THESIS ON MECHANICAL AND INSTRUMENTAL ENGINEERING E30

Research of the Effect of Correlation at the Measurement of Alternating Voltage

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree or examination.

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MASINA- JA APARAADIEHITUS E30

Korrelatsiooni mõju uurimine vahelduvpinge mõõtmisel

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Abstract

This work is of use for the electrical laboratory of AS Viru Energia. A proposal was made to the laboratory calibrating voltage and current measuring transformers to establish a group working standard of alternating voltage with a full list of metrological characteristics.

The aim of the work was to find out the present level of voltage transformer calibration in Estonia. A method of defining the dispersion and correlation coefficient of the physical quantity under measurement has been considered. The efficiency of the offered method of defining dispersion estimation has been proved by using the group working alternating voltage standard.

A new method was proposed for evaluation of the relative deviation of the scale factor and phase displacement of the secondary voltage of the calibrated standard with respect to the secondary voltage of the reference standard using the method of forecasting parameter drift of the group working standard.

When determining the expanded uncertainty of the scale factor during voltage transformer calibration, both the contact resistance voltage and the temperature gradient were taken into account.

As a following step the influence of large random deviations on the correlation coefficient of interacting quantities was studied.

The proposed calibration method for measuring thermoelectric voltage transducers is based on the studies carried out in the Metrosert electrical measurement laboratory in order to verify the developed model of alternating voltage measurement. A method was proposed to reduce the measurand’s dimension. The „expert-statistical” method used has made it possible to reach the best estimate of physical values**.** The measuring complex can be presented as linear multiples. Statistical analysis has served as a tool to attain the best estimation of a measurand of alternating voltage, dependent on the correlated input quantities.

Keywords: model of measurement, measuring transformers**,** uncertainty budget**,** thermoelectric transducers**,** method to reduce the measurand's dimension.

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CONTENTS

LIST OF PUBLICATIONS

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1. Barashkova T., *Methods of estimations covariations at measurement of alternating voltage***,** Sistemi obrobki informacii, 2006, 7(56), pp 7–10
2. Barashkova T., *On the effect of correlation by the measurement of alternating voltage*, Proc. Estonian Acad. Sci. Eng., 2006, 12/3-1, pp 208–217
3. Barashkova T., Laaneots R., *L`Expérience de covariation entre des valeurs devant les mesures d'une tension alternative*, In: Proceedings 12th International Metrology Congress METROLOGIE 2005. Lyon-France: Collège Français de Métrologie, 2005, 5p
4. Barashkova T., *The importance of order correlation*. In: Proceedings of the 4th International Conference Industrial Engineering – New Challenges to SME. Tallinn: DAAAM International Vienna, Tallinn University of Technology, 2004, pp 124–126
5. Barashkova T., Laaneots R., *Uncertainty of results of measurement***.** Monograph (in Russian). Tallinn: TTÜ kirjastus, 2003, 75p
6. Barashkova T., *Using of correlation analysis in the electrical measurements.* In: Proceedings OST−03 Symposium on Machine Design. Oulu: Oulun Yliopisto Konetekniikan Osasto, 2003, pp 156−164
7. Barashkova T., *Interlaboratory comparison of voltage transformer*. In: Proceedings of the 3rd International Conference Industrial Engineering – New Challenges to SME. Tallinn: DAAAM International Vienna, Tallinn Technical University, 2002, pp 11−14
8. Barashkova T., *The way of realization of algorithm of formation and estimation of parameters of the group-working standard of variable voltage*. In: Proceedings OST−01 Symposium on Machine Design. Stockholm: Universitetsservice US AB, 2001, pp 175−181

INTRODUCTION

The correlation to be found of the quantities under investigation serves as a solution for a measuring problem. To find the best functional relationship between measurands correlation analysis is to be made use of, as a strict functional dependence is very rare to be realized.

If the degree of influence of each input quantity on the measurement results of output quantities is determined the measurement problem will be solved with the least uncertainty.

Finding out distinctions between the estimates in different measurement schemes often serves as the purpose of an experiment. For example, when implementing an etalon complex it may turn out that an estimate of a rms value of AC voltage differs from the estimate of the same value received under dissimilar conditions of experiment. It should be verified, therefore, that the difference was not caused by random deviations of the experiment. A research into correlation at a measurement makes such verification possible as the random deviations relax the correlation between the values.

When estimating any output values it cannot be declared with certainty that the tightness of correlation of input values could be neglected. Therefore, in practice, when estimating any dependence, methods of statistical estimations able to characterize the covariance of dependent quantities must be used. If linear dependence is investigated tightness of correlation between input quantities needs to be estimated by means of the selective correlation coefficient**.** Operating just a small number of sampled input values, it is not possible to be sure that the function is linear. Likewise, in the absence of sufficient amount of statistical data it is impossible to be sure that the correlated random values follow the Gaussian distribution model. The deficit of input data implies the possibility for the functional relationship to be of a monotonic non-linear nature. Besides that, for comparison of results of the measurements accomplished at different moments of time, it is expedient to apply the criteria of uniformity of several correlation coefficients. In measurement practice metrologists often content themselves with statements, that the correlation coefficient can be neglected, that perfect conditions of measurements are kept in the laboratory, and that the standard is of ideal linear characteristics.

Employing the zero method (FLUKE Corporation, 1994) when measuring alternating voltage a source of direct voltage with linearity characteristics better than these of Fluke 792 A AC–DC transfer standard and an unknown source of AC voltage is supposed to be used. The linearity of the Fluke 792 A AC-DC transfer standard and that of a DC voltage source is to be verified. Besides that, as conditions in measuring laboratories are different, the zero method of measurement (rms) cannot be considered universal.

Based on the above-said a variant of covariance calculation system has been elaborated by the author leading to excellent results of measurements. An experimental research into laws of the field of alternating voltage measurement serves as the basic methodology. The main feature of the work is that methods of multivariate mathematical statistics have been applied at experimental data processing.

In metrological practice routine statistical investigations based on the simple scheme of pair comparison technique can be met.

By changing the habitual scheme of comparison of standards, a wide array of calibration standards of a working standard level has been implemented in the electrical laboratory of AS Viru Energia, thus providing the laboratory with a unique and varied measurement capability. Taking into account the correlation coefficient in descriptive statistics made it possible to reach the present level of voltage transformer calibration in Estonia comparable with the Finnish standard. The results of a comparison indicated that the measurement capabilities of the electrical laboratory of AS Viru Energia are good.

In the work also methods of determining correlation coefficients at measurement of alternating voltage are considered.

An expanded statistical analysis of samples is brought, on the basis of which independent conclusions have been drawn not confirming some preliminary statements. Mathematical transformations are given with the purpose of creating a real mathematical model for estimation of alternating voltage values. Statistical methods in conformity with the tasks, characteristics of the chosen parameters and schemes of experiments have been applied.

The scheme of experiments developed for the determination of alternating voltage estimation permitted the multivariate statistical analysis to surpass the limits of sufficiency for reaching reasonable conclusions. In the modern metrological practice a minimal set of statistical procedures can be observed. The developers of modern measuring appliances recommend a simplified calibration technique for etalons, referring to the contemporary advanced production technology. According to the recommendations of the company Fluke there is no need for repetitive measurements due to the stable semiconductor sensor used in the Fluke 792 A AC–DC transfer standard, the sensor guaranteeing the repetitiveness and reproduction of measurement results. The value of an alternating voltage is determined applying the correction coefficient δ, i. e. considering the difference between the values of direct and alternating voltages divided by the mean value of direct voltage. However, measurement conditions in metrological laboratories are not always ideal and clinging to traditional ways may result in insufficient informedness on the possibilities of statistical analysis. To keep the purposes and tasks of the research from becoming too narrow an expert-statistical method (Ajvazyan, 1988) [2] has been applied for alternating voltage estimation.

The characteristics of an alternating voltage source (rms. AC source) cannot be subjected to a direct quantitative measurement and there exists no objectively conditioned scale for it. It is natural to assume that an intuitive expert (professional) perception of this characteristic can be depicted as a somewhat deformed value of the function of some correlated input quantities. The deformation is of a random nature and is caused both by the ability of an expert to resolve issues and the existence of a number of values only slightly influencing the output function but not included in the correlated input quantities. Then the model interconnecting the intuitive representation of the characteristic under investigation and the function of the correlated input quantities can be transformed into an ordinary regression model. The specificity of the regression model lies in its providing (with expert help), instead of direct measurements of the characteristic examined, some special data on it values. These data are presented in the form of a collating plan. Therefore the task of estimation of an alternating voltage source is set with the exactness of a certain monotonic transformation. Theoretically the amount of correlated input quantities can be infinitely large. Therefore the output function under investigation serves as a measure of dimensionality reduction. By the form of the received function one can judge the contribution of each input quantity into the measurement uncertainty of the output value of a physical quantity.

In the work descriptive statistics are used, i.e. results of experiments are represented with the help of diagrams and with the correction factor applied.

During the research work a book in co-authorship with Rein Laaneots (T. Barashkova and R. Laaneots, 2004) [3] was written. In the book the theoretical bases of calculation of measurement results are considered and some practical recommendations on estimation of uncertainty components are offered.

Some principles described in the book have been applied in the electrical laboratory of AS Viru Energia at calibration of current and voltage measuring transformers.

As a result of joint work with the engineers of AS Viru Energia the laboratory has been granted the certificate of accreditation. The book has also appeared useful for scientific workers of the chemical laboratory of Oil Shale Research Institute.

1 A SURVEY OF DEVELOPMENT AND CALIBRATION OF THE ALTERNATING VOLTAGE STANDARD

1.1 An overview of methods of calculating the uncertainty of electrical voltage measurement

Many calibrations and testing laboratories have had great difficulties in transferring the documents for calculating the uncertainty of measurement into practice. On the other hand, simplified methods can very often be used, especially in the field of electrical measurements. The model function can be obtained where the quantity measured is given by a sum (difference) or a product (quotient) of the input quantities, and the standard uncertainty of the output estimate by the square-root-sum of the absolute or relative standard uncertainties of the input estimates. The model function represents the procedure of measurement and the method of evaluation. It therefore is not surprising that people who have to carry out an uncertainty analysis have problems in setting up the model function, the more so as hardly any supporting software is available. For non-correlated input quantities, there are two types of model functions, which occur quite frequently and are very easy to be treated mathematically. If the model function is a sum or difference of the input quantities, the square of the standard uncertainty for the output quantity will be given by the sum of the squares of the standard uncertainties of the input quantities, multiplied by the squares of the sensitivity coefficients. If the model function is a product or quotient of the input quantities, the square of the relative standard uncertainty for the output quantity will be given by the sum of the squares of the relative standard uncertainties of the input quantities, multiplied by the squares of the sensitivity coefficients. In the field of electrical measurements, a small number of measuring methods is widely used: direct measurement, comparison of two quantities using a differential or balance method and measurement by substitution. A direct measurement is applied when a measuring instrument is to be calibrated by means of a calibrator or a standard or when a calibrator or standard is checked with a measuring instrument. In the case of the calibration of a measuring instrument, the relation between its input quantity and the indicated value is of interest.

The method of direct measurement is applied for transferring a voltage from primary etalons to the secondary when the equipment of the comparator is the part of etalon. When the comparator is removed from the etalon the differential method is applied.

The differential method (see Fig. 1.1) directly compares the unknown output quantity (measuring value pick-up MP) with the reference quantity (input quantity, reference value pick-up RP), the difference between these two quantities being measured with a differential measuring instrument DM. Its indication is another input quantity. For the balance method, the differential measuring instrument DM is replaced by a null indicator NI. To balance it an adjustment pick-up AP is necessary, which generates another input quantity. In this case, the model function is the sum of the input quantities and the square of the standard uncertainty associated with the sum of the squares of the standard uncertainties of the input quantities. The substitution method is similar to the differential method except that the difference between the output and reference quantities is not directly measured but that the two quantities are measured one after another using the same measuring instrument and forming the ratio of the two quantities. As with the substitution method the output and reference quantities are of almost the same value and the two are measured using the same instrument, both quantities are strongly correlated. (Bachmair, H. A. 1999) [4].

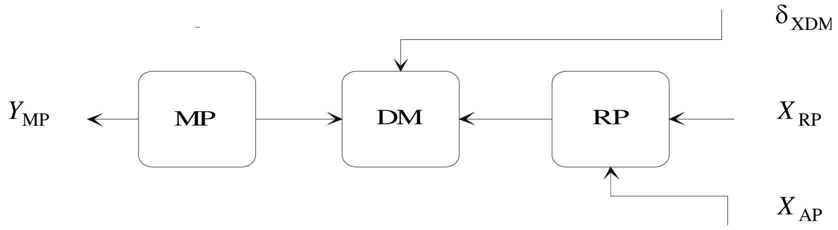

Figure 1.1 Differential method

In case of a differential method of measurement the mistake of transfer of the size of a unit of physical quantity is determined both by the characteristics of the comparator, and parameters of the secondary standard. The account of the sources of influence is a prerequisite for reliable measurements. Sources of influence:

- Measuring instruments: uncertainty of measurement, internal and external adjustments, resolution, noise, drifts
- Environmental conditions: temperature, electromagnetic fields, line distortions
- Circuit design: input and output impedance, line and contact resistances, isolation resistances, wiring, shielding, earth connections, thermal emf's, sources of noise
- Operator: reading and software errors, influence of the experimenter himself.

In conditions of fast development of engineering it is possible to provide unity of measurements in the field of an alternating voltage by increasing the requirements to accuracy and reliability of measurements. Standard uncertainty can guarantee accuracy and reliability of a result of measurement.

Standard uncertainty-parameter, connected with the result of measurements and describing dispersion of values which could be well-grounded is attributed to the measured value. The basic quantitative expression of uncertainty of measurements, at which result is defined through values of other quantities, is total standard uncertainty. When it is necessary, extended uncertainty is calculated.

An estimate of a measured value is calculated as a function of estimates of input values. Previously amendments are made on all known sources of uncertainty having systematic character. Then the standard uncertainty of input quantities is calculated. In the recommendations of "Guide to the Expression of Uncertainty in Measurement" (ISO, 1993) [5] the methods of determining possible correlation coefficient of estimations of input quantities are given, and also the order of an estimation of uncertainty of output quantities measurement is given.

However in metrological practice the uncertainty budgets do not contain the information about calculations of correlations coefficient. If the uncertainty budgets do not contain enough information, the result of measurement is difficult for repeating. At representation of results of measurements the Guide recommends to give enough information to make it possible to analyze or to repeat the process of reaching the result of measurements and calculation uncertainty of measurements:

- Algorithm of reception of result of measurements
- Algorithm of account of all corrections and their uncertainties
- Uncertainty of all used data and ways of their reception
- Algorithms of calculation total and expanded uncertainty (including meanings of correlations coefficients) (see Fig. 1.2).

The methods of mathematical statistics are applied to idealized multiple measurements (Rabinovich, S. G. 2000) [6]. In essence, in certain cases, these methods constitute the classical theory of measurement errors. Sometimes they are supplemented with some new results. The estimates obtained from statistical data must be consistent, unbiased and efficient. An estimate of a physical quantity is said to be consistent if, as the number of observations increases, it approaches the true value of the estimated quantity. In the case when several unbiased estimates can be found, the estimate that has the smallest variance is, naturally, regarded as the best estimate. The smaller the variance of an estimate, the more efficient the estimate is. Methods for finding estimates of a measured quantity and indicators of the quality of the estimates depend on the form of the distribution function of the observations. For a normal distribution of the observations, the arithmetic mean of the observations can be taken as an estimate of the true value of the measured quantity. If the available data are consistent with the hypothesis that the distribution of the observations is normal, then in order to describe fully the distribution, expectation and the variance must be estimated. When the probability density of a random quantity is known, its parameters can be estimated by the method of maximum likelihood.

It is known (Rabinovich, S. G. 2000) [6] that the measurement of voltage with the help of a potentiometer is a direct measurement. However, when the uncertainty of the potentiometer and the uncertainty of the standard cell are standardized separately, and also when measurements are performed using a voltage divider, the uncertainty of the result of such a measurement is estimated by methods that are specifically designed for indirect measurements. It is well known that when working with such potentiometers at first the potentiometrical current I_p is adjusted in the circuit with accurate resistors so that the voltage drop on the section of the circuit with the resistance R_s would balance the emf of the standard cell U_s. Next, the standard cell is disconnected and the measured voltage U_p is connected to the potentiometer circuit. By switching the potentiometer, a fraction of the resistors of the potentiometer is introduced into the comparison circuit such that the voltage drop on their resistance R_p would compensate U_p. If I_p is precise then the voltage drop U_p can be found from the formula $U_p = \frac{R_p}{R_s}$ if the emf of the standard cell U_s and the ratio $\frac{R_p}{R_s}$ are known. $U_p = U_s \cdot \frac{R_p}{R_s}$ Then the processing of experimental data obtained in a measurement consists of two steps. In the first step we estimate the value of the measurand, and in the second step we calculate the inaccuracy of this estimate. In an indirect measurement the first step traditionally is based on the assumption that the estimate x^j of the measurand X^j can be obtained by substituting x^i for X^i:

$$x^j = f(x_1^i, x_2^i, \dots, x_N^i) \tag{1.1}$$

The second step is solved by expansion of the function (1.1) in a Taylor series. Usually the Taylor series is written in the form of an approximate value of the given function, which is brought to its true value with the help of corrections. Thus, we shall write the series in such a form, that the approximate value of the function is expressed by adding something to its true value.

For a long time the traditional method has been used. The estimate of the measurand given by (1.1) is incorrect when the measurement equation is nonlinear. Thus, for nonlinear indirect measurements, the estimation of the measurand given by the traditional method is biased. The bias of the measurement result can be taken into account by correction δ.

The essence of the method of reduction and its place in theory of indirect measurements, as pointed out in the book (Rabinovich, S. G. 2000) [6], is as follows. Assume that $x_1^i, x_2^i, \dots, x_N^i$ are measurement results of arguments from a measurement vector x^j. Recall that a measurement vector compiles measurements of all the arguments performed under the same conditions, and at the same time. Each dependent indirect measurement always consists of a definite number of measurement vectors. Substituting the results from the *j*th vector into the measurement equation, we obtain the *j* th value of the measurand. Let us designate it y_{ij}. This transformation is obviously justified as it reflects the physical relationship between a measurand and measurement arguments.

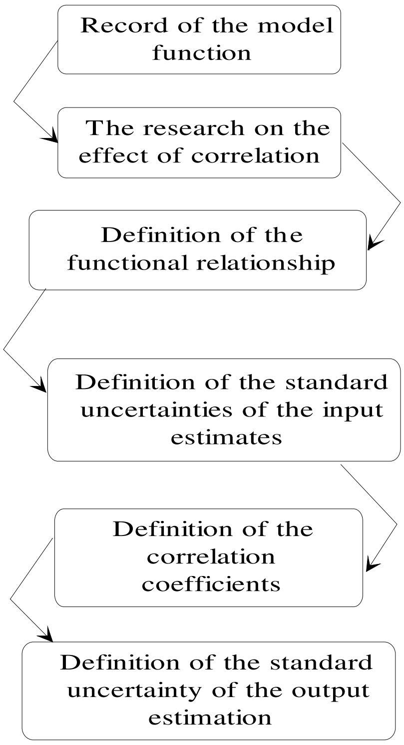

Figure 1.2 Consecution of the uncertainty calculation

It is known that the factor of correlation of measured physical values, on which the random deviations are imposed, is less on modulus than factor of correlation of initial values. On the one hand, casual deviations can loosen the researched correlation connection between initial values. On the other hand, for independent quantities measured the coefficient of correlation can appear distinct from zero owing to random dispersion of results of measurement.

It is therefore possible to conclude, that the casual deviations affect the significance of the coefficient of correlation. The similar situation is typical at defining AC–DC transfer error and requires the application of methods of determining uncertainty estimates of measured values using correlation analysis.

1.2 High-precision comparison of alternating voltages standards

A feature of etalon calibration in the field of alternating voltage is the very wide range of frequencies (10 Hz-1000 MHz) and the range of voltage 1–1000 V at frequencies up to 100 KHz and 1–3 V at frequencies up to 1000 MHz. Thus there is a number of additional conditions when realizing the measurements.

That, for example, in order to the national etalon reproduced the size of volt with the greatest accuracy, it is necessary to fulfill a number of requirements: the instability of temperature of an environment in the location of the collated converters should not exceed 0.1 °C/h; the level of electromagnetic disturbance should not exceed 0.1–0.5 mV/m; total inertia (inertia of the measuring converter plus inertia of the compensator) for each of the collated etalons should be close; the input resistance of the used compensator (measuring potentiometer) at checking new generation of primary converters on the basis of film integrated thermoelements should not be less than 10^8 Ω. The methodology of checking the etalons of an alternating voltage has also a number of features.

At collating the measuring converters are switched parallel in one section of a line of transfer. For this purpose T-joint is used. It is especially important at calibration of etalons in a range of high frequencies, if the graduation of the etalons in meaning of unit of an alternating voltage will be carried out with the help of the etalons of capacity of an alternating current in coaxial paths. Thus a voltage of high frequency is normalized in the certain section of a coaxial line by results of measurements of capacity and complete input resistance of the measuring converter. The mentioned tee-joint represents a symmetric T-junction. In tee-joint the requirements to equality of distances are observed: distances from its central plane, where the measuring voltage from the generator is fed up to a plane which is taking place through cross section of output connectors of both shoulders of tee-joint where the collated converters are connected.

At collating a voltage in the central plane of T-joint is normalized most often. If the electrical length between sections in which the voltage is measured varies there can be an additional deviation dominant on high frequencies. Thus, at calibration of the etalons of an alternating voltage a special technique is necessary considering the specificity of precision means of measurements and conditions of performance of precision measurements (Bajkov, V. M., et al. 2000) [7].

Statistical methods and approaches are applied practically at each step in the quality assurance of measurement, from definition of the measurement problem and demands on measurement methods, through development and application of measurement methods, to presentation and interpretation of measurement results. The international standardization committee (ISO), in its technical committee TC69 SC6, is actively engaged at present in work concerning the application of statistics in measurement and testing. A Nordtest Handbook (Arnesen, Y. J., et al. 1999) [8] makes several references to modern standards in this area, and use is made of standard terminology. The handbook is intended to give the measurement and calibration engineer both a clear picture of the most important steps in a measurement task as well as of statistical methods and written standards appropriate to be used at each stage in order to improve measurement quality. Quality control of process capability and product characteristics can be expressed in quantitative or numerical terms when statistics is used. In Nordtest Handbook links are brought to an international statistical handbook (Statsoft), where examples are given, e.g. of control diagrams.

To increase the accuracy of measurements, only in the field of constant voltage, special techniques of performance of measurements on the basis of methods of mathematical statistics and mathematical modeling are used. It is necessary to note, that the intensity of researches in this direction has appreciably increased. For comparison of results of the measurements which have been carried out in different time, the model of linear regression a voltage of a measure in time is used (in the field of constant voltage). In 1995–1996 such researches were carried out on the basis of KRISS (Korea).

For the analysis and processing of measurement results computer technologies-programs were used realizing a multidimensional hierarchical method of splitting of experimental data on classes and a forecasting method on the basis of linear model with graphic visualization of the results of the analysis and the forecast. In the field of measurements of constant voltage the method of multiple linear regression of a voltage on the data describing a condition of measurements is successfully used. To lower estimations of instability of voltage measures, changes of conditions of measurements (temperature, humidity, atmospheric air pressure in the room and noise of the measuring equipment) are taking into account. At present research into instability of constant voltage measures using a nonparametric method of the main component (Al`shin, B. I., et al. 2001) [9] is being carried out (in VNIIFTRI).

Nowadays the network of secondary etalons of voltage is created on the basis of Josephson's effect. For accurate measurement of a voltage of Josephson's transitions chains made on technology 'superconductor – isolator – normal conductor – isolator – superconductor' (SINIS), an original technique is applied allowing to lessen the influence of noise on uncertainty of measurement due to the choice of optimum time of measurement.

A high-precision comparison of DC voltages generated by a 10 GHz SINIS (superconductor – insulator – normal conductor – superconductor) Josephson non-hysteretic junction array and a 70 GHz SIS Josephson junction array are described in paper (Karpov, O. V., et al. 2001) [10]. The paper also describes an interesting method of minimizing the measurement uncertainty. The result of DC voltage measurements can be disturbed by a variety of factors such as noise and thermal emf in measuring circuits, null drift, and noise of the measuring system. These factors increase the statistical uncertainty of the DC voltage measurements. If to consider a voltage difference to be measured across the SINIS and SIS arrays as a stochastic non-stationary signal, the pure voltage difference across the arrays, total thermal emf. at the measuring circuitry, noise and possible null drift of the measuring system, and white additive noise with a null mean value are included to the model function. The coefficients of sensibility of the measurement model function are determined under the condition of minimizing the white additive noise. The sampling of a voltage difference with the number of data points is characterized by a sampling mean and sampling dispersion. Estimates of the mean and the dispersion of the above-described non-stationary signal are performed in accordance with the statistical model.

In this decade intellectual systems of measurements realizing sampling method have been created. If the time interval between samples and Analog to Digital Conversion discreteness tends to zero, the set of digital data will allow us to calculate any characteristics of an electrical circuit. Metrological maintenance of any systems of measurement provides the transferring them the sizes of units of measure from the etalons. At the same time the existing reference complex in the field of electrical measurements on alternating current does not allow to solve this task or its solving is very difficult.

To increase the accuracy of measurements in the field of alternating voltage new precision means of measurements on the basis of essentially new methods of measurements based on quantum effects are created. Theoretical and experimental researches of the employees (NIST, US) (Al`shin, B. I., et al. 2001) [9] promoted the creation of the equipment of a new generation, based on the idea of using Josephson's effect for reproduction of unit of a voltage of an alternating current. Since 1995 leading metrology laboratories of the world, such as NIST (US), PTB (Germany), NPL (Great Britain), ETL (Japan), KRISS (Korea), BIPM (France), have been engaged in problems of exact reproduction of both the form and the amplitude of signals of an alternating voltage with the help of a quantum digital synthesizer of alternating voltage. The tendency of replacement of the analog equipment by modern precision digital measuring engineering is observed. The electrodynamics processes in Josephson's transitions are investigated. There are only theoretical calculations, suitable for creation of the generator of an alternating voltage of the given form on strongly shunted Josephson's transitions.

Josephson's transitions are raised by series of periodic impulses of short duration. The breadboard models of digital synthesizer of sine wave signals in a range of frequencies up to 20 Hz and synthesizer of signals of the rectangular form in a range of frequencies up to 10 Hz are created. The software for management of synthesis of analog signals of an alternating current is the integral part of the quartz digital synthesizer of an alternating voltage. The creation of the etalons of an alternating voltage on Josephson's effect will allow us to increase the accuracy of measurement by 1–2 orders in all parts of the calibration circuit. For the estimation of accuracy of synthesis of an alternating voltage the methods of computer modeling are used. In algorithms of some program modules the regression methods of the analysis (Karpov, O. V., et al. 2001) [10] are realized.

The calibration of electronic voltage standards as working standards is well described in the references of the metrology laboratory PTB, Germany. The direct calibration of electronic voltage standards using the Josephson's effect would be the most accurate method. However, the high accuracy of a Josephson's voltage standard cannot be transferred to an electronic voltage standard due to the high noise and short-term fluctuations of such a device. At the PTB, voltage calibrations are carried out using a working standard consisting of a group of four electronic voltage standards selected for low drift and noise. On the basis of the history of these calibrations, the individual drift rate of each output voltage is determined. Using this drift rate and the value at the time of the last calibration, each output voltage can be forecasted for the respective date and time. Both, the voltage standards to be calibrated and the four standards forming the working standard are connected to a multiplexing switch with 16 inputs. This switch is made up of magnetically latching relays and is connected to the controlling computer via a serial interface isolated by a fibre optic cable. The relays are wired in such a way that the difference voltage of every two inputs can be routed to a digital voltmeter in both forward and reversed polarity. Only a single voltage level is calibrated at a time in order to minimize errors due to the leakage resistance of the relays. The voltage differences are measured using the digital voltmeter. Random fluctuations of both the group-working standard and the standard to be calibrated result in a scatter of the daily measurements. The voltage to be determined is calculated as the output voltage of one standard of the working standard group plus the voltage difference measured by the digital voltmeter plus the thermal EMF. A correction for the drift of the output voltage is applied by adding the drift rate multiplied is the time interval since the last calibration to the value of the last calibration (Funck, T., Pesel, E., and Warnecke P. 1999) [11].

The SI electrical units in the measurement of electrical current, voltage, power, and energy are defined as DC quantities. The ampere and the volt can be realized directly in terms of force using either electrodynamics or electrostatic techniques, and one can be derived from the other with a determination of the ohm. The units are normally maintained in terms of the volt and the ohm by the use of the AC Josephson's effect, standard cells, calculable capacitors, and standard resistors and their dissemination is by means of standard cells, solid-state voltage references and standard resistors. In order to measure AC quantities in terms of these units it is necessary to transfer from AC to DC. AC–DC Transfer standards are required for this purpose, and are fundamental to the electrical system of measurements. It is conceivable that at some time in the future the units could be redefined in terms of AC quantities, but additional difficulties associated with realization an AC and the need for an AC source, equivalent to the standard cell, make this unlikely. Thermal converter, in one form or another, is widely used in both national and industrial laboratories as the basis of AC–DC Transfer standards (Inglis, B. D. 1992) [1].

The standard-carrier of a constant/alternating current of 792 A model meets the highest requirements to measurements of parameters of an alternating current. Using patent sensor RMS manufactured by Fluke and technology of thin-film resistors, the device 792 A provides exclusive accuracy of measurements of size of carry. Besides that, the device 792 A provides a wide range of voltage and frequencies. The high level of input voltage in comparison with output voltage of thermocouples makes it possible to use a digital multimeter, instead of a specialized zero-indicator. It does not only simplify the process of measurements, but also makes the measurements more precise. The device 792 A has excellent characteristics of signal-noise, minimal reversal deviations, and is characterized by a good thermal stability.

In the 1980`s more and more high accuracy multimeters appeared on the market because the industry needed more accurate test and measurement equipment to monitor more tightly the quality of their production processes. High performance multi function calibrators replaced single function calibrators, calibrating $6^{1/2}$ and $7^{1/2}$ digits high performance voltmeters with a positive result that the number of to be maintained calibrators decreased. It was also the second half of the 1980`s where Fluke introduced the first calibrator with a new maintenance philosophy, called "Artifact Calibration". This calibrator was the 5700 A. Artifact calibrations are performed at the interval as defined by the specifications. When the calibrator workload requires the user to use the calibrator`s 1 year specifications, Artifact Calibration is performed once a year. If the workload requires the usage of the 90 days specifications, Artifact Calibration is performed every 90 days. Artifact Calibrations should also return the instrument to the accuracy the calibrator had when it was produced. To relate the 5700 A Artifact Calibration process to the traditional metrology principles it is important to understand the functions of some key components and circuits. The 5700 A incorporates internal reference standards, an internal ratio device and a null detector (Korthout, J. 1997) [12].

For complete calibration of all ranges and functions only three measures – measures 10 V of constant currents, measures of resistance 1 Ω and 10 κΩ are required. The calibrator independently operates process, which takes about a hour.

AC–DC difference or an AC-DC transfer error is one of quantities, on which meaning the national comparison of the accredited laboratories is carried out. Such comparison is carried out on national calibration program BNM–COFRAC "Electricité–Magnétisme". The AC–DC difference is given on a test report for the transfer standard as the percent (or ppm) difference of the AC response of the standard with respect to its DC response and is defined as the relation of a difference between working meaning of an alternating voltage and average meaning of a constant voltage to the value of the last one. The measurements should be carried out at 20 °C or at 23 °C. Uncertainty of measurements should reflect the ability of laboratories to measure a difference of potentials of an alternating current (Blanc, I., Antoine, J. C. 1997) [13].

1.3 Conclusions of Chapter 1

1. The AC–DC transfer etalon is one the basic electrical standards, by which the AC voltage are deduced from their DC counterparts. The DC voltage standard is established using a Josephson's voltage standard. The replacement of emf's measures by quantum measures has resulted in the use of standard cells in the working etalons. In the long term in the etalons of different levels the measures of voltage on stabilitrons will be used. In metrological practice the comparison

etalon on the basis of Josephson’s effect is put into operation. The AC voltage standard in the frequency range 10 Hz to 1 MHz is derived from the DC voltage standard by the following two methods.

– Direct synthesizing of AC waveform by the use of high-precision D/A converter
– Comparison of electric power between AC- and DC-voltage by converting the power to force or heat.

The direct synthesizing of sinewave is applied at creation of the primary etalons of an alternating voltage. When developing basic standards it is possible to apply a method of comparison with the use of AC–DC Transfer standards of model 792 A.

2. For increasing the accuracy of measurements in the metrology practice researches as to the use of methods of mathematical statistics are being done. In the "Guide to the Expression of Uncertainty in Measurement" the formulas for calculation of standard uncertainty of an output values measurement result in the case of correlated and non-correlated estimations are given. However, at collating of the etalons the results of calibration for non-correlated input values are given, not proving their independence.

3. A steady tendency of replacement of the analog equipment by modern precision digital computer facilities is observed, where digital-analog or analog-digital converters serve as the basic measuring converter. On the global market of measuring engineering the company FLUKE delivers devices, which meet the highest requirements to the measurements of alternating current parameters.

4. At realization of international collation of the standards of an alternating voltage the basic task of the methodological approach consists in the analysis of hardware and methodical components of uncertainty of collating means of measurements. To lessen the specified uncertainties international standardization of the conditions of performance of high-frequency measurements is necessary.

5. The purpose of the submitted work is the development of a secondary standard of alternating voltage. For achievement of the specified purpose it is expedient to solve the following tasks:

– To develop the methods of estimation of uncertainty of an alternating voltage etalons model in a case of non-equally accurate and correlated measurements.
– To adapt the methods of multidimensional mathematical statistics for a technique of performance of measurements to reduce the estimate of instability of an alternating voltage.

- To take into account the variability of alternating voltage measurement conditions with the functional dependence of the measurand on the conditions listed unknown.
- To analyze the possibility of reducing the dimensionality of the analyzed formula of measurements and selecting the most informative parameters.
- To investigate the influence of random deviations on the factor of correlation between physical quantities at alternating voltage measurement.

2 METHODS OF CORRELATION COEFFICIENT ESTIMATION

2.1 The concept of correlation

Sources of uncertainty are said to be **correlated** if they track each other. It means that if one is going up, then the other is most likely to be going up (or down) too. Statisticians have developed very sophisticated methods (called analysis of variance, sometimes abbreviated ANOVA) to figure out just how correlated two different quantities are. This analysis ends up with a number, called the correlation coefficient. The correlation coefficient can be any number between 1 and 0. A correlation coefficient of 1 implies perfect correlation, or in other words, whenever one quantity moves up the other moves up or down in an exact proportional relationship. An example of two quantities, which are perfectly correlated, is the voltage and current in a resistive circuit. A correlation coefficient of zero implies that there is no relationship between the two quantities, at least as far as can be determined from the data analyzed.

In metrology in particular, causality is usually more easily determined. It is rare to have correlation without causality, although not impossible. The most common cause of correlation is where a single physical quantity (let's say voltage reference accuracy) affects two or more of the uncertainties in a measured quantity (for example, voltage measurement uncertainty and current measurement uncertainty, both part of power measurement uncertainty). In this case, if one was measuring a power quantity (watts, vars, Wh, etc.) the voltage reference uncertainly would affect both the current and voltage component of the power measurement in exactly the same way. Fortunately, the existence of such a situation does not preclude the use of the RSS method. (Interestingly, if a measurement is the ratio of voltage and current, for example impedance, the voltage reference uncertainty will cancel. Taking advantage of such cancellations wherever possible is an important part of high-performance system design.)

To proceed having correlated quantities do the following: first add the correlated uncertainties together before squaring. Only those items correlated to each other should be added together before squaring. If there are two groups of correlated items, i.e. A and B are correlated to each other, and C and D are correlated to each other, but neither A nor B is correlated to C or D, then you would add A and B together, square, and add to the sum, and then add C and D together, square, and add to the sum.

Simple linear correlation. Pirson's correlation, also named simple correlation, assumes that two considered variables are measured. It defines a degree of proportionality of the values of two variables to each other. It is important, that the value of factor of correlation *r* does not depend on units applied at measurement. For example, correlation between growth and weight of the person will be the same, irrespective of if the results of measurement are in inches and foots or in centimeters and kilograms. Proportionality simply means the linear dependence. The correlation is high if the dependence can be depicted on the graph in Fig. 2.1 as a straight line (with a positive or negative angle of inclination). The straight line is called a regression line or a straight line constructed by the least squares method. The last term is connected with fact that the sum of squares of the distances calculated on an axis of ordinates from the observable points up to the straight line is minimal.

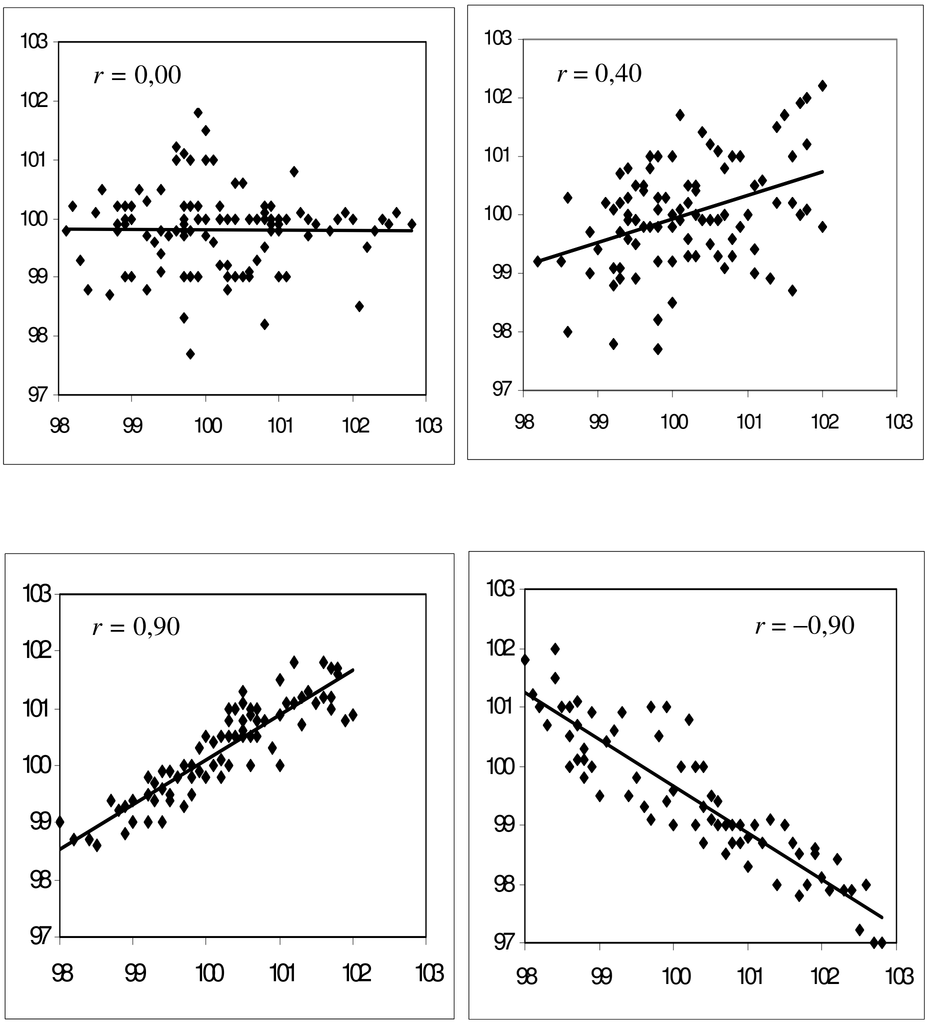

Figure 2.1 **Dependences between the digital values, estimating correlation**

It must be noticed that the use of squares of distances leads to that the estimations of parameters of a straight line strongly react to spike. Now a question rises: How to interpret the values of correlations? The factor of correlation r represents a measure of linear dependence of two variables. If to square it the received value of factor of determination r^2 represents a share of a variation, common for two variables, i.e. a degree of dependence or coherence of two variables. To estimate the dependence between variables, it is necessary to know both the value of correlation and its importance.

The significance of correlations. The significance level calculated for each correlation represents the main source of the information about reliability of correlation. The significance of a certain factor of correlation depends on sample volume. The criterion of the significance is based on the assumption that the distribution of the rests, i.e. deviations of results of supervision from regression straight line for dependent variable Y_{ij}, is normal with constant dispersion for all values of independent variable X^j.

Spikes. By definition, the spikes are atypical, sharply allocated supervision. As at construction of a straight line of regression the sum of squares of distances from observed points up to a straight line is used, the spikes can essentially affect an inclination of a straight line and, hence, the value of factor of correlation. Therefore individual spike (whose value is squared) is capable essentially to change an inclination of a straight line and, hence, the value of correlation (see Fig. 2.2).

Let's notice, that if the sample of the data is rather small, addition or the exception of some data, which probably are not spikes, is capable to render essential influence on a straight line of regression and factor of correlation. It is shown in Fig. 2.3**.**

Usually it is considered that the spikes represent random deviations, which should be supervised. Unfortunately, there is no standard method of automatic removal of spikes. To be not confused by the received values, it is necessary to check up each important case of significant correlation on the diagram of dispersion. Obviously, the spikes are able not only to artificially increase the value of the factor of correlation, but also to really reduce the existing correlation.

The diagram of dispersion. The diagram of dispersion visualizes the dependence between two variables *X* and *Y*. Data are represented by points in bidimentional space where axes correspond to variables (X^j – horizontal axis, and Y_{ij} – vertical axis). Again there is a question: Why are dependences between variables important? Generally speaking, the ultimate goal of any research or the scientific analysis consists in a finding of dependences between variables. The philosophy of science teaches that there is no different way of representation of knowledge except in terms of dependences between quantities or the qualities expressed by any variables. Thus, development of a science always consists in finding new connections between variables.

The correlation coefficient for simultaneous repeated measurements. Estimates $x_{i,k}$, $x_{j,k}$ for two values X_i, X_j can appear correlated. It means that there is an unknown third value which influences the magnitude of two other mentioned values. Correlation between these two values is possible, if they are received simultaneously. If values are received in the period shorter than a constant of time of the third value changing, it is possible to consider them correlated too.

Estimation of covariance. The estimation of covariance $s(\bar{x}_i, \bar{x}_j)$ characterizes a degree of correlation of two arithmetic means and is usually positive, though its negative values are also possible. In the theory of mathematical statistics (Aleksakhin, S. V, et al. 2001) [14] covariance of scalar random variables X_i, X_j refers to expected value of product of the centered first random variable x_i^0 and the conjugated centered second random variable $\overset{-0}{x}_j$:

$$s(x_i, x_j) = \mathrm{M} x_i^0 \bar{x}_j^0 \qquad (2.1)$$

In practical computations the formula

$$s(x_i, x_j) = \frac{1}{n-1} \sum_{k=1}^{n} (x_{i,k} - \bar{x}_i)(x_{j,k} - \bar{x}_j) \qquad (2.2)$$

is used as an unbiased and consistent estimation of covariance.

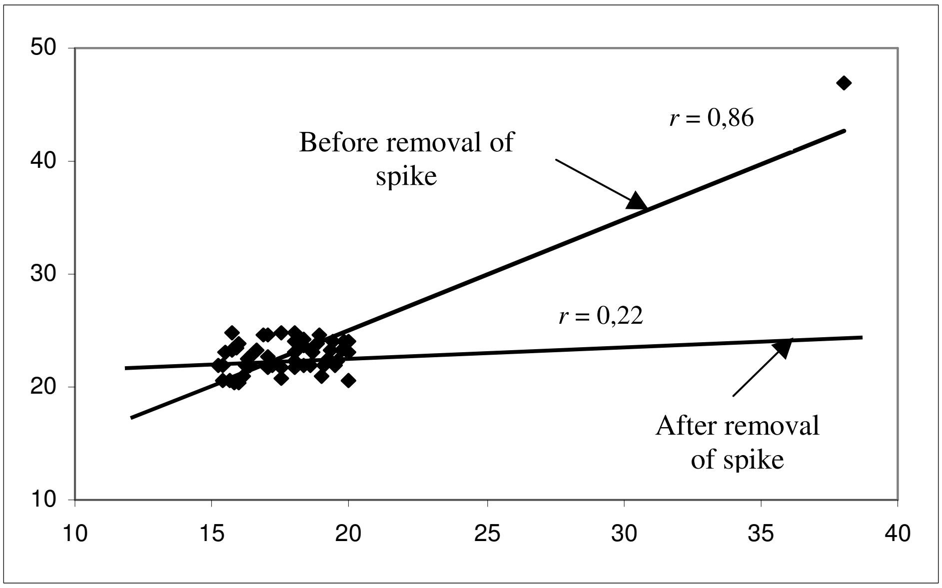

Figure 2.2 **Dependence before and after removal of a spike**

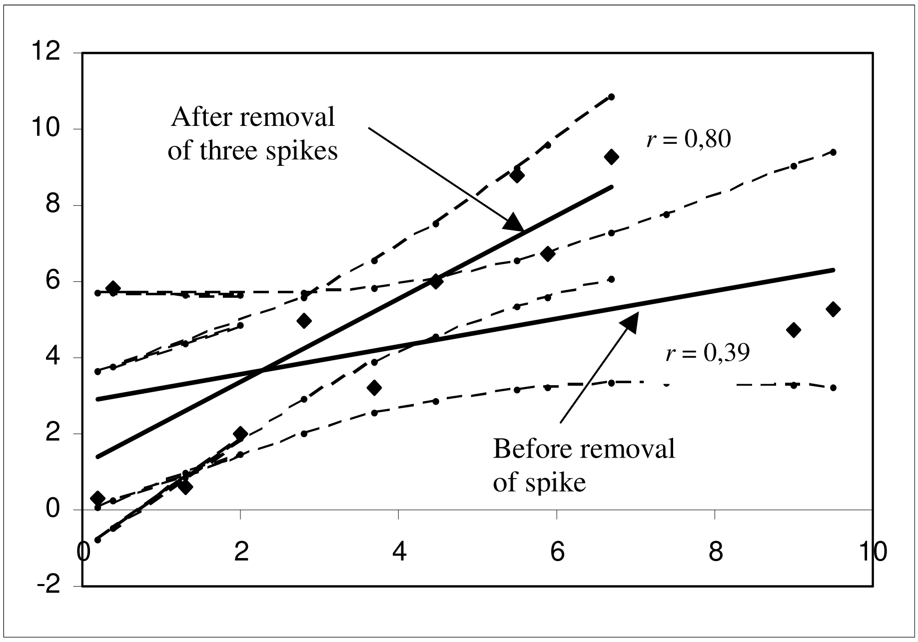

Figure 2.3 Dependence before and after removal of spikes

With unbiasedness provided the symmetry of area of possible values of a random variable distribution function is guaranteed, and consistency provides a more compressed distribution of the random variable around its mean.

Proceeding from estimations $s(x_i)$, $s(x_j)$, it is possible to calculate the experimental covariance $s(\bar{x}_i, \bar{x}_j)$ and factor of correlation $r(\bar{x}_i, \bar{x}_j)$ of two arithmetic means:

$$u(\bar{x}_i,\bar{x}_j) = s(\bar{x}_i,\bar{x}_j) = \frac{s(x_i,x_j)}{n} = \frac{\sum\limits_{k=1}^{n}(x_{i,k}-\bar{x}_i)(x_{j,k}-\bar{x}_j)}{n(n-1)} \tag{2.3}$$

$$r(\bar{x}_i,\bar{x}_j) = \frac{u(\bar{x}_i,\bar{x}_j)}{u(\bar{x}_i)\cdot u(\bar{x}_j)} = \frac{\sum\limits_{k=1}^{n}(x_{i,k}-\bar{x}_i)(x_{j,k}-\bar{x}_j)}{\sqrt{\sum\limits_{k=1}^{n}(x_{i,k}-\bar{x}_i)^2\sum\limits_{k=1}^{n}(x_{j,k}-\bar{x}_j)^2}} \tag{2.4}$$

Here the received values of the coefficient of correlation will be limited by an interval

$$\left|r(\bar{x}_i,\bar{x}_j)\right| \le 1$$

It is necessary to stress that the number of realisation of X_i and X_j must be the same. Moreover, each pair of these realisations must be obtained under the same conditions, for example, at the same time and at the same temperature, using measuring instruments with the same dynamic characteristics. The theory of correlations says that realisations x_i and x_j must belong to the same event k. In the case of an indirect measurement, one event is the set of matched measurement results of all arguments. This event corresponds to a point in the multidimensional space with arguments as coordinates. We shall call this point a measurement vector. At the measurement of alternating voltage of the AC–DC Transfer Standard each pair of measurements of the AC voltage and DC voltage is a measurement vector.

A component of uncertainty $u(x_i, x_j)$ in view of correlation of two values is calculated as a product of their uncertainties and the coefficient of correlation (Barashkova, T., Laaneots, R. 2003) [3], i.e.

$$u(x_i, x_j) = u(x_i) \cdot u(x_j) \cdot r(x_i, x_j) \qquad (2.5)$$

So, the correlation of two values results from influence of the third value specifically influencing the other two. If the coefficient of correlation is positive, the ratio of these values considerably reduces this influence, while at a negative coefficient of correlation the mentioned product practically eliminates the influence of the third value.

2.2 Sources of uncertainty

Metrologists, that is, people engaged in the science of metrology or measurement, generally use the term "uncertainty" rather than "error" when talking about a measurement process. "Error" means "mistake," i.e. something done wrong. "Uncertainty" means the amount by which a measured value deviates from the true value.

Measurement uncertainty is caused by a number of factors. Some of these are: initial calibration uncertainty, temperature sensitivity, power supply variations, sensitivity to signal conditions, measurement noise, and drifts over time. Properly determined, a guaranteed specification, which takes all of this into account, will ensure measurement results, which are within a desired window. The designer of the equipment or system must take all of these factors into account when designing the product to maximize its performance. The results of the analysis done by the designer form the basis to determine the guaranteed specifications at a later date.

Uncertainty of result of measurement reflects the absence of exact value of the measured magnitude, i.e. a variable. The result of measurement after making the amendment on known systematic effects is still only an estimation of value of the measured magnitude owing to the uncertainty arising because of random effects and the inexact amendment of result on systematic effects. The result of measurement (after making the amendment) can be (it is unknown on how much) very close to value of the measured magnitude, can have negligible error even if it can have large uncertainty. Thus, uncertainty of result of measurement should not be confused to the unknown rest of an error (Laaneots, R. 1995) [15].

In practice there are every possible sources of uncertainty of measurement. Here are some of them:

- incomplete definition of the measured value
- imperfect realization of definition of the measured value
- non-presentation sample, i.e. the measured sample can not represent the measured magnitude
- inadequate knowledge of effects from the environment conditions influencing measurement, or imperfect measurement of environment conditions
- subjective systematic mistake of the operator at taking an indications of analog means of measurements
- resolution or a threshold of sensitivity of means of measurements
- inexact knowledge of constants and other parameters taken from external sources and used at data processing
- inexact knowledge of properties of etalons, standard samples of substances, materials used during measurements
- assumptions and the approximations which are present at a measurement technique changes at repeated supervision of the measured magnitude under obviously identical conditions.

Uncertainty of result of measurement is characterized by the parameter connected with result of measurements and describing the dispersion of values which can enough reasonably be attributed to the measured magnitude. Usually the measurement possesses a number of imperfections which explain dispersion of results of measurements. The contribution of some imperfections to results data spread can be estimated and then it is possible to make the amendment for compensation of these effects. After making the amendments the estimation of uncertainty should begin with identification of all of its essential components. For example, if at calibration of a voltmeter an etalon of voltage of direct current imported from a laboratory of higher level is used, the following components of uncertainty can be present:

- uncertainty of calibration
- of transportation
- of time and temperature stability of the etalon
- from noise factors.

Let's consider each of the components more in detail.

All information on uncertainty of calibration of an etalon is contained in the certificate on the calibration, written out, for example, by the national accredited laboratory. Using these data, a consumer can easily estimate this component of uncertainty.

The transportation of an etalon from one laboratory to another can essentially contribute to the spread of results of collating an etalon and the calibrated means of measurements. The knowledge of behaviour of the etalon in conditions of transportation is necessary for an estimation of the effect of transportation. The conditions of an environment can be different in two places. During transportation, e. g. a voltage etalon, loss of capacity is possible.

Time stability is potentially the most significant component of uncertainty. In low-level laboratories annual calibration of etalons is carried out, as a rule, without too much anxiety as to how the means of measurement will be used in the period between calibrations. In high-level laboratories capable to determine physical quantities drift the behaviour of an etalon in the period between calibrations is investigated. The results of such researches allow them to carry out weekly or monthly updating of the values kept by the etalon, knowing their speed of drift.

The temperature stability of the majority of electric etalons is characterized by their temperature factors. In the specification of these means of measurements the temperature factors are usually specified in percentage on Celsius degree. With information concerning temperature factors absent, or when highest accuracy of measurements is required, these factors should be measured. The measurements must be carried out with a correction depending on temperature applied. The knowledge of local temperature considering the effect of density of devices is very important. For example, if devices are placed on shelves the temperature surrounding them will be some degrees higher than local temperature of air surrounding the shelves.

Thermal noise of resistors, shot noise of electronic devices, noise of quantization are the noises known. To decrease the influence e.g. of noise quantization on the result of measurement, a direct way exists – the use of binary numbers with a lot of bits or creation of noise proof systems. In any case, knowledge of the measuring device is essential at determination of this component of uncertainty. During an estimation of the noise component of uncertainty measurements are repeated at various time intervals. Thus it is possible to determine the short-term changes of physical quantities under typical conditions of work. Sometimes the best operating conditions can be achieved at a feed from battery blocks. However, one must be aware of the fact that at switching the battery from a mode of feed to a charging mode there can be slow changes of output voltage of the device under action of internal changes of temperature. In some laboratories measurements are carried out at a network feed that leads to an emergence of additional noise component of measurement uncertainty.

2.3 Methods of simplified calculation of the correlation coefficient

In this chapter, the author provides a variant of the covariance calculation system. Certain possibilities to improve reliability of results obtained by means of correlation analyses are considered.

Thus, any estimated coefficient of correlation connected with two estimates of measured values can be determined making use of several methods.

2.3.1 Maximum likelihood method

Let two aggregates of random values $\boldsymbol{U}_0 = (u_{01}, u_{02}, u_{03}, \ldots, u_{0n})^T$ and $\boldsymbol{U}_x = (u_{x1}, u_{x2}, u_{x3}, \ldots, u_{xn})^T$ be given, put down as columns. Both the aggregates $u_{(0,x)i}, (i = 1,2,\ldots,n)$ form two samples from larger aggregates for $U_{0,x}$ with probability densities $f(U_0, \sigma_0)$ and $f(\boldsymbol{U}_x, \sigma_x)$. In this case, the elementary probability to obtain exactly these samples for independent random values equals

$$f(\boldsymbol{U}_0, \sigma_0)\, f(\boldsymbol{U}_x, \sigma_x)\; d\boldsymbol{U}_0\, d\boldsymbol{U}_x$$

The joint probability density determined as

$$l(\boldsymbol{U}_0, \boldsymbol{U}_x, \sigma_0, \sigma_x) = f(\boldsymbol{U}_0, \sigma_0)\, f(\boldsymbol{U}_x, \sigma_x)$$

is referred to as a likelihood function of the sample data. In case of dependent random values, which follow mutual normal distribution, the likelihood function of the sample data may be entered as follows (Aleksakhin, S. V, et al. 2001) [14]:

$$l(\mathbf{U}_0, \mathbf{U}_x, \sigma_0, \sigma_x, \rho) = \\ = \frac{1}{2\pi\sigma_0\sigma_x\sqrt{1-\rho^2}} \times \\ \times e^{-\frac{1}{2(1-\rho^2)}\left[\frac{(\mathbf{U}_0-\mu_{U_0})^2}{\sigma_0^2} - 2\rho\frac{(\mathbf{U}_0-\mu_{U_0})(\mathbf{U}_x-\mu_{U_x})}{\sigma_0\sigma_x} + \frac{(\mathbf{U}_x-\mu_{U_x})^2}{\sigma_0^2}\right]} \tag{2.6}$$

With the method of maximum likelihood the value of correlation coefficient ρ can be determined. As a value of the unknown parameter ρ let such value be selected, which maximizes the likelihood function. The maximum of this function is to be solved and found as follows:

$$\frac{\partial L}{\partial \rho} = \frac{\partial}{\partial \rho} ln\left[l(\boldsymbol{U}_0, \boldsymbol{U}_x, \sigma_0, \sigma_x, \rho)\right] = 0 \tag{2.7}$$

where

$$L = ln\left[l(\boldsymbol{U}_0, \boldsymbol{U}_x, \sigma_0, \sigma_x, \rho)\right]$$

Solving the equation (2.7), we obtain the value of the unknown parameter

$$\rho \equiv r(\boldsymbol{U}_0, \boldsymbol{U}_x) = \frac{E(\boldsymbol{U}_0 - \mu_{U_0})(\boldsymbol{U}_x - \mu_{U_x})}{\sigma_0 \sigma_x} \tag{2.8}$$

Here mutual uncertainty, covariation of quantities $\boldsymbol{U}_0, \boldsymbol{U}_x$, is determined by the following average of distribution

$$u(\boldsymbol{U}_0, \boldsymbol{U}_x) = E(\boldsymbol{U}_0 - \mu_{U_0})(\boldsymbol{U}_x - \mu_{U_x}) \tag{2.9}$$

And the dispersion of random values is determined by the ratio (2.9)

$$\sigma_{0,x}^2 = E(\mathbf{U}_{0,x} - \mu_{0,x})$$
$$\sigma_{0,x}^2 \equiv u^2(\mathbf{U}_{0,x}) \qquad (2.10)$$

Thus, it is very important that random values be subject to the normal law of distribution. In this case, it is possible to estimate the coefficient of correlation according to the formula (2.8), with the known estimates of covariance and average root-mean-square deviations.

2.3.2 Indirect measurement of an output value

Let's assume, that two input values $\boldsymbol{U}_0$ and $\boldsymbol{U}_x$, having corresponding estimations $\boldsymbol{U}_{0\approx}$ and $\boldsymbol{U}_{x\approx}$, depend on a set of non-correlated variables $(Q_1,Q_2,\ldots,Q_n)$ (Guide to the Expression of Uncertainty in Measurement, 1993). Thus, $\boldsymbol{U}_0=F(Q_1,Q_2,\ldots,Q_n)$ and $\boldsymbol{U}_x=G(Q_1,Q_2,\ldots,Q_n)$. Some of variables $(Q_1,Q_2,\ldots,Q_n)$ can actually appear only in one function. If $u^2(q_1)$ represents estimated dispersion, connected with an estimation q_1 by variable Q_1, then the estimated dispersion connected with $\boldsymbol{U}_0$ is expressed by the equation

$$u^2(U_{0\approx}) = \sum_{i=1}^{n}\left[\frac{\partial F}{\partial q_i}\right]^2 u^2(q_i) \qquad (2.11)$$

For an estimation $\boldsymbol{U}_{x\approx}$ of the value $\boldsymbol{U}_x$ it is possible to receive a similar expression, i.e.

$$u^2(\mathbf{U}_{\mathrm{x}\approx}) = \sum_{i=1}^{n}\left[\frac{\partial G}{\partial q_i}\right]^2 u^2(q_i) \qquad (2.12)$$

Estimated covariance connected with $\boldsymbol{U}_{0\approx}$ and $\boldsymbol{U}_{x\approx}$ is expressed as

$$u(\mathbf{U}_{0\approx},\mathbf{U}_{x\approx}) = \sum_{i=1}^{n}\frac{\partial F}{\partial q_i}\frac{\partial G}{\partial q_i}u^2(q_i) \qquad (2.13)$$

As only those members for which $\frac{\partial F}{\partial q_i} \neq 0$ and $\frac{\partial G}{\partial q_i} \neq 0$ at given n bring in the contribution to the sum, covariance is equal to zero, if any of variable $(Q_1,Q_2,\ldots,Q_n)$ is not common for functions F and G. Estimated factor of correlation $r(\boldsymbol{U}_{0\approx},\boldsymbol{U}_{x\approx})$, connected with two estimations $\boldsymbol{U}_{0\approx}$ and $\boldsymbol{U}_{x\approx}$, is determined from the equation (2.4), thus $u(\boldsymbol{U}_{0\approx})$ and $u(\boldsymbol{U}_{x\approx})$ are calculated from equations (2.11) and (2.12).

2.3.3 The determination of Spearman rank correlation coefficient

For example, in the third series of the experimental data a monotonic dependence between measurement values $\boldsymbol{U}_0$ and $\boldsymbol{U}_x$ is observed. Spearman rank correlation coefficient can be determined (Aivazyan, S.A., et al. 1988) [2] as

$$r_s(\mathbf{U}_{x\equiv}, \mathbf{U}_{x\approx}) = 1 - \frac{6\sum\limits_{i=1}^{N}(n_{0i} - n_{xi})^2}{N(N^2-1)} = 1 - \frac{6\sum\limits_{i=1}^{N} d_i^2}{N(N^2-1)} = 0{,}103 \qquad (2.14)$$

where

n_{0i} – rank of input value $\boldsymbol{U}_{x\equiv,i}$

n_{xi} – rank of input value $\boldsymbol{U}_{x\approx,i}$

N – quantity of pair supervisions ($\boldsymbol{U}_{x\approx}, \boldsymbol{U}_{x\equiv}$)

Table 1. Complete result of calculation of r_s

i	$\boldsymbol{U}_{x\approx,i}$, mV	$\boldsymbol{U}_{x\equiv,i}$, mV	n_{xi}	n_{0i}	$d_i^2 = (n_{0i} - n_{xi})^2$
1	912.6830	912.68150	7	1	36
2	912.6843	912.68215	9	10	1
3	912.6811	912.68205	2	9	49
4	912.6820	912.68175	3	4.5	2.25
5	912.6821	912.68160	4.5	2	6.25
6	912.6835	912.68165	8	3	25
7	912.6828	912.68175	6	4.5	2.25
8	912.6806	912.68200	1	8	49
9	912.6821	912.68180	4.5	6	2.25
10	912.6881	912.68185	10	7	9

$$\overline{U}_{x\approx} = 912.6823 \text{ mV}\,; \overline{U}_{x\equiv} = 912.6819 \text{ mV}\,; \sum_{i=1}^{N=10} d_i^2 = 182$$

Estimated upper limit of conceivable deviations of rank coefficient of the Spearman correlation:

$$t_{\lim} = r_s\sqrt{\frac{N-2}{1-r_s^2}} = 0.29 \qquad (2.15)$$

Value of $t_p(\nu)$ from the distribution for probability β and degree of freedom $\nu = N - 2$:

$$t_p(\nu) = t\left[N-2; \beta\right] = t\left[8; 68.27\,\%\right] = 1.07 \qquad (2.16)$$

If $t_{\lim} > t_p(\nu)$, it is assumed that Spearman rank correlation coefficient is statistically significant.

2.4 Conclusions of Chapter 2

1. In case of dependent random values, which follow mutual normal distribution, the probability function factor of linear correlation can be determined. No "Guide to the Expression of Uncertainty in Measurement" [5] contains the derivation of the formula of definition of factor of correlation of input quantities estimations. One of the possible derivations is presented in Chapter 2.
2. The correlation coefficient determined according to equation (2.4) shall be taken into consideration while estimating uncertainty of the measurement of any quantities.
3. In Chapter 2 a variant of a system of estimating the correlation coefficient of measurement results is presented, considering covariance evaluated by statistical as well as by non-statistical information. If the estimation of mutual uncertainty and covariance is determined using formula (2.4), it is possible to receive a generalized estimate of the correlation factor as a result of two measurements.
4. In Chapter 2 also the statistical estimation covariance is determined by the Spearman rank correlation coefficients.
5. The method of covariance estimation developed can be applied in metrological practice. The variant of the system of correlation coefficient calculation is a universal means for covariance estimation
6. A way to estimate the correlation coefficient is presented if, for example, deficiency of initial data is observed

3 THE CONSIDERATION OF THE EFFECT OF CORRELATION ON ESTIMATES OF PHYSICAL QUANTITIES

If the input values are correlated, the influence of correlation coefficient on the result of an estimation of a physical quantity must be taken into account. Below how it is done is depicted.

3.1 Combined uncertainty of output quantity estimation

Let us assume that it is necessary to find a combined standard uncertainty of output measurable quantity $u_c(y)$, represented in the form of linear approximation of the correlated input quantities, with the use of standard uncertainty. Let us calculate this uncertainty with the aid of the model of estimations $y = f(x_1, x_2, \ldots, x_{nx})$ (Barashkova, T., Laaneots, R. 2003) [3] by the formula

$$\begin{aligned} u_c^2(y) &= \sum_{i=1}^{n_x} \sum_{j=1}^{n_x} c_i c_j u(x_i) u(x_j) r(x_i, x_j); \quad i \geq 1, \quad j \leq n_x \\ c_i &= \frac{\partial f}{\partial x_i} \end{aligned} \qquad (3.1)$$

Here four cases are possible differing in the amount of correlation of input values. In the first case, when input quantities are not correlated (correlation coefficient) is absent), the estimate of combined dispersion is defined by the formula

$$u_c^2(y) = \sum_{i=1}^{n_x} c_i^2 u^2(x_i); \quad \text{for} \quad i \neq j, \quad r(x_i, x_j) = 0 \qquad (3.2)$$

If there exists a linear functional positive dependency between all input quantities, the correlation coefficient is equal to one and the estimation of combined dispersion is determined by the formula

$$u_c^2(y) = \left[\sum_{i=1}^{n_x} c_i u(x_i) \right]^2; \quad \text{for} \quad r(x_i, x_j) = 1 \qquad (3.3)$$

If the correlation coefficient satisfies the conditions $0 \leq r(x_i, x_j) \leq 1$ and $i \neq j$, then the estimate of combined dispersion is determined by the formula

$$u_c^2(y) = (1 - r) \sum_{i=1}^{n_x} c_i^2 u^2(x_i) + r \left[\sum_{i=1}^{n_x} c_i u(x_i) \right]^2 \qquad (3.4)$$

Formula (3.4) represents a general case of determining the combined standard uncertainty of one output quantity in the case of uniform positive correlation of all input quantities with a correlation coefficient smaller than one, and with a correlation coefficient equal to one.

Of formula (3.4) two equations can be derived satisfying two limit conditions. If $r=1$ we shall have equation (3.3), and if $r=0$ – formula (3.2).

If the values of variance dispersion σ_i^2 and correlation coefficient $\rho_{i,j}$ are unknown then, in practice, their estimations $u^2(x_i)$ and $r(x_i, x_j)$ are used instead. Taking into account this substitution and assuming the general case of n_x arguments formula 3.5 is received. Since different correlation coefficients can exist between all input quantities, then in the case of $-1 \le r(x_i, x_j) \le 1$ the equality (3.1) becomes

$$u_\mathrm{c}^2(y) = \sum_{i=1}^{n_x} c_i^2 u^2(x_i) + 2\sum_{i=1}^{n_x-1} \sum_{j=i+1}^{n_x} c_i c_j u(x_i) u(x_j) r(x_i, x_j) \qquad (3.5)$$

Formula (3.5) illustrates the law of the distribution of uncertainties. Also note that to the formula (3.5) the correlation coefficient $r(x_i, x_j)$ is substitute as algebraic values, with characteristic signs.

For the illustration of the above statement we shall give an example from the work (Barashkova, T., Laaneots, R. 2003) [3]. Ten resistors, each with the nominal value of the resistance $R_i = 1000\ \Omega$, are calibrated with negligible measurement uncertainty by the measurement standard of resistance $R_E = 1000\ \Omega$. The certified reference standard is characterized by the standard uncertainty $u(R_E) = 100\ \mathrm{m}\Omega$. The model of calibration of each resistor is represented by the formula $R_i = \alpha_i R_\mathrm{E}$. For each resistor $\alpha_i \approx 1$ and $u(\alpha_i) \approx u(\alpha)$ – the standard uncertainty of the measured relation α_i is the same for each calibration. Resistors are connected in series with wires of negligible resistance for obtaining the reference resistance R_ref with the nominal value $10\,\mathrm{k}\Omega$.

$$R_\mathrm{ref} = f(R_i) = \sum_{i=1}^{10} R_i$$

For each pair of resistors $r(x_i, x_j) = r(R_i, R_j) = +1$. The traditional method of calculating the correlation coefficient estimate makes use of the following equation:

$$r(R_i, R_j) = \frac{u^2(R_\mathrm{E})}{R_\mathrm{E}^2 u^2(\alpha) + u^2(R_\mathrm{E})} = \left[1 + \left(\frac{u(\alpha)}{u(R_\mathrm{E}/R_\mathrm{E})}\right)^2\right]^{-1} \qquad (3.6)$$

If equations (2.11), (2.12) and (2.13) are used we obtain

$$\begin{aligned} u^2(R_i) &= R_\mathrm{E}^2 u^2(\alpha) + u^2(R_\mathrm{E}) \\ u(R_i, R_j) &= u^2(R_\mathrm{E}) \end{aligned} \qquad (3.7)$$

Thus, if $u(\alpha) \to 0$ and $r(x_i, x_j) = r(R_i, R_j) \to 1$, then $u(R_i) \to u(R_\mathrm{E})$.

Since for each resistor $\dfrac{\partial R_\mathrm{ref}}{\partial R_i} = 1$ and $u(R_i) = u(R_\mathrm{E})$, then the value of the combined standard uncertainty $u_\mathrm{c}(R_\mathrm{ref})$ can be attained by formula (3.3), thus

$$u_c(R_{\text{ref}}) = \sum_{i=1}^{10} u(R_E) = 10 \cdot (100\,\text{m}\,\Omega) = 1\,\Omega \qquad (3.8)$$

3.2 The dependence of the correlation coefficient on random deviations

It is a well-known fact that casual deviations affect the essential influence on the correlation rate between the physical units. The correlation link studied between the initial variables can be weakened

- if estimates of casual factors are not interrelated
- if the estimates are not dependable on the measured parameters
- if they are normally distributed
- if they have zero mathematical expectations and final dispersions

In other words, the correlation rate of measured variables under effect of casual deviations can be lower by the absolute volume than correlation rate of initial signs. On the other hand the measured correlation rate for independent sizes may be differing from zero as a consequence of casual dispersion of the results being measured.

Thus, we came to the conclusion that casual deviations affect the significance of the correlation rate. The situation mentioned is typical at measuring too small values and demands the application of an alternative method of determining dispersion estimates of measurands making use of correlation analysis. To evaluate the effectiveness of the suggested method of determining dispersion estimates the mentioned group-working standard of variable voltage (Barashkova, T. 2002) [16] is being under investigation. It consists of N unit-keepers of physical value.

A much more convenient and reliable method of determining dispersion estimates consists in double measurement of estimates of physical values f_1, δ_1 and f_2, δ_2, kept by group standard with the following statistical processing of the results. For the two arrays received average $\bar{f}_1, \bar{\delta}_1$ and $\bar{f}_2, \bar{\delta}_2$ and standard deviations $\sigma_{f_1}, \sigma_{\delta_1}$ and $\sigma_{f_2}, \sigma_{\delta_2}$ of relative and angle corrections of keepers must be calculated by collating with a reference standard. Further we define correlation coefficients r_f, r_δ which should be considered as autocorrelation rates of parameters f_1, f_2 and δ_1, δ_2.

3.2.1 The technique of correlation analysis applied in electrical measurements

Making two cycles of measuring parameters f and δ we get the following array of values:

$$\begin{vmatrix} \boldsymbol{f}_{11} \\ \boldsymbol{f}_{21} \\ \boldsymbol{f}_{31} \\ \vdots \\ \boldsymbol{f}_{i1} \end{vmatrix} \quad \begin{vmatrix} \boldsymbol{\delta}_{11} \\ \boldsymbol{\delta}_{21} \\ \boldsymbol{\delta}_{31} \\ \vdots \\ \boldsymbol{\delta}_{i1} \end{vmatrix} - \text{for the first moment of time}$$

$$\left| \boldsymbol{f}_{12}\ \boldsymbol{f}_{22}\ \boldsymbol{f}_{32} \dots \boldsymbol{f}_{i2} \right| \quad \left| \boldsymbol{\delta}_{12}\ \boldsymbol{\delta}_{22}\ \boldsymbol{\delta}_{32} \dots \boldsymbol{\delta}_{i2} \right| - \text{for the second moment of time}$$

For the received arrays average values of $\bar{f}_1, \bar{\delta}_1$ and $\bar{f}_2, \bar{\delta}_2$ and standard deviations $\sigma_{f_1}, \sigma_{\delta_1}$ and $\sigma_{f_2}, \sigma_{\delta_2}$ are calculated under formulae similar to the case with the parameter f_1.

$$\bar{f}_1 = \frac{1}{N} \sum_{i=1}^{N} f_{i1} \qquad (3.9)$$

$$\sigma_{f_1} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (f_{i1} - \bar{f}_1)^2}\ , \qquad (3.10)$$

where

f_{i1} – relative correction of i-keeper, obtained at the first collation of the secondary voltage of i-standard and reference standard.

Then correlation rates which should be considered as autocorrelation rates in this case are defined.

$$r_f = \frac{\sum_{i=1}^{N} (f_{i1} - \bar{f}_1)(f_{i2} - \bar{f}_2)}{(N-1)\,\sigma_{f_1}\,\sigma_{f_2}} \qquad (3.11)$$

$$r_\delta = \frac{\sum_{i=1}^{N} (\delta_{i1} - \bar{\delta}_1)(\delta_{i2} - \bar{\delta}_2)}{(N-1)\,\sigma_{\delta_1}\sigma_{\delta_2}} \qquad (3.12)$$

where

δ_{i1} – corresponding angle correction of i-standard, set in minutes and obtained at the first collation of i-standard and reference standard;

f_{i2} – relative correction of i-keeper, obtained under the repetitive collation of the secondary voltage of i-standard and reference standard;

δ_{i2} – corresponding angle correction of i-standard, set in minutes and obtained at the repetitive collation of i-standard and reference standard.

It is supposed that data of two arrays must not essentially differ as the unit of a physical value, kept by the group-working standard, is stable in time. Let correlation rate r_f characterize the measure of linear dependence between values f_1 and f_2. Let's admit that $f_1^* = a f_2 + b$ is a linear function of the best average quadratic approach to the value f_1. Let us designate the estimate of amendment deviations e.g. by Δf :

$$\Delta f = f_1 - (a f_2 + b)$$

In this case the mathematical expectation of the estimate Δf is equal to zero and the relation of its dispersion to the dispersion of the estimate f_1 is determined only by value of a correlation rate:

$$\frac{\sigma^2_{\Delta f}}{\sigma^2_{f_1}} = 1 - r_f^2 \tag{3.13}$$

If the estimates of casual factors, causing the diversity of the measured values happen to be independent, then the statistical characteristics mentioned are linked with the following interrelation:

$$\sigma^2_{f_1} = \sigma^2_{\Delta f} + \sigma^2_{f_1^*} \tag{3.14}$$

Formula (3.13) can be presented in this way

$$r_f^2 = \frac{\sigma^2_{f_1^*}}{\sigma^2_{\Delta f} + \sigma^2_{f_1^*}} = \frac{\sigma^2_{f_1^*}}{\sigma^2_{f_1}} \tag{3.15}$$

It is not hard to see that (3.13) provides an alternative chance to define the estimates of parameter dispersions, kept by the given group standard.

3.2.2 Analysis of calculations of dispersion estimates of the measurand

1. Definition of relative correction $\gamma_1(f_1^*)$ using a simple ratio of dispersion analysis (3.14)

It should be noted that under high casual deviations absolute corrections of estimates of average quadratic deviations σ_{f_1} and $\sigma_{\Delta f}$ are equal. Taking the condition of equality σ_{f_1} and $\sigma_{f_1^*}$ we'll get

$$\gamma_1(f_1^*) = \frac{2 \cdot \Delta \sigma_{\Delta f}}{\sigma_{f_1^*}} \tag{3.16}$$

where

$\Delta \sigma_{\Delta f}$ – the absolute correction of the deviation estimate Δf

Based on the results of *N*-fold measuring of a parameter f_{i1} for the same object we define the absolute correction $\Delta\sigma_{\Delta f}$. At the normal law of distribution of the possible values of the measured quantity with the confidence probability $p = 0{,}99$ and the coverage factor $k = 3$ the estimate sought for is equal to

$$\Delta\sigma_{\Delta f} = 3\sigma_{\Delta f}$$

Thus

$$\gamma_1(f_1^*) = \frac{6\sigma_{\Delta f}}{\sigma_{f_1^*}} \tag{3.17}$$

The confidence interval for relative correction of any keeper is equal

$$\Delta\sigma_{f_1^*} = 6\sigma_{\Delta f} \tag{3.18}$$

2. Definition of the relative correction $\gamma_2(f_1^*)$ using the autocorrelation coefficient

Under conditions of high casual deviations, taking into account the formula (3.15), it is possible to write down that

$$\gamma_2(f_1^*) = \frac{\Delta r_f}{r_f} + \frac{\Delta\sigma_{f_1}}{\sigma_{f_1}} = \frac{\Delta r_f}{r_f} + \frac{\Delta\sigma_{\Delta f}}{\sigma_{f_1}} \tag{3.19}$$

In this case the 2-fold casual value f_1 and f_2 are made use of. Under conditions of big casual deviations at measuring a normal casual value the correlation rate between f_1 and f_2 is equal to r_f'. In the absence of casual deviations the rate of correlation link between initial casual values is defined by the value r_f. In conformity with the main rules of correlation analysis

$$r_f' = \frac{r_f}{1 + \frac{\sigma^2_{\Delta f}}{\sigma^2_{f_1^*}}} = r_f \frac{\sigma^2_{f_1^*}}{\sigma^2_{f_1}}$$

In this case at determining r_f the following value can be taken as an absolute correction:

$$\Delta r_f = r_f - r_f \frac{\sigma^2_{f_1^*}}{\sigma^2_{f_1}} = r_f(1 - r_f^2) \tag{3.20}$$

Using the last formula, the expression for $\gamma_2(f_1^*)$ gets the following form:

$$\gamma_2(f_1^*) = 1 - r_f^2 + \frac{3\cdot\sigma_{\Delta f}}{\sigma_{f_1}} \tag{3.21}$$

Confidence interval for relative correction of any keeper i

$$\Delta\sigma_{f_1^*} = \sigma_{f_1}(4 - r_f^2) \qquad (3.22)$$

The last expression is simplified by the conditions of equality

$$\sigma_{f_1} \text{ and } \sigma_{\Delta f} \qquad \sigma_{f_1} \text{ and } \sigma_{f_1^*}$$

Having made an analogous consideration for the correlation rate r_δ between values δ_1 and δ_2, we get the following conclusions of dispersion and correlation:

$$\Delta\sigma_{\delta_1^*} = 6\sigma_{\Delta\delta} \qquad (3.23)$$

$$\Delta\sigma_{\delta_1^*} = \sigma_{\delta_1}(4 - r_\delta^2) \qquad (3.24)$$

3.2.3 An example of using correlation analysis in electrical measurements

As a result of experiment the following data arrays were received:

$$\begin{vmatrix} 0.03\,\% \\ 0.03\,\% \\ 0.037\,\% \end{vmatrix} \quad \begin{vmatrix} -3.3\,\text{min} \\ -3.13\,\text{min} \\ -2.88\,\text{min} \end{vmatrix} - \text{for the first moment of time}$$

$$\left|0.0293\,\%,\ 0.0265\,\%,\ 0.0258\,\%\right| \quad \left|-3.2\ \text{min}, -2.48\ \text{min}, -2.87\ \text{min}\right| -$$

for the second moment of time

The average values of the relative and angular corrections of the keepers in accordance with each moment of time are equal:

$$\bar{f}_1 = 0.032\,\% \qquad \bar{f}_2 = 0.027\,\%$$

$$\bar{\delta}_1 = -3.1\,\text{min} \qquad \bar{\delta}_2 = -2.85\,\text{min}$$

The average quadratic deviations of the relative and angular corrections of the keepers in accordance with each moment of time:

$$\sigma_{f_1} = 0.0040\,\% \qquad \sigma_{f_2} = 0.0019\,\%$$

$$\sigma_{\delta_1} = 0.21\,\text{min} \qquad \sigma_{\delta_2} = 0.36\,\text{min}$$

Based on the formulas (3.11) and (3.12) the factors of correlation are found:

$$r_f = -0.93$$

$$r_\delta = 0.51$$

Based on the formulas (3.15) and (3.22) the corrected ratings of dispersion of the relative and angular corrections of the keepers with the appropriate confidence intervals are found

Finally,

$$\sigma^2_{f_1^*} = (0.0037\,\%)^2 \qquad \Delta\sigma_{f_1^*} = 0.013\,\%$$

$$\sigma^2_{\delta_1^*} = (0.11\,\mathrm{min})^2 \qquad \Delta\sigma_{\delta_1^*} = 0.11\,\mathrm{min}$$

3.3 Conclusions of Chapter 3

1. The received results allow us to draw a conclusion about the efficiency of applying the autocorrelation factor to determine rating dispersion especially at large casual deviations.
2. In Figures 1 and 2 the results of comparisons of the correlation analysis and dispersion analysis are brought

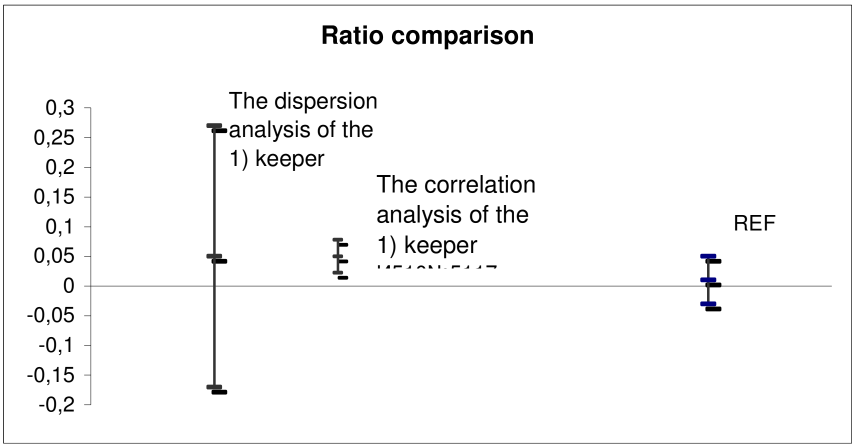

Figure 3.1 **Ratio comparison**

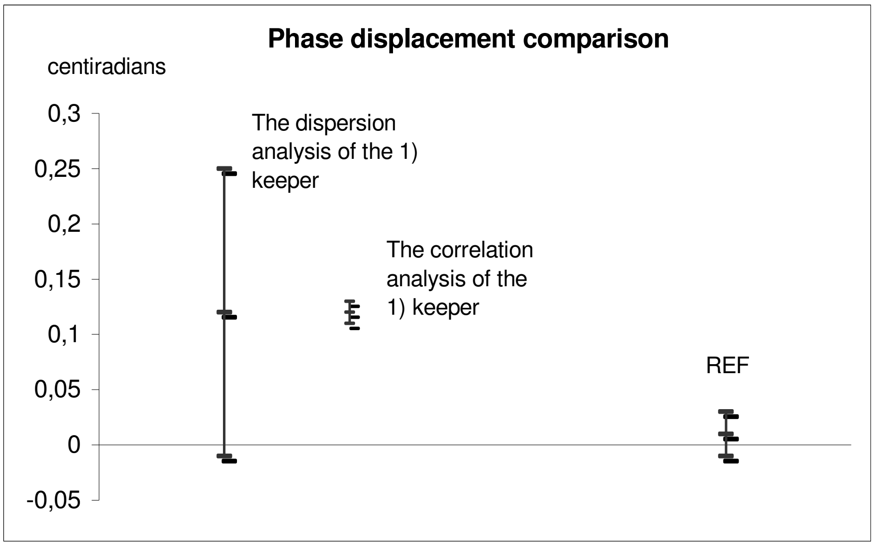

Figure 3.2 **Phase displacement comparison**

4 RESEARCH ON THE EFFECT OF CORRELATION AT THE MEASUREMENT OF ALTERNATING VOLTAGE

4.1 The concept of alternating voltage measurement

The AC voltage is defined by the root-mean square value of the sinusoidal waveform

$$U_{rms} = \sqrt{\frac{1}{T}\int_{0}^{T} U(t)^{2}\,dt} \tag{4.1}$$

According to the definition, it is possible to compare AC voltage with DC voltage through the heat produced. In the thermal method, DC and AC voltage are alternately applied to the heater of a thermal converter. Then the amounts of joule heating are compared by measuring the temperature of the heater with a thermocouple. When DC and AC voltages of equal power are applied to the input of an ideal thermal converter, output emf's should be the same for both of the inputs. However, in the case of an actual thermal converter, the output emf's are influenced by the effect of non-joule heating and frequency characteristic of heater circuit. The "AC–DC Transfer difference" is defined by the equation (Hitoshi Sasaki, Kunihiko Takahashi. 1999) [17]

$$\delta = \frac{U_{0\approx} - U_{0\equiv}}{U_{0\equiv}}\bigg|_{U_{x\approx}=U_{x\equiv}} \tag{4.2}$$

The standard AC–voltage is defined by the rms. value of the amplitude of alternating waveform. For the realization of the AC–voltage standard, the thermal AC–DC Transfer Standard has been used as the most precise way in the audio frequency range. In the fast–reversed DC method, the AC quantity and the DC quantity are alternately applied to a thermal voltage converter. The AC–voltage is derived by the DC–voltage standard. The method of comparison of AC and DC quantity by the use of AC–DC Transfers is shown in Figure 4.1.

In Figure 4.1 direct synthesizing of AC sinewave by the use of high-precision digital/analog converter is shown and comparison of electric power between AC- and DC-voltage by converting the power to heat. In the latter case, converters may be recognized as a reference standard.

This chapter describes a technique of measuring alternating voltage. The described methods are based on calibrating the AC digital voltmeter through the AC–DC difference of thermal converter. The calibrated voltmeter can then be used to measure AC voltage.

In this chapter the methods of estimation of alternating voltage which allow to make the result of measurements more precise in case of unequally exact and the correlated results of observations are considered.

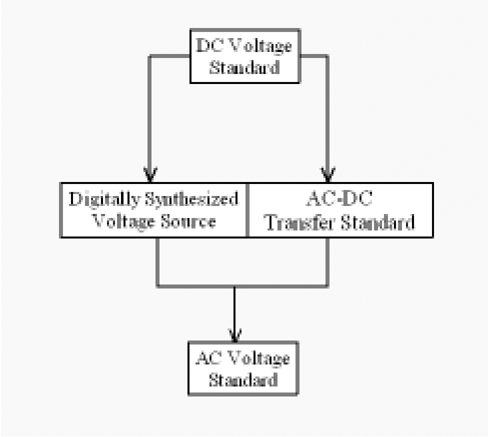

Figure 4.1. **The methods to derive AC voltage standard from the DC voltage standard.**
Method 1: Direct synthesizing of sinewave by high-precision D/A converter.
Method 2: Comparison of AC and DC quantity by the use of AC–DC transfers standards.

4.2 An overview of calibration of an alternating voltage source

The use and calibration of the AC–DC Transfer Standards, meant for AC measurement, has been made easier those last years by the exploitation of the models FLUKE 792 A and 5790 A.

In principle, the alternating voltage is determined by sequentially and reiteratively applying it and a known DC voltage to the resistive input of thermal voltage converter (TVC). The DC voltage is adjusted until the TVC's output voltage is unchanged when the input is switched between the DC and AC voltages. When this condition is met, the traceable value of the known DC voltage at the input is transferred to the AC voltage.

The two most widely-used types of thermal voltage converter are the solid-state true rms. sensor and the single-element vacuum thermocouple converter (SEVTC). The multijunction thermocouple (MJTC) and the log/antilog converter are less widely used in AC–DC Transfer devices. The MJTC is a thermal converter, while the log/antilog converter is not. Instead, it uses operational amplifiers and transistors.

A solid-state thermal converter was introduced by FLUKE in the early 1970s. In comparison to vacuum thermocouple-based transfer standards, FLUKE rms. sensor-based standards are easier to use, have a greater number of self-contained voltage ranges, and allow the completion of transfers at higher voltages in a minute or less on all ranges. The 5790 A is a completely self-contained microprocessor-controller, automated AC measurement standard. Its operator push button selects its mode of operation to make AC voltage measurements, AC–DC voltage transfers, and various current measurements. It can be computer controlled via the IEEE–488 bus or an RS 232 data link. The 5790 A will automatically scale the voltage and compare it to an internally-generated DC reference voltage. This mode of operation is very accurate and requires no operator intervention to accomplish the measurement. In its voltage transfer mode, the operator connects the AC and DC sources to its inputs. The operator needs only to reverse the polarity of the applied DC when making the transfers. The 5790 A automatically computes and uses the average value of the forward and reversed DC during the transfer. FLUKE 792 A reduces the time required to make highly accurate, manual AC–DC transfers. The improvement in performance is obtained by use of the Fluke rms. sensor and Fluke thin-film resistors, and by placing the high voltage input resistor in close thermal contact with an efficient heat sink. In comparison to the single-element vacuum thermocouples, this converter has a number of advantages. These include the fact that its output voltage at full input is about 2 V instead of the 7 mV or so obtained from a vacuum thermal converter. As it was mentioned above the solid-state true rms. sensor is used in the FLUKE 792 A and 5790 A. This device uses two transistors and a diffused resistor fabricated on a single monolithic chip (Inglis, B. D. 1992) [1]. Assemblage as a differential amplifier allows to converting alternating voltage to the direct voltage (Fig. 4.2). When the measured alternating voltage U_{rms} is applied to resistor R_1 circuit, the heat emitted on it according to Joule effect heats the transistor T_1 emitter-base junction. The growing collector current of this transistor brings the differential amplifier in the condition of detuning that results in a loss of voltage on the resistor R_2. The heat emitted in this resistor heats emitter-base junction of transistor T_2, returning the amplifier into the condition of re-established equilibrium. As soon as the equilibrium condition is achieved, the direct voltage of the output U_{out} theoretically would be equal to current value of voltage U_{rms}.

The “Laboratoire Central des Industries Electriques” and BNM associated laboratory developed an automatic system to calibrate AC–DC Transfer Standards. AC–DC Transfer Standards are calibrated by Null method, circuit of which can be seen in Figure 4.3. Difference of potentials of alternating voltage is delivered in a parallel way to the two transfer thermals. The resistance divider $K2$ is fixed to approximate rapport of 0.95 and the resistance divider $K1$ is adjusted to obtain zero reading of nanovoltmeter $U_{d\approx} = 0$. The effective value of applied alternating voltage corresponds to an indicated value of voltmeter $U_{x\approx}$ and nanovoltmeter $U_{d\approx}$.

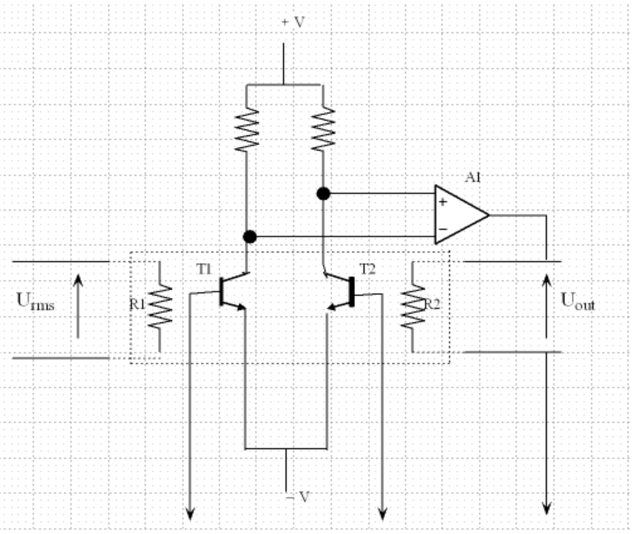

Figure 4.2 **Basic RMS Sensor**

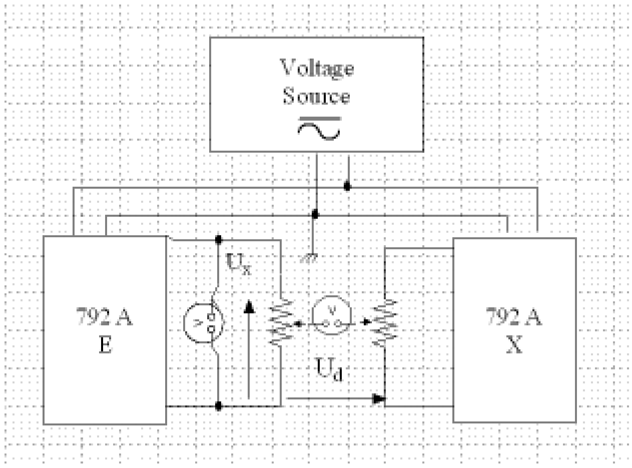

Figure 4.3 **Measurement setup for calibrating the thermal voltage converter FLUKE 792 A**

Without changing the position of the dividers $K1$ and $K2$, two transfer thermal circuits are applied, in a parallel way, a positive direct voltage whose value is approximately equal to the effective value of alternating voltage applied before. Indicated values of voltmeter $U^{+}_{x\equiv}$ and $U^{+}_{d\equiv}$ are stored. The same operations are repeated with the reverse direct voltage and the values of voltmeters $U^{-}_{x\equiv}$ and $U^{-}_{d\equiv}$ are stored. The value of the traceable deviation is calculated as follows (Blanc, I., Manceau, J. 2003) [18]:

$$\delta = \frac{2 \cdot U_{x\approx}}{U_{x\equiv}^{+} + U_{x\equiv}^{-}} - \frac{2 \cdot (K_1 \cdot U_{x\approx} - U_{d\approx})}{K_1 (U_{x\equiv}^{+} + U_{x\equiv}^{-}) - (U_{d\equiv}^{+} + U_{d\equiv}^{-})} + \delta_E \tag{4.3}$$

where

δ – the value of the traceable deviation of the Test Transfer Standard,
δ_E – the value of the traceable deviation of the Standard Transfer Standard

Definition of the value of traceable deviation by the above-stated formula is not complete as it doesn’t give the full report of uncertainty of the obtained result. It is difficult to evaluate the uncertainty of equality of current value of alternating voltage and static voltage applied to two transfer thermal circuits. The estimates of covariations and correlation coefficients for all correlated input quantities are not indicated. It is not proved that the number of input quantities is optimal. The “Laboratoire Central des Industries Electriques” and BNM associated laboratory have good technical recourses that help them to obtain good results of etalon calibration.

During the FLUKE 792 A AC–DC Transfer Standards calibration

nanovoltmeter of the KEITHLEY 2182
AC and DC sources FLUKE 5700

were made use of.

Considering the observations pointed out above, the uncertainty of the calibration of AC–DC Transfer Standards FLUKE 792 A with the use of high-precision technical equipment may prove to be less than the values in Table 1.

Table 1. Complete result of δ calculation of the Test Transfer Standard FLUKE 792 A

Voltage of a measurement	Frequency of measurement	
	40 Hz	1 kHz
1 V	$9 \cdot 10^{-6}$	$9 \cdot 10^{-6}$
2 V	$5 \cdot 10^{-6}$	$5 \cdot 10^{-6}$
3 V	$5 \cdot 10^{-6}$	$5 \cdot 10^{-6}$
5 V	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$
10 V	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$

At the “Laboratoire Central des Industries Electriques” and BNM associated laboratory the high-precision thermal transfer standard of the alternative/direct current was used for calibrating the precision transfer thermal FLUKE 5790 A. The principle of calibration is based on the method, whose circuit can be seen in Fig. 4.4.

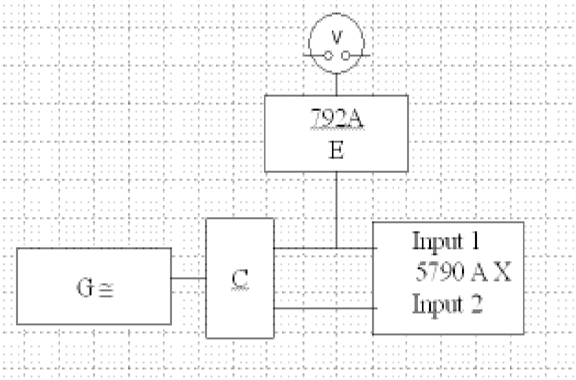

Figure 4.4 **Measurement setup for calibrating the thermal voltage converter FLUKE 792 A**

Initially alternating voltage will be given in parallel to two transfer thermals. Indicated values of voltmeter and FLUKE 5790 A, in conformity with $U_{E\,x\approx}$ and $U_{x\approx}$, are written at active entrance "Input 1" of FLUKE 5790 A. At active entrance "Input 2" of FLUKE 5790 A direct voltage is applied to the circuit of the transfer thermal FLUKE 792 A, and it is regulated to the value $U^{+}_{E\,0\equiv}$, in conformity with the value of alternating voltage $U_{E\,x\approx}$, previously recorded. An analogous operation is conducted with the reverse DC voltage $U^{=}_{E\,0\equiv}$. The entrance "Input 2" of FLUKE 5790 A is switched by the switchboard C to the circuit of the positive direct voltage DC Source. After them a direct voltage is adjusted to the value $U^{+}_{0\equiv}$, corresponding to the value of the previously recorded alternating voltage $U_{x\approx}$. The same operations are repeated with the reverse direct voltage $U^{=}_{0\equiv}$. The value of a traceable deviation is calculated by the formula

$$\delta = \frac{\left|U^{+}_{E\,0\equiv}\right| - \left|U^{+}_{0\equiv}\right| + \left|U^{-}_{E\,0\equiv}\right| - \left|U^{-}_{0\equiv}\right|}{\left|U^{+}_{0\equiv}\right| + \left|U^{-}_{0\equiv}\right|} + \delta_E \qquad (4.4)$$

where

δ – the value of the traceable deviation of the Test Transfer Standard,
δ_E – the value of the traceable deviation of the Standard Transfer Standard

The calculation formula is not complete. The dependence of a traceable deviation on the equality of initial AC voltages U_{ea} and U_{xa} with the AC voltages, appropriate to DC voltages is not clear. The mutability of calibration conditions of the Test Transfer Standard is not taken into account.

The absence of correlation between the quantities at calibration of the Test Transfer Standard has not been proved. To achieve the best possible accuracy at calibration of the Test Transfer Standard FLUKE 5790 A, the metrologists should have considered the above-stated observations. The values of the traceable deviation of the Test Transfer Standard δ_x (Table 2) can approach the result of calibration in the laboratory LNM.

Table 2. Complete result of calculation of δ of the Test Transfer Standard FLUKE 5790 A

Voltage of a measurement	Frequency of measurement	
	40 Hz	1 kHz
1 V	$3 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$
2 V	$3 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$
3 V	$3 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$
5 V	$3 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$
10 V	$3 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$

Lately, a high-precision thermal transfer AC/DC standard has been used for calibration of AC generators. The measurement setup proposed by the Slovenian Institute of Quality and Metrology is shown in Fig. 4.5 (Blanc, I., Manceau, J. 2003) [18]. This measurement setup is for calibrating the DMM at the selected voltage-frequency points, at which the TVCs AC–DC voltage difference is well characterised. To achieve the best possible accuracy by measuring AC voltage with DMM, the DMM should first be calibrated. Actually AC voltage is compared to DC voltage, which can be measured with much lower uncertainties. When the switch is connected to the AC voltage source, the AC voltage is measured with DMM at the mid point of the T junction with the thermal converter. At that point, the difference between AC and DC voltage is well defined by measuring the AC–DC voltage difference with the thermal converter. When the switch is connected to the DC voltage source, the DC voltage measured with DMM and thus the AC voltage at the mid point of the T junction can be absolutely defined. The measurement of DC voltage can actually be done only at the beginning of the measurement, but with TVC as the main load connected to the measurement circuitry. In Fig. 4.6 a circuitry for calibrating the AC generator at voltage-frequency points for technique of measuring alternating voltage with digital multimeter is shown. Measurement setup for measuring the AC voltage of the AC generator is straightforward. The corrections of DMM, which were evaluated in the calibration of DMM, are now applied to the reading of the DMM. The proposals of the paper (Lapuh, R., Svetik, Z. 1997) [19] are not confirmed by calculations. In the present thesis it is stated that various uncertainty components enter the proposed measurement method.

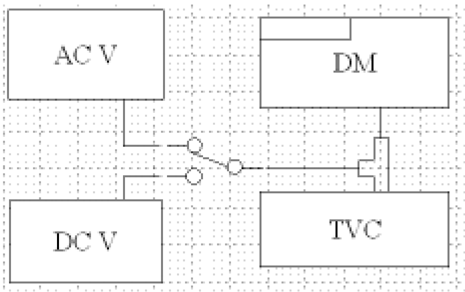

Figure 4.5 **Measurement setup for calibrating the DMM at the selected voltage-frequency points, at which the TVCs AC–DC voltage difference is well characterised**

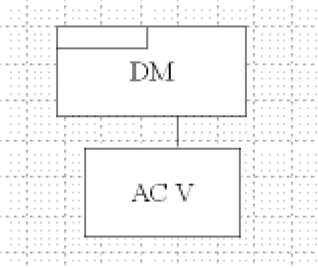

Figure 4.6 **Measurement setup for calibrating the AC generator at voltage-frequency points, at which the DMM was calibrated**

The list of the mentioned parameters is not complete. If we confine ourselves to the mentioned parameters, then it should be proved that precisely their contribution to the total uncertainty budget is the greatest. At the calibration of DMM it is expedient to apply the principle of parametric lowering of dimensionality.

Investigating Fluke 792 A as a Transfer Standard of voltage unit is included into the plan of creating a voltage reference standard with the frequency range from 10 Hz to 1 MHz in Estonia. The first stage in the creation of the alternating voltage standard requires an implementation of a new method in uncertainty calculation on the measurement model with standard in case of results with unequal accuracy and correlation. For successful implementation of the new method it is necessary to use methods of multidimensional mathematical statistics, that allow us to take into account the changing measurement conditions and noise level of measurement devices without using an unknown functional dependence of the measured value on all conditions mentioned. Adapting the multidimensional mathematical statistics methods to the measurement methods during creation of etalon complex would decrease the estimate of output voltage instability. The developed method would allow us to define the values of the components of combined uncertainty of measurement results.

4.3 The research on the effect of correlation at the measurement of alternating voltage

At definition of estimations of any output quantity it is impossible to confirm with confidence, that the narrowness of dependence of input quantity can be neglected. Therefore in practice it is necessary to estimate any investigated dependence on sampling data, using such methods of estimations of statistics, which would characterize the covariation of the dependent quantity. If linear dependence is investigated the narrowness of dependence between input quantities needs to be estimated by means of selective correlation coefficient**.** It is impossible to confirm that dependence is linear dealing with a small volume of sample of initial data. At deficiency of initial data the functional dependence of input quantity can be a monotonic nonlinear. Besides that, for comparison of results of the measurements executed at different time, it is expedient to apply the criterion of uniformity of several correlation coefficients. In the measuring practice metrologists often state, that the correlation coefficients can be neglected and that perfect conditions of measurements are kept in the laboratory, and that the etalons possess ideal linear characteristics.

Using of the Null Method (Inglis, B. D. 1992) [1] at measurement of an alternating voltage (rms. AC source of a voltage} relies on linearity of a source of direct voltage (DC source of a voltage) with the best characteristics, than Fluke 792 A AC–DC transfer standard and AC source of a voltage. Linearity of a transfer standard of a unit of voltage and linearity of a DC source of a voltage need to be checked up. Besides, as conditions in measuring laboratories are different, Null Method of measurement rms. AC source of a voltage cannot be considered universal. In this article, developed by the author, a variant of covariance calculation system is presented, which leads to the precise results of the measurements and is based on

- the least-squares method
- criteria of uniformity of several correlation coefficient
- "expert-statistical" method

Use of the above methods has allowed to increase the reliability of the results of alternating current voltage measurements.

4.3.1 Least-squares method

Doubts in the linearity of a DC source of voltage and Fluke 792 A AC–DC transfer standard can be dissipated by means of the least-squares method. It is expedient to check up the efficiency of this method in the experiment with an unknown alternating voltage source (AC Voltage Source). AC and DC voltages are compared, using Fluke 792 A. The suitable limit of measurement of 792 A is chosen. An unknown AC voltage of known frequency, for example 50 Hz, is fed on the input of the transfer standard 792 A. DMM multimeter indication is stabilized and recorded. The forward and reverse DC voltages, which correspond to the level of AC voltage, are consistently fed to the input of the 792 A etalon. Values of DC voltage are adjusted up to the value corresponding DMM indication, written down at alternating voltage. These values are fixed. The average value of DMM indication corresponding to the forward and reverse DC voltage is determined. DMM indications at the alternating and the average direct voltage on the input of Fluke 792 A are recorded. Similar measurements are carried out on each limit of measurement in an interval from 1V up to 10V within five days.

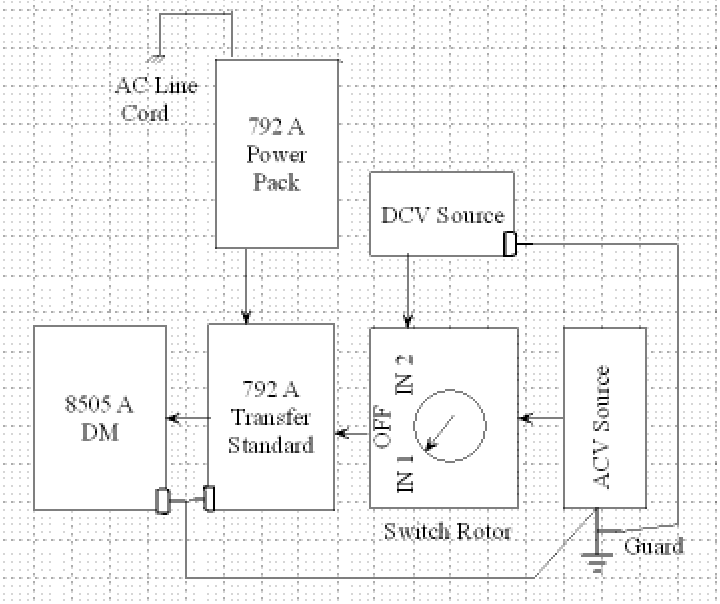

Figure 4.7 **Calibrating an AC Voltage Source**

The linearity between input voltage values $(U_{0\approx}, U_{0\equiv})$ and approximately equal output voltage values $(U_{x\approx}, U_{x\equiv})$ is restored by definition of unknown values of parameters of regression (Hitoshi Sasaki, Kunihiko Takahashi. 1999; Aleksakhin, S. V., Baldin, A. V., Nikolaev, A. B., Stroganov, V. 2001) [17, 14].

$$\begin{aligned} U_{x\approx} &= a_{\approx} + \frac{dU_{x\approx}}{dU_{0\approx}} U_{0\approx} \\ U_{x\equiv} &= a_{\equiv} + \frac{dU_{x\equiv}}{dU_{0\equiv}} U_{0\equiv} \end{aligned} \tag{4.5}$$

The problem of an optimum choice of parameters of regression is put as follows:

$$L = \sum_{i=1}^{n} (U_{xi} - a - \frac{dU_x}{dU_0} U_{0i})^2 \to \min \tag{4.6}$$

The simple solution of minimization problem leads to the following system of equations:

$$a = \frac{\sum_{i=1}^{n} U_{xi} - \frac{dU_x}{dU_0} \sum_{i=1}^{n} U_{oi}}{n} = \overline{U}_x - \frac{dU_x}{dU_0} \overline{U}_0$$

$$\frac{dU_x}{dU_0} = \frac{\sum_{i=1}^{n} (U_{0i} - \overline{U}_0)(U_{xi} - \overline{U}_x)}{\sum_{i=1}^{n} (U_{0i} - \overline{U}_0)^2} \tag{4.7}$$

where $(\overline{U}_x, \overline{U}_0)$ – average sizes of corresponding values.

Parameters of regression $(a, \frac{dU_x}{dU_0})$ completely define the position of a straight line on a coordinate plane. The choice of a dependent and independent variable essentially affects parameters of a straight line. We shall consider two direct regressions:

$$U_0 = a^0 + (\frac{dU_0}{dU_x})^0 U_x$$

$$U_x = a^x + (\frac{dU_x}{dU_0})^x U_0 \tag{4.8}$$

Generally the factors of regression are connected by the equations

$$a^0 = -a^x \frac{dU_0}{dU_x}$$

$$(\frac{dU_0}{dU_x})^0 (\frac{dU_x}{dU_0})^x = r^2 \tag{4.9}$$

$$\sqrt{(\frac{dU_0}{dU_x})^0 (\frac{dU_x}{dU_0})^x} = r \tag{4.10}$$

If the above-stated direct regressions are identical, the correlation coefficient is equal to unity. We shall define the estimates of variances:

$$s^2\left[(\frac{dU_x}{dU_0})^x\right] = \frac{\sum_{i=1}^{n} (U_{xi} - a^x - (\frac{dU_x}{dU_0})^x U_{0i})^2}{(n-2) \sum_{i=1}^{n} (U_{0i} - \overline{U}_0)^2}$$

$$s^2\left[(\frac{dU_0}{dU_x})^0\right] = \frac{\sum_{i=1}^{n} (U_{0i} - a^0 - (\frac{dU_0}{dU_x})^0 U_{xi})^2}{(n-2) \sum_{i=1}^{n} (U_{xi} - \overline{U}_x)^2} \tag{4.11}$$

$$s^2\left[r\right]=\frac{1}{4}\left[\begin{array}{l} s^2\left[(\frac{dU_0}{dU_x})^0\right](\frac{dU_x}{dU_0})^x/(\frac{dU_0}{dU_x})^0+ \\ +s^2\left[(\frac{dU_x}{dU_0})^x\right](\frac{dU_0}{dU_x})^0/(\frac{dU_x}{dU_0})^x \end{array}\right] \tag{4.12}$$

By a simple simplification Equation (4.12) is led to relation (4.13)

$$s^2\left[r\right]=\frac{1}{4}\left(\frac{\sum_{i=1}^{n}(U_{xi}-a^x-(\frac{dU_x}{dU_0})^x U_{0i})^2}{(n-2)\sum_{i=1}^{n}(U_{xi}-\overline{U}_x)^2}+\frac{\sum_{i=1}^{n}(U_{0i}-a^0-(\frac{dU_0}{dU_x})^0 U_{xi})^2}{(n-2)\sum_{i=1}^{n}(U_{0i}-\overline{U}_0)^2}\right) \tag{4.13}$$

The less the size of estimations of variances, the more adequate the model is.

On the basis of the experimental data received by means of the transfer standard of unity of the voltage Fluke 792 A, the difference between voltage of alternating and direct current Δ' is calculated using the least–squares method. It is expedient to compare the received values with apparent error Δ of the AC voltage source. Results of such comparison, proceeding from experimental data of one day of measurements are presented in Table 1 and in Fig. 4.8.

Table 1. Complete result of calculation of Δ and Δ'

i V	$U_{x\approx}$ V	$U_{0\approx}$ V	$U_{x\equiv}$ V	$U_{0\equiv}$ V	$\Delta=\frac{U_{0\approx}-U_{0\equiv}}{U_{0\equiv}}$ $\times\ 10^{-6}$	$\Delta'=\frac{U'_{0\approx}-U'_{0\equiv}}{U'_{0\equiv}}$ $\times\ 10^{-6}$
1	0.91272248	10	0.91272226	9.999710	29	23
2	0.82148018	9	0.82147801	8.999700	33	25
3	0.73022863	8	0.73022799	7.999750	31	24
4	0.63898620	7	0.63898690	7.000200	29	22
5	0.54769387	6	0.54769273	5.999791	35	26
6	0.45641487	5	0.45641467	4.999860	28	25
7	0.36509764	4	0.36509701	3.999830	43	28
8	0.27380322	3	0.27380349	2.999890	37	27
9	0.18248528	2	0.18248517	1.999900	50	33
10	0.09111343	1	0.09111147	0.999960	40	65
$(U_{0\approx})_{i1}=89\cdot10^{-5}+10.95\,(U'_{x\approx})_{i1}$ $(U_{x\approx})_{i1}=-8.1\cdot10^{-5}+0.091(U'_{0\approx})_{i1}$ $r=0.998$				$(U_{0\equiv})_{i1}=87\cdot10^{-5}+10.95(U'_{x\equiv})_{i1}$ $(U_{x\equiv})_{i1}=-7.9\cdot10^{-5}+0.091(U'_{0\equiv})_{i1}$ $r=0.998$		

The apparent error of the AC voltage source (Fig. 4.8) has proved to be larger than a relative difference between voltages of alternating and direct current Δ' calculated with the least-squares method. This fact testifies to the expediency of using the least-squares method at calibration of the alternating voltage source.

4.3.2 Criterion of uniformity of several correlation coefficients

The conclusion about expediency of application of the least–squares method at calibration of alternating voltage is made on the basis of experimental data of one day of measurements. For statistical check of the above-mentioned conclusion "the criterion of uniformity of two or several selective correlation coefficient"(Aivazian, S. A., et al. 1988) [2] with use of Fisher's distribution is applied. Proceeding from results of the measurements of a relative difference Δ' (Fig. 4.9) fulfilled within five days, it is possible to regard the distinction in values of selective correlation coefficient $r(U_{x\approx}, U_{x\equiv})$ as statistically insignificant. Really, dependence between two estimates of values $U_{x\approx}$ and $U_{x\equiv}$ is characterized by the correlation coefficient

$$r(U_{x\approx}, U_{x\equiv}) = \frac{u(U_{x\approx}, U_{x\equiv})}{u(U_{x\approx}) \cdot u(U_{x\equiv})} \tag{4.14}$$

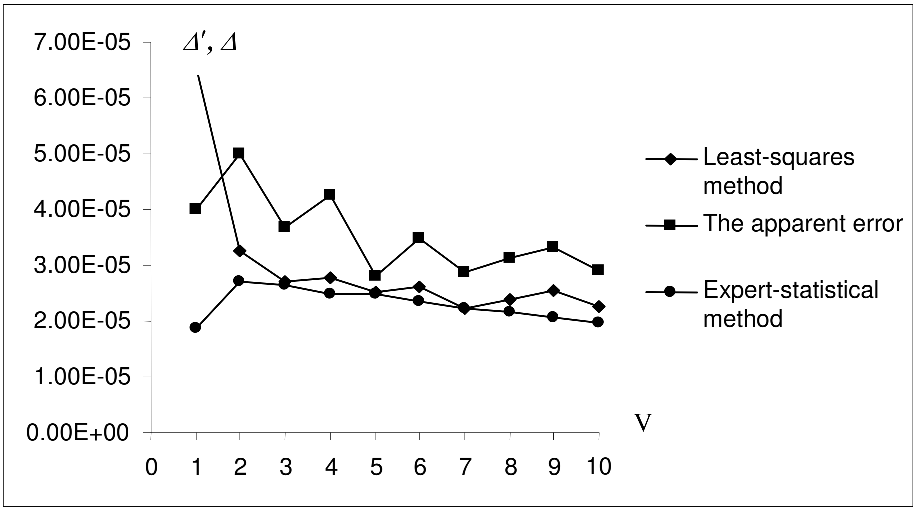

Figure 4.8 **Complete result of calculation of Δ and Δ' from experimental data of one day of measurements**

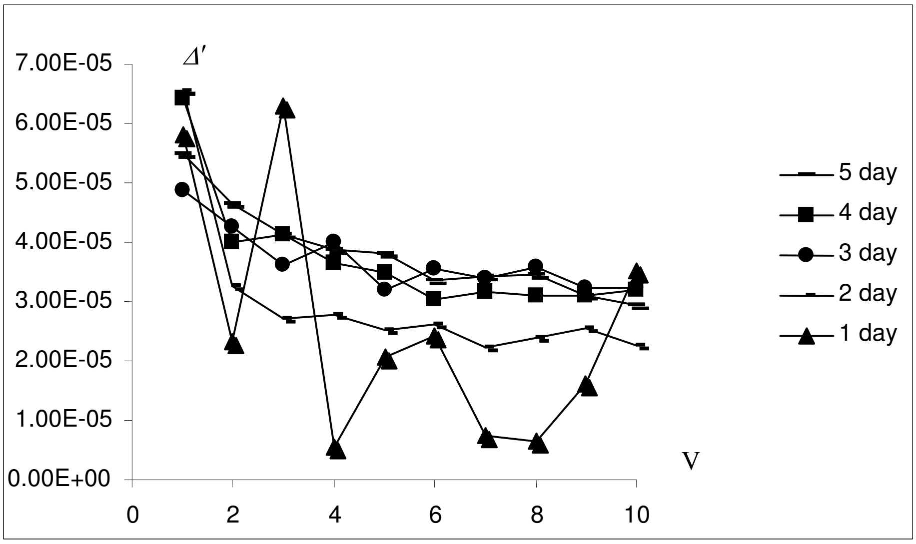

Figure 4.9 **Complete result of calculation of Δ' with the least-squares method from experimental data of five days of measurements**

For the chosen limit of measurement under the formula (4.14) the correlation coefficient $r_j (j = \overline{1 \ldots 5})$ on samples of volumes n_j are determined. Use of r_j' – the transformed value r_j – is more preferable at checking the importance of correlation dependence, when the number of measurements n_j is small. By means of R. Fisher's transform the above-stated estimates of selective correlation coefficient according to five days of measurements were determined.

$$r_j'(U_{x\approx}, U_{x\equiv}) = \operatorname{arcth} r_j(U_{x\approx}, U_{x\equiv}) = \frac{1}{2} ln \frac{1 + r_j(U_{x\approx}, U_{x\equiv})}{1 - r_j(U_{x\approx}, U_{x\equiv})} \qquad (4.15)$$

As the best estimate of correlation coefficient the value

$$r' = \frac{\sum\limits_{j=1}^{5} (n_j - 3) \operatorname{arcth} r_j}{\sum\limits_{j=1}^{5} (n_j - 3)} \qquad (4.16)$$

was used.

To check the hypothesis about the absence of distinctions in initial data (at definition of a relative difference Δ'), the sum was calculated

$$\overline{\chi}^2 = \sum_{j=1}^{5}(n_j-3)\,\mathrm{arcth}^2\, r_j - \frac{\left[\sum_{i=1}^{5}(n_j-3)\,\mathrm{arcth}\, r_j\right]^2}{\sum_{i=1}^{5}(n_j-3)} \tag{4.17}$$

In Table 2 the course of calculations of the sum (4.17) is presented

Table 2. Complete result of calculation of $\overline{\chi}^2$

Day j	n_j	r_j	r'_j	n_j-3	$(n_j-3)\cdot r'_j$	$(n_j-3)\cdot(r'_j)^2$
1	10	−0.5768021	−0.6576571	7	−4.6035997	3.02759001
2	10	0.4699071	0.5099511	7	3.5696577	1.82035090
3	10	−0.4120857	−0.4381209	7	−3.0668465	1.34364963
4	10	0.1319427	0.1327164	7	0.9290150	0.12329556
5	10	−0.0757765	−0.0759220	7	−0.5314543	0.04034909
$\overline{\chi}^2 = 5.96$				35	3.7032277	6.3552352

As the sum (4.17) has appeared less than the critical value χ^2, determined on the table of corresponding distribution, at any confidence probability *P* and number of degrees of freedom *j*=4 with reliability *P* it is possible to consider, that initial data of five days of measurements are statistically homogeneous.

4.3.3 Expert-statistical method

The general number of the parameters influencing the investigated value of an alternating voltage is large. If these parameters are registered on every i-limit of measurement the multivariate measurements will turn out. It is necessary to subject these available multivariate measurements to statistical processing for reception of more reliable objective function.

$$\begin{aligned} U'_{0\approx} &= f(U_{x\approx}, U_{x\equiv}, U_{0\approx}, U_{0\equiv}) = \\ &= \alpha + \beta_1 U_{x\approx} + \beta_2 U_{x\equiv} + \beta_3 U_{0\approx} + \beta_4 U_{0\equiv} \end{aligned} \tag{4.18}$$

The "expert–statistical" method (Aivazian, S. A., et al. 1988; Barashkova T., Laaneots, R. 2005) [2, 20] has made it possible to receive the best estimation of value of an alternating voltage of 50 Hz frequency, dependent on the correlated input quantities.

1. Statistical part of initial data. As it was already mentioned above, input variables $U_{x\approx}, U_{x\equiv}, U_{0\approx}, U_{0\equiv}$ were measured on each i-limit of measurement

every j-day of experiment. Therefore the statistical part of initial data is represented in the form of

$$\boldsymbol{X}^{j}=\begin{pmatrix} U_{x\approx}^{1}, U_{x\approx}^{2}, \ldots, U_{x\approx}^{i} \\ U_{x\equiv}^{1}, U_{x\equiv}^{2}, \ldots, U_{x\equiv}^{i} \\ U_{0\cong}^{1}, U_{0\cong}^{2}, \ldots, U_{0\cong}^{i} \\ U_{0\equiv}^{1}, U_{0\equiv}^{2}, \ldots, U_{0\equiv}^{i} \end{pmatrix} \tag{4.19}$$

2. Expert part of initial data concerns the data on the estimations $U'_{0\approx}$, received after corresponding statistical processing of "expert" data (Table 1). Data about $U'_{0\approx}$ are represented in the form of

$$\boldsymbol{Y}_{ij}=\begin{pmatrix} (\boldsymbol{U}'_{0\approx})_{11}, (\boldsymbol{U}'_{0\approx})_{21}, \ldots, (\boldsymbol{U}'_{0\approx})_{i1} \\ (\boldsymbol{U}'_{0\approx})_{12}, (\boldsymbol{U}'_{0\approx})_{22}, \ldots, (\boldsymbol{U}'_{0\approx})_{i2} \\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots \\ (\boldsymbol{U}'_{0\approx})_{1j}, (\boldsymbol{U}'_{0\approx})_{2j}, \ldots, (\boldsymbol{U}'_{0\approx})_{ij} \end{pmatrix} \tag{4.20}$$

where

$(U'_{0\approx})_{ij}$ – the expert estimate of a alternating voltage, received in a frequency range 50 Hz on i-limit of measurement in j-day of experiment.

3. Estimation of unknown parameters of criterion function is reduced to the usual scheme of the regression analysis. The criterion of the least-squares method (Aivazian, S. A., et al. 1988) [2] assesses the parameters of objective function as the solving of optimization problems of a kind:

$$\sum_{j=1}^{5}\sum_{i=1}^{10}\frac{1}{\sigma_{ij}^{2}}\left[(U'_{0\approx})_{ij}-f(U_{x\approx}, U_{x\equiv}, U_{0\approx}, U_{0\equiv})\right]^{2}\rightarrow \min \tag{4.21}$$

where

σ_{ij} characterizes the uncertainty of an estimation of result on i-limit of measurement on j-day of experiment.

The optimization problems solution (4.21) looks as follows

$$\begin{aligned} U'_{0\approx} &= 3{,}17\cdot 10^{-5}+0{,}092794403\cdot U_{x\approx}-0{,}092794692\cdot U_{x\equiv}+ \\ &+6{,}67365\cdot 10^{-7}\cdot U_{0\approx}+0{,}983076135\cdot U_{0\equiv} \end{aligned} \tag{4.22}$$

The received functional dependence made it possible to determine the contribution of each input quantity to uncertainty of an alternating voltage estimation that, in turn, led to the improvement of the model of measurement (Fig. 4.10).

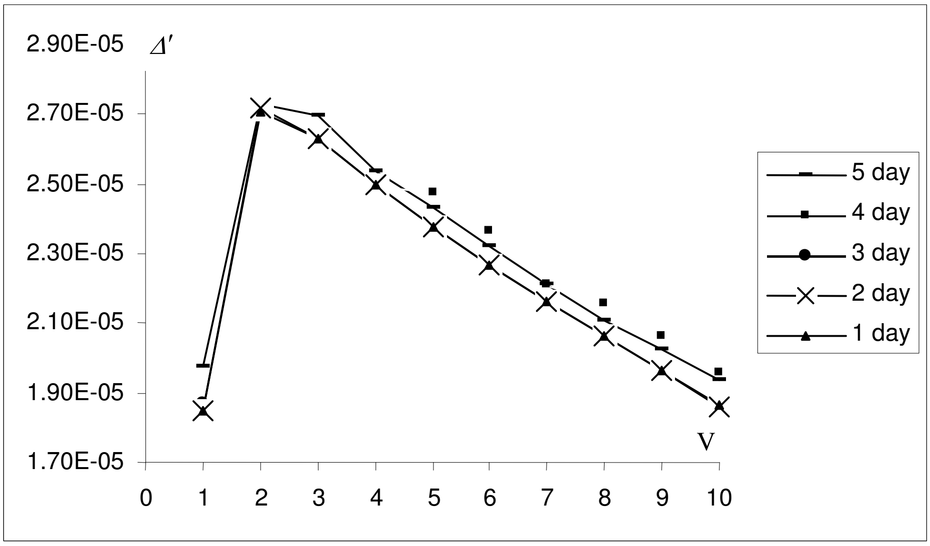

Figure 4.10 **Complete result of calculation of Δ' with the "expert-statistical" method from experimental data of five days of measurements**

4.4 Conclusions of Chapter 4

The presented variant of system of alternating voltage calculation allows to create in Estonia the reference standard of alternating voltage from 100 mV up to 1000 V within the limits of frequencies from 10 Hz up to 1 MHz on the basis of the transfer standard of unity of voltage Fluke 792 A. The fulfilled experimental researches of this etalon and results of the international checking have shown, that the reference standard can create an alternating voltage, for example, from 1 V up to 10 V with the relative expanded uncertainty from $17 \cdot 10^{-6}$ up to $28 \cdot 10^{-6}$.

CONCLUSIONS

Many metrology laboratories experience difficulties when implementing in practice the documents on calculation of uncertainty. For the measurement results to be approved it is necessary to bring the metrological characteristics of standards in line with international requirements, to deliver the uncertainty budget. The electrical laboratory of Viru Energia calibrates voltage and current measuring transformers. Therefore, a proposal was made to the laboratory to establish a group working standard of alternating voltage with a full list of metrological characteristics. The group working standard was made from three transformers with equal rated transformation ratios and one reference standard. The transformation ratio of the reference standard was two times higher than that of the other transformers within the group working standard. During implementation of the comparison of pairs technique, the secondary coils of the compared transformers were connected in opposition (subtractive polarity) through a voltage divider. The primary coils of the transformers with equal rated transformation ratios were connected in series with each other and in parallel with the primary coil of the reference standard. A new method was proposed for evaluation of the relative deviation of the scale factor and phase displacement of the secondary voltage of the calibrated standard with respect to the secondary voltage of the reference standard with the use of the group working standard parameters drift forecast method.

The following stage of the project targeted the uncertainty budget of the established group working standard and comparing it with the Finnish standard. When determining the expanded uncertainty of the scale factor during calibration of the voltage transformer, both the contact resistance voltage and the temperature gradient were taken into account. The expanded uncertainty of the relative deviation of the scale factor during calibration of the voltage transformer in the laboratory of Viru Energia AS, Kohtla-Järve, proved to be at the same level as the results of calibration in the National Standards Laboratory, Helsinki. The quantitative characteristics of the expanded uncertainty of the phase displacement of secondary voltage of the calibrated standard relative to the secondary voltage of the reference standard did not reach the level of the Finnish ones.

At the next stage, the influence of large random deviations on the coefficient of correlation between related measurands was studied. When the correlation was taken into account, the quantitative characteristics of the expanded uncertainty of the scale factor and phase displacement of the secondary voltage of the calibrated standard with respect to the secondary voltage of the reference standard were obtained, which were better than the Finnish ones. It can be stated that the correlation is necessary to be taken into account.

The proposed calibration method for measuring thermoelectric voltage transducers was based on the studies carried out in the Metrosert electrical measurement laboratory in order to verify the developed model of alternating voltage measurement. A method was proposed to reduce the measurand's dimension. A sample correlation coefficient was taken as the dimension reduction criterion. The relative difference (deviation) of the alternating current voltage from the equivalent direct current voltage is usually taken as the measurand. The value of this measurand within the operating frequency range is the metrological characteristic of the calibrated thermoelectric transducer. The uncertainty of the alternating voltage standard is estimated to be at the level of the root-mean-square deviation of the results of measurement of the relative difference between the direct current voltage and alternating current voltage. There is a regularly renewed calibration certificate on the transfer standard FLUKE with a table of expanded uncertainty regarding frequency and voltage. Following the recommendations of the company FLUKE, the uncertainties brought in by other means of measurement are excluded due to the specific nature of the measurements. Thus, the uncertainty of the results of calibration of alternating current voltage standards with the use of thermoelectric transducers comprises the FLUKE uncertainty and the uncertainty of the relative correction. Such laboratories as Laboratoire Central des Industries Electriques, Laboratoire National de Métrologie (LNM), using a simple method for estimating the alternating current voltage, i.e. Zero method, have obtained inferior metrological characteristics than those obtained in estimation with the use of alternating current voltage measurement model. The method, described in the paper, allows taking into account the variability of the conditions in the measuring laboratory without using any indeterminate functional relation. Using the developed method, any laboratory can raise the quality of measurement as well as apply for certification of its quality management system as being compliant with the requirements of ISO/IEC 17025 standard. The method, described in the paper, is based on the expert evaluation of the measurand. Precision instruments can perform the role of experts the same as a group of specialists. In the Metrosert laboratory, a small scale experiment has been carried out to verify the efficiency of the model of precise measurement of alternating voltage. The main emphasis was made on modelling the experiment with the use of a random number generator. The experiment results with the modelling method description were sent to the LNM laboratory. After clarification of some points, the metrology experts working with the primary standards of alternating current voltage, promised to test the described model. The proposed method would allow to produce a good reference standard on the basis of the transfer standard of the alternating current voltage unit FLUKE 792A. Having the evidence of the continuous stability of the source of direct current voltage, having measured the temperature gradient and stability lapse rate and using the results of international comparisons as expert estimates, the measuring laboratories can obtain accreditation to have the right for the calibration of alternating current voltage standards.

In the project, such methods of covariance estimation have been studied, which allow to make the measurement results more precise in case the observation data have different degrees of precision and are correlated. To compare the results of the measurements accomplished at different times, a test of the homogeneity of several correlation coefficients has been applied. It is a known fact that during the estimation of any output value it is impossible to be sure that the input values' correlation ratios can be neglected. Therefore, in practice any function under investigation has to be estimated with the use of sampled data and such methods of statistics estimation, which will specify the covariance of dependent variables. For example, if the function under investigation is hypothetically linear, the input values' correlation ratio is estimated with the use of a sampled correlation coefficient, applying statistical or empirical methods. Operating just a small number of sampled input values, it is not possible to be sure that the function is linear. Likewise, in the absence of sufficient amount of statistical data it is impossible to be sure that the correlated random values follow the Gaussian distribution model. The deficit of input data implies the possibility for the functional relationship to be of a monotonic non-linear nature. The following issues have been solved within the project in order to raise the trustworthiness of the correlation analysis results. The methods have been developed to estimate the uncertainty of standard model of alternating current voltage in case of correlated and unequal precision measurement results. Methods of multivariate mathematical statistics have been included in the measurement methodology in order to reduce the instability estimates of alternating current voltage. The variability of measurement conditions of alternating voltage has been taken into account for the situation, when the precise functional relationships between the measurand and the mentioned conditions are not known. The possibilities to reduce the degree of the measurements' equation and the number of informative parameters have been analysed. Also, the influence of random deviations on the correlation ratio of random values in measurement of alternating voltage has been studied.

The implementation of the above-mentioned methods has allowed improving the reliability of the measurement results of alternating current voltage. The statistical analysis has made it possible to obtain the best estimation of the alternating voltage measurand. Estonia does not possess a reference standard for alternating current voltage. It is very important for a state to have a standard that produces the required alternating current voltage with a relative uncertainty under $30 \cdot 10^{-6}$. The tasks solved in the project will make it possible to produce in Estonia, on the basis of the transfer standard of the voltage unit Fluke 792 A, a reference standard of alternating current voltage within the range from 100 mV to 1000 V with frequency within the range from 10 Hz to 1 MHz.

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KOKKUVÕTE

On teada, et ükskõik missuguse mõõtetulemuse hindamisel ei ole võimalik kindlalt väita, et mõõdetavate lähtesuuruste omavahelise sõltuvuse võib arvestamata jätta. Seetõttu on praktiliselt igat mõõtetulemust ja selle saamiseks kasutatavat mõõtmise mudelit ehk sõltuvust vaja hinnata väljavõtteliste andmete alusel, kasutades seejuures statistilisi hindamismeetodeid, mis iseloomustavad mõõtmise mudelisse sisestatud suuruste omavahelist korrelatsiooni. See on eriti oluline vahelduvpinge täpsetel mõõtmistel.

Antud töös alustati korrelatsiooni mõju uurimist vahelduvpinge mõõtmisel Viru Energia Elektrilaboratooriumis grupiviisiliselt töötava vahelduvpinge-etaloni loomisel. Kuna Viru Energia Elektrilaboratoorium kalibreerib pinge- ja voolu mõõtetransformaatoreid, siis mõõtetranformaatorite kõikvõimalike metroloogiliste karakteristikute määramiseks oli vaja välja arendada vastav vahelduvpinge etalon. Selle eesmärgi saavutamiseks toimunud uurimistöö käigus töötati välja põhialused vahelduvpinge grupiviisiliselt töötava etaloni loomiseks. Väljaarendatud grupiviisiliselt töötav etalon koosneb kolmest ühesuguste nominaalsete transformatsioonikoefitsientidega transformaatorist ja ühest pinge tugietalonist. Seejuures pidi tugietaloni transformatsioonikoefitsient olema kaks korda suurem kui teistel transformaatoritel. Nimetatud mõõtevahendite grupi mõõteskeemi realiseerimisel paariviisilise võrdlemise kaudu võrreldavate pingetransformaatorite sekundaarmähised lülitati sisse vastassuunaliselt läbi pingejaguri. Samal ajal lülitati ühesuguste nominaalsete transformatsioonikoefitsientidega pingetransformaatorite primaarmähised sisse järjestikku ning paralleelselt tugietaloni primaarmähisega. Nimetatud uute toimingute tulemusena tuli välja töötatada ka uus meetod kalibreeritava etaloni sekundaarpinge mastaabiteguri ja faasinihke suhtelise kõrvalekalde hindamiseks tugietaloni sekundaarpinge suhtes. Meetod, mis põhineb grupiviisiliselt töötava etaloni parameetrite triivi prognoosil, töötati välja ja juurutati.

Järgnevalt uuriti loodud grupiviisiliselt töötava etaloni vahelduvpinge väärtust ja selle liitmääramatust moodustavate hinnangute määramatusi selle etaloni võrdlemise teel vastava Soome analoogiga. Pinge mõõtetransformaatori kalibreerimisel mastaabiteguri laiendmääramatuse hindamisel võeti arvesse nii pinge kontakttakistitel kui ka temperatuuri gradient. Võrdlusmõõtmiste tulemusel saadud mastaabiteguri väärtuse suhteline kõrvalekalle ühe ja sama pingetransformaatori kalibreerimisel Viru Energia Elektrilaboratooriumis ja Soome Riiklikus Etalonlaboris andis võrreldavaid tulemusi. Seejuures hinnati etaloni-koormuskandja FLUKE määramatust alalisvoolu- ja vahelduvvoolupinge suhtelise erinevuse ruutkeskmise kõrvalekalde tasemega. Firma FLUKE soovituste kohaselt määramatused, mis tulevad sisse teiste mõõtevahendite samaaegsest kasutamisest pinge mõõtmisel, kõrvaldatakse lähtuvalt mõõtmiste eripärast. Sellest tulenevalt termomuundurite kasutamisel on vahelduvvoolu-pingeetalonide kalibreerimistulemuste määramatuse koostisosadeks nii FLUKE oma määramatus kui ka suhtelise mõõtehälbe karakteristikad tugietaloni sekundaarmähise pinge suhtes ja need ei olnud Soome Etalonlaboris saadud vastavate väärtustega samal tasemel.

Sellest tulenevalt tuli järgmiste uuringute käigus uurida näivalt suurte juhuslike mõõtehälvete (kõrvalekallete) mõju koostoimivate sisendsuuruste korrelatsiooni tegurile. Arvestades korrelatsiooni ja tehes väljatöötatud arvutusmetoodikaga ümberarvutused kalibreeritava etaloni sekundaarmähise pinge mastaabitrguri ja faasinihke laiendmääramatuse arvuliste karakteristikate määramisel tugietaloni sekundaarmähise pinge suhtes, saadi Soome Etalonlaboris saadud vastavate väärtustega võrreldavad tulemused. Seega võib järeldada, et sisendsuuruste kui ka väljundsuuruste omavahelist korrelatsiooni peab arvestama pingeetalonide kalibreerimisel.

Uurimistöö käigus töötati järgnevalt välja termoelektriliste pingemuundurite kalibreerimismeetod AS Metrosert elektriliste mõõtmiste laboratooriumis loodud muutuvpinge mõõtmise mudeli kontrollimiseks. Väljatöötatud kalibreerimismeetodi korral on mõõdetavaks suuruseks võetud vahelduvvoolu pinge kõrvalekalle temaga ekvivalentsest alalisvoolu pingest. Selle suuruse väärtus vastavas sageduste diapasoonis määrab ära kalibreeritava vahelduvpinge etaloni määramatuse. Uurimistulemused näitasid, et sellel meetodil vahelduvpinge mõõtmine vahelduvpinge etalonide kalibreerimisel andis väiksema määramatusega tulemused, kui laboratooriumid, nagu Laboratoire Central des Industries Electriques ja Laboratoire National de Métrologie (LNM), kes kasutasid lihtsat vahelduvvoolupinge mõõtmise meetodit ehk nullmeetodit. Töös kirjeldatud väljaarendatud meetod võimaldab arvestada muutuvaid tingimusi mõõtmisi läbiviivas laboratooriumis ilma, et sellega kaasneksid tundmatud funktsionaalsed sõltuvused. Kasutades seda meetodit, võib iga elektrilisi suurusi mõõtmisi teostav laboratoorium tõsta mõõtmiste kvaliteeti. Töös kirjeldatud meetod põhineb mõõdetava suuruse eksperthinnangule. Ekspertideks võivad olla nii grupp spetsialiste kui ka pretsessioossed mõõtevahendid. AS Metrosert elektriliste mõõtmiste laboratooriumis viidi läbi katsetused mudeli töövõime kontrollimiseks vahelduvvoolu pinge täpseks mõõtmiseks. Eksperimendi põhirõhk oli suunatud katse modelleerimiseks, kasutades juhuslike arvude generaatorit. Eksperimendi tulemused ja modelleerimise viisid saadeti LMN laboratooriumisse. Metroloogid selles laboratooriumis, kes kasutavad vahelduvvoolu esmaseid ehk primaarpinge-etalone, olid pärast mõningate momentide täpsustamist valmis kirjeldatud mudelit katsetama.

Väljaarendatud metoodika võimaldab vahelduvvoolu pingeühiku hoidja ja edastaja etalon-koormuskandja FLUKE 792A alusel elektriliste suuruste mõõtelaboratooriumeil luua endale tugietaloni. Selle tugietaloni alusel, omades alalisvoolu pingeallika pikaajalise stabiilsuse näitajaid, mõõtes temperatuuri- ja stabiilsuse gradiente ning kasutades ekspertandmetena rahvusvaheliste võrdluskatsete tulemusi, võivad nimetatud mõõtelaboratooriumid kalibreerida vahelduvvoolu pinge tööetalone.

Põhjalikult on uuritud erinevaid koovariatsiooni hindamise meetodeid, mis lubavad täpsustada ebaühtlaste ja korrelatiivsete suuruste mõõtmisel saadud vaatlushinnanguid. Uuringutulemused näitasid, et erineval ajal tehtud mõõtmiste tulemuste võrdlemiseks tuleb kasutada mitme korrelatsiooniteguri ühtlustamise kriteeriumit. On teada, et hinnates ükskõik millist väljundsuurust, ei saa kindlalt väita, et kitsaste piiride korral võib mitte arvestada sisendsuuruste korrelatsiooni. Seepärast on praktikas vaja igat uuritavat sõltuvust hinnata valikandmete alusel, kasutades hindamise aluseid, mis iseloomustaksid suuruste sõltuvuse koovariatsiooni. Kui uuritav sõltuvus on hüpoteetiliselt lineaarne, siis sisendsuuruste piirkonda hinnatakse valikulise korrelatsiooniteguri abil empiiriliselt või kasutades statistilisi meetodeid. Kuid seda, et sõltuvus on lineaarne, ei saa kinnitada, kui opereeritakse lähteandmete valiku väikese mahuga. Analoogiliselt ei saa veendunult kinnitada, omamata piisavas koguses statistilist materjali, et juhuslikud sõltuvad suurused alluvad normaaljaotusele. Lähteandmete defitsiidi (vähesuse) korral, võib sisendsuuruste funktsionaalne sõltuvus omada ka monotoonset mittelineaarset iseloomu.

Korrelatsiooni tulemuste analüüsi usaldusväärsuse suurendamiseks on töös lahendatud järgnevad probleemid. On välja töötatud meetodid vahelduvvoolu pingeetaloni mudeli määramatuste hindamiseks hajuvate punktide ja korreleeritud mõõtetulemuste korral. Nimetatud meetodites on kasutatud mitmedimensioonilist matemaatilist statistikat, et vähendada hindamisel vahelduvvoolu pinge ebastabiilsust. Samuti on meetodis arvestatud vahelduvvoolu pinge mõõtmiste tingimuste muutlikkust juhul, kui pole teada mõõdetava suuruse täpsed funktsionaalsed sõltuvused antud tingimustel. Igakülgselt on analüüsitud mõõtmiste taseme dimensioonide alandamise ja informatiivsete parameetrite vähendamise võimalusi. Samuti on uuritud juhuslike kõrvalekallete mõju vahelduvvoolu pinge mõõtmisel juhuslike suuruste korrelatsioonitegurile.

Ülalnimetatud meetodite kasutamine võimaldas tõsta vahelduvvoolu pinge mõõtmiste tulemuste usaldatavust. Statistiline analüüs võimaldas saada mõõdetava vahelduvvoolu pinge kõige parema hinnangu. Eestis ei ole veel riigi jaoks välja arendatud vahelduvvoolu pinge tugietaloni. Riigi jaoks on aga väga tähtis omada niisugune etalon, mis võib hoida ja edastada vahelduvvoolu pinge väärtust suhtelise määramatusega, mis on väiksem kui $30{\cdot}10^{-6}$. Käesolevas uurimistöös lahendatud ülesanded võimaldavad niisuguse vahelduvvoolu tugietaloni välja arendada pinge vahemikus 100 mV kuni 1000 V sageduspiirkonnaga 10 Hz kuni 1 MHz etalon-koormuskandja FLUKE 792A alusel.

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1984	Teaduslik Uurimisinstituut НПО ЭНЕРГИЯ – Projekteerimine

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Määramatuse hindamise alused elektriliste suuruste mõõtmisel

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Исследование условий получения статистически однородных результатов калибровки (1995–1997)

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2003	TUT Education Center – Tutoring for Learning
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Estimation of uncertainty of measurement at the measurement of electrical quantities

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