MEĐUNARODNO REGIONALNO SAVETOVANJE O ELEKTRODISTRIBUTIVNIM MREŽAMA

REGIONAL CONFERENCE AND EXHIBITION ON ELECTRICITY DISTRIBUTION

Crna Gora, Herceg Novi, 5 - 8. oktobar 2004. / ***Montenegro, Herceg Novi, October 5 - 8, 2004***

OPTOELECTRONIC SYSTEM FOR CURRENT AND VOLTAGE MEASUREMENT IN HIGH-VOLTAGE SYSTEMS

J. Radunović, Z. Stojković, S. Petričević, P. Mihailović, S. Stanković, M. Barjaktarović
Faculty of Electrical Engineering, Belgrade, Serbia and Montenegro

ABSTRACT

The paper presents the operating principle and the design of an original instrument for the simultaneous measurement of r.m.s. values of current and voltage in high voltage power systems at industrial frequency. The measurement of current is performed using the Faraday effect, and the measurement of voltage using a resistive voltage divider, constructed from quality high-voltage, low capacitance resistors. The knowledge of the measured quantities enables control and management power systems, and allows the possibility to predict the failures of certain elements and subsystems. In that manner, besides better quality of the delivered electric power, the reliability of the operation of the power system is also improved.

The paper presents the results of several years of research by this team, funded by the Ministry of Science, Technologies and Development of the Republic of Serbia.

INTRODUCTION

While measuring current and voltage in an electric power system, two specific problems arise. One of them is the problem of measurements at high voltages, and the other is connected with electromagnetic disturbances, to which the measuring equipment is exposed. The conventional measuring equipment, based on the direct measurement of current and voltage using induction-based measuring transformers, requires a flawless high-voltage protection. Because of that the conventional systems are bulky and expensive. A permanent maintenance and control of insulator materials is necessary, especially that of the insulator oil. Besides these special maintenance requirements, a problem occurring during measurements are distortions caused by hysteresis and ferroresonance effects, as well as the problem of saturation.
The quick technological development of optoelectronic devices during the last decade offered a possibility to use the theoretically well-known nonlinear optical effects to implement and certify in practice optoelectronic measurement systems for electric power applications [1,2,9]. In this paper it is used the Faraday effect to measure current, while it is used a voltage divider produced of high-quality high-voltage resistors with low capacitanse to measure voltage.

CURRENT MEASUREMENT

The measurement of current flowing through a conductor is performed indirectly, by measuring its magnetic induction . The crystals exhibiting the magnetooptic effect (Faraday effect) are used for that purpose. The effect is manifested by a polarization plane rotation of the plane-polarized light propagating along the crystal if the crystal is in magnetic field. The angle of the rotation θ is given by the relation [3,4]

$$\theta = V \cdot B \cdot L, \tag{1}$$

where L is the crystal length, B is the intensity of the magnetic induction oriented along the crystal, and V is the Verdet constant. The light is guided to the crystal using an optical fiber. Upon its emergence from the fiber a polarizer is used to perform its linear polarization. The polarization plane is rotated in the crystal. After leaving the crystal the light traverses the analyzer. The light intensity on the photodetector is now, according to the Malus' law

$$\Gamma(B) = k\,\Gamma_0 \cos^2(\varphi - V \cdot B \cdot L), \tag{2}$$

where Γ_0 is the light intensity at the beginning of the optical fiber, k is the light attenuation constant on the way from the source to the photodetector, and φ is the angle between the optical axes of the analyzer and the polarizer.
Assuming that there is a linear dependence between the intensity I of the current flowing through the conductor and the magnetic inductance due to the current, expression (2) can be written as

$$\Gamma(I) = \Gamma + \Delta\Gamma(I) = k\Gamma_0/2 \;+\; k\Gamma_0/2 \; \cos(2\varphi - 2cV \cdot I \cdot L), \tag{3}$$

where c is a constant connecting the electric current intensity and the magnetic induction B, and is dependent on the geometry of the sensing head.
The first term in this expression does not depend on the current we intend to measure, but it may vary during the measurement process due to the bending of the fiber or to a decrease of the light source intensity. To ensure measurement independent on these irrelevant but variable parameters, it is necessary to provide in the accompanying measurement system the measurement of the relative change of intensity at the photodetector, i.e.

$$\Delta\Gamma(I)/\Gamma = \cos(2\varphi - 2cV \cdot I \cdot L). \tag{4}$$

The highest sensitivity and linearity of the measurement are obtained when the angle between the optical axes of the analyzer and the polarizer is $\varphi = 45^{o}$. In that case this equality becomes

$$\Delta\Gamma(I)/\Gamma = \sin(2cV \cdot I \cdot L). \tag{5}$$

From here it is determined the intensity of electric current by measuring the relative change of the light intensity at the photodetector $\Delta\Gamma(I)/\Gamma$. The measurement range is determined by the condition

$$\theta = cV \cdot I \cdot L < 45^{o}. \tag{6}$$

The construction of this sensor for the measurement of electric current intensity at industrial frequency consists of a sensing head which is actually a magnetic field concentrator (Fig. 1). It is a magnetic circuit with a gap. The conductor is placed inside the magnetic circuit, and the crystal with the polarizer, the analyzer and the necessary optical system are placed within the gap with a length l. The light is guided by a fiber from the optical source to the polarizer, and the other fiber is used to guide the light from the analyzer to the photodetector. For the concentrators designed to envelop conductors with a diameter up to several centimeters and with a magnetic permeability μ_r>1000, it is theoretically possible to increase the sensitivity, i.e. the modulation depth, up to several tens of times if the length of the gap is decreased. Regretfully, the degree of modulation depends on two parameters, the crystal length and the width of the gap in the magnetic circuit. It increases with the increase of the length of the crystal L, but also increases with the decrease of the gap width l. It follows that it is necessary to find the optimum values for a given geometry of the concentrator and the dimensions of the crystal. Practical calculations show that in that case the degree of sensitivity can be increased not more than 2,5 times [5]. However, the importance of the concentrator is not only in this, but also in the fact that its use practically ensures that position of the conductor inside the sensing head does not influence measurement accuracy, as well as an elimination of the influence of the surrounding conductors.

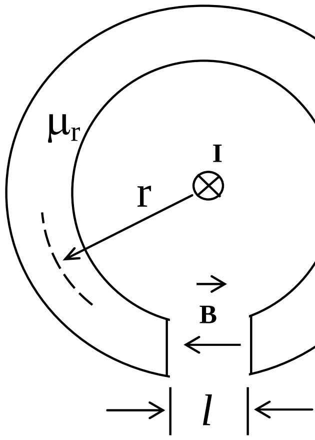

Fig.1. *Representation of the sensing head.*

The block diagram of the electronic circuit of the measuring system is shown in Fig. 2. The photocurrent from the photodetector is converted to voltage by a transimpedance amplifier stage (TrA in Fig. 2). According to (5), this signal contains a component $\Delta\Gamma$ varying in time, and a component Γ which practically only weakly changes in time, and whose changes only disturbs the measurement.
The new implementation of the sensing head improves the level of the useful signal several times, so that the method utilized in this work, in contrast to the method used in [6,7,8,9], does not require two channels of an AD converter for separate measurements of $\Delta\Gamma$ and Γ, but only a single channel instead. Now after the AD conversion of the signal these two measured components of the signal are subsequently divided in microprocessor by software processing. In this way the value of the current intensity $I(t)$ at the given instant is obtained in the digital form. Further processing gives the effective value of the current to be shown in the LCD display. By the RS232 interface it is possible to send the complete signal to a PC for advanced signal processing.
Contrary to the papers [6,7,8,9], the second channel can be now utilized for voltage measurement. The idea is to do it using a high-voltage resistor-type divider whose role is to linearly scale the high voltage present in the conductor and to adapt it to the measurement over the second channel. In this manner a combined method was realized which measures current in optical way and voltage in the conventional electric way.

VOLTAGE MEASUREMENT

The measurement of high voltage is done utilizing a resistor-based voltage divider produced from high-quality resistors. The resistance of the resistor R1 (Fig. 2) which is in contact with high voltage conductor, is 10 MΩ (model SGP 148S, manufacturer EBG). It is designed for the maximum voltage of 50 kV DC, which allows its operation at 35 kV of effective steady-state voltage. The resistance of the resistor R2 is 10 kΩ, and its steady-state voltage, with a value of 35 V. The capacitive current here is negligible.
The voltage signal from the R2 is fed by a BNC cable to the electronic measurement circuitry. The signal arrives first to the input inverter amplifier (InA, Fig. 2) which adapts the level of the measured signal voltage to the input voltage range of the AD converter, which performs its digital conversion. The signal processing is done by a microprocessor. The measured value is displayed at the LCD display, and the RS232 interface allows to send the complete signal to a PC for advanced signal processing.

ELECTRONIC MEASUREMENT SYSTEM

A block drawing of the electronic measurement system is given in Fig. 2. The measured signal for the current *I(t)* is the amplitude modulated photocurrent from the photodetector. This photocurrent is converted in the transimpedance stage (TrA, Fig.2) to a voltage signal to be introduced into the first channel of the AD converter. The measured signal for the voltage *U*(*t*) is scaled down to low voltage with an effective value of 35 V using the voltage divider. Thus obtained signal is led to the input inverter amplifier (InA, Fig. 2) which adapts the voltage level to 3.5 V effective value, corresponding to the input level of the AD converter. In this point an overvoltage protection to 90 V is implemented using a gas discharge tube. This voltage signal is introduced to the AD converter through the second channel. The AD converter is 20-bit sigma-delta converter which performs signal digitalization in a frequency range 0-10 kHz. The digitized values from the AD converter are collected by the AT89S8252 microcontroller and stored into a static memory (SRAM). The sampling frequency of the AD converter is 28800 Hz, a total of 576 points are stored during one period at 50 Hz. From thus obtained time series the effective values of the current and the voltage are calculated in the microcontroller and shown at the display of the instrument. The time series of both measured signals can be led by an RS232 interface to a PC.

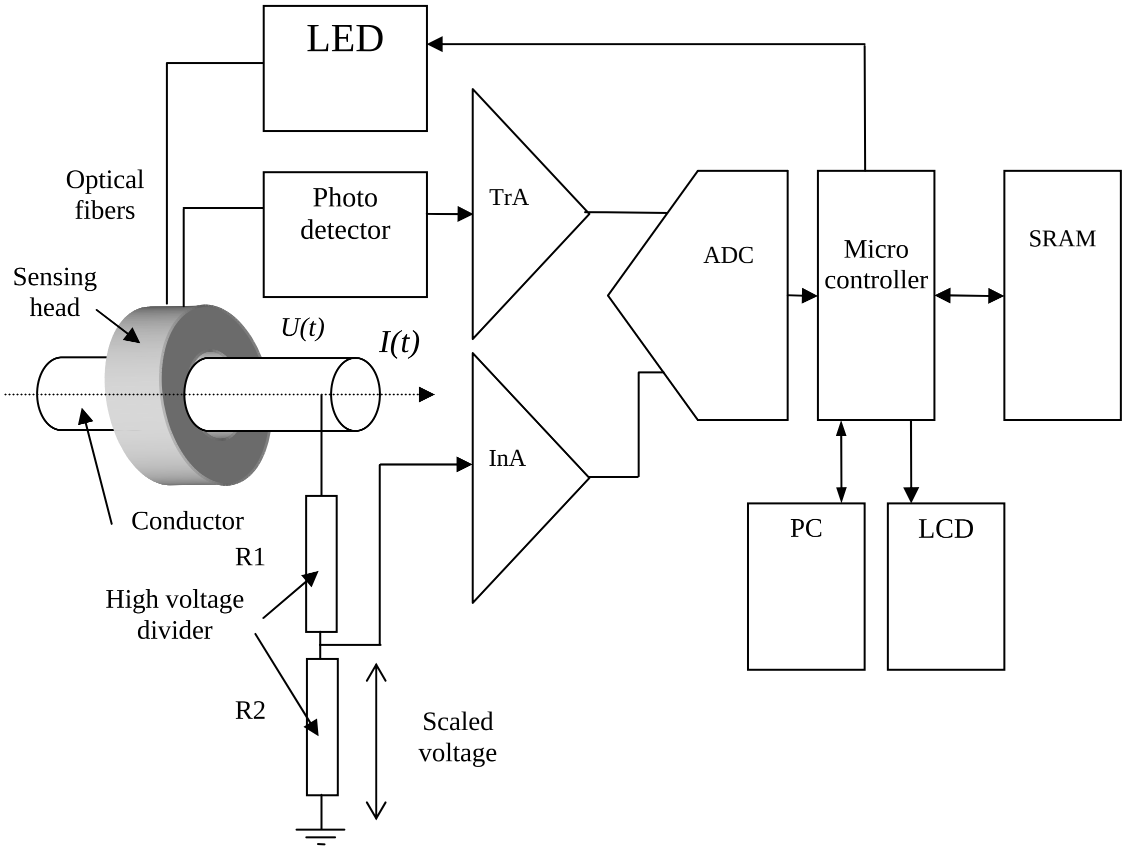

Fig. 2 *Block-representation of the electronic circuit*

In this way the most important requirement of the measurement is fulfilled, that for a synchronous measurement of current and voltage. The obtained digital values of the current and the voltage after AD conversion originate from the identical moments of time and thus it is possible to determine accurately the current voltage phase relationship. Also, the measurement allows storing in 576 points the values of the current and the voltage during a single period at 50 Hz, while up to 7 periods of voltage and current can be stored in the memory of the instrument. It is possible to decrease the number of points per period, to encompass more periods and thus achieve a better accuracy of harmonic analysis.

CALIBRATION

The method of current measurement described here is nonlinear, thus it is necessary to calibrate the instrument in the whole measurement range, while the method of voltage measurement is linear and the calibration is done for it only in two points of the measurement range (zero and maximum voltage). The calibration of the instrument for the current measurement requires the calculation of a conversion table containing all possible digital values of the measured signal which may occur during measurement (depending on the required resolution of the device) and the corresponding effective values of the current. To calculate this table, it is necessary first to perform calibration measurements for several current standards, i.e. to form a calibration table containing the measured values of the effective current in these standards and the corresponding digital signatures of the measured signal values. Now the interpolation polynomial is calculated using this calibration table and used to generate a fixed conversion table and store it to the memory. In this manner the results on the LCD are displayed by directly reading the conversion table, i.e. the interpolation polynomial is not calculated over and over again, which significantly accelerates the measurement procedure.

CONCLUSION

In this paper it is implemented an optoelectronic system for the measurement of current and voltage in high-voltage systems. It is possible to use it to measure currents in the range from several A to 1000 A, and voltages from several kV to 35 kV. The achieved accuracy is ± 1% of the measured value. The measurement system has a high resolution, which enables a high dynamic range of the measurement of current and voltage. Thus there is no need to change the instrument range while performing measurements on different lines with various nominal voltages and currents. In contrast to the method used in [6,7,8,9] where it was necessary to utilize a two-channel AD converter to measure current, the improve design of the magnetic concentrator in this case enabled conversion of the current signal by using only one channel of the AD converter. In this way it was possible to use the second channel for the signal led from the voltage divider. This ensured the fulfillment of the most important requirement of the measurement, i.e. the synchronous measurement of current and voltage. The time series of the both measured signals can be sent by an RS232 interface to a PC for a further and more complex processing. Let us remind that all of these measurements are performed at high voltage. Both of the sensors, for the current and the voltage measurements, can be mounted to an insulator po1e and the complete design can be implemented to use the instrument as a portable device and to perform measurement without any interruptions in the operation of the power system.

REFERENCES

1. Ulmer A.E., 1990, “A high-accuracy optical current tranducer for electric power systems”, IEEE Trans. Power Delivery, Vol. 5, No.2.

2. Katsukawa H., Ishikawa H., Okajima H., Cease T., 1996, “Development of an optical current transducer with a bulk type Faraday sensors for metering”, IEEE Trans. Power Delivery, Vol.11, No.2.

3. Mašanović G., Radunović J., 1997, “Magnetic field sensor based on Faraday effect”, J. Electrotech. Math., No.1, pp.21-30.

4. Radunović J., Mašanović G., Petričević S., Elazar J., Mihailović P., 1998,: “Fiber-optic sensor for contactless measurement of electric current intensity”, Proc. 1st Conf. JUKO-CIRED, Zlatibor. (in Serbian)

5. Zlatanović S., Mihailović P., Mašanović G., Radunović J., 1999,: “Optican current sensor with ferromagnetic ring”, Proc. XLIII Conf. ETRAN, pp.186-188. (in Serbian)

6. Mihailović P., Petričević S., Stanković S., 2000,: "Frequency characteristic of measurement probe of a fiber optic sensor for assessment of quality of electric current ", Proc. XLIV Conf. ETRAN, pp.199-202. (in Serbian)
7. Mihailović P., Petričević S., Radunović J., 2002,: "Fiber optic system for measurement of current intensity at high voltage", Proc. III Conf. JUKO-CIRED, Vrnjačka Banja. (in Serbian)
8. Radunović J., Petričević S., Mihailović P., Mašanović G., Stanković S., Barjaktarović M., 2003,: "Optoelectronic measurement systems in power engineering", (invited paper) Proc. XLVII Conf. ETRAN, Herceg Novi. (in Serbian)
9. Mihailović P., Petričević S., Stojković Z, Radunović J., 2004,: " Development of a Portable Fiber Optic Current Sensor for Power Systems Monitoring", IEEE Transactions on Instrumentation and Measurement, Vol. 53, No.1, pp. 24-30.

Contact: prof. Dr Jovan Radunović, Faculty of Electrical Engineering, 11000 Belgrade,
Bul. Kralja Aleksandra 73, radun@Infosky.net, radunovic@etf.bg.ac.yu