The Rogowski coil and the voltage divider in power system protection and monitoring

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SUMMARY

New solutions are proposed for measuring current and voltage in power system protection and monitoring. The main driving force in the development has been the need to standardise and optimise the MV-switchgear design and manufacturing, which in practice rules out the conventional instrument transformers because of their large size and higher costs. From the switchgear manufacturer's point of view also the costs related to planning work and logistics have to be taken into account.

The well-known principles of the Rogowski current sensor and the voltage divider are shown to be capable of meeting the new requirements. These sensors have become technically feasible due to the introduction of microprocessors in the secondary equipment.

In addition to discussing the benefits of the novel sensors the test results concerning their technical performance are given in the paper. The characteristics in terms of temperature dependence, crosstalk, frequency response and long term stability are satisfactory. Possible measures to improve the qualities are proposed. In the last chapter the impact of the sensors on the performance of protection is discussed.

1. INTRODUCTION

The technical and economical requirements set on medium-voltage (MV) switchgear have been increasing in recent years. The most requested properties are:

- Small dimensions.
- Quick planning and implementation of installations.

- Flexibility to allow for future additions:
  improvement of protection and monitoring functions, improvement of communication systems, increases of distributed power.
- High reliability, electromagnetic compatibility and minimised need for maintenance.

The new switchgear technology capable of meeting these requirements provides the following features:

- Integration of functions and components to the maximum extent permitted by the state of the art.
- Standardised solutions and prefabrication.
- Non-conventional, innovative measurement devices.
- Modern secondary equipment.

The sensors discussed in this paper are the Rogowski coil for current measurement and the resistive divider or capacitive divider for voltage measurement. Their main benefits are:

- Small size - helps to optimise the use of space in the switchgear
- Lighter weight means less material usage and lower life cycle costs (LCC)
- Large dynamic range - permits minimisation of number of sensor types needed and improvement of some protection functions.
- Protection and measurement functions combined.
- High reliability and safety.
- Lower losses mean lower LCC and also reduction of the temperature rise in a switchgear, which makes possible improvements in switchgear design.
- Low cost

These novel sensors also utilise the advantages of modern secondary equipment better than conventional instrument transformers. Numerical protection relays need only information concerning the primary currents and voltages and have the necessary capacity to process the measurement data. Lower cost and smaller size gives a possibility to measure the voltage from the load side. That voltage information is used for novel protection algorithms and for swichgear control functions.

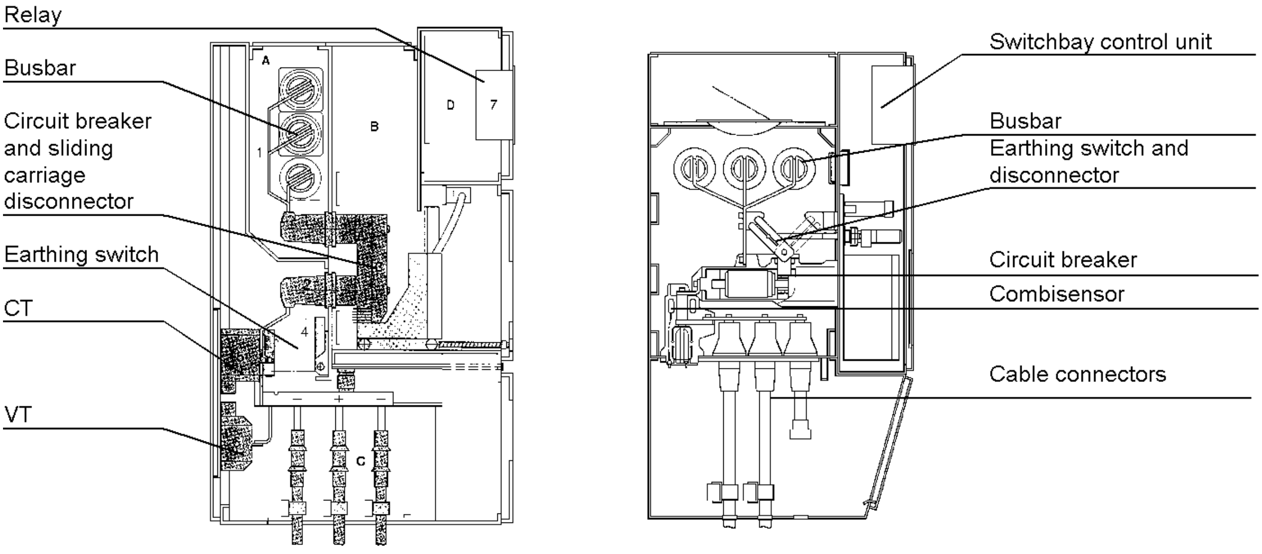
2. THE IMPACT OF SENSORS ON SWITCHGEAR

One of the long-term trends in MV switchgear design has been towards smaller size. In conventional switchgear, current transformer (CT) and voltage transformer (VT) takes a significant part of the total volume of the cubicle. The volume of the sensors is less than 1/3 of the volume of conventional instrument transformer. The smaller size results in switchgear having a volume of only 45 % (Gas Insulated Switchgear, GIS) or 58 % (Air Insulated Switchgear, AIS) of a conventional switchgear cubicle (see fig. 1 and 2.).

Fig. 2. Integrated combi sensor in AX1 panel (AIS). HxWxD 2240x650x1050 (ABB Distribution AB)

Another trend in the switchgear industry is the aim for shorter delivery times. Here the complicated logistics of conventional CT's and VT's is a major problem. To specify a transformer, the information on load current and its future trend, rated voltage, secondary burdens, accuracy classes, etc. must be known. The variety of different combinations means in practice, that instrument transformers are manufactured individually, according to order. The new sensors, on the other hand, have a very wide linearity range. The result is, that for rated currents 40 ... 1250 A and for rated voltages 7,2 ... 24 kV only one model is needed. The improvement in the logistic chain is obvious.

2.1. Current measurement



ZS1 HxWxD 2200x800x1500

ZX1 HxWxD 1900x600x1050

Fig. 1. Two different switchgear generations. Left ZS1 (24 kV, 25 kA, AIS) with conventional CTs and VTs and right ZX1 (24 kV, 25 kA, GIS) with sensors (ABB Calor Emag Schaltanlagen AG).

After careful studies, the Rogowski coil (RC) was chosen as the current sensor [1,2].

The RC comprises a toroidal winding, and the current carrying conductor is arranged to pass through the centre of the toroid. The output of the sensor is a voltage, which is proportional to the derivative of the current. The proportionality factor depends on the geometry of the coil.

2.2. Voltage measurement

For voltage measurement, the principle of a resistive voltage divider was chosen. This sensor gives a voltage signal, which is proportional to the primary phase-to-earth voltage. This measurement principle leads to inherently good characteristics in terms of large dynamic range and high linearity.

Another solution is to use a capacitive divider for voltage measurement having basicly the same properties as the resistive divider. The capacitance is integrated to the design of a bushing type sensor.

2.3. Secondary equipment

Unlike electromechanical relays, the modern secondary devices are not powered by instrument transformers. They need only information concerning the primary currents and voltages, whereby the above-described sensors possess the ideal characteristics:

- Direct compatibility with electronics.
- No matching transformers needed.
- Improved accuracy.

2.4. The Protection Schemes

The nonlinearity of magnetic cores in CT's and VT's sets inevitable physical limitations on the measurement range and accuracy. Therefore, these novel sensors give benefits that are not achievable with conventional technology including:

- Both large measuring range and high accuracy.
- Integration of protection and measurement functions using the same sensors for both.

Some modifications are necessary in the realisation of the protection schemes:

- Digital subtraction for obtaining the phase-to-phase voltage.
- U_0 by digital addition of the phase-to-earth voltages.
- I_0 by digital addition of the phase currents
  Alternatively, a separate I_0 sensor could be used. However, the use of additional sensor does not comply with the ideas of compact switchgear and minimal wiring.

2.5. Reliability and safety

The sensors have a positive impact on the reliability of switchgear. Risk of damage by human error is reduced by the use of the sensors due to the following factors:

- Easy installation.
- No direct damage caused by incorrect wiring.
- Safe opening and short-circuiting of the sensor secondary circuits possible without overvoltages or overheating.
- Small output voltages.

Unlike the VT's, the voltage dividers do not give rise to ferroresonance. The risk of harmful overvoltages is thus minimised.

2.6. Examples

Example of a realised sensor is given in fig. 2, where the new sensor is integrated to a new medium voltage panel. In Fig. 3 new sensors are compared to conventional instrument transformers. Fig.4 shows a combi sensor (combined current and voltage measuring unit) illustrating the good integration properties of the new sensors.

Combined sensor bushing type sensor shown in fig 2.include the following functions:

- Current sensor
- Voltage sensor
- Capacitive divider for voltage indication
- Bushing between the different enclosures of the switchgear
- Integrated primary terminal for tubular bus connection
- 400-series outer cones bushing

Fig. 3. VT, Voltage Sensor, CT and Current Sensor (left to right)

Fig. 4. Combi sensor (combination of current and voltage sensor)

3. CURRENT SENSOR

The measurement principle of the RC has been known since 1912. A RC is a uniformly wound coil, which has a non-magnetic core. The simplest possible shape of a Rogowski coil is a toroidal air-core coil. The air-core coil has many advantages compared to an iron core CT, which is the most common solution in current measurement in MV switchgear.

A RC can be made by winding wire on a flexible tube and then bending the ends together. In this paper we concentrate on the toroidal shaped RC (see fig. 5), where the winding is made very precisely to achieve good accuracy and stability.

The current going through the coil induces voltage e given by the following approximate formula:

$$e = -\mu_0 N A \, \mathrm{d}I/\mathrm{d}t = H \, \mathrm{d}I/\mathrm{d}t \qquad (1)$$

where μ_0 = permeability of free space
N = turn density [turns/m]
A = single turn area [m^2]
H = coil sensitivity [Vs/A]

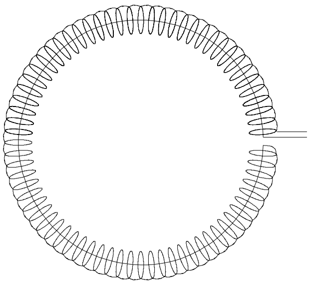


Fig. 5. An example of a Rogowski coil. The return loop is in the centre of the

Because of its non-magnetic core, the RC does not have any non-linear effects like saturation. It also permits isolated current measurement, has very wide bandwidth up to a megahertz, it does not load the primary circuit and it is small in size and weight. From most viewpoints, the RC is the ideal current sensor for applications where measurement of DC-current is not necessary. The only drawback has been the fact that the output is proportional to the time derivative of the current and must be integrated. The accuracy of the analogue integrators used earlier was inadequate. Nowadays integration is done digitally.

Because the RC does not saturate, it can be used to measure currents from a few amps to hundreds of kiloamps. The lowest and highest value depend mainly on the measuring electronics. The high linearity has the following advantages:

- Reduced number of different ratings needed
- Accurate measurement of high fault currents (fault location, circuit breaker condition monitoring)
- Improved differential protection schemes (see chapter 8.)

3.1 Accuracy of the Current Sensor

When the core and the winding are made carefully, an overall accuracy of 0,5 % can be achieved for sensors of medium voltage switchgear. The most important sources of inaccuracy are:

- Temperature changes.
- Assembly tolerances.
- Effect of the other phase currents (cross talk)
- The non-infinite length of the primary conductor (e.g. 90° angle very near the coil).

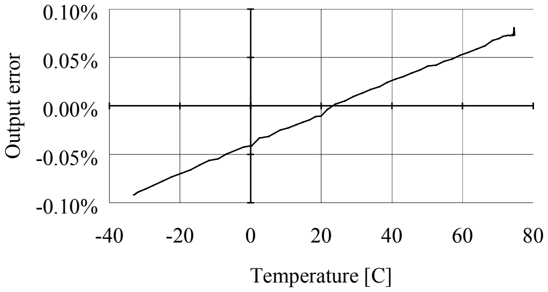


Fig. 6. Typical temperature dependence of Rogowski coil current sensor.

Better accuracy is required in revenue metering, ±0,2% being the minimum requirement. By analysing the error types listed above the following improvements can be found.

The temperature dependence (see fig. 6) can be lowered by using special materials with very small physical temperature coefficient. Another possibility is to measure the temperature of the sensor and then compensate the temperature dependence.

Assembly tolerances can be handled with proper mechanical installation. In many cases the current sensor is integrated into some other equipment such as a bushing so that assembly tolerances do not cause any significant error.

Cross talk (how other phase currents affect the one to be measured) can be minimised by proper design of the sensor. Crosstalk of standard sensor is shown in fig. 7.

Phase angle accuracy is very important in many protection algorithms. The problem with an iron core CT is that phase displacement varies with the current, the worst case being during under- or over-excitation. This is not a problem with RC's because phase displacement error is small and does not vary with current.

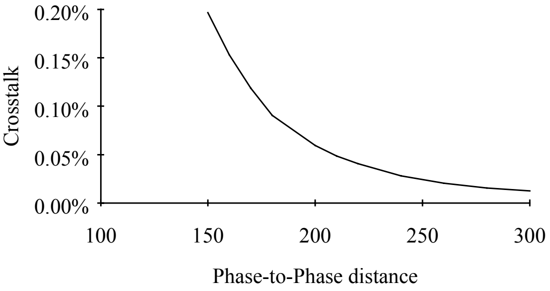


Fig. 7. Calculated crosstalk for a Rogowski coil as a function of the phase-to-phase distance.

3.2 Frequency range

In practical cases with RC's designed for 50 Hz the usable frequency range is from a few Hz to 100 kHz. For monitoring, protection and power quality measurements this is more than enough. Fig. 8 shows typical measurement results of the frequency response.

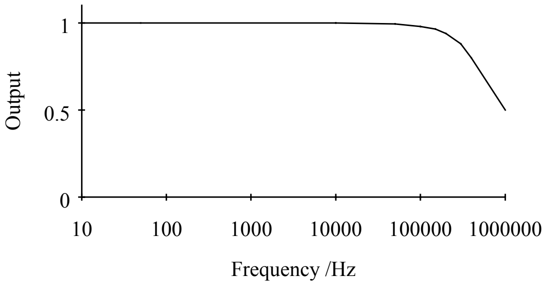


Fig. 8. Typical Rogowski coil frequency

3.3 EMC

The nominal output current of a conventional CT is 5 A. The impedance level of the output is very low and the signal level is high. In a RC current sensor with a practical core size the sensitivity for 50 Hz signals can be of the order of magnitude of a few millivolts per ampere. The low signal level can be a problem in difficult EMI environments such as MV switchgear if the EMC aspects are not taken into account by design and testing.

4. VOLTAGE SENSOR

Voltage sensors used to measure the voltage in MV switchgear are impedance (resistive or capacitive) voltage dividers (see fig 9). They have many advantages compared to magnetic VT's:

- Non saturable.
- Linear.
- Small and lightweight.
- Does not cause ferroresonance.

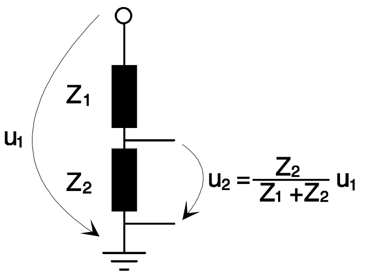


Fig. 9. The principle of the impedance voltage divider.

Because of the high linearity the number of different types can be considerably reduced. The same sensor can be used in 7,2 kV to 24 kV networks.

In isolated networks the ferroresonance can be a problem. The result of this phenomenon in many cases is that if a conventional VT is connected between phase and earth, it is thermally overloaded and destroyed. Resistive voltage sensors do not cause ferroresonance and it is not destroyed by this phenomenon. It can even be used to measure the phase-to-earth voltages during this abnormal situation.

A resistive voltage divider must be able to withstand all normal and fault situation voltages as well as test voltages. This sets very high demands on the divider. In practice this means that the resistance of the divider must be very high. When the impedance level is high, the handling of stray capacitances is very important.

4.1 Accuracy of the resistive Voltage Sensor

The accuracy is dependent on the accuracy of the resistors, or more exactly on the accuracy of the division ratio. Both resistances are allowed to vary, if the change is in the same direction. The main sources of inaccuracy are:

- Resistance temperature coefficient.
- Resistance voltage coefficient.
- Drift of resistors (voltage, temperature).
- Stray capacitance.
- Effect of the adjacent phases (cross talk).

Normally the accuracy ±0,5% is achieved. In revenue metering, an accuracy of ±0,2% is the minimum

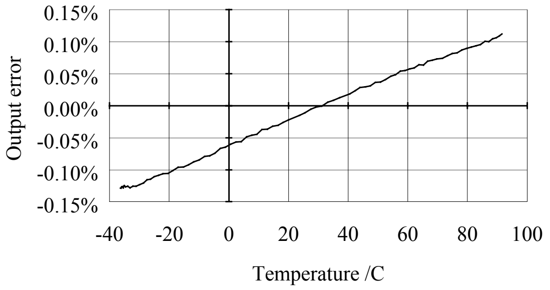


Fig. 10. Typical resistive divider temperature dependence.

requirement. This can be attained by following improvements.

Temperature compensation and the resistance voltage coefficient can be handled by suitable materials and mechanical design of the resistor. The choice of the material is also very critical to the long-term accuracy.

Stray capacitance and crosstalk can be calculated using field calculation programs. The capacitance between adjacent phase and the divider must be as low as possible.

Due to the temperature dependence of the dielectric constant of the epoxy resin being 1 % for the temperature range of -40 ±C … +70 ±C the accuracy quaranteed is 3 %. When better accuracy is requested a resistive divider must be used.

4.2 Accuracy of the Capacitive Voltage Sensor

The accuracy is dependent mainly on the temperature dependence of the dielectric constant of the epoxy resin being 1 % for the temperature range of -40 ±C … +70 ±C. The other sources of inaccuracy are:

- Drift of capacitors (ageing of insulation).
- Stray capacitance.
- Effect of the adjacent phases (cross talk).

Due to the temperature dependance accuracy quaranteed is 3 %. When better accuracy is requested a resistive divider must be used.

4.3. Frequency range

Due to the high impedance level of the resistive divider, the frequency response is not so wide as it is with the RC. However frequencies up to a few kHz can be measured (see fig. 11). This is enough for monitoring, protection and power quality measurements.

4.4. EMC

The nominal output level of conventional VT´s is 100 V. In resistive or capacitive voltage dividers the output signal level is about 1 V. Acceptable characteristics in terms of EMC must be ensured by design and testing of the system in real environment.

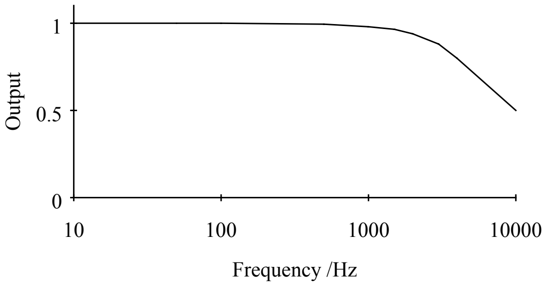


Fig. 11. Typical resistive divider frequency response.

5. LONG TERM EXPERIENCES

Long term experiences are necessary to be able to estimate the usability of the new technology.

Long term experiences using RC are good. Long term accuracy, according to the measurements made in real environments is very high.

Several samples of resistive voltage dividers were assembled in a test field in summer 1993. The test voltage over the divider was 20 kV AC (75 % overvoltage). Regular testing, including accuracy tests, indicates that the divider works well. The highest change recorded in the division ratio has been below 0.04%.

6. STANDARDISATION ACTIVITY

Two IEC TC 38 working groups (WG 23 and WG27) have prepared standards on the basis of the existing standards for instrument transformers taking in count the special requirements for the new sensor technology (EMC etc.). IEC 60044-7 [3] was issued 1999-12. Draft of IEC 60044-8 [4] will be issued during 2000. Both of the standards include specifications for analogue output for voltage and current sensors. IEC 60044-8 includes also a specification for digital point-to-point link for up to seven current signals and up to five

voltage signals.
IEEE Power System Relaying committee have issued a proposal for sensor standard [5].

7. COMPARISON OF THE SENSOR PROPERTIES

The properties of the new sensors are compared to that of the conventional instrument transformers in table 1.

PROPERTY	**CT / VT**	**I / U -SENSORS**
SIGNAL	5 A / 100 V	150 mV / 2:√3 V
SECONDARY BURDEN	1 - 50 VA	× 4 Mohms
ACCURACY	Measuring: 0.2 % - 1 % Protection: 5 % - 10 %	Multipurpose 1 %
DYNAMIC RANGE	40 x In / 1,9 x Un	Unlimited
LINEARITY	Unlinear	Completely linear
SATURATION	Distortion of the output signal	Do not exist
FERRORESONANCE	Destructive (VT)	Do not exist
TEMP. COEFFICIENT.	No influence	Compensated
EMC	No influence	Shielded
SHORT-CIRCUITED SECONDARY	Destructive (VT)	Harmless
OPEN SECONDARY	Destructive (CT)	Harmless
WEIGHT	40 kg (CT + VT)	8 kg (combi sensor)
LCC	HIGH	LOW
DIFFERENT TYPES TO COVER ALL THE APPLICATIONS	millions	2

Table 1. Comparison of the properties of conventional instrument transformers versus new voltage and current sensors.

8. PROTECTION SCHEMES AND SENSORS

The main advantages of sensors in protection applications are their non-saturability and wide frequency range. The non-saturability has clearly a positive impact on the performance of the protection system in terms of better selectivity and shorter operate times. The wide frequency range facilitates development of new protection algorithms based on high frequency measurements of current and voltage.

Fig. 12 illustrates a substation secondary system utilising sensors. All the feeders have their own voltage measurement devices, which facilitates the measurement of voltage behind the circuit breaker.

In this chapter two examples of such traditional protection schemes are given that gain from the use of sensors.

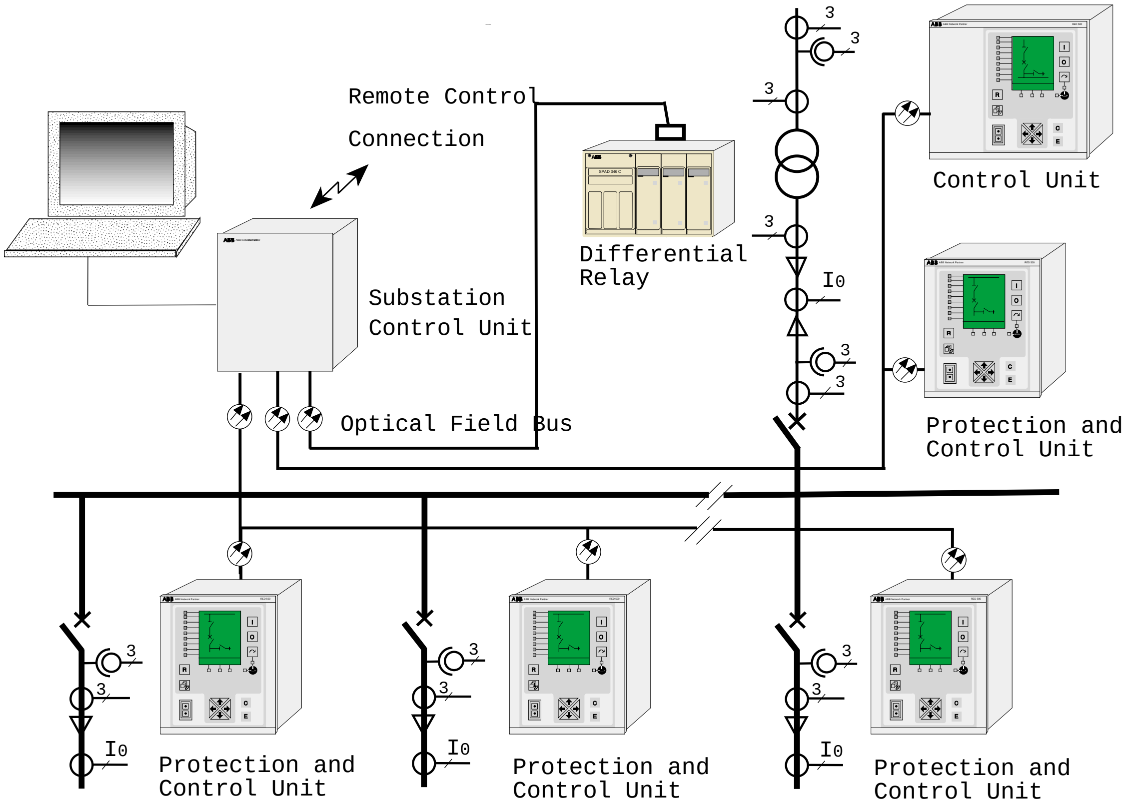


Fig. 12. A schematic drawing of a substation secondary system utilising sensors for measuring current and voltage.

8.1. Differential protection

Differential protection of power transformers is one of the most demanding applications as to the quality of current measurements. The saturation of CT's causes apparent differential current resulting in non-selective trippings in case of high through-fault currents if no measures are taken against them. In principle there are a few different ways to tackle this problem. The sensitivity of the protection scheme may be set suitably to allow for the apparent differential current.

Normally this is done by requiring the higher differential current for tripping the higher is the so-called stabilising current. The stabilising current is the average of the phase currents of the HV- and MV-side of the power transformer. This solution tends to lead to inadequate sensitivity in many cases.

Another approach is to simply make the operate time of the differential relay long enough to prevent nuisance trippings caused by through-fault currents. This alternative, however, is ruled out in practice because the relay would fail to perform efficiently enough its main function, protecting the transformer.

The third alternative to stabilise the relay against saturation of CT's due to through-fault currents is to block its operation, if the harmonic content of the differential current exceeds a certain limit. The second harmonic is normally utilised. This solution has the advantage that it also prevents undue trippings at inrush currents caused by switchings of transformers. There is, however, a risk of lengthened operate times when the fault occurs in the transformer itself, if the accuracy limit factors of the CT's are not high enough.

The only absolutely safe way to prevent undue trippings due to the saturation of CT's is to make the accuracy limit factor high enough. This may lead to excessively high requirements on the accuracy limit factor, if the time constant of the DC-component is long.

In stead of oversizing the CT it may also be linearised by an air-gap in the core. Both alternatives lead to increased costs. The linearisation also causes some disadvantages from the protection point of view. E.g. the magnetising current becomes higher and there may be a slowly decaying discharge current in the secondary after the primary current has ceased to flow.

There is thus a need to find a compromise between different requirements set on differential protection if CT's are used. A non-saturable current sensor, however, makes it possible to combine selectivity, good sensitivity and fast operation at a reasonable price.

8.2. Over-current protection

Over-current protection is another area, where the saturation of CT's causes problems if not as serious ones as with differential protection. In definite time mode of operation the saturation is not normally harmful provided that peak-values of the secondary current exceed the setting of the relay.

However, if there is a high DC-component in the fault current and its time constant is long, there is a risk of delay in operation, especially if there is a remanent flux in the CT-core. This possible delay has to be taken into account by making the time grading of overcurrent relays long enough to maintain selectivity. If there are many successive relays, the operate time of the last in chain may be harmfully long.

Saturation has bigger influence on the operate times of inverse time overcurrent relays. The delay is of the same order of magnitude as the time constant of the DC-component, if the accuracy limit factor of the CT is chosen based on the AC-component only. The operation will be more seriously delayed in case the AC- component is high enough to saturate the CT even without any DC-component. Consequently also the time grading has to be long to ensure selectivity.

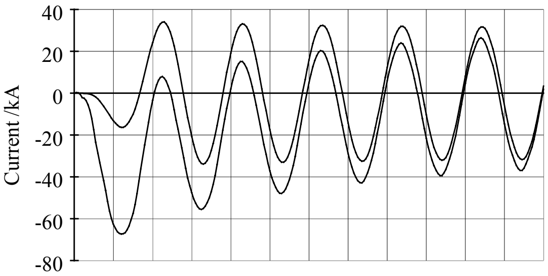


Fig. 13. Primary current with a large DC-component measured by a shunt and a transient recorder (the lower curve) and the same current measured by Rogowski coil and a numerical relay (the higher curve). The relay performed Fourier-transform to derive the 50 Hz component of the current.

The selectivity of directional over-current protection depends significantly on the accuracy of phase-angle measurement, which is often drastically worsened by saturation. The longer is the time constant of the DC-component the longer time settings are necessary.

The RC facilitates shorter operate times to be used without endangering selectivity, which leads to shorter time grading and better overall performance of protection. An additional advantage is that the RC does not measure the DC-component of the fault current. (See Fig. 13) Since the DC-component is a random variable, its absence increases the accuracy of protection.

BIBLIOGRAPHY

[1] P. Mähönen, M. Moisio, T. Hakola and H. Kuisti, "New Sensors in Protection Relay Applications", 1995, CIRED95 Conference publication.

[2] G. Mauthe, V. Lohmann and F. Frey, "Enhanced customer value achieved by integrated protection, monitoring and control concepts", 1995, CIRED95 Conference publication.

[3] IEC 60044-7. Part 7: Electronic voltage transformers. First edition 1999-12.

[4] IEC 60044-8. Part 7: Electronic current transducers. TC38WG27 committee draft for voting, internal 20.12.1999.

[5] IEEE Power System Relaying Committee: Trial Use Standard for Low Energy Analogue Signal Inputs to Protective Relaying. Draft 8.15