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APPLICATION OF COMBINED CURRENT AND VOLTAGE SENSOR FOR PROTECTION AND METERING IN GIS SYSTEMS.

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ABSTRACT

Gas insulated switchgear (GIS) is an ideal system for installations in a limited space, if a high availability is required. The new combined sensors are a perfect base for a wide range of applications in protection, metering and control in the field of gas insulated substations.
The two most important functions performed in this combined sensor are the measurement of current and voltage for protection, metering and control.
The principle of Regowski coil is used for current measurement and of the capacitive voltage divider for voltage measurement. Signals are converted to digital values and forwarded through fiber optical cable to local control cubicles. This data acquisition is an important part of an intelligent control and protection technique for GIS system.
This paper describes the design of a combined sensor, block diagram and Accuracy features of such sensors. Good properties of the sensor permit its use for measurement, protection and control. Moreover, insulating gas density and temperature, also enables evaluating and recording the signals.
The simple layout of this combined sensor significantly improves dielectric capability in comparison with conventional designs.
Measuring techniques have been developed to asses and improve measuring and dynamic accuracy. Results show that the combined sensor is of better quality than known for conventional inductive instrument transformers.
Combined current and voltage sensors for GIS fulfill the requirements for protection, metering and control which add several advantages for the user.

تعتبر المهمات المعزولة بالغاز (GIS) نظاما مثاليا للتركيب في الأماكن ذات المساحات المحدودة والمطلوب فيها الإتاحية العالية. وتستخدم الحساسات المدمجة الجديدة علي نطاق واسع في انظمه الوقاية والقياس والتحكم في مجال محطات المحولات المعزولة بالغاز.

وتقوم هذه الحساسات بوظيفتين هامتين وهما قياس الجهد وقياس التيار لأغراض الوقاية والتحكم. ويستعمل مبدأ روجويسكي (Rogowski coil) لقياس التيار ومقسم الجهد ذو المكثف لقياس الجهد. ويتم تحويل قيم إشارات الجهد والتيار إلي إشارات رقمية تنتقل من خلال الكابلات الضوئية إلي غرفة التحكم. وتجمع هذه الإشارات الرقمية لتكون جزء هام من نظام التحكم الذكي ونظام الوقاية الحديثة للمعدات المعزولة بالغاز (GIS).

ويشرح هذا البحث تصميم ونظرية الحساسات المدمجة وتركيب ومواصفات مثل هذه الحساسات الدقيقة ومميزاتها عن محولات التيار ومحولات الجهد التقليدية. علاوة علي ذلك فان هذه الحساسات يمكنها أيضا قياس كثافة ودرجه حرارة الغاز العازل وتسجل هذه القياسات بدقه متناهية.

والتركيب البسيط لمثل هذه الحساسات تحسن إلي حد كبير إمكانيات العزل وتزيد من اعتمادية النظام الكهربي بالمقارنة بالنظم الأخرى التقليدية. وقد تم تطوير وتحديث وسائل القياس لتحسن وتزيد من الحساسية الديناميكية لقياس التيار والجهد تحت جميع الظروف.

وقد أثبتت النتائج أن الحساسات المدمجة ذات جودة مرتفعة عن مثيلاتها في النظم التقليدية لمحولات القياس ذات القلب الحديدي.

وتحقق الحساسات المدمجة لقياس الجهد والتيار في النظم المعزولة (GIS) جميع متطلبات الوقاية والقياس والتحكم والتي تضيف كثيرا من المميزات الهامة لمستخدم هذه النظم الحديثة.

Keywords: Gas, Current, Voltage, Sensors, Protection, Transformers, CT/VT, Pisa, Control, Regowski Coil, IEC60044-2, IEC44-1, Over current Relays.

1. INTRODUCTION

New solutions are proposed for measuring current and voltage in power systems. The main driving force in the development needs to standardize and optimize the GIS 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 combined Regowski current sensor and the voltage capacitive divider are shown in Fig.1 to be capable of meeting the introduction of electronic interface (PISA).

In addition to discussing the benefits of the combined sensors, the test results concerning their technical performance are given in the paper.

The technical and economical requirements set on GIS 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 minimized need for maintenance.

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

- Integration of functions and components to the maximum extent required.
- Standardized solutions and prefabrication.
- Non-conventional measurement device.
- Modern secondary equipment.

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

- Small size
- Help optimize the use of space in the switchgear.
- Large dynamic range-permits minimization of number of sensor types needed and improvement of some protection functions.
- Protection and measurement functions combined.
- High reliability and safety.
- Low cost.

These new sensors also utilize the advantage 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.

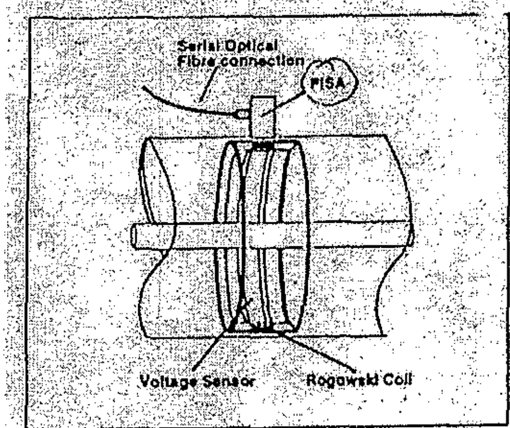


Fig. 1: Combined UI-sensor for GIS with electronic Interface (PISA)

2. REPLACEMENT of CTs AND VTs BY SENSORS

The replacement of conventional current and voltage transformers by sensors are amongst the most obvious advantages of the intelligent GIS. Numerical control and protection equipment does not need high power input signals anymore. Low voltage and small current signals are sufficient and therefore heavy expensive instrument transformers can be replaced by low power and compact sending devices. Many significant difficulties with the traditional measurement systems can then be immediately eliminated:

2.1 Difficulties with conventional CT/VTs

- Conventional current and voltage measurement transformers have been designed to feed the electromechanical relays. The high input power requirements of these protection devices (up to 60 VA and 5A) have led to heavy physical sizes of the measurement transformers and as a result, to high costs.
- In order to meet the accuracy class and stability requirements of the measurement system, the connecting leads between the measurement transformers and the relays have to be considered carefully.
- Measurement and protection applications call for very large dynamic range of the electric signals. The saturation of the transformer cores limits the dynamic range of conventional CT/VTs. Therefore different current transformer cores and voltage transformer taps have to be provided in parallel for the different applications in the secondary systems

for metering and protection purposes have traditionally been treated as completely separate.

- At high short circuit current levels, the saturation of the current transformer cores distorts the measured current signal. Complicated and expensive protective devices are needed to reshape the distorted signal in order to enable proper operation of the protection system.
- High over-voltages due to ferro-resonances excited by the non-linearity of measurement transformers have repeatedly caused damage in surrounding high voltage transmission equipment. This effect is well known, however it is difficult to avoid it completely. It is one of the critical tasks of substation engineering to consider this effect and to foresee remedial measures. For example the grading capacitors of breakers have to be adjusted the surrounding q] equipment to limit this effect.
- Given their complex dielectric structure, voltage transformers represent a weak point in the dielectric insulation of the transmission system. They are responsible for a significant proportion of flashover in the transmission grid.

2.2 Alternative Measurement Principles

Due to the drawbacks of conventional instrument transformers shown above as well as the fast development of numerical protection equipment, alternative measurement devices were developed and have been exposed to longer field tests. These new sensors are based on various physical principles, some of the sensors are already available as products in the market, and however the application range is still limited.

There are two basic categories of physical principles for the current and voltage sensors: The first category (semi- Conventional) is based on conventional Electro-magnetic measurement techniques but with strongly reduced power output compared to today's current and voltage transformers; the second category is based on other kinds of physical effects usually of optical nature, which is not the subject of this paper.

2.2.1 Sensors Based on Semi-Conventional Electromagnetic Measurement Principles

The first category of semi-conventional current and voltage sensors is the subject of this paper which is mainly based on the traditional inductive, capacitive or resistive sensing technique but with a low power output. This technique offers optimal solutions in the case of small insulation distances between the high and the ground potential such as GIS and Medium voltage equipment. In high voltage applications with air insulation, the difficulty of these semi-conventional technologies is to bridge the insulation between the high and the ground potential with the measured signal. However, solutions based on Electromagnetic sensors do also exist for air insulated equipment.

Due to the reduced power of semi-conventional sensors, the electronic interface (PISA) between the sensor and the data processing units is included or even completely integrated in the solution. A semi-conventional sensor for GIS is shown below, Fig. 1, Fig 2.

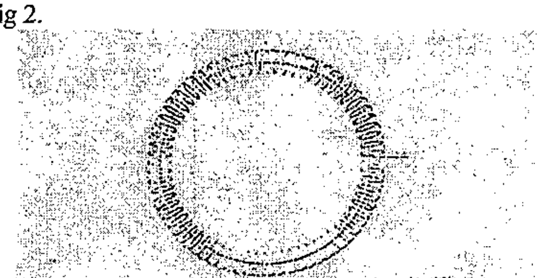


Fig.2. An example of a Rogowski coil. The return loop is in the centre of the winding.

2.2.2 Combined Current Voltage Sensor for GIS

Combined current and voltage sensor has been developed to replace the conventional current and voltage transformers.

The current sensor is based on a Regowski coil (air-cored current transformer) Fig. 2. The voltage sensor is based on capacitive divider principle (see Fig. 3). Since the Regowski coil is linear, saturation need not to be taken into account for the protection algorithms. Also the capacitive ring, as a voltage sensor, is linear and very simple in terms of insulation. This solution including the integrated electronic interface (PISA) will be explained in more detail below.

3. PROPERTIES OF THE COMBINED CURRENT AND VOLTAGE SENSOR

The following functions are provided in the primary part: Current and voltage measurements and additionally density measurement and sensor data storage.

3.1 Current Measurement

The current measurement is based on the well known principle of a Regowski coil (RC). The coil is homogeneously wound on a toroidal diamagnetic core. The function of which is only to give the coil certain mechanical stability.

Output voltage U over the coil flowing through the coil

$$Ui(t) = M \frac{di(t)}{dt}$$

The proportionality factor M is dependent only on geometry of the coil and can be computed approximately using the following equation.

$$M = \frac{\mu o\, n.A}{2.\pi.r}$$

Where: μo = permeability of free space
n = number of coil turns
A = cross-section of one turn
r = effective radius of the core.

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 where the winding is made very precisely to achieve good accuracy and stability.

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 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 analog integrators used earlier was inadequate. Nowadays integration is done digitally.

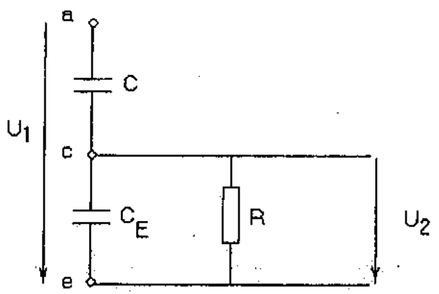
Because the RC does not saturate, it can be used to measure currents from a few amps to hundreds of kiloamps. The lowest and highest values depend mainly on the measuring electronics. The high linearity has the following advantages:

-Reduced number of different ratings needed.
-Accurate measurement of high fault currents.
-Improved differential protection schemes.

3.2 Voltage Measurement

The measurements electrode together with high voltage conductor works in fact as a cylindrical, coaxial, high voltage capacitance [1, 2, 3].

That capacitance C is defined by the following expressions:



$$C = \frac{2 . \pi . \varepsilon 0 . \varepsilon r . b}{\ln(D/d)}$$

Where:
D, d -diameters,
b -length.

Fig.3

Compressed gas capacitors are known to be very stable and therefore they are widely used for reference measurement of high voltage.

The second values CE consists of the ground capacitance. As known, a solid or liquid dielectric is neither in the temperature nor in the long time domain stable enough for high precision measurements. The solution can be (and in our case is) to shunt this capacity with a stable resistor R, the resistance of which is small enough to obtain an output voltage free from influence of C_E.

The output voltage U_2 is given in this case by:

$$U(t) = R . C. \frac{d\, u_1 (t)}{dt}$$

where: U1 – high voltage.

It is obvious that the signal is – as in the case of current – proportional to the first derivative of measured value. Due to the simplicity and reliability of this element, each combined sensor is equipped with one capacitive resistive divider only. As the voltage measurement in the high voltage plant usually is redundant (i.e. installed at several points), there is no reason to spend an additional voltage electrode per sensor.

3.3 Functions of PISA

PISA is an acronym for Process interface for sensors and Actuators. It is an electronic device for data acquisition, formatting and transmitting the measured data over a process bus as shown in Fig. 4.

The enclosure of a PISA is designed in the class IP54 (IEC 144) and it provides a good cooling effect (thermal conductance better than 1.5 W/K).

Acquisition; ROM – memory element; inputs: u, i, p, θ - voltage, current, density and temperature.

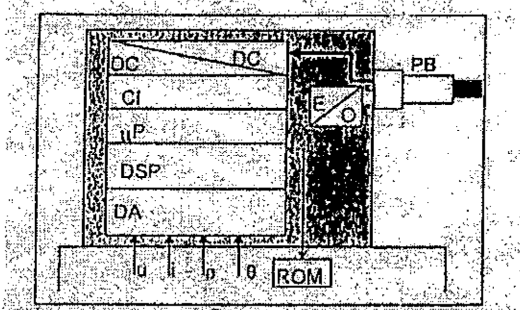


Fig.4 PISA - Block diagram:
PB - system cable consisting of optical process bus and power supply; E/O - data converter (electric optic); DC-DC - power supply; CI - communication interface; µP - microprocessor; DSP - digital signal processing; DA - data Acquisition.

3.3.1 Data Acquisition

Both analogue signals (voltage and current) are amplified, filtered and led to the A/D converter.

Because of the high dynamic range of the current signal, an automatic multi-range current signal conversion is applied.

The internal clock, which is synchronized from the process bus, triggers at equal intervals the A/D conversion and the data are shifted to the DSP (Digital Signal Processor).

The DSP obtains the complete information as the density, temperature and acquisition time values are accessible at any time.

3.3.2 Data Processing

The main function of the DSP (Fig. 5) is to reproduce the original voltage and current signals from the sensor outputs. Due to the fact that both signals are transmitted as time derivatives of the primary values, the integration constitutes the main part of this data processing.

To increase the accuracy, all computable dependencies are taken into consideration and use for correct calculation of original values.

Those reproduced original values u (t) and i (t) are internally presented as two tables of data:

- With an original sample rate.
- And with a reduced sample rate.

The reduced set is designed to be transmitted over the process bus. The former may be transmitted over a fast data link or can be used for disturbance recording as well as for further evaluation.

In fact it is designed to evaluate in the DSP global values like e.g. power frequency, true rms., power frequency amplitude and phase, power components (active, reactive), harmonics ratio, line impedance and others.

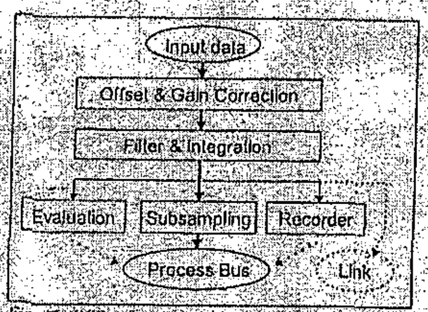


Fig. 5: DSP software overview

4• CALIBRATION

In the final state of manufacturing the calibration of each sensor is carried out. The sensor parameters as e.g. Regowski coil constant M or high voltage capacity C varies slightly in the production.

4.1 Calibration Procedure

The calibration is performed in a number of successive steps, which are controlled by a PC (Fig. 6 and 7).

Before calibration the ROM gets the unique number and/or name of sensor to enable automatic identification of the tested object.

The calibration consists of two main procedures: current sensor calibration and voltage sensor calibration, after which individual sensor parameters are written into a data bank and the ROM.

Current calibration is to be carried out under low voltage so that the sensor needs not to be filled with gas. The current source is not required to be very stable; the reference current transducer however, must be exact. The signals from both calibration PISAs are collected in the PC and the actual Regowsku coil factor is evaluated. The actual temperature of the sensor will be stored together with other test parameters and results in the PC. This set of measurements is repeated some times for various current values (min. 30 runs). The statistic evaluation of results is done and the sensor parameters are stored in the data bank.

Voltage calibration is carried out at high voltage in the GIS test bay. It can be easily combined with a routine power frequency voltage withstand test. A compressed gas capacitor based voltage divider has proven to be suitable as a reference voltage transducer. The measuring procedure is similar to the first one.

The memory on the sensor (ROM) will be filled with the sensor calibration data either after each phase of calibration or after the whole procedure from the data bank.

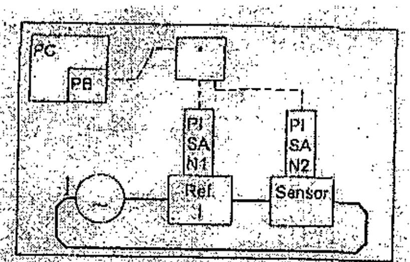


*Fig. 6 Lay-out of current calibration circuit; PC+PB - personal computer with process bus interface; * - star coupler; PISA N1 and N2 - calibration PISAs; I - current source; Ref. I - reference current transducer.*

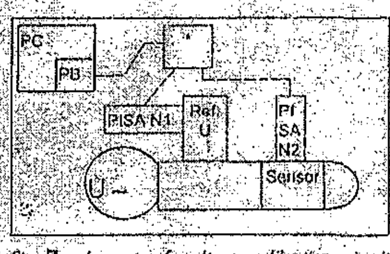


*Fig. 7 Layout of voltage calibration circuit; PC, PB, *, PISAs - as above; U - high voltage source; Ref. U - reference voltage transducer.*

4.2 Comparison with Conventional Instrument Transformers

The accuracy tests are based on the IEC *requirements for instrument transformers* (IEC 60044-2, IEC 44-1). The philosophy of an analogue bridge accuracy test is transferred to the digital technique. The test set-up is the same as per Fig.6 & 7. The subtraction of signal PISA-N1 (Reference) from signal PISA-N2 (in this case actual sensor under test) can be easily the part of an evaluation program, and all types of classic errors (amplitude, phase, composite) can be automatically computed and integrated in the test report.

5. TRANSIENT BEHAVIOR OF THE SENSOR

For protection purposes the transient answer of u/i measurement system is important. The sensor, however, is linear (as shown before) so that no saturation occurs.

Another problem known from conventional instrument transformers is the low frequency characteristic which can be defined as time constant of the transmission of the sensor. Differently from conventional instrument transformers, where the DC transmission performance is a characteristic which cannot be adjusted, the combined sensor allows adjusting the time constant according to the requirements of the customer as per Fig. 8. This is done in the DSP software...

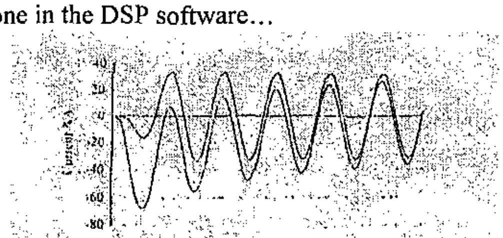


Fig. 8. Primary current with a large DC-component measured by a shunt and a transient recorder (the lower curve) and the same current measured by Rogowski coil and a numerical relay (the higher curve). The relay performed Fourier-transform to derive the 50 Hz component of the current.

5.1 *Protection Systems and Combined 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 short operateing times. The wide frequency range facilitates development of new production algorithms based on high frequency measurements of current and voltage. Fig. 9 illustrates a substation secondary system utilizing sensors. All the feeders have their own voltage and current measurement devices, which facilitates the measurement of voltage behind the circuit breaker.

Two examples of protection schemes are given, that utilizes the use of new combined sensors.

6. 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 tripping 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 stabilizing current. The stabilizing current is the average of the phase current of the HV- and MV- side 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 maltrippings 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, that is protecting the transformer.
The third alternative to stabilize 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 normally exceeds a certain limit. The second harmonic is normally utilized. This solution has the advantage that it also prevents undue tripping at inrush currents caused by switching 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 under trippings due to the saturation of CT's is to make the accuracy limit factor high enough. This may lead to excessively high limit factor. This may lead to excessively high requirements on the accuracy limit factor, if the time constant of the DC-component is long.
Instead of oversizing the CT it may also be linearized by an air-gap in the core. Both alternatives lead to increased costs. The linearization also causes some disadvantages from the protection point of view. E.g. the magnetizing 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 sensor are used. A non- saturable current sensor, described in this paper, however, makes it possible to combine selectivity, good sensitivity and fast operation at a reasonable price.

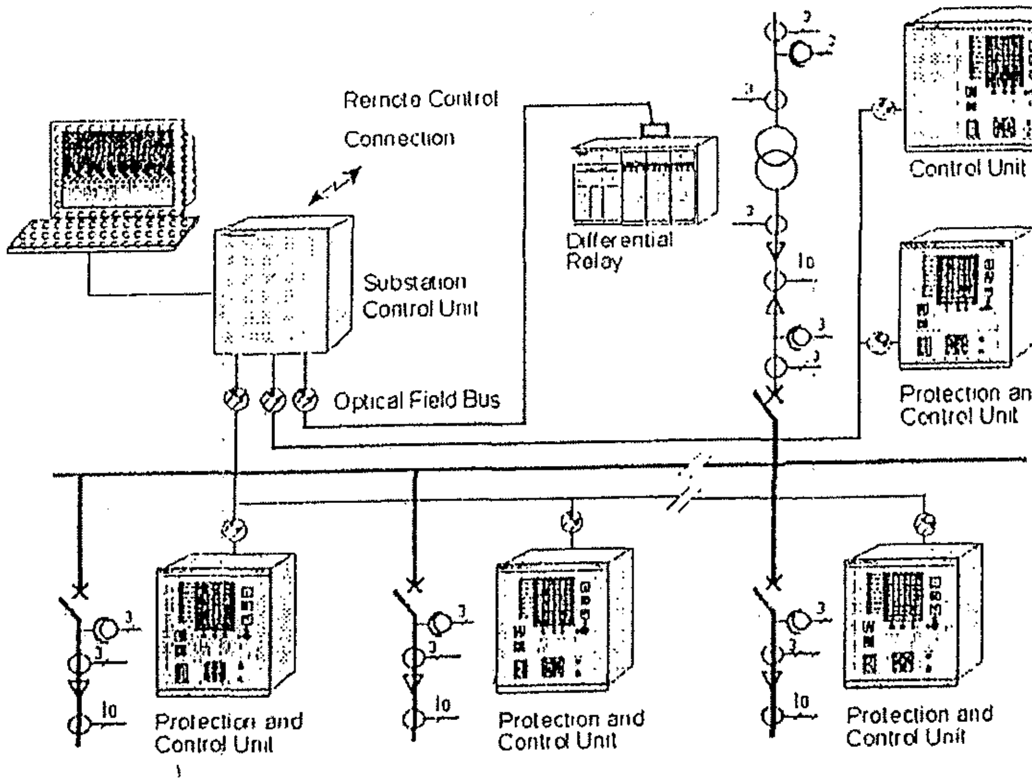


Fig. 9 A schematic drawing of a substation secondary system utilizing sensors for measuring current and vc

6.1 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 relay, 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.

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.8). Since the DC-component is a random variable, its absence increases the accuracy of protection.

7. CONCLUSION

Combined current and voltage sensors fulfill the requirements for revenue metering and for protection because:

- The influences of temperature, temperature gradient in gas, density, on the sensor parameters, can be easily compensated.
- Overcoming maloperation of protection systems due to linear performance and no saturation of current sensor.
- The same sensor can be used for protection and metering due to excellent linearity of both measurements.
- The calibration of the combined sensor is possible in the digital system.
- The transient behavior can be adjusted by software and is easier to handle than in a conventional instrument transformer.
- The long term stability is well established.

The application of such a combined sensor and of the intelligent control and protection brings the following additional advantages for the user:

- Lower cost as compared to conventional systems.
- The engineering effort is considerably reduced due to the universality of the combined sensor.
- The sensor requires less space in the substation, offers more flexibility in layout and more functionality than conventional instrument transformers.
- The simple design of the combined sensor significantly improves dielectric capabilities and enhances reliability in comparison with traditional designs.
- The sensor is an important part of the overall development philosophy leading to intelligent high voltage plants.

Therefore, it is strongly recommended to use such combined sensors in the new GIS projects in the Egyptian unified power system.

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