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MICROCOMPUTER BASED DEVICES FOR TESTING THE ACCURACY OF INSTRUMENT TRANSFORMERS

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Abstract. The paper presents a review of several new devices for instrument transformer accuracy testing which are developed in the Electrical Engineering Institute "Nikola Tesla", Belgrade, Yugoslavia. Instrument transformer on–site accuracy testing device, type INST–2, based on the compensated current comparator method is described. Computer controlled device for the automatic testing of current transformer accuracy, type ASK–2, permits the automatic testing in the mass production of low voltage current instrument transformers with both good metrological characteristics and the excelent efficiency. Both hardware and software instrument improvements made in the computer based on device for precise laboratory accuracy tests of instrument transformers, type INST–2A, are pointed out.

1. Introduction

Instrument transformers are a necessary element in AC electric circuits. They are used for measurement, protection and control. Especially important is their role in electrical energy measurement because of enormous financial transactions resulting from the recorded energy consumption. Inherent errors of instrument transformers form part of the total electrical energy measurement error. Electrical energy measurement will be more accurate if instrument transformers of a higher class of accuracy are used. This, in turn, requires methods and devices for testing the instrument transformers accuracy. Traditional devices for accuracy testing, such as the Shering–Alberty

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[1], Hole's [2] and Keller's [2] compensators, do not satisfy metrological requirements concerning measurement range, accuracy and efficiency. Therefore, there is a real need to modernize devices for testing the accuracy of instrument transformers.

From the metrological standpoint, modern devices for testing measurement transformer accuracy are characterized by high precision and direct reading of the amplitude and phase errors; on the technological level, they use electronic components and microcomputers. The Electrical Engineering Institute "Nikola Tesla" has been testing instrument transformers accuracy continuously for more than 40 years [4]. During this period, several measurement methods and dozens of different devices have been developed in this field. Significant results have been achieved, especially in the development and application of current comparators [5,6], so that the Institute is among the leading manufacturers of measurement equipment in this field [7]. Modem scientific and technological trends are applied to the development and improvement of measurement devices. We have developed several types of electronic apparatus for testing of measurement transformer accuracy whose operation is supported and improved by the use of microcomputers. This paper presents a review of these new devices for instrument transformer accuracy testing.

2. Instrument transformer on-site accuracy testing device type INST-2

Testing of instrument transformers on-site at the power plant must satisfy not only the standard metrological requirements concerning accuracy of measurement, but must also fulfill some additional specific conditions. These include ease of use, measurement efficiency, reliability and the ability) to perform under load, especially easy maneuverability inside the installation. Clearly, instrument transformer accuracy testing inside the HV plant is done amidst strong electromagnetic fields which influence the operation of electronic devices. The transport of this large, heavy and mechanically sensitive equipment is not an insignificant problem. Therefore, any reduction in the number of devices necessary, their dimension or weight is very significant for measurements in the field. The application of the compensated current comparator in measuring the accuracy of instrument transformers is an ideal example of this.

2.1. Method of the compensated current comparator

Development and the application of the current comparator for current instrument transformer accuracy testing [8] is, in effect a new, different approach with a deeper metrological significance [9]. The idea of the current comparator is based on Ampere's law on the circulation of the magnetic field vector

$$\oint_L \vec{H} d\vec{I} = \sum_1^n N_i I_i \tag{1}$$

which is in practice achieved using a toroidal magnetic core made of high penneability material with four windings, as shown in Fig. 1.

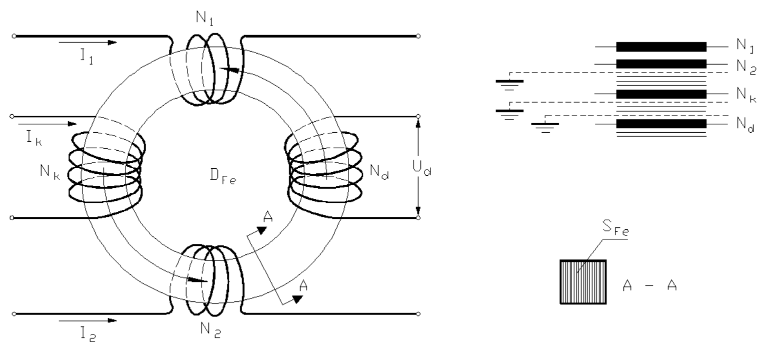

Fig. 1. Schematic diagram of the current comparator

The voltage at the ends of the detection winding is determined from

$$U_d = 2\mu_0 \mu_r N_d \frac{S_{Fe}}{D_{Fe}} \sum_1^n \underline{I} \tag{2}$$

Equation (2) expresses the basic idea of the current comparator as well as the resulting metrological advantages. The comparison of currents is based on the ratio of turns, which is constant in time and insensitive to outside ambient influences. Voltage U_d is the measure of inequality of electromagnetic forces. It depends on the constructive parameters of the current comparator, the number of turns N, the magnetic permeability μ and the length and cross section of the magnetic circuit S, all of which are design parameters. The sensitivity of the current comparator is in practice three orders of magnitude above the sensitivity of classical measurement methods. Although simple in principle, the current comparator is in fact a very complex and technologically subtle metrological solution.

For carefully constructed current comparators, AC currents are compared with an error under $1 \cdot 10^{-7}$. Due to its evident metrological advantages, the current comparator has been applied in other areas, such as the precise comparison of resistors, capacitors, measurement of DC currents, etc.

The method of the compensated current comparator (CCC) [10] permits the current comparator to replace the reference transformer and primary current source. As shown in Fig.2, the current comparator is supplied from a controlled current source I_{2N} on the secondary winding side N_2.

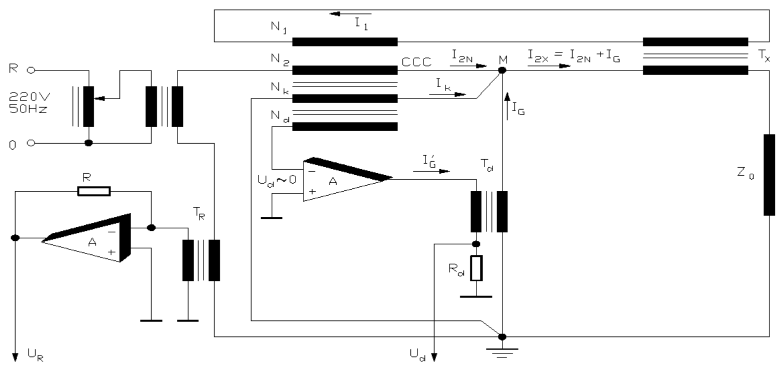

Fig. 2. Method of compensated current comparator

In the primary winding of the comparator, N_1, and the primary of the current transformer under test, T_x, a current I_1 is flowing which induces current I_{2x} in the secondary of the tested transformer. In order to secure the transfer of energy from the secondary to the primary, it is necessary for the current transformer to have a corresponding magnetic circuit. This role is played by the magnetic shield, which has a dimension sufficient to transfer the rated power (order of 2 kW). The magnetic shield, therefore, has a double function. Thus, this current transformer transforms the secondary current into the primary with a given, non-negligible error. The basic idea behind this device is that the compensation winding, N_k, with its current, I_k, almost completely compensates this error. The compensation winding of large cross section copper wire has a low impedance and presents a nearly ideal current loop through which flows the error current of the current comparator, but also the error current of the transformer under test. The detection winding voltage reflects only the current error I_G of the tested transformer. This is nullified by the feedback loop current I'_G, placing the measurement core into a state of zero magnetic flux [11]. This current is in correspondence with the complex error of the tested transformer, which is measured by the complex compensator. At first, these compensators had manual balance adjustment (types KSK-5, KSK-6, KSK-7), then came digital complex compensators with direct error reading INST-1 and finally, using microcomputers, the model INST-2 significantly improved the level of processing of the measurement signal [12]. Using INST-2, the accuracy of voltage and current transformers can also be tested using the differential method and the reference transformer.

2.2. Principle of operation of INST-2

INST-2 electronically processes two voltages, the reference voltage U_R and the differential voltage U_d. The first voltage U_R corresponds to the secondary current or voltage of the reference transformer T_N, while the differential voltage U_d corresponds to the complex error of the measurement transformer T_x. The vector diagram of these voltages is given in Fig.3, which shows their basic harmonics with a defined amplitude and phase error.

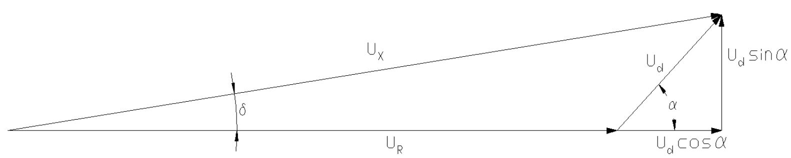

Fig. 3. Voltage vector diagram for the differential method.

Equations which describe the ratios of these voltages and their relation to the complex error $\underline{G}$, amplitude error g_a and phase error g_f of the measurement instrument are

$$\underline{G} = g_a + jg_f \tag{3}$$

$$\underline{G} = \frac{\underline{U}_x - \underline{U}_R}{U_R} = \frac{\underline{U}_d}{U_R} \tag{4}$$

$$g_a = \frac{U_d \cos\alpha}{U_R} \tag{5}$$

$$g_f = \delta \cong \tan\delta = \frac{U_d \sin\alpha}{U_R + U_d \cos\alpha} \tag{6}$$

Equation (6) contains two approximations; firstly, the angle δ has been replaced by $\tan\delta$ and secondly, the term $U_d \cos\alpha$ has been neglected. The first approximation, for a phase error of $100'$ creates a difference of only $0.028'$. If we neglect the term $U_d \cos\alpha$, this generates a relative error of the phase error equal to the amplitude error of the tested transformer

$$\frac{\Delta g_f}{g_f} = g_a \tag{7}$$

According to expression (7), if the amplitude error is 1%, then the error in measuring a phase error of $50'$ is equal to $0.5'$, which is acceptable. Namely, in high accuracy class instrument transformers (e.g. 0.1), for a phase error of $10'$ the error is only $0.01'$. In instrument transformer accuracy testing devices in which the signals are processed by a microcomputer, these approximations can be avoided. Moreover, the accuracy of error measurement depends mostly on the accuracy with which signals UR and Ud are processed according to expressions (5) and (6). The error in measuring the amplitude and phase error, expressed through partial errors of individual variables, is equal to

$$\Delta g_a = \frac{\partial g_a}{\partial U_d} dU_d + \frac{\partial g_a}{\partial U_R} dU_R + \frac{\partial g_a}{\partial \alpha} d\alpha \tag{8}$$

$$\Delta g_a = \frac{\partial g_f}{\partial U_d} dU_d + \frac{\partial g_f}{\partial U_R} dU_R + \frac{\partial g_f}{\partial \alpha} d\alpha \tag{9}$$

or, in relative terms

$$\frac{\delta g_a}{g_a} = \frac{dU_d}{U_d} + \frac{dU_R}{U_R} + \sin\alpha \frac{d\alpha}{\cos\alpha} \tag{10}$$

$$\frac{\delta g_f}{g_f} = \frac{dU_d}{U_d} + \frac{dU_R}{U_R} + \cos\alpha \frac{d\alpha}{\sin\alpha} \tag{11}$$

The first two terms in equations (10) and (11) are the relative errors in the measurement of U_R and U_d, while the third term is the relative error in the measurement of $\cos\alpha$, i.e. $\sin\alpha$. This is only a simple error analysis. A detailed analysis would completely process measured signals and would take into consideration all the electronic circuits used.

The composition of INST-2 can be seen from the block diagram in Fig.4

Voltages U_R and U_d are taken from the reference transformer T_N and the tested transformer T_x, respectively, using current-voltage transformers T_R and T_x [13]. The secondaries of these instrument transformers are connected to the zero sequence impedance of operational amplifiers A_1 and A_2, operating as a current-voltage converter. The differential voltage U_d and the reference voltage U_R are amplified to an optimum level using amplifiers A_1 and A_2. Both voltages are brought to two identical electronic low frequency band filters which separate the first harmonic necessary to define the amplitude and phase error of the tested instrument transformer. The electronic phase inverter uses the reference voltage to generate four control voltages shifted in phase by $\pi/2$, π, $3\pi/2$ and 2π in respect to the reference voltage [14]. In phase controlled rectifiers (phase discriminators) FD_1 and FD_2, these control voltages are used to separate the following components from the differential voltage

$$U_a = U_d \cos\alpha \tag{12}$$

$$U_b = U_d \sin\alpha \tag{13}$$

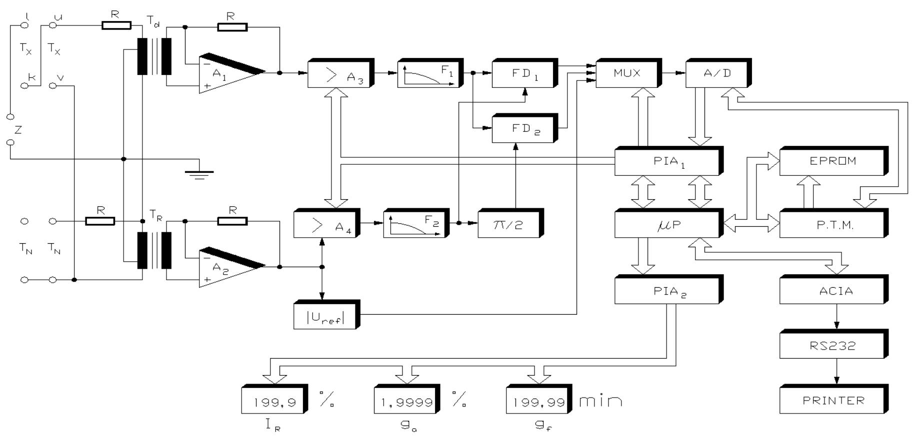

Fig. 4. Block diagram of INST-2

Now, only one more step is necessary to obtain the amplitude and the phase error: expressions (12) and (13) should be divided by the reference voltage. This basically mathematical calculation is performed using the microprocessor μP. Multiplexer MUX brings the voltages U_a, U_b and U_R to the A/D converter where analog signals are transformed into corresponding digital signals. Apart from mathematically processing these signals, the microprocessor in fact monitors all the device elements, binding them into a smoothly functioning unit.

2.3. Description of the device

INST-2 for testing instrument transformer accuracy is a portable device, used primarily for field measurements. The device is mounted in a standard 19" rack measuring $465 \times 320 \times 260mm$.

INST-2 has several interconnected modules on PCBs (Europa format). This approach was dictated by the complexity of the device, ease of adjustment, testing and servicing. The analog part is technologically based on low offset and low noise integrated circuits OP77 and OP37, made by PMI. The digital part uses "Motorola" chips, such as the μP 6802, PIA 6821, PTM 6840, ACIA 6850, etc. We used a 14-bit A/D converter, type 7135 by Intersill. The $13mm$ high digital 7-segment LED displays type HDN 1033 permit easy and clear reading of measured errors. This hardware is supported by specially developed dedicated software used for the mathematical calculations with signals, the visual presentation of measured errors on digital displays and the graphical printing of measurement results on a digital printer. The mathematical processing of the measured signals includes zero correction, calibration, division of two digital signals, averaging and roundoffofmeasurement results. In order to increase reliability, the most important elements of the device are monitored and the device is additionally protected against operation in irregular conditions (inverted terminals of the tested transformer, operation outside the measurement range, etc.).

Upon analyzing the measurement errors of individual electronic modules, as well as that of the device as a whole, we have estimated the following:

- measurement uncertainty in amplitude error measurement is $\pm 0.2\%$ of the measured error and $\pm 0.02\%$.
- measurement uncertainty in phase error measurement is $\pm 0.2\%$ of the measurement error and $\pm 0.02\%$.

Comparative measurements using the Hole compensator have confirmed this estimate. The other measurement and technical characteristics of INST-2 are:

- Measurement ranges for the amplitude error are $\pm 2\%$ and $\pm 20\%$ with respective resolutions of the readout of 0.0001% and 0.001%.
- Measurement ranges of phase errors are $\pm 200'$ and $\pm 1000'$ with a resolution of $0.01'$ and $0.1'$, respectively.
- Testing the accuracy of current instrument transformers in the range of 5secondary currents of $1A$ and $5A$.
- Testing the accuracy of voltage instrument transformers in the range of 5% to 200% with rated secondary voltages of $100\sqrt{3}V$, $100V$, $200\sqrt{3}V$.

- Rated frequency is $50Hz$.
- Operating temperature range is $10°$ to $40°$.
- The device is supplied from a $220V \pm 10\%$ network.
- Series digital interface RS232.

Operation of INST-2 is extremely simple. Connection to other elements of the circuit (ET, T, load, etc.) is uniquely defined through corresponding connectors and terminals. The reading of the measured error values is performed directly from corresponding displays or they are registered on a digital printer.

Therefore, working with this device is both efficient and comfortable. Both properties are especially significant when performing measurements on transformers under load. The permitted overhaul time of HV installations is limited, while measurements require care and special HV protection measures.

3. Computer controlled device for the automatic testing of current transformer accuracy

The mass production of low voltage current instrument transformers requires accuracy measurements during manufacture and final product control. As this is a relatively cheap mass produced article, the classical measurement methods are impractical from both the technical and economical standpoints. A significant advance was made by automating the accuracy testing of current instrument transformers [15]. With this device (ASK-1), developed for the transformer manufacturer Energoinvest from Sarajevo, the test process lasted a little over 30 seconds. Modem technology, especially the breakthroughs made in industrial electronics and the application of microcomputers, have enabled an increase in the efficiency of measurements. Thus, a new computer based device has been developed for the transformer manufacturer Minel-Zrenjanin, for automatic testing of current instrument transformers (ASK-2) [16]. The composition of this device is shown in Fig.5.

The basic components of this measurement system are: a voltage controlled current source (VCCS), compensated current comparator (CCC), the tested transformer (T_x), test load (B), reference transformer (T_R), analog (AE) and digital (DE) electronic blocks, computer (PC) and printer.

This system is valuable because it uses an original concept for applying the compensated current comparator. static current controller and computer control and measurements. The operator inputs the data on the tested transformer, chooses the test options and the manner and form of registration. The accuracy testing of a single current measurement transformer lasts un-

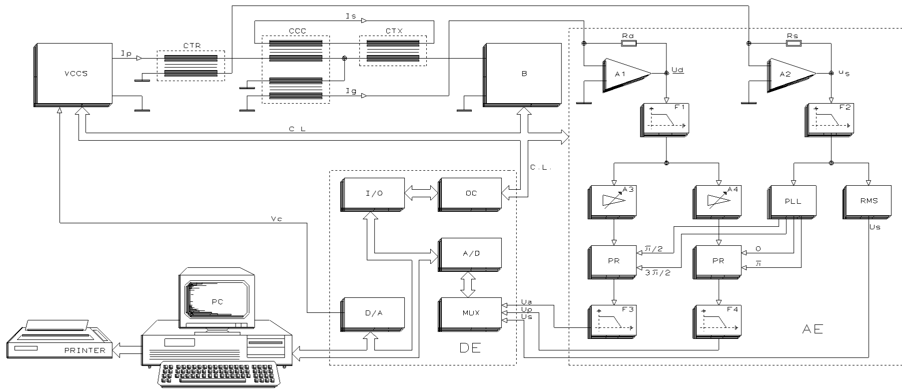

Fig. 5. Block diagram of the automatic current measurement transformer accuracy testing device.

der ten seconds.

CCC performs the current comparison and simultaneously supplies electrical energy to the circuit through the secondary winding of the comparator. The current in the detection winding I, i.e. the voltage U, after passing through the current-voltage converter (A) corresponds to the error current I of the tested transformer

$$\underline{U}_d = K \cdot N_d \cdot \frac{N_2}{N_k} \cdot R \cdot \underline{I}_g \tag{14}$$

CCC is of standard construction. The magnetic circuit of the measurement core is made of high permeability material (ultraperm 10) in the form of a toroid measuring $250 \times 220 \times 15mm$. The detection winding has 2500 turns of lacquered copper wire $0.2mm$ in diameter. The magnetic circuit is simetrized, while the measurement core and the detection winding are electrostatically and magnetically shielded. The compensation winding has five sections with a total of 200 turns of $3mm$ diameter copper wire. The secondary winding also has five sections identical to the compensation winding. The primary winding has several sections with the corresponding number of turns and cross sections for currents ranging from $5A$ to $1000A$.

Electronic circuits used for processing analog measurement signals are identical to the ones found in INST-2, but the A/D converter and the digital part are different. The digital circuit is based on a PC 286 standard configuration computer to which two electronic cards are added: an VO board with 24 inputs–outputs and a 12 bit A/D and D/A converter.

This device has a new feature: the electronic adjustment of the reference current which was in the past done by an autotransformer and servomotor. This approach, however, has certain drawbacks in the speed and precision of adjustment and also in the maintenance of the motor and the autotransformer. The developed static stabilized voltage controlled and computer regulated current source has shown itself as a very good substitute. Thanks to this concept, a very efficient adjustment of the reference current is possible in less than $1s$ per reference point. Therefore, the total test time of a current transformer has been reduced to less than $10s$. Electromagnetic noise, always present in electronic current sources and which influences measurements, is eliminated using corresponding hardware and software procedures.

The elements of ASK-2 are modullarly distributed into several separate cases which are interconnected with corresponding cables and connectors. Device ASK-2 permits the automatic testing of current instrument transformer accuracy in the primary current range of $5A$ to $1000A$ for secondary currents of $1A$ and $5A$, both for standard values of reference currents (5, 10, 20, 100 and 120% of the rated current) and for arbitrarily chosen values in the range of 5% to 200% of the rated current at reference loads in the range of $1VA$ to $60VA$, for both 25% and 100% of the rated load.

The ASK-2 has been subjected to a detailed analysis and testing in order to verify the accuracy and the efficiency of measurements and reliability of operation. Individual elements were tested as well as the device as a whole. The results of tests can be summarized as follows:

- Error of CCC in the whole range of rated primary and secondary currents does not exceed $1 \cdot 10^{-5}$ and $0.02'$
- The reference current can be adjusted with an error below 1% and a harmonic factor under 2%.
- The reference load is defined with an error below 2%.
- The influence of temperature on the accuracy of measurements is felt only in the analog part of the device and is less than $0.02\%/10°C$.
- The total estimated, declared error of the device is under ±0.5% of the measured amplitude error and ±0.02% and ±0.5% of the measured phase error and $\pm 0.5'$.
- The effective accuracy testing time of a current measurement transformer, for the standard set of test points is $9.5s$.

Due to good metrological characteristics, this device can be used to test current instrument transformers with accuracy ratings from 0.1 to 3. Its testing speed places this device among the most efficient of its kind. Finally, and very importantly, this has been achieved without sacrificing the accuracy of measurement.

4. Computer based device for precise laboratory accuracy tests of instrument transformers, type INST-2A

4.1 Introduction

Modern computer devices for measurement transformer accuracy testing have shown themselves very efficient and practical in measurements performed on-site and in factories. However. the same type of device is also suitable for precise laboratory accuracy testing of reference instrument transformers [17]. Here, the primary requirement is high accuracy. In order to fulfill this condition, it was necessary to undertake certain hardware and software modifications on INST-2, which resulted in device type INST-2A [18].

4.2. Description of the hardware

The hardware of INST-2A can be seen from the block diagram in Fig.6.

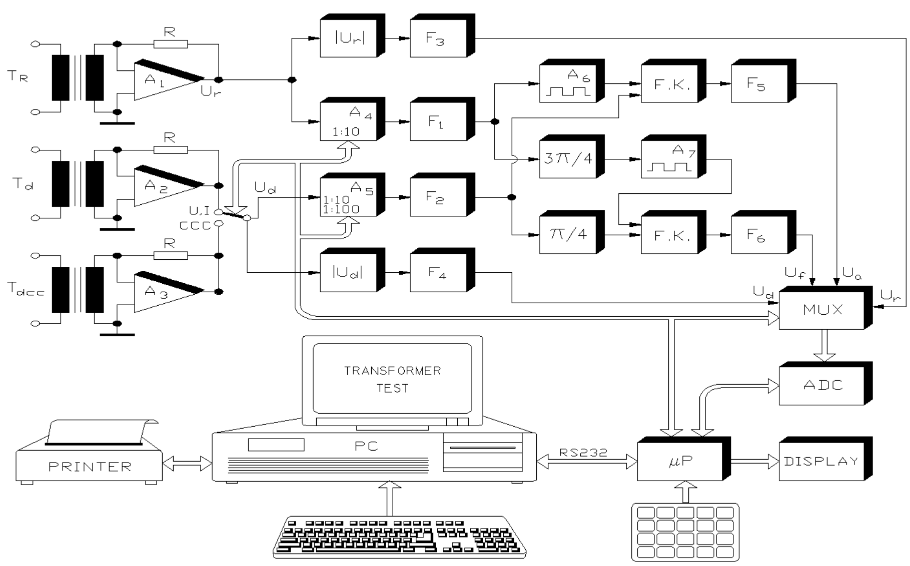

Fig. 6. Block diagram of INST-2A

It is immediately clear that the structure of this new device is very similar to INST-2. The differences lie mainly in the applied technological and constructive approaches, in the selection of the electronic components and in the specially careful testing and adjustment. In the analog section, changes were introduced in the phase discriminator, so that the phase shift of $\pi/2$ is achieved by shifting the reference voltage U_R by $\pi/4$ and the differential voltage U_d by $3\pi/4$. The digital section uses the more modern microcontroller SAB8031, instead of the 6802 microprocessor and its corresponding environment. There is also a PC which allows a more sophisticated processing of the measured signals. This new device also uses the modular concept: PCB's connected by cables in a common 19" rack. On the front of the rack we find the display for reading the reference current, the amplitude and phase error, the keyboard for choosing the type of operation and the measurement range, signal elements, the main switch for turning the device on and a push button for resetting the protection circuit. On the back are the connection terminals and connectors for joining the device to other elements of the circuit for testing the accuracy of instrument transformers.

4.3. Description of the software

Special care was paid in the development of the software. The result is a custom made program for the precise testing of measurement transformer accuracy. It contains several software blocks:

- operational block
- measurement block
- mathematical–logical block
- data base
- control–signalizing block and
- block for the graphical and numerical presentation of measurement results.

The operational block initializes the device, chooses functions and the rated values of the tested transformer. The measurement block automatically selects the gain and controls the analog multiplexer and A/D converter. The mathematical–logical part processes the results, performs calibration, averaging, elimination, roundoff and indication of measurement results. The elimination of coarse errors is a subprogram in the algorithm for finding the mean value of measurements, performed in order to decrease chance errors. We used Schoven's criterion for the deviation of individual results from the mean value. This turned out to be a good approach which increases the accuracy of measurement results. All significant parts of the device are under constant software monitoring. Both the correct and irregular operation are indicated by corresponding signal lights. The graphical and numerical presentation of measurement results has been adapted to the ergonometrical requirements of efficient and comfortable operation. The final results of instrument transformer accuracy tests are printed in the form of a report which, apart from the results themselves, contains also all the other relevant test data. The report is both printed and stored in the data base. The technical characteristics of INST-2A are:

- Testing of voltage instrument transformers by the differential method, for secondary voltages $100/\sqrt{3}$, $110/\sqrt{3}$, $120/\sqrt{3}$, $200/\sqrt{3}$, $100, 110$ and $120V$
- Testing of current instrument transformers by the differential method and the method of current comparator for secondary currents $1A$ and $5A$.
- Measurement ranges for the amplitude error are $\pm 0.2\%$ and $\pm 2\%$ and for the phase error $\pm 10'$ and $\pm 100'$.
- the maximum resolution in the reading of the amplitude error is 0.0001% and $0.0001'$ for reading the phase error.
- the accuracy of amplitude error measurement is estimated to be 0.1% of the measured value and $\pm 0.0002\%$
- the accuracy of phase error measurement is estimated to be ± 0.1 of the measured value and $\pm 0.0001'$.
- current test load up to $60VA$ with error below $\pm 1\%$.
- voltage test load up to $180VA$ with error below $\pm 1\%$.
- temperature range for the declared device error is $18°C$ to $28°C$.

Device INST-2A is a modern measurement device with good metrological characteristics. Strong software support of the measurement, mathematical processing, visual graphical presentation and the printing of results enables an accurate and reliable, efficient and comfortable operation.

5. Conclusion

The devices presented in this paper for the testing of instrument transformer accuracy form part of the class of modern microcomputer based measurement systems. According to their metrological and technical characteristics, these devices are among the best devices of this kind in the world. Scientific and technical advances open up new possibilities and approaches in this area of metrology. An example worth noting is the idea put forth by specialists from PTB on the digital separation of error components based on the discrete Furrier analysis of the measured signal [19] or the concept of the virtual instrument for testing measurement transformer accuracy, developed in Institute Nikola Tesla" for testing the accuracy of instrument transformers with nonstandard transformer ratios [20].

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