Overview of measuring methods and equipment for calibration of instrument transformers

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***Abstract*— Instrument transformers are an important and inevitable element of AC current and voltage measurement techniques. They have been in use for more than a century. In parallel with the development of technical characteristics and improvement of instrument transformers measurements, the measurement methods and measuring equipment developed too. The significant parts of the development in this field are measuring methods, measuring devices, and systems for testing the accuracy of measuring transformers. The measurement accuracy is the most important characteristic of instrument transformers since that is the important factor in the accurate billing of electricity. The tradition in the field of testing instrument transformer's accuracy at the Electrical Engineering Institute Nikola Tesla is more than 60 years long. From the very beginning, the experts of the Institute have been active participants in the development of this field, both domestically and internationally. They have contributed to the development of measuring systems and standards for testing and calibration of instrument transformers, which have found application in laboratory calibration of the national metrology laboratories, as well as in industry. This paper provides an overview of the development of measuring methods for testing and calibration of instrument transformers, as well as a wide range of measuring devices and standards based on different measuring methods. The concrete application of measuring methods in the field of calibration in national institutes of metrology and research metrological laboratories is presented. The paper also presents the application of different measuring devices and systems in the industry, for intermediate and final control of measuring transformers as products in the instrument transformer manufacturers. A special review in this paper is dedicated to the contribution of the experts of the Electrical Engineering Institute Nikola Tesla in this field.**

***Index Terms*—Instrument transformers, accuracy, measuring methods, calibration, standard transformers**

I. Introduction

Instrument transformers are unavoidable elements in the electric circuits and systems for measuring alternating voltage, current, power and energy. Their role is to adjust (transform) the real values of voltage and current (voltages of several hundred and thousands of volts and currents of several hundred to thousands of amperes) to the appropriate optimal levels of measuring, control and protection systems. Furthermore, galvanic separation of the working energy system from the metering and protection system achieves by them.

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The electric voltage, current, power and energy measurement, as well as regulation and protection in power facilities, cannot be imagined without the use of instrument transformers.

According to their purpose instrument transformers are divided in two main groups: measuring instrument transformers and protective instrument transformers. In this paper emphasis is on instrument transformers for a measuring purpose.

Their role in the billing metering of electricity is especially important, where the overall accuracy of energy measurement directly depends on the accuracy of measuring transformers [1]. In the production - transmission - distribution chain, electricity is measured at least three times. Therefore, it is also financial interest, especially in the conditions of a deregulated market, to measure energy with the least possible error. Consequently, measuring transformers as well as electricity meters belong to legal metrology. Legal metrology regulations and domestic and international standards precisely define the conditions of application, calibration, as well as the deadlines for periodic review of these types of measuring instruments [2, 3, 4, 5, 6, 7].

The main direction of development of measuring transformers, in addition to improving their reliability, is to reduce the error of transformation of primary quantities into secondary ones. Improving the accuracy of instrument transformers is conditioned by the development of measuring methods and devices for measuring and determining its errors. Historically, the subject of measuring transformers dates back to the beginning of the twentieth century [8, 9]. The development of measuring methods and devices for errors measurement of measuring transformers depended primarily on the technical and technological capabilities of the time in which it took place. Consequently, the first methods and devices were based on a square electrometer [10, 11]. Modern devices have been developed on the most modern microprocessor technologies and virtual instrumentation [12, 13, 14, 15, 16].

The EEINT has the international reputation in the development and application of devices and systems for accuracy testing of instrument transformers for more than 60 years. Devices for accuracy testing of measuring transformers based on different measuring methods, developed at the EEINT, have been used in all manufactories for instrument transformers in the former Yugoslavia, as well as in many other testing laboratories of distribution companies and transmission networks. These devices have shown a number of advantages over other solutions, especially in the on-site

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testing of measuring transformers, in factory serial quality control, as well as the most accurate measurements [17, 18].

New generations of devices for accuracy testing of the instrument transformers, developed at the EEINT in the last ten years, have been used at the following manufacturers: MINEL -FEPO Zrenjanin (Serbia), FMT - Factory of instrument transformers Zajecar (Serbia), "Energoinvest" (Bosnia and Hercegovina), EMO-Ohrid (Macedonia), Končar – Instrument Transformers (Croatia), MBS - Instrument transformers (Germany). In the EEINT special attention is paid to the development of measuring devices for application in the most accurate measurement in this field. Such measuring systems have been developed and made for the National Research Council of Canada (NRC) and the Hydro Qebek High Voltage Testing Laboratory, also in Canada.

II. Complex Error

Electric voltage and current are vector quantities. Therefore, their complex transformation error is defined by ratio (amplitude) error and phase displacement. Like any measurement transformation, this one is also followed by certain errors. In a case of vector quantities, discrepancy from the ideal transformation is characterized by a complex error $\underline{G}$. The complex error of measuring current and voltage transformers is defined as the fundamental harmonic of current, i.e., voltage. The complex error includes the ratio (amplitude) error, g, and the phase displacement, δ, expressed in mathematical form:

$$\underline{G} = g + j\delta \qquad (1)$$

Ratio error of current transformer g in %, in accordance to standard [4] is defined as:

$$g = \frac{K_N \cdot I'' - I'}{I'} \cdot 100 \qquad (2)$$

where K_N is the rated transformation ratio.

The phase displacement δ in min (1%=34.4min=1crad), is defined as the phase shift of the secondary current I'' in relation to the primary current I' [4].

The ratio error and phase displacement of the current transformer are defined by its:

- constructive and technological parameters: material, shape and dimensions of the magnetic circuit, number of ampere-turns, length and cross-section of the wire, geometry of the primary and secondary winding;
- operating parameters: secondary load, ratio of measured current to rated, frequency, distortion and shape of measured primary current;
- ambient conditions: temperature and pressure.

The ratio error of voltage transformer g in (%), in accordance to standard [5] is defined as:

$$g = \frac{K_N \cdot U'' - U'}{U'} \cdot 100 \qquad (2)$$

where K_N is rated transformation ratio

The phase displacement δ in (min), of voltage transformers is defined as the phase shift of the secondary voltage U'' in relation to the primary voltage U'. The ratio error and phase displacement of the voltage transformer are also defined by its constructive, technological, operating parameters and ambient condition.

The main difference between current and voltage transformers is that the initial design parameter in current transformers is the magnetic excitation force, while in voltage transformers this is the magnetic induction. However, in the constructive, technological and physical sense, there are significant differences between current and voltage transformers, which results from different operating modes. The current transformer operates in the short-circuit mode, and the voltage transformer in the idling mode.

The functional connections between parameters and ratio error and phase displacement are known. Therefore, it is possible to analytically calculate their values for a given current or voltage transformer, which is usually done during design.

The main parameters in designing current and voltage transformers as well as in declaring their errors (accuracy classes) are secondary burden and reference currents and voltages. The limits of errors for declared classes by standard, for current measuring transformers are defined in accordance to percentage of rated currents (i.e., reference currents) and for secondary burden between ¼ and rated value [4]. In the same way, the limits of errors for declared classes for voltage measuring transformers are defined in accordance to percentage of rated voltage (i.e., reference voltage) and also for secondary burden between ¼ and rated value [5]. This method of errors declaring corresponds to their nonlinear character. The accuracy class of measuring transformer directly affects its application.

However, the true (more accurate) error values are obtained only by measuring the accuracy of the measuring transformer.

III. The Measuring Methods and Devices for Accuracy Testing

From the early beginning of the application of measuring transformers, back in 1892, [19], there was a need for their accuracy testing. The errors of these first current transformers were in the order of about 3% for ratio error and approximately 200 minutes for phase displacement [8]. In that time, these errors had been determined by direct measurement of primary and secondary currents and phase shift. In addition to the error of the measurement method, limitations have also appeared in the application of analog measuring instruments [20]. For example, the limits of current measurement with analog measuring instruments were 200A. Appropriate shunts and pre-resistors were used for currents higher than this value.

With the rapid technological development, the applications

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of precise standard measuring transformers [21] have begun. With the progress in the production and application of new magnetic materials, in the thirties of the last century, the errors of measuring transformers have been reduced to 0.1% and 5min [22].

A.*Classical methods and devices for accuracy testing of instrument transformers*

The first methods for accuracy testing of instrument transformers appeared at the beginning of the last century [23, 24, 25]. The most important methods, whose influences extend to the present days, are compensation, differential and current comparator methods.

The compensation method, Fig 1, is basically a direct comparison of two alternating voltages generated on precision reference shunts (for current transformer testing) or voltage dividers (for voltage transformers testing), one in the primary circuits and the other in the secondary circuits of the transformer under test, (T_X).

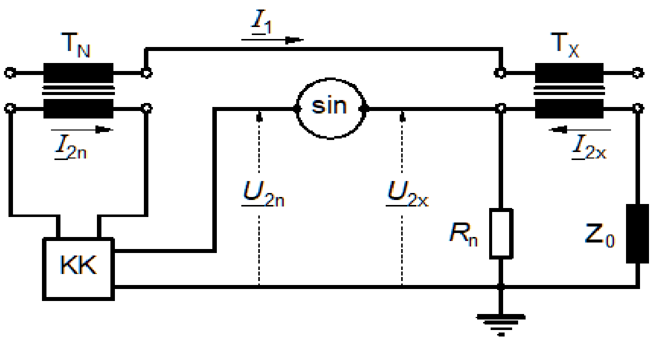

Fig.1. Compensation method for current transformer accuracy testing [17].

The compensating method was usually used in laboratory testing. The main reason for that is demand for satisfactory high accuracy of the elements that is incorporated in complex compensator (precise resistors and voltage dividers), and that are also temperature and time stable. In addition, there is also a problem of additional load in secondary circuits of transformer under test that is not negligible. The main advantage of this method is the ability to accuracy testing of the instrument transformers of non-standard transformation ratio.

The differential method is attributed to F. B. Silsbee and is related to 1917 [23]. This method was perfected by Hole (W. Hohle) in 1934 [26]. The essence of this method, Fig. 2, is to measure the differences between two quantities. In this method the secondary voltages (or currents) of the device under test (current or voltage transformer), (T_X) and of the standard transformer (T_N) of approximately equal transformation ratios are compared. In order to achieve comparison as accurate as possible, the standard current transformer should have a negligibly error.

The basic elements of the devices for accuracy testing based on differential and compensational methods are complex compensator (KK) and selective zero indicator (SIN), Fig. 1, and Fog. 2.

Around 1930, measuring devices based on the compensation method and the complex compensator [27, 28] appeared. The best accuracy of such early commercial devices was about 0.02% and 2 min. There are many solutions of complex compensators, but from the point of view of accuracy testing of instrument transformers, the most significant is certainly the work of scientists Schering and Alberti [24].

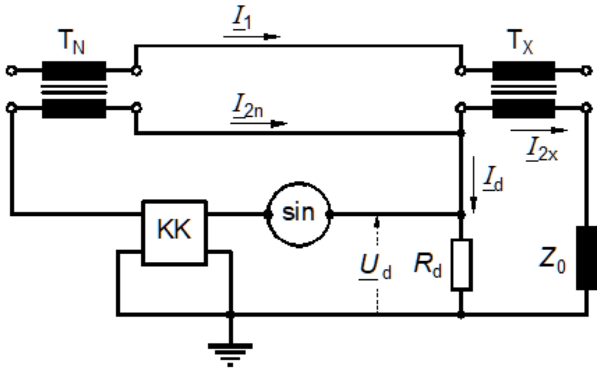

Fig.2. Differential method for current transformer accuracy testing [17].

Measuring device, so-called Hole's compensator based on differential method has also found wide practical application [29].

With the selective zero indicator, the equality of two voltages is determined at a certain (basic) frequency. This implies two requirements: indicator should be sufficiently sensitive to the basic measured voltage and also insensitive to parasitic (disturbing) voltages as well as to higher harmonics of the measured voltage. Two types of selective zero indicators have been used: a classic solution with a vibrating galvanometer and an electronic zero indicator.

Technological improvements and modifications of this compensator and selective indicators, made in the 1930s, especially in the late 1960s, made these instruments indispensable in the laboratories for testing and calibration of measuring transformers, for a long time during the last century.

The third, important measuring method that has remained until today is based on the application of a current comparator. The idea of the current comparator was first presented in 1917 by the American physicist Baker [25]. He suggested measurement of the difference between the two currents by using windings on a magnetic core. The current comparator with a compensating winding was first used in 1930 by the English scientist Bruges [30], and the German physicist Reihe used it as a test device for the accuracy testing of current transformers [31]. This, therefore, long-known but, then technically and technologically imperfect method, experienced its reaffirmation in several metrological laboratories in the 1950s. The current comparator was first used in the comparison of alternating currents, and later for accurate measurement of resistance, capacity, etc. The

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Electrical Engineering Institute Nikola Tesla (EEINT), mostly thanks to Ilija Obradovic, Petar Miljanic and Srdjan Spiridonovic, is the pioneers in this field. The first device for measuring the accuracy of current transformers is being realized then. This work, which have been continued to these days, is marked by a series of successful results and articles The very name "current comparator", today is internationally accepted technical term, first appeared in the works of experts from the EEINT [32].

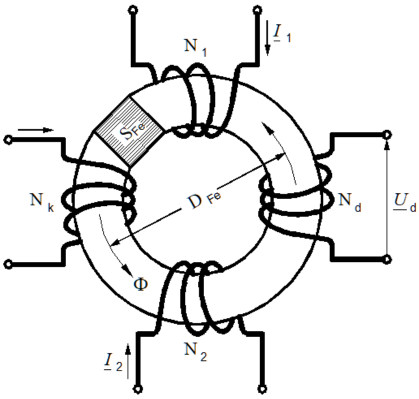

Fig.3. A simplified scheme of current comparator [35].

Significant progress in the construction and manufacture of current comparators has been achieved through the joint work of associates of the Canadian NRC (National Research Council) and the EEINT [33].

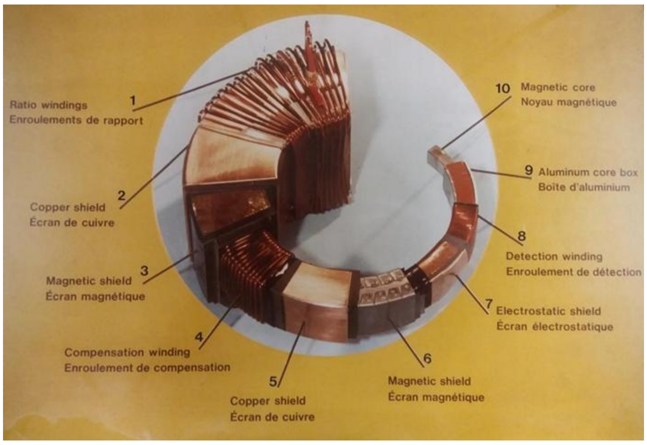

Fig.4 The structure of current comparator [17].

An ideal transformer is a transformer for which the equality of magnetomotive force applies [33]. In reality, a part of the primary magnetomotive force is spent on magnetizing of the core and losses in it. This is the main reason for the error of the current measuring transformer. If the magnetic flux in the core is artificially reduced to zero, then the current transformer becomes ideal. In that way the comparison of the currents reduces to the turn ratio of primary and secondary windings. This ratio is stable during the time and insensitive by temperature changes. This gives the possibility of a very accurate comparison of two alternating currents, which is the basic idea of the current comparator [34].

Fig. 3 shows simplified scheme of a current comparator. To measure the magnetic flux in the core of the current comparator, the detection coil N_d is used, and compensating coil N_k brings the magnetic flux to zero [35]. Practical realization of current comparator is more complex as shown in Fig. 4.

With carefully construction and realization of current comparators, it is possible to achieve its ratio error within the range from 10^{-6} to 10^{-7}, and the phase displacement in the order of 0.01 min.

B. The recent methods and devices for accuracy testing of instrument transformers

In the last years of the 20th century, with the application of modern electronic solutions and microcomputer techniques, measuring methods and devices for accuracy testing of instrument transformers have been significantly improved [36, 37]. Possibilities and advantages of PC hardware and software support are not only in the field of increasing efficiency, or reliability of work, but also in increasing measurement accuracy. Modern devices are based on the general tendency in electronics that the processing of the measuring signal is realized in digital form. The differences between the individual solutions of these devices are most often in the way of further digital processing of measuring signals [17, 38, 39, 40, 41].

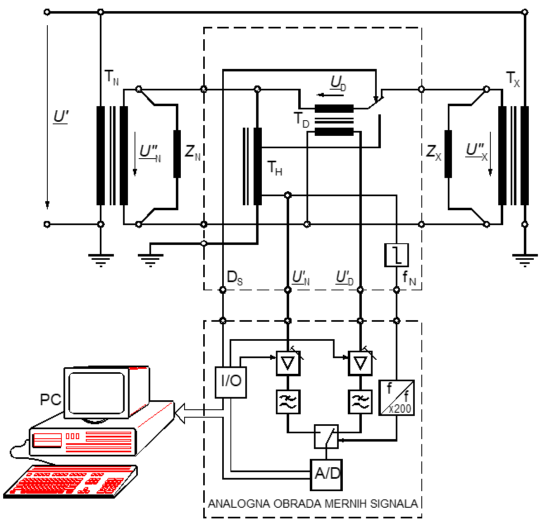

Fig. 5 The structure of DFT measuring method developed by PTB [46].

The application of the measuring method of discrete Fourier transformation (DFT) for the accuracy testing of measuring transformers originates from the laboratory for measuring transformers of the National Metrology Institute of Germany (PTB) which has a long tradition in the field of metrology, even from the early beginning in 1877 [42]. This laboratory has developed several important measuring devices for accuracy testing of the measuring transformers, known as: Schering-Alberti's [24], Hole's [26] and Keller's compensator [43]. PTB experts have significantly contributed to the development of measuring methods and measuring techniques

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in the field of measuring transformers. As a result of recent research in PTB, the method of discrete Fourier transform was applied, first for testing the accuracy of current measuring transformers [44], and later for testing voltage measuring transformers [45].

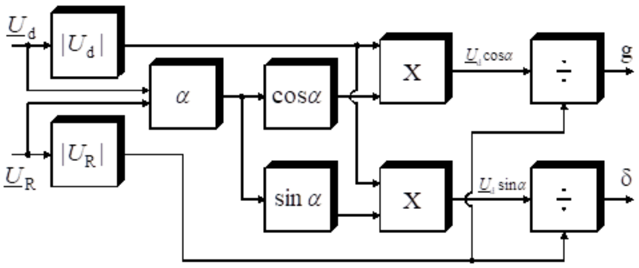

Fig. 6 The structure of measuring method based on orthogonal voltage components [48].

The structure of DFT measuring method developed by PTB experts is shown on Fig. 5 [46]. The device for accuracy testing of instrument transformers based this method, Fig. 5, have following characteristics: measurement range of ± 0,2 % and ± 2 % for ratio error, ± 0,2 crad and ± 2 crad for phase displacement; resolution of 0.000001%, accuracy ± 0,5 % of measuring value and ± 0,05 % of measuring range. This device was capable to measure in a full range from 1% to 200% of rated current, i.e., of rated voltage.

The structure of measuring method based on orthogonal voltage components is shown in Fig. 6

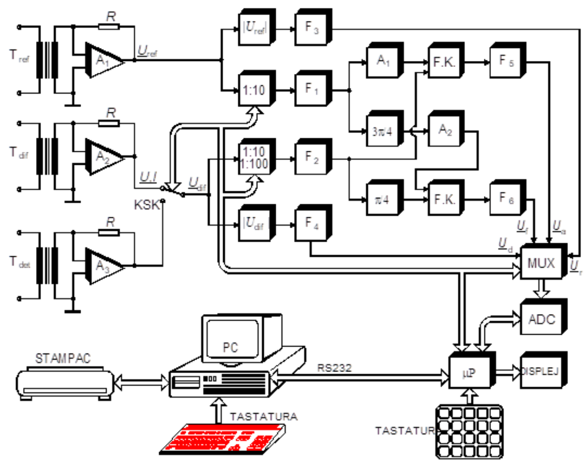

Fig. 7 Block scheme for device for instrument transformer accuracy testing, type INST-2A [47].

Basically, this is a differential method that enables measurement of fundamental harmonic of two voltages and its phase angle, but with some original solutions [47, 48]. The device based on this method is shown in Fig. 7. Novel solution of current-voltage transformer was applied for both differential and detection voltage, as well as for reference voltage. In this way, the adjustment of voltage measured signals to the optimal level was achieved, with minimal degradation of basic signals, and the conversion of current measuring signals into voltages. This initial level of analog processing of measuring signals is very important for the overall accuracy of the device. The second improvement is in electronic bloc that is applied phase regulated rectifier which makes phase shift between $\underline{U}_r$ and $\underline{U}_d$. The phase shift of $\pi/2$ by this phase rectifier is obtained as discrepancy between phase shift of $3\pi/4$ for $\underline{U}_r$ and phase shift of $3\pi/4$f or $\underline{U}_d$ [48]. Another recent improvement of differential measuring method is two phase conversion method [49]. The method is based on the measurement of phase angles between three relevant voltages, Fig. 8. The measured ratio error and phase displacement are than presented as a function of two angles. Structure scheme presented in Fig.8 consist of commercial dual channel power analyzer, electronic module and PC. The electronic module integrates: an amplifier, two summing circuits, circuits for $\pi/2$ phase shift and multiplexer. The input voltages U_R and U_d are subjected to relatively simple analog processing in the electronic module, and as such, are brought through multiplexer to a dual-channel power analyzer. The PC manages the operation of the electronic module and the dual power analyzer according to the given program [39, 49, 50].

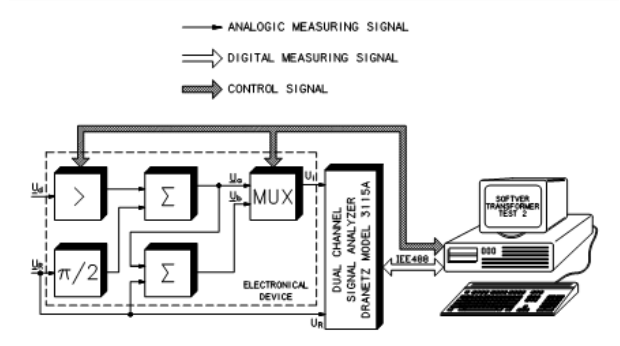

Fig. 8 The structure scheme of two phase conversion method realization [49]

IV. EEINT'S METHODS AND DEVICES

Measuring systems for accuracy testing instrument transformers based on measuring methods mentioned above usually consist of: standard current/voltage transformer, standard current/voltage burden, device for accuracy testing and measuring transformer under test.

In this field of measurement, methods that are used for testing and calibration purpose are basically the same. The difference is in the accuracy of the standard transformer and the device for accuracy testing which is applied [51].

The experts from EEINT continuously follow the development in this field. Devices for accuracy testing of instrument transformers based on different measuring methods as well as standard transformers developed at the EEINT, have been used for manufactory testing, on-site testing in the power and distribution facilities and for calibration in national metrology laboratories.

The first devices for current and voltage measuring transformer testing were developed in seventeens in last century, Fig. 9. These measuring systems are based on current

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comparator methods.

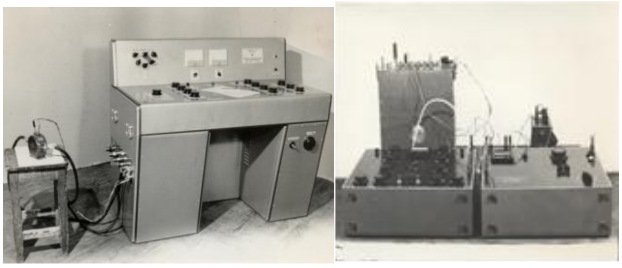

Fig. 9 Devices for current measuring transformer accuracy testing, type KSK-6 (1965) and KSK-7 (1968), respectively.

For accuracy testing of measuring voltage transformers EEINT experts developed measuring system type NIT-2p applied both for laboratory and on-site testing in distribution facilities, Fig 10. The system is based on classical differential method for accuracy testing of voltage transformers that assumed comparison between voltage transformer under test and standard voltage transformer. In that case transformer under test and standard transformer had to have the same transformation ratio.

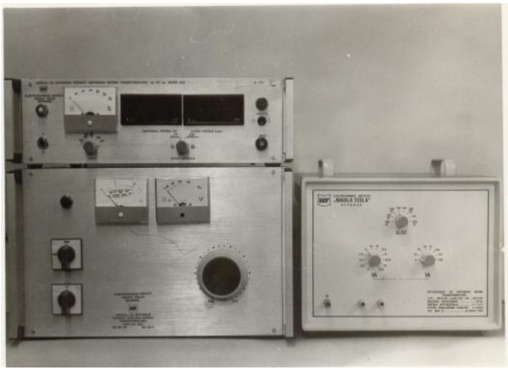

Fig. 10 System for voltage transformers accuracy testing, type NIT-2p (1981.)

With the development of instrument transformers industry in former Yugoslavia, the need for faster and more efficient routine accuracy testing appeared. This demand is satisfied with development of first automatic systems for accuracy testing of current transformers [52, 53], shown in Fig 11 and Fig 12.

Fig. 11 System for automatic accuracy testing of current measuring transformer, type ASK-1 [52]

Fig. 12 System for automatic accuracy testing of current measuring transformer, type ASK-2 [53]

Automatic systems for routine testing of measurement current transformers have been further developed together with new technological achievements. Together with ISKRA AMESI, Slovenia, in 2012, EEINT realized robotized system for routine testing of current transformer, Fig 13. Among the other routine tests according to standard [2], this system can perform accuracy testing of 7 current transformers synchronously. EEINT developed and manufacture the standard transformer, standard burden and device for accuracy testing based modified differential method and multiplexing concept [54].

Fig. 13 Robotized system for current transformers accuracy testing in MBS factory Germany (2012.) [54]

Three years later, for Instrument transformers factory FMT Zajecar, EEINT developed and made device for simultaneously testing of 3 current transformers [55], Fig. 14.

Fig. 14 Automatic device for accuracy testing of 3 current transformers simultaneously [55]

Based on the experience in the realization of different measuring devices in this field, in 2001, EEINT was designed and built a mobile laboratory for on-site accuracy testing of measuring transformers, Fig 15. This mobile laboratory was

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used by “Elektrostopanstvo”, Macedoni, for accuracy testing of measuring transformers in the distribution facilities [56].

Fig. 15 Mobile laboratory for accuracy testing of measuring transformers [56]

Experts from EEINT have made a special contribution to the development of standards and high-precision devices for use in national metrology laboratories. Standard current transformer with electronic compensation of errors type EST-3000 [57] was designed and made together with device for measuring transformers accuracy testing, type INST-2A [47] for Directorate for Measures and Precious Metals (DMDM). This system represents the national standard of Serbia in the field of measuring transformers.

In period from 2016 to 2019 in EEINT three high accuracy systems developed for the needs of National metrology institutes of Canada (NRC) and Singapore (A*Star), as well as for laboratory of power transmission system of Quebec (Hydro Quebec), Canada. In these measuring systems, a differential method with a special construction of a standard transformer and measuring device was applied [58]. The high accuracy of the standard transformer was achieved by an unconventional two stage design. The transformer's detection core is made of high permeability magnetic material, whereas the working core is made of a standard magnetic material for current transformers. The primary and secondary windings are evenly wound around the cores and magnetically and electrostatically shielded. The compensation winding is not connected to the secondary winding but instead to a separate differential transformer winding. This way, the N_{sc} winding of the Ts transformer is not burdened with a voltage created by the full secondary current I_{ss} and the N_{ds} winding impedance, but with a significantly smaller voltage created by a small compensation current I_{sc} and the N_{dc} winding impedance, Fig 16. This makes the impedance seen by the N_{sc} winding smaller and the compensation much thus more effective. This improvement leads to at least two to three times lower measurement errors [58]. The system is verified by simultaneously comparison with NRC system for current transformer accuracy testing – national standard of Canada. The obtained discrepancies in ratio and phase errors were within a few μA/A or μrad, respectively. Practical realization of mentioned measuring system is shown in Fig. 17. The method of simultaneously comparison is developed and firstly applied at EEINT [59].

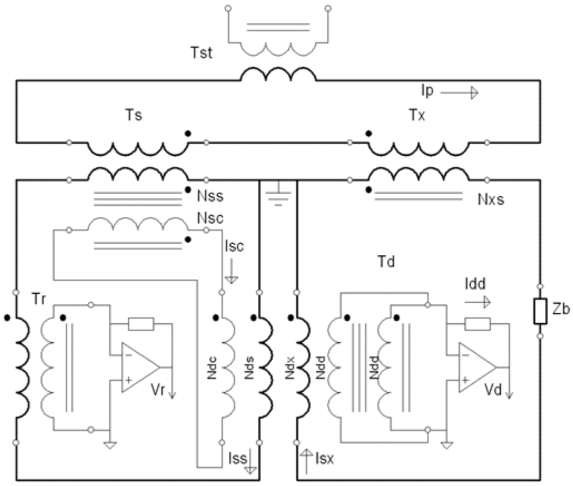

Fig. 16 Block diagram of the differential CT calibration system with special construction of two stage standard transformer T_s and differential T_d transformers [58]

V. NEW GENERATION OF MEASURING TRANSFORMERS

Digitalization of distribution and power facilities is the process that is part of much large movement, the Industrial Revolution 4.0 conventional transformers are no longer suitable for use in such systems. Therefore, new generations of current and voltage transformers and sensors have been developed that can be applied in digitized distribution and power facilities [60, 61, 62]. New types of measuring transformers and sensors require the development of new suitable measuring methods and devices for their testing. Some new proposals for accuracy testing of new generation of instrument transformers, so-cold low power instrument transformers are given in serial of EN/IEC standards [60]. It can be noted that these international standards recommend in the use of current comparators as a part of some proposed measuring systems for accuracy testing of low power instrument transformers.

Fig. 17 Practical realization of NRC measuring system for accuracy testing of current transformer

VI. CONCLUSION

The measurement accuracy is the most important characteristic of measuring transformers since that is the important factor in the accurate measurement of the high

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voltage and currents. The billing of electricity, as well as the power measurement at low power factors, is the explicit examples where accuracy of instrument transformers has very important role. The need for accurate measurement current and voltage by measuring transformers influenced both the improvement of their characteristics and the development of methods for determining their accuracy. The accuracy of measuring methods and measuring equipment for the accuracy testing of measuring transformers has improved along with technological progress.

This paper presents a historical overview of the development of measuring methods and devices in the field of measuring transformers. Also, the paper presents the most important trends in the development of measuring methods and devices for different applications. The systems for accuracy testing of measuring transformers in manufacturing process as well as high accuracy equipment for laboratory calibration of standard transformers are presented. Special attention was given to the contribution of EEINT experts in this field, both in the past and present.

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