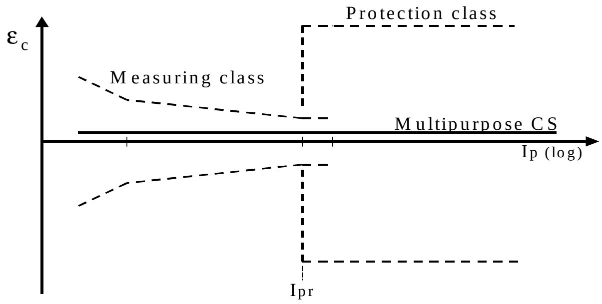

Fig. 8 Accuracy limits for a multipurpose current sensor and a typical accuracy curve

4.4 Correction factor

The amplitude error of a current sensor is in the practice constant and independent of the primary current. Hence it can be corrected in the IED by using a correction factor, measured separately for every sensor. A sensor fulfilling the requirements of e.g. class 3 *without* the correction factor can be corrected to fulfil the requirements of class 1 *with* the use of the correction factor. Voltage sensors can easily be corrected before encapsulating and subsequently a correction factor is not needed.

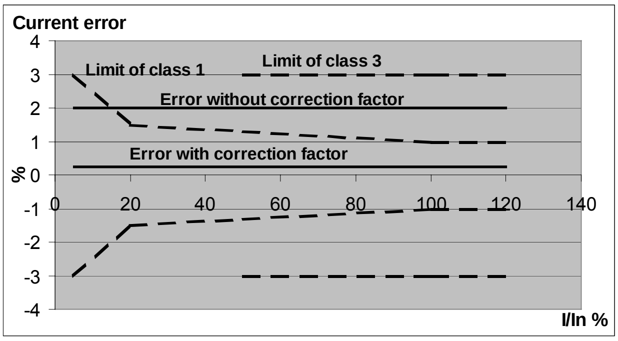

Fig 9 Correction factor

4.5 Secondary signals, wiring and burdens

Secondary signal level
The secondary signal rated level for voltage transformers is appr. 60 V, during fault conditions it can be appr. the twice. For current transformer is the rated signal mostly 5 A, during fault conditions it can be hundreds of amperes.

For sensors the rated secondary voltage is below 1 V. During fault condition the output voltage of a voltage sensor is appr. the twice. The direct output from a current sensor is even at full short-circuit current small. An extreme example: if the transformation ratio is 80 A/0,150 V the voltage of the transmitted signal will be only 75 V at 40 kA. Because the internal impedance is very high, such a signal is still harmless for people and equipment

Secondary wiring
As mentioned above separate secondary circuits for measurement and protection are not needed in sensor applications. The secondary wiring from a voltage or current sensor to the IED can then be made with a single cable. In the case of a combi-sensor the voltage and current secondary cables can even be combined in one.

Due to the low signal level the secondary wiring is prone to disturbances and therefor must the cable be properly shielded. The secondary cable is typically a double-shielded cable, one of the shields is earthed in one end of the cable and the other shield in the opposite end. By using cable connectors the correct connection will easily be made.

Burdens
The losses in the cable are negligible but the cable capacitance affects the phase displacement. Accuracy tests of the sensor are therefore made with the cable connected. A cable of suitable length must be ordered and the maximal length of the cable is limited.

To ensure that the shieldings are correctly connected and the accuracy requirements are fulfilled the secondary cable must not be

- shortened
- lengthened
- branched

On the other hand, if the sensor is ordered with a suitable cable, the secondary connections are very easily made. No burden calculations need to be made when once checked that the burden of the IED is suitable for the sensor.

Faulty secondary connections
Faulty connections in instrument transformer secondary circuits are always dangerous. A short-circuit in the secondary side of a voltage transformer will cause a short-circuit which always will damage the transformer if the circuit is not fused. A full short-circuit on the secondary terminals will make the transformer explode within a minute. An open circuit in the secondary side of a current transformer can easily cause overvoltages higher than the withstand voltage of secondary terminals, terminal blocks and secondary equipment.

The transmitted signal from a sensor is always a voltage. The internal impedance of both voltage dividers and Rogowski coils are high enough to make both type of sensors short-circuit proof.

4.6 Frequency response

Instrument transformers are fulfilling the accuracy specifications only at rated frequency. At higher frequencies the accuracy is decreased, at 1000 Hz the additional error is appr, 2 %. At lower frequencies the additional error increases fast, at 25 Hz it is appr. 5 %. The rated voltage factor and accuracy limit factor are strongly dependent on frequency.

All sensors described in this paper are linear without any additional error between 10 and 1000 Hz. The behavior at lower and higher frequencies is mainly depending on the capacitances in the secondary cable.

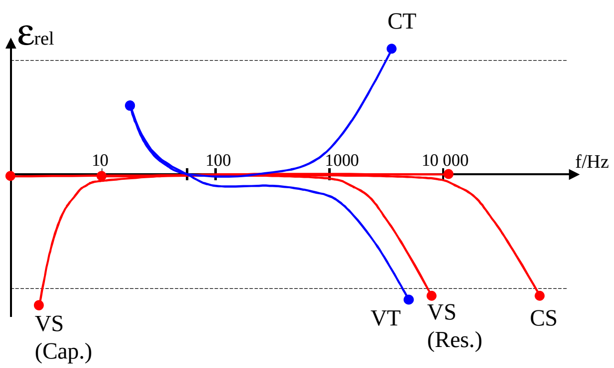

Fig 10 Frequency response for current transformer (CT), voltage transformer (VT), current sensor (CS) and voltage sensor (VS)

4.7 Extreme voltages and currents

Voltage transformers are factory tested at increased frequency, 250 - 400 Hz, to avoid saturation. If such a test voltage is not available when the switchgear is tested, the voltage transformers must be disconnected during testing.

All sensors can be retested with rated frequency without extra arrangements.

Current transformers can suffer from remanence e.g. after a fast current switch-off. Because the sensors do not make use of ferromagnetic components no remanence occur, and there is no risk for the sensor to be outside the accuracy specifications.

4.8 Direct voltages

Voltage transformers are very sensitive for direct voltages and must subsequently be disconnected during dc-testing of cables. Resistive voltage dividers can withstand a dc voltage high enough for most cable testing. (24 kV sensor 70 kV dc). In most cases the sensors need not be disconnected for the dc test.

4.9 The impact on equipment size

As sensing elements are noticeably small and the same elements are used for both measurement and protection, current and voltage sensors can easily be combined in one device, a combisensor, still smaller than a conventional current transformer.

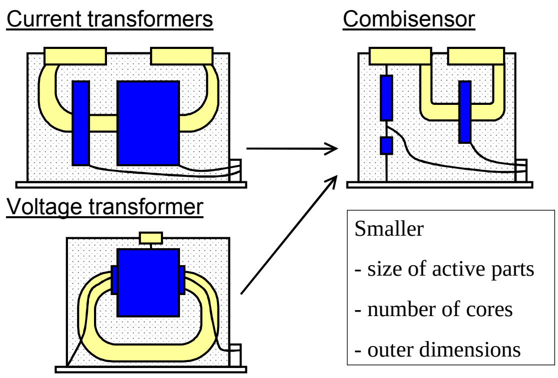

Fig 11 Size of instrument transformers and sensors

The small dimensions of sensing element make it possible to integrate them in other components as bushings, insulators, housings and circuit breakers.

4.10 Ferroresonance

<u>Voltage transformers</u> are one of the most sensitive components used in the medium voltage network, the failure rate is appr. ten times so high as for current transformers. The reason is the primary winding build up of thousands of turns of a very thin wire. This winding plays a double role in the development of voltage transformer failures:

- In some networks the unlinear inductances of the primary windings form a resonance circuit together with the earth capacitances of the network. Under unfavorable circumstances a so called ferroresonance can occur in this circuit causing high overvoltages, saturation of the core and high primary overcurrents. The resonance frequency is often below the nominal frequency of the network.
- On the other hand the primary winding is very sensitive to all kind of overvoltages and overcurrents, especially subharmonics and dc-components.

The risk for ferroresonance can be reduced, but not completely eliminated, with a damping resistor.

Voltage sensors are resistive or capacitive, and they are linear. They do not cause ferroresonance and they are not sensitive to overvoltages or -currents caused by other components. There is no need of damping resistors.

4.11 Varieties and delivery time

Instrument transformers are linear only within a very limited range of current or voltage. As a consequence, most instrument transformer units have been electrically tailor-made for one certain rated current or voltage, for a certain secondary burden and moreover, different secondary windings have been needed for measurement and protection. Thousands of different types have been needed to cover even the most common applications and a far-reaching standardization has never been realized.

One single sensor can be rated for several switchgear rated currents or voltages, both for measurement and protection. The number of varieties needed to cover the most common applications are so small that the sensors can be delivered from stock, which will strongly affect the delivery time

Easy engineering and uncomplicated mounting are other factors shortening the manufacturing time for the swichgear.

4.12 The impact of new relay technology

Besides the impact on switchgear dimensions and design, sensor technology supporting modern protection and control IEDs, gives required qualifications for building more intelligent switchgear. The main reason for this is the improved ability of modern IEDs to perform complex calculations when accurate input data is available. From the sensor point of view, the key properties are their ability to exact reproduce primary currents and voltages, inclusively harmonics and high-frequency disturbances, up to highest values, e.g. short-circuit currents.

Switchgear features enhanced by modern relays and sensors

- Better selectivity
- Improved fault location
- Better disturbance analyses
- Power quality measurements
- Remote monitoring and control
- Easy maintenance
- Optimized maintenance program
- Simplified IED testing

4.13 Shortcomings. The actual situation and further development

Instrument transformer technology is a ripe technology and proven solutions for most measurement and protection application already exist. Sensors for medium voltage applications are under development and there are still some advantageous application lacking.

Revenue metering
- Class 0,2 sensors can be manufactured , but a inexpensive and reliable solution is still missing.
- Meters are still missing
- External accredited/certified laboratories for rouine testing are not accessible

Differential protection
- In most cases are cables with a length >10 m needed. Because so long cables will seriously affect the phase displacement of the sensor an uncomplicated solution is not yet available

I_0-measurement
- "Cable current sensors" are not manufactured. I_0 is easily calculated by the IED from the three phase currents, but the sensitivity is in most cases not good enough for protection.

The behavior of instrument transformers is well known. The unlinearity leads to complicated applications, but there is a lot of experiences and the limits for the applications are well known.

Sensors, on the other hand are linear which in most cases leads to simple applications. Their behavior as successors to instrument transformers is skillful in most applications. Experiences of some exacting applications with great demands, complicated but realizable with instrument transformers, are still missing. But usually linear components facilitate more uncomplicated solutions than unlinear ones. The exact limits for additional future applications are unknown and partly depending on the future development of the IED technology

5. Experiences

Medium voltage sensors (ABB sensors) are until now been installed at 261 customers in 56 countries

6. Conclusions

Some instrument transformer disadvantages can be defeated with the introduction of sensors based on alternative principles like the Rogowski coil and resistive or capacitive dividers. New types of relays are needed, but a number of advantages can be achieved:

Size
The active parts are smaller than in a conventional instrument transformer. Different secondary windings for measurement and protection are not needed. Current and voltage sensors can easily be combined in one single combisensor, still smaller than a traditional current transformer, or be integrated in other components as insulators, bushings, housings and circuit breakers. The small dimensions have an positive impact on cubicle dimensions, the use of high-valuable raw materials and environmental friendliness.

Performance
Because of the good linearity and absence of saturation is the information transmitted from the sensors to the IED, especially during fault conditions, more accurate than the corresponding secondary information from an instrument transformer. Improved ability of new relays to perform complex calculations gives the qualifications for versatile relay functions and more intelligent switchgear.

Standardization
The good linearity make it possible to cover several rated currents and voltages as well as measurement and protection applications with one single sensor. The standardized secondary connection with one cable to one single secondary equipment makes it possible to have only one secondary rating. As a consequence a minimum of versions are needed and they can be standardized for delivery from stock. This will give simple order-specific engineering, short delivery times, easy and fast installation as well as uncomplicated and compact cubicle design.