VYTAUTAS DAUNORAS

A METHOD FOR REMOTE MONITORING OF ELECTRICAL ENERGY METER ERRORS

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES, ELECTRICAL AND ELECTRONICS ENGINEERING (T 001)

Kaunas
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KAUNAS UNIVERSITY OF TECHNOLOGY

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This doctoral dissertation was prepared at Kaunas University of Technology, Faculty of Electrical and Electronics Engineering, Department of Electronics Engineering during the period of 2016–2021.

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

VYTAUTAS DAUNORAS

NUOTOLINĖS ELEKTROS APSKAITOS PRIEMONIŲ PAKLAIDŲ STEBĖSENOS METODAS

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INTRODUCTION

Electricity meters are widely used in consumer economies where electricity is consumed, industrial workshops, in the provision of general services such as lighting and air conditioning, for the purposes of accounting and the performance of energy audits. In addition to traditional commercial electricity metering equipment, the use of prepaid, sub-accounting, and total accounting meters is becoming more widespread, as well as the use of network status verification meters [1–4]. Different smart sockets, smart plugs, and smart meters used as additional elements for renewable energy inverters, etc., form a constantly expanding fleet of electricity meters (EM).

Commercial accounting meters fall within the scope of legal metrology regulation field, and their measurement results are used for the billing of consumers. Besides, based on the readings of electricity meters, a consumer can decide on the energy efficiency of premises, industrial sites, etc. The development of smart meters in the European Union is expected to reduce electricity consumption by 3% due to the emerging opportunities for consumers to adjust their energy behaviour [5]. Thus, trust in the accuracy of energy meter measurement is relevant not only for the correct billing for the supplied and consumed energy in commercial accounting but also for decision-making and the evaluation of energy efficiency improvement measures.

Due to the abundancy of commercial and non-commercial energy metering devices in the market, their metrological maintenance costs are high in terms of the costs of meter dismantling, transportation, installation of replacing meters, verification or calibration services. Therefore, to reduce the costs of metrological maintenance, statistical (selective) verification methods are used, which allow deciding on the compliance of a homogeneous group of meters with the requirements of standards based on the metrological verification of only a small number of meters.

Statistical verification intervals for electricity meters in various countries of the world are relatively long, e.g. in Lithuania, such a period is 12 years, and the metrological characteristics of meters are not verified until the end of this period. Of course, meters can be pre-verified upon a consumer's complaint. However, if the increase in error is not apparent, a meter that does not meet the metrological requirements can be operated for many years, leading to financial losses for the supplier or the consumer. A steady increase in the energy measurement error of smart EMs is not the main reason for non-compliance with the specified requirements [6] since the failures of the internal components of meters can lead to a sudden change in error and significant economic losses to the supplier or the consumer [7]. For these reasons, a more intensive search for new ways to remotely monitor and verify the errors of EMs occurs and raises a question of how to use the obtained results for metrology maintenance during the use. In solving the above-mentioned problems, a scientific problem arises: there is a lack of knowledge on how to remotely monitor and verify the errors of electricity meters without interrupting the electricity supply to the consumer, and how to determine the uncertainty of error estimation achieved by such verification methods.

Various scientific publications and technical reports consider the possibility of verifying the errors of EMs without transporting them to a certified laboratory. These methods are united by the fact that the meter under test (MUT) is not dismantled from its place of use. Depending on the reference meter (RM) or the value of the reference measurement, for instance, the connection of the reference load to the MUT, two types of remote monitoring can be distinguished:

- On-site verification of a meter, which requires the transportation of the RM to the MUT operation site.
- Remote meter verification, when the RM and the MUT are located apart from each other but connected by a data communication channel.

The scientific hypothesis of the paper is formulated as follows: the active power measurement error of an EM can be remotely estimated with acceptable accuracy, without dismantling it from the place of operation and without interrupting the electricity supply to the consumer, with the use of a reference energy meter connected to the same distribution subnet as the meter under verification. The assumptions that are followed in making the hypothesis are: the influence of the systematic error introduced by the medium (electrical network) transmitting the unit of measurement on the accuracy of remote verification is negligible, and the impact of random errors can be reduced to the desired limit by applying multiple measurements and processing their results.

Although the remote verification methods of EM errors in legal metrology are not yet envisaged or standardized, they could be tested in the areas of personal or industrial accounting (sub-accounting). It is expected that in the field regulated by legal metrology, the results of remote error verification methods could play a supporting role in the choice of time intervals for extraordinary verifications.

When developing methods for remote verification of EM errors and the technical solutions to implement them, it is expedient to strive for the following features in terms of attractiveness to the consumer and reduction of metrological maintenance costs:

1. The dismantling and transporting of an EM to an accredited laboratory is no longer required;
2. The consumer does not need to be disconnected from the electricity network during the verification of EM errors;
3. Individual establishment of an EM error can be ordered as a one-off or periodic service.

Aim and tasks of the work

The aim of this doctoral dissertation is to develop and investigate a method of remotely verifying the errors of electricity metering devices in low-voltage electricity distribution networks with the use of a synchronized reference measuring device connected at the electrical subnet input.

The following **objectives** were formulated in order to achieve the aim:

1. To propose a method for remotely monitoring the errors of electricity meters, enabling the performance of error verification remotely without interrupting the electricity supply to the consumer.
2. To analyse the possibilities of using the method in the fields of legal and industrial metrology.
3. To verify a remote MUT error monitoring method by mathematical modelling, establishing the limits of systematic measurement error in a typical low-voltage electricity distribution network.
4. To analyse the impact of network and loads on the uncertainty of remote error monitoring of the MUT.
5. To create an experimental system implementing the method and with its help to perform the verification of the remote MUT error monitoring method experimentally in a typical low-voltage distribution network, establishing the uncertainty of the MUT error estimation.

The scientific novelty of the work

The main scientific contributions to the field of electrical and electronic engineering are:

1. A new method for remote verification of EM errors without interrupting the electricity supply to the consumer using a synchronized reference meter switched on at the subnet input has been proposed.
2. The errors achievable by the proposed method in typical low-voltage electricity distribution networks have been established.

The practical value of the work

The results obtained in the dissertation were used to develop a remote method for the verification of active power errors and to calculate the uncertainty of the multiplicative estimation of active power adjustment gain achieved by it. In the case of implementation of the developed method, the expected value will mean better protection of economic interests of both the electricity consumers and suppliers by enabling continuous verification of the meter fleet condition without sending service personnel to the meter installation site, without dismantling and transporting the meter to the metrology laboratory. The verification method developed is not intended to replace the existing metrological verification procedures provided for in the national legislation; however, it does allow the verification of the condition of each electricity meter at intervals between metrological inspection, and its results can be used to identify individual meters whose metrological characteristics do not meet the requirements of relevant standards.

The results of the research performed during the preparation of the dissertation were used in the implementation of:

- Kaunas University of Technology interdisciplinary/inter-field research project “Method of calibration and diagnostics of remote electricity metering devices (ELENOT)” (2017).

- Research project “Investigation of the methods of synchronization of low-voltage power network parameter verification with the use of distributed measuring instruments” (2018), funded by the fund of Kaunas University of Technology.

Statements presented for defense

1. A new remote method for monitoring EM errors has been developed based on the comparison of the active power readings of the tested meter with the RM readings. This method makes it possible to achieve a systematic error of the measurement multiplicative correction factor error of the test meter of not more than 0.31%, independently of other energy-consuming loads in the same low-voltage distribution network.
2. The proposed method may be used in the field of legal metrology to detect more quickly (before the end of the verification interval) those EMs the error of which exceeds the permissible limit, and in the field of industrial metrology to detect an increase in EM error and, if necessary, to adjust readings.
3. Short-term fluctuations influence the random error in determining the multiplicative correction factor of the active power of a remote meter in power loads and power consumption in the distribution network, the effect of which can be effectively reduced by applying multiple measurements along with averaging and filtering procedures.
4. The application of the proposed remote verification method can help to achieve a standard relative uncertainty of the multiplicative correction factor of the tested meter of no more than 9.4%, when the measured power in the place of installation of a reference meter does not exceed 5 kW, and does not exceed 0.5 kW in the place of installation of the tested meter, with the TM accuracy class 1 or 2, and the RM accuracy class 0.2 or 0.5.

Structure of the dissertation

This doctoral thesis consists of an introduction, four chapters, conclusions, a list of literature, and a list of scientific publications on the thesis. The volume of the work is 114 pages. There are 15 tables, 55 equations, and 77 figures. The list of references consists of 101 titles. The content of the thesis is organized as follows:

The first chapter reviews local and remote methods of estimating the error of electricity meters.

The second chapter describes the proposed method for monitoring the errors of remote electricity meters, analyses the possibilities of application of the proposed method in industrial and legal metrology, reviews the time-synchronization methods, as well as an experimental study of PLC synchronization possibilities in typical low-voltage distribution networks.

The third chapter describes the investigation of the systematic error of the method in modeling, presents the obtained results, and studies the possibilities of reducing random errors due to power fluctuations in the distribution grid to measure the consumption of instantaneous active power.

The fourth chapter describes experimental verification of the remote electrical energy meter error monitoring method and the active power adjustment gain uncertainty analysis.

Approbation of the work

The scientific results obtained during the preparation of the dissertation have been presented in eight publications: three of them are articles included in the list of reference publications of the Institute of Scientific Information (ISI Web of Science) with a citation index, five publications in international conference materials presented in the following cities: Split (Croatia), Bologna (Italy), Liverpool (Great Britain), and Turin (Italy). The results have been also presented at a conference that took place in Lithuania, Pabariukai Village, Kelmė District, and in a competition of scientific papers in Vilnius.

OVERVIEW OF METHODS OF METROLOGICAL MAINTENANCE DURING EXPLOITATION

Statistical verification

Given the large number of electricity meters installed and commercial electricity meters covered by legal metrology, their metrological monitoring has always been cost-sensitive. The European Council's Measurement Instruments Directive (MID) 2014/32/EU [8] requires periodic inspections of electricity, water, gas, and district heating meters. However, the interval between periodic checks is rather long and dependent on national regulations. According to the information provided by WELMEC [9], the initial verification period may range from 16 to 20 years in different European countries. Alternatively, based on random experimental monitoring results, it is possible to determine the conformity of the meters of the same batch of production and extend their operating range. Table 1 gives a brief overview of the typical inspection intervals in different countries.

Table 1. In-service inspection of EM in different countries [10]

Country	Note, reference
Germany	Verification and compliance testing of active electromechanical/electronical EMs 16/8 years
Italy	Periodic verification after 18 years in-service for electromechanical EM, 15 years for static low-voltage EM
Austria	Inspection every 8–20 years dependent on meter type
Croatia	8–16 mandatory re-verification period for electricity meters
Slovenia	Statistical re-verification every four years
Lithuania	First reverification after 12 years with the possibility to extend service for six years
Japan	Domestic meters dependent on rated current are tested every 7–10 years
The USA, New York state	Periodic testing at least once every eight years for watthour meters installed at customer's premises
Canada	The initial reverification period is 6–10 years

At present, the statistical verification interval is decided in advance by national metrological regulations (Table 1), and no feedback on errors of operating meters is considered. Regardless of the origin of the meter error caused by errors above the permitted limit (degradation of accuracy or sudden change due to failure of internal components), continuous error monitoring may contribute to better awareness about the metrological status of a single meter in the lot of meters. Decisions arising from this may include meter replacement, replacement of the group of meters, or carrying out statistical verification before the end of the planned verification period.

A MODEL OF REMOTE ERROR MONITORING SYSTEM FOR ELECTRICITY METERS

The remote error monitoring system diagram is shown in Fig. 1.

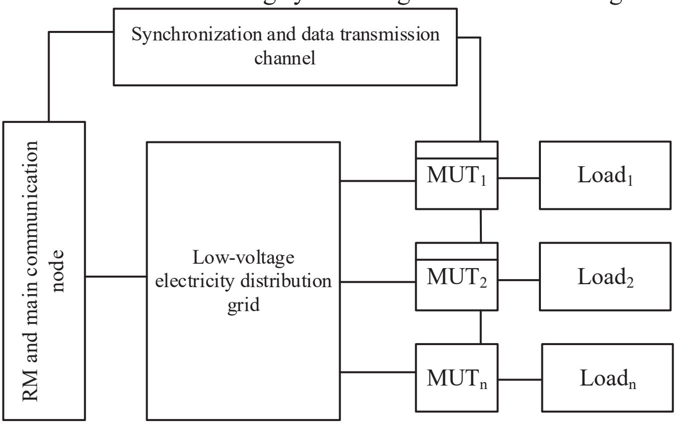

Fig. 1. A diagram of the remote error monitoring system of EMs

In this framework, the specific features of metrological surveillance are:

1. MUT error estimation is conducted in the range of a consumer's typical

power consumption instead of verification points specified in the verification methodology. The purpose of remote error monitoring is not to conduct legal verification but to obtain an estimate of the metrological status of the meter.

2. Dynamic conditions of the interconnecting media may influence a selection of error monitoring interval. For example, a lower overall energy consumption in the grid and lower level of power fluctuations in the grid may be considered as criteria for choosing a preferable day time (night), seeking to minimize the MUT error estimation uncertainty.
3. The remotely monitored error can be determined by averaging a series of error estimates acquired from repeated measurements seeking to reduce random estimation errors. Random estimation errors are caused by internal MUT and reference meter errors and short-term energy consumption and voltage fluctuations in the interconnecting media.
4. Remote error monitoring requires measurement synchronization and data collection channels.
5. Estimating MUT error in its operating conditions reflects the real cost (risk of loss) of meter inaccuracy.

MUT adjustment gain is established; it can be used to correct the electricity meter readings and assess the current error. The proposed method for calculating the remote MUT error or adjustment gain is illustrated in Fig. 2, and the sequence diagram of its implementation steps is illustrated in Fig 3.

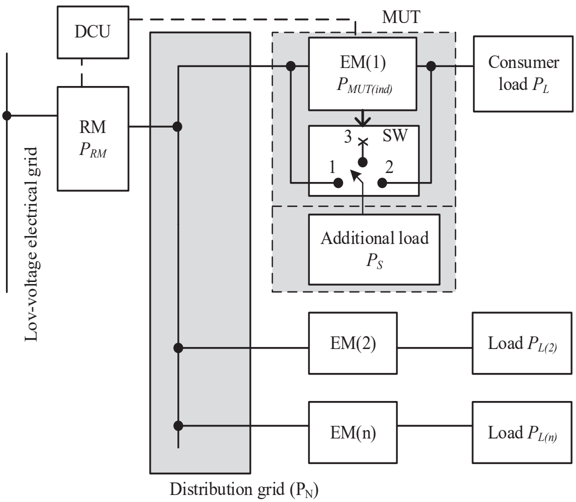

Fig. 2. A diagram of remote error monitoring method implementation: RM is a reference meter, MUT is a meter under test, DCU is a data collection unit, SW is a switch block, P_S- power consumed by the additional load, P_L is consumer's load power measured by MUT.

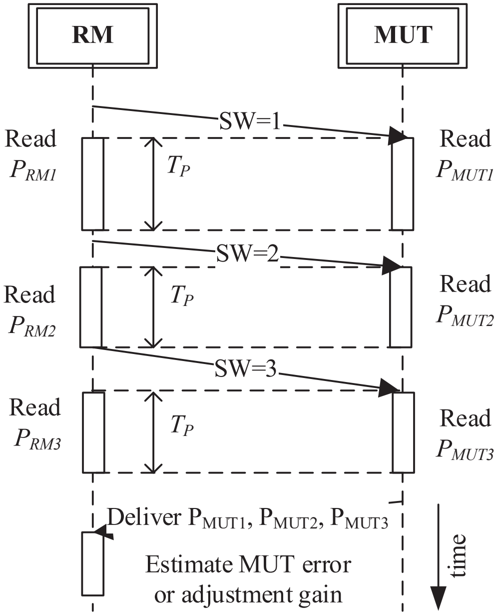

Fig. 3. A sequence diagram of the MUT adjustment gain estimation.

The key assumptions made for the derivation of method equations are:

1. A reference meter is installed similarly at the input of a low voltage distribution grid as shown in Fig. 2,
2. A small active power load (stimulus) can be temporarily turned on and off at the location of the MUT,
3. During remote error monitoring, RM and MUT may acquire synchronized active power readings,
4. Changes in power losses and voltage drop due to stimulus state (on or off) are insignificant provided the 1% target error of the estimated adjustment gain,
5. During the acquisition of active power readings by RM and MUT necessary for adjustment gain estimationof the MUT, all electrical loads in the distribution grid are constant.

This method aims to determine the value of the active power adjustment gain of the tested electricity meter. The active power adjustment gain is defined as follows:

$$C_p = \frac{P}{P^*} \tag{1}$$

where P is the nominal active power supplied to the MUT, and P^* is the active power indicated by the MUT.

The proposed approach consists of the following steps (Fig. 3):

- Synchronous acquisition of P_{RM1} and P_{MUT1} that correspond to load P_S connection before MUT (switch position SW1).
- Synchronous acquisition of P_{RM2} and P_{MUT2} that correspond to load P_S is connected in parallel to load P_L (switch position SW2).
- Synchronous acquisition of P_{RM3} and P_{MUT3} that correspond to load P_S being disconnected (switch position SW3).
- Assessment of the MUT adjustment gain.

The active electricity balance for each switch SW position may be expressed as follows:

$$\begin{gathered} P_{RM1} = P_{N1} + P_S + c_p \cdot P_{MUT1}, \\ P_{RM2} = P_{N2} + c_p \cdot P_{MUT2}, \\ P_{RM3} = P_{N3} + c_p \cdot P_{MUT3}; \end{gathered} \tag{2}$$

when

$$P_{N(j)} = P_{\Sigma load(j)} + P_{loss(j)}, j = \overline{1,3} \tag{3}$$

where $P_{\Sigma load(j)}$ is the sum of active powers of all network loads except P_L and P_S, $P_{loss(j)}$ is the active power losses in distribution network wires due to currents flowing to network loads, $P_{RM(j)}$ is the power measurement results acquired by RM at the moment of a j-th position of SW, j is the switch SW position (Fig. 2).

Power losses in cables of the distribution network are proportional to the power delivered to the load. Therefore, according to the diagram in Fig. 3, it is assumed that

$$\begin{gathered} P_{loss(1)} = n \cdot (P_S + c_p \cdot P_{MUT1}) + P_{\Sigma loss(1)}, \\ P_{loss(2)} = n \cdot (c_p \cdot P_{MUT2}) + P_{\Sigma loss(2)}, \\ P_{loss(3)} = n \cdot \left(c_p \cdot P_{MUT3}\right) + P_{\Sigma loss(3)}, \end{gathered} \tag{4}$$

where n is the coefficient relating active power losses in the power delivery route from the point of RM connection to the point of MUT connection, $P_{\Sigma loss(j)}, j = 1,3$ is active power losses in network wires are due to currents flowing to loads except loads connected behind the MUT. Then it is possible to express the estimate of adjustment gain

$$C_p = \frac{P_{RM1} - P_{RM3}}{P_{MUT2} - P_{MUT1}} + C_E \tag{5}$$

where C_E is a correction coefficient aiming to account for error due to assumptions made in deriving expression (5). Because C_E is dependent on the characteristics of the distribution sub-grid between the MUT and RM, it can be considered a random quantity. Averaging of measurement results of P_{RM1}, P_{RM3}, P_{MUT1} and P_{MUT2} obtained in the sequence leads to the following expression of the adjustment gain

$$C_p = \frac{\overline{P_{RM1}} - \overline{P_{RM3}}}{\overline{P_{MUT2}} - \overline{P_{MUT1}}} + C_E. \quad (6)$$

Since the term C_E is constant in the fixed location of the MUT installation, the averaging does not influence its value, i.e. $\overline{C_E} \equiv C_E$.

INVESTIGATION OF ERRORS IN THE METHOD OF REMOTE ERROR MONITORING OF ELECTRICITY METERS

Investigation of systematic method error

A modelling method has been used to check the limits of systemic error and the impact of different electricity network loads on the proposed remote error monitoring of electricity meters. A system model shown in Fig. 4 was built using the PowerSim toolbox from Matlab/Simulink.

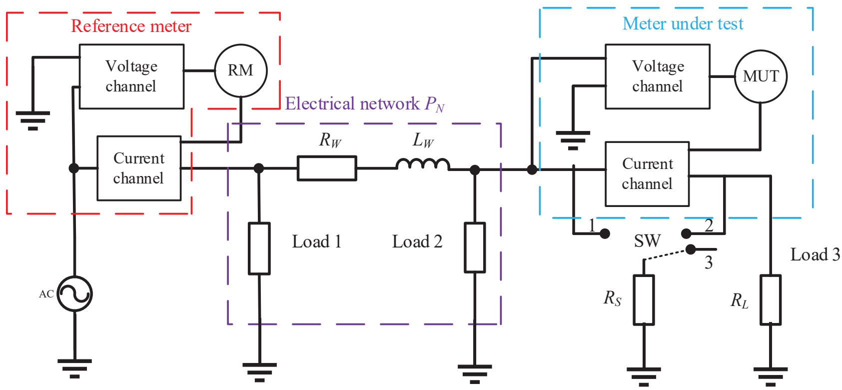

Fig. 4. A model for monitoring the errors of remote electric meters, including RM and MUT, connected to the electrical network

Loads denoted correspondingly as Load 1, Load 2, and Load 3 were modelled according to diagrams shown in Fig. 5. When adjusting the internal non-linear load parameters, its active power was set at approximately 100W (Fig. 6). Higher active non-linear load power was achieved by connecting the corresponding number of such loads in parallel. Table 2 shows various combinations of types and levels of network loads used during modelling.

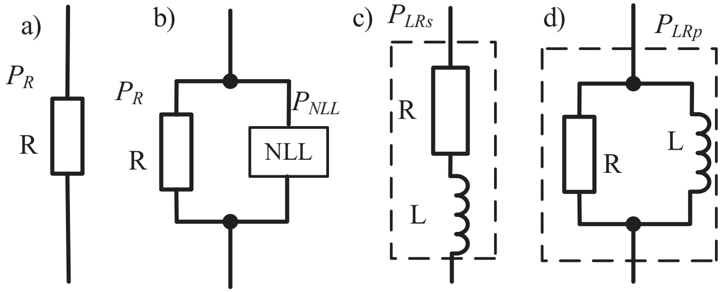

Fig. 5. Types of load modes, (a) resistive, (b) resistive with a parallel non-linear load, (c) serial inductive and resistive, (d) parallel inductive and resistive

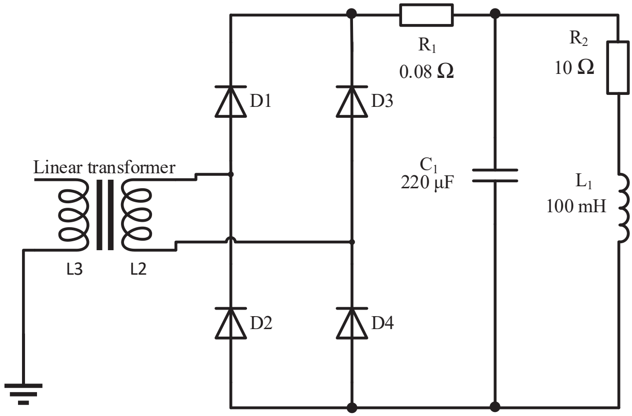

Fig. 6. Non-linear load model

In the non-linear load model, the component values were determined empirically so that the active power consumption would be approximately 100W. To investigate the effect of higher power non-linear loads, several non-linear load models (Fig. 6) were connected in parallel (Fig. 4).

The analysis of the results in Table 3 shows that the error $e_{sis}(C_p)$ increases as the active loss of the power distribution line increases. As a rule, the electricity distribution network is designed following recommendations that the power losses in distribution lines do not exceed 5% of the active power supplied. Based on the data in Table 6, even with higher power losses in low voltage power distribution lines and very low power factor values (0.5 and below) (lines 3, 4, 7, 8, and 13), the absolute error value $|e_{sis}(C_p)|$ did not exceed 0.26%. It should be expected that even with exceedingly low power factor values, the systemic method error is small. Thus, in real-life circumstances, the adjustment gain error change may not be more significant than the resulting error.

Table 2. Load parameters used for modelling

Case number.	Load 1 parameters			Load 2 parameters				Load 3 parameters				
	Type	P_r, W	R, Ω	Type	P_r, W	R, Ω	P_{NLL}, W	Type	P_r or P_{LRS} or P_{LRp}, W	R, Ω	P_{NLL}, W	L, mH
1	a	1056	50	a	552	90	no	b	292	170	279	no
2	a	1056	50	b	292	170	278	b	292	170	278	no
3	a	1056	50	a	527	90	no	b	948	50	443	no
4	a	1056	50	b	279	170	266	b	948	50	442	no
5	a	1056	50	a	553	90	no	a	553	90	no	no
6	a	1056	50	b	292	170	279	a	552	90	no	no
7	a	1056	50	a	554	90	no	c	461	10	no	100
8	a	1056	50	b	293	170	279	c	461	10	no	100
9	-	no	no	-	no	no	no	d	1043	50	no	150
10	-	no	no	-	no	no	no	d	1044	50	no	70
11	-	no	no	-	no	no	no	d	1052	50	no	150
12	-	no	no	-	no	no	no	d	1053	50	no	70
13	-	no	no	-	no	no	no	d	1066	50	no	10

Note: no – Not connected.

Table 3. Modelling results and used conditions

Case number.	$e_{sis}(c_p)$, ppm	P_{losses}, %	ΔU, %	PF_{RM}	PF_{MUT}	R_W, Ω	L_W, uH
1	-46	3.1	3.1	0.99	0.98	1.37	53
2	-491	3.2	3.2	0.99	0.98	1.37	53
3	-338	5.6	5.3	0.99	0.99	1.37	53
4	-799	6.5	5.3	0.99	0.99	1.37	53
5	266	3.1	3.0	1.00	1.00	1.37	53
6	-46	3.1	3.1	1.00	1.00	1.37	53
7	-2638	8.4	2.9	0.83	0.30	1.37	53
8	-2557	7.6	2.9	0.85	0.30	1.37	53
9	-16	1.4	0.8	0.69	0.68	0.34	42
10	-279	4.2	0.8	0.42	0.40	0.34	42
11	14	0.6	0.4	0.69	0.68	0.14	38
12	-28	1.7	0.4	0.41	0.40	0.14	38
13	-2268	69.4	0.8	0.11	0.06	0.14	38

Notes: R_w = 1.37 Ω corresponds to the copper wire of 100 m length and 2.5 mm^2 cross section, R_w = 0.34 Ω corresponds to the copper wire of 100 m length and 10 mm^2 cross section, Rw = 0.14 Ω corresponds to the copper wire of 100 m length and 10 mm^2 cross section, R_S = 5 kΩ.

Investigation of random method error due to power fluctuations

Power fluctuations are caused by voltage fluctuations and the behaviour of shor duration loads. A typical experimentally measured short duration power and voltage fluctuations acquired with the sampling period of 0.1 seconds are shown in Fig. 7.

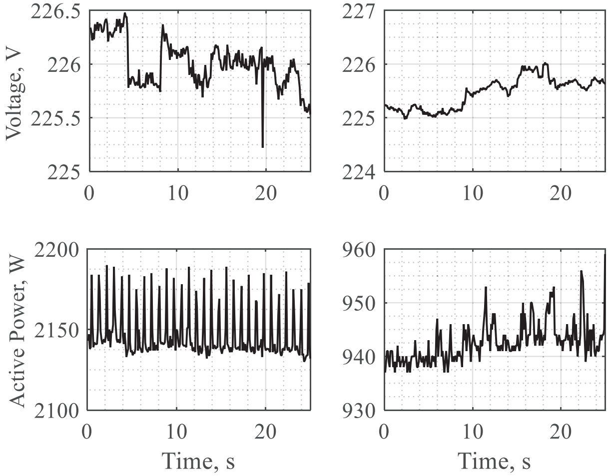

Fig. 7. Power and voltage fluctuations in the distribution grid

Assume that a particular load P_S is connected during the selected period (T_T) (Fig. 8), using the remote method of calculating the MUT adjustment gain (Fig. 2). Power fluctuations must be reduced to determine the value of the adjustment gain using MUT and RM. The influence of fluctuations can be reduced by repeatedly toggling the load and averaging the obtained electric active power estimates.

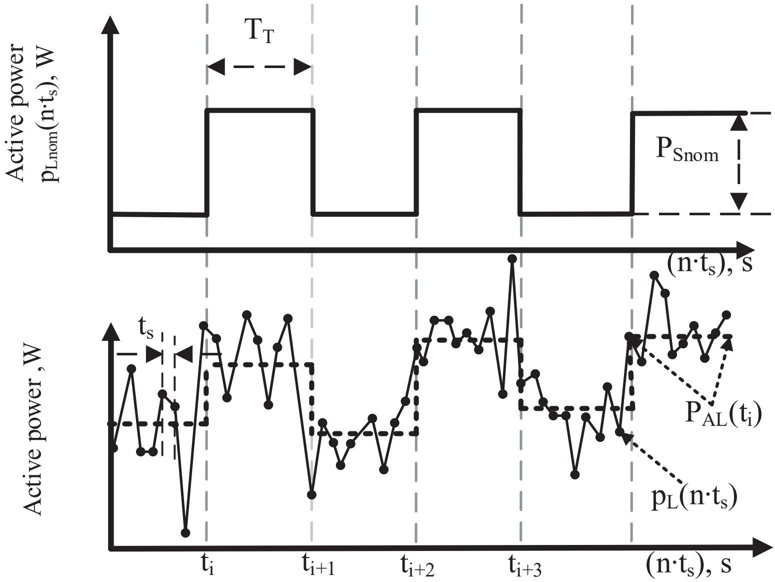

Fig. 8. Measurement of toggled 10 W load (T_T – toggling load period, P_{Snom} – nominal additional load power, t_s – sampling period, n – number of active power samples, $P_{AL}(t_i)$ – effective active power for specific time interval t_i, P_{Lnom} – an estimate of active power with a sampling period t_s, $P_L(n \cdot t_s)$ – active power sample.

The representation of the spectral content of nominal load activities (consumer devices on/off cycles), power fluctuations, and the load P_S toggling is shown in Fig. 9. We assume that the customer's loads are switched on/off most of the time, with the period not larger than T_{Lmin}=5 s. Assuming typical usage of home appliances, office equipment, etc., a more frequent On/Off switching is little probable.

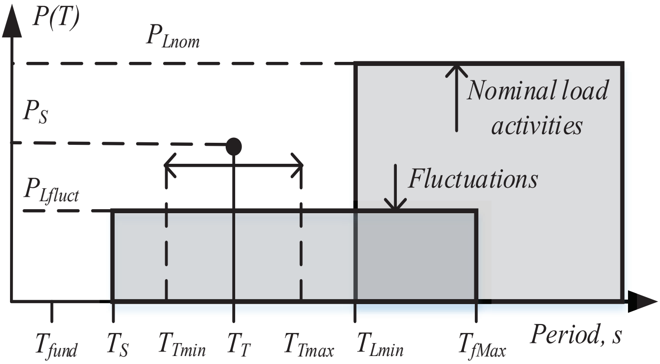

Fig. 9. The spectral content of power fluctuations T_{fund} – fundamental period 20 ms, T_S – sampling period (1 s or 0.1 s), T_{Tmin} and T_{Tmax} are the minimum or maximum duration of the additional load on the interval (T_T), T_{Lmin} – the minimum speed of the user loads on/off or operating mode, T_{fmax} – the maximum duration of fluctuations, P_S – the value of additional toggling load (~10 W), P_{Lnom} – nominal user load power, P_{Lfluct} – the level of fluctuations of active power in watts.

Short-term fluctuations of the RMS are due to times ranging from 0.5 fundamental cycles to 1 minute. Voltage fluctuations generally appear as variations of the envelope or random voltage changes with intermittent duration. It was found that power fluctuations that need to be suppressed are within the period range T_S=0.1 s to T_{fmax}=10 s.

The load P_S toggling period T_T is selected in the range from $T_{Tmin}>T_S > T_{Tmax}$ Typical values considered are from T_{Tmin} =1 s to T_{Tmax} =10 s.

Summarizing the definitions introduced in this chapter, the research goal is to determine the influence of power fluctuations upon the standard deviation $\sigma\left[M\{\Delta p_{fA}\}\right]$ of mean $M\{\Delta p_{fA}\}$ and how effectively fluctuations may be suppressed by averaging a set of acquired Δp_{fAi} samples.

A dataset made available by the authors of [11] (Dataset 1) was utilized in the dissertation for estimating the variance of power fluctuations in a distribution grid.

To examine the suppression of fluctuations, Δp_{fAi} and Δp_{fMi} samples in a 1-hour interval were acquired and correspondingly $\sigma\left[M\{\Delta p_{fA}\}\right]$ and $\sigma\left[M\{\Delta p_{fM}\}\right]$ were estimated using different averaging (toggling) intervals. The obtained results are plotted in Fig. 10. The active power profile of Dataset 1 (resolution 1 s) contains 3600 samples within 1 hour.

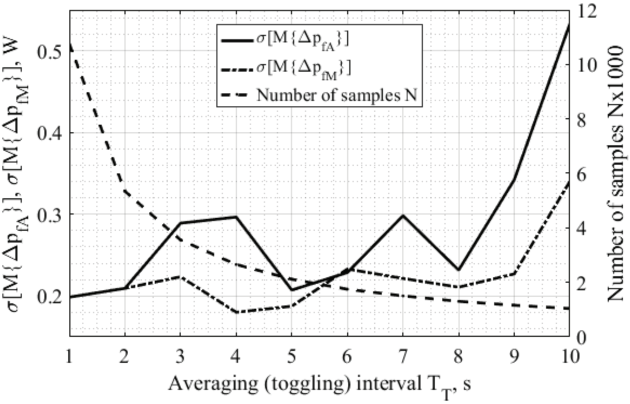

Fig. 10. Spectral estimation of $\sigma\left[M\left\{\Delta p_{fA}\right\}\right]$ and $\sigma\left[M\left\{\Delta p_{fM}\right\}\right]$ (3 hours 1-second resolution, outlier threshold level $\Delta P_{TH} = 20W$, Dataset1, $T_T = 5\ s$)

74 power profiles from Dataset 1 were used to estimate the statistical dependence of $\sigma\left[M\left\{\Delta p_{fA}\right\}\right]$ vs the duration of averaging time assuming $T_T = 5\ s$. The average and the worst-case scenarios were calculated and are shown in Fig. 11. The estimated values of $\sigma\left[M\left\{\Delta p_{fA}\right\}\right]$ after 3 hours of averaging are shown in Table 4.

Table 4. Standard deviation after 3hours of averaging

Outlier rejection level	Average case scenario *σ[M{ΔpfA}], W*	Worst case scenario *σ[M{ΔpfA}]*, W	Minimum number of rejected outliers	The average number of rejected outliers	Maximum number of rejected outliers
No outlier rejection	4.45	72.96	-	-	-
ΔP_{TH} =100 W	0.98	4.24	3	64	262
ΔP_{TH} =50 W	0.55	1.89	13	98	374
ΔP_{TH} =20W	0.20	0.62	23	150	502

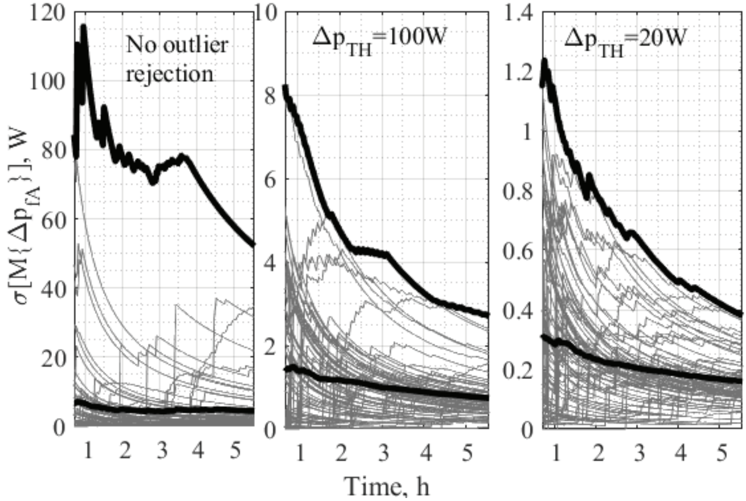

Fig. 11. Estimation of standard deviation $\sigma[M\{\Delta p_{fA}\}]$ from 74 active power profiles of Dataset 1, worst and average case scenarios are highlighted. (T_T =5 s)

EXPERIMENTAL VERIFICATION OF THE METHOD AND ANALYSIS OF THE UNCERTAINTY OF THE ACTIVE POWER ADJUSTMENT GAIN

Research Methodology

Experimental measurements were carried out in typical low voltage grids, i.e., in a private house and in an apartment building, to test the method for remotely monitoring the errors of energy meters. One of the EMs was selected as the RM, and the other as the MUT. The RM was sending instructions to toggle additional load according to the step sequence diagram in Fig. 3. A distributed active power measurement system is shown in Fig. 12.

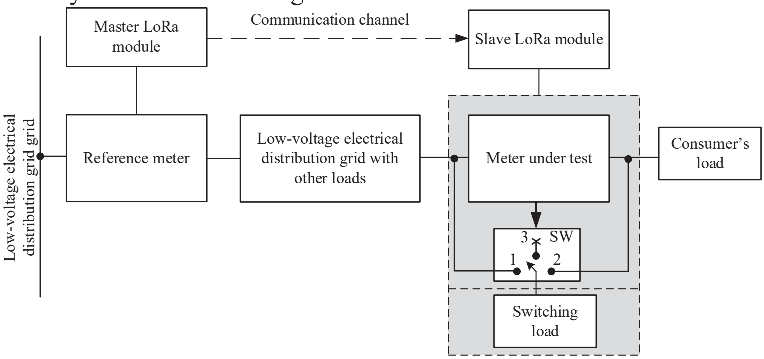

Fig. 12. Experimental system block diagram

Two LoRa communication modules were used to synchronize data and send commands between meters. The master module was configured to sending commands to the Slave LoRa communication module, which transfers them to the MUT for toggling additional load according to the command received. The slave module was configured to receive commands sent by the master module and transmit them immediately to the MUT.

Experimental method verification in low voltage network

The method was experimentally tested in a private house and a multi-apartment building. The private house was chosen because it was possible to know all loads in the grid. The number of devices switched on is lesser than in a multi-apartment building, leading to lower power fluctuations on the network.

DATASETS

The first set of data, SET1, was experimentally collected in a residential two-story private house (built in 1933, new electrical installation installed in 2010, and rated installation power is 10 kW). The RM measured the entire power consumption of the first floor, while the MUT measured power consumption in the bedroom. The list of connected devices to each of the EMs is listed in Table 5.

Table 5. List of connected devices to energy meters (SET1).

Meter	Connected devices
Reference meter	Kitchen: microwave oven, electric kettle, refrigerator, electric steam, electric oven. Bedroom: LCD TV, table lamp, 15 W USB charger, modem. Living room: Television, stereo system. Bathroom: Washing machine.
Meter under test	Bedroom: LCD TV, table lamp, 15 W USB charger, modem

The active power readings collected per day in a private house are shown in Fig. 13.

The second set of data, SET2, was experimentally collected in a residential five-story apartment building (built in 1973, apartment rated power is 6kW). The experiment was conducted in a five-story multi-apartment building with an RM connected to the electrical panel of one of the three electric phases of the multi-apartment building. The phase was used for feeding ten separate apartments. The MUT was connected at a third-floor apartment. The active power profile of the data set SET2 is shown in Fig. 14.

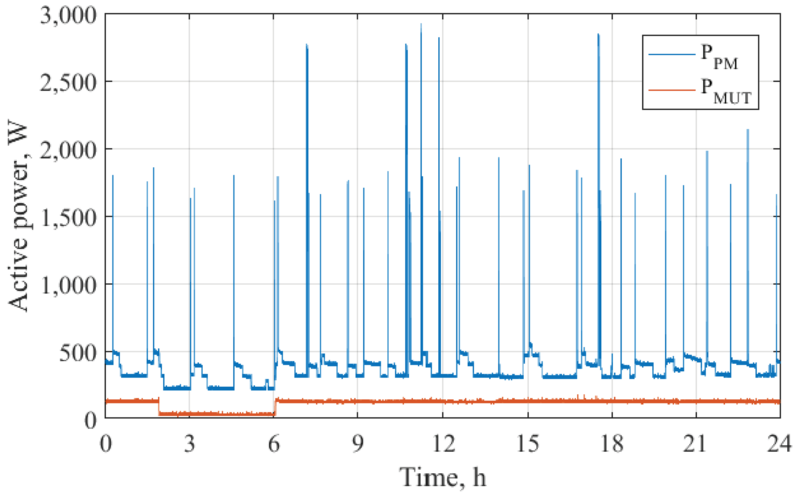

Fig. 13. RM and MUT-measured active power profiles in a private house over a 24-hour period (SET1).

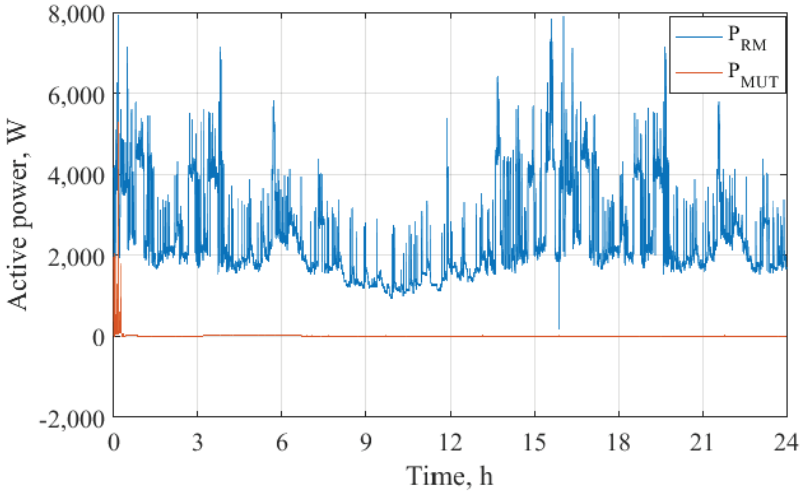

Fig. 14. RM and MUT-measured active power profiles in a multi-apartment building over a 24-hour period(SET2).

Results

The error of an active power adjustment gain was calculated following the expression (6) using datasets SET1 (Fig. 15) and SET2 (Fig. 16).

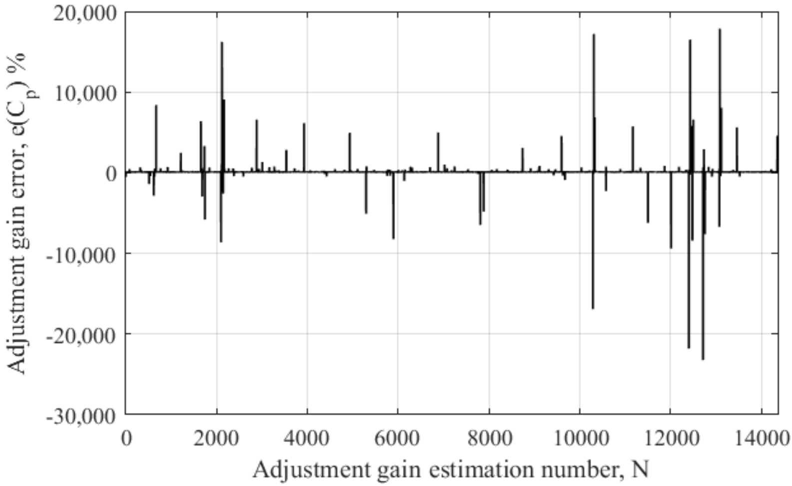

Fig. 15. The values of adjustment gain errors using data set SET1

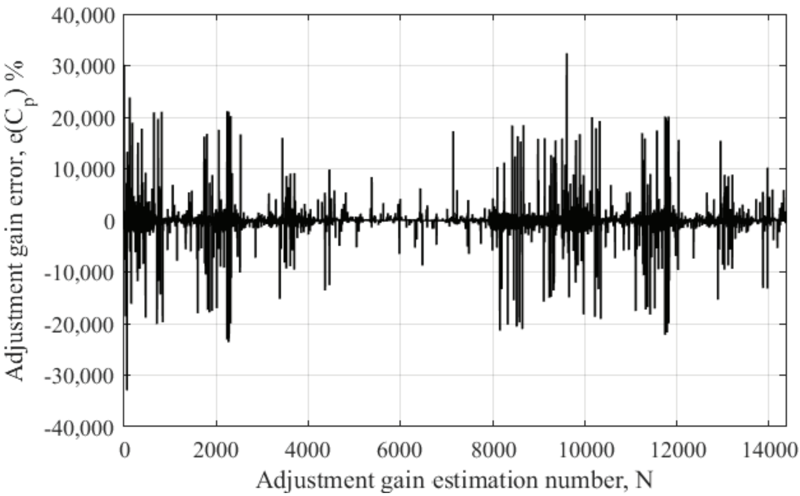

Fig. 16. The values of adjustment gain errors using data set SET2

We can see that there are cases where the error of an adjustment gain exceeds values of 10,000%. These values can be explained since the active power consumption of the electic grid is not stable and varies according to the number of connected devices and the users' activity. Therefore, one of the essential assumptions of the method is no longer valid because the active power consumed in the network during the MUT error monitoring must be constant. Power steps distort the average adjustment gain and lengthen the adjustment gain finding time (Fig. 17). The range of mean values of the adjustment gain with a probability of 95% is described:

$$\pm\Delta = e\left(M(C_p)\right) \pm 2\delta\left(e\left(M(C_p)\right)\right) \quad (17)$$

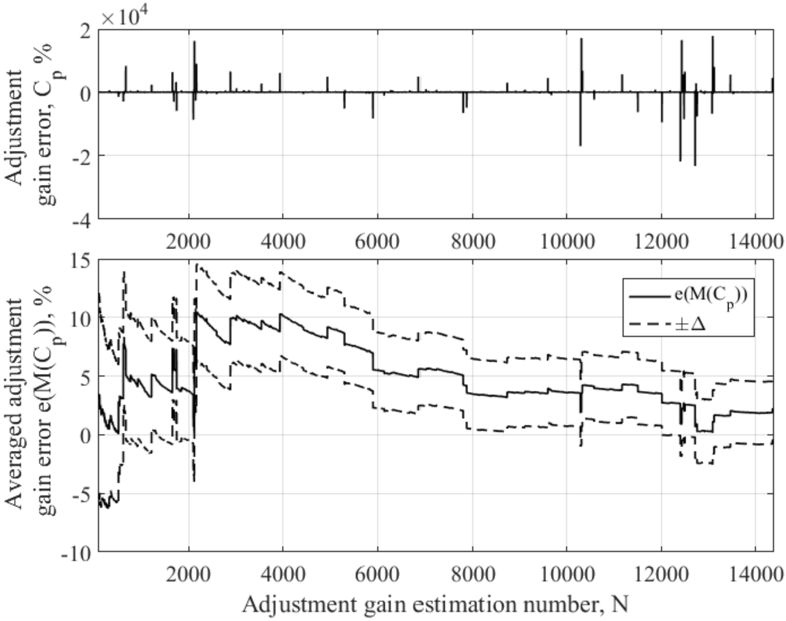

Fig. 17. Adjustment gain error (above) and adjustment gain error dependent on the number of averaged adjustment gain values (SET1)

Therefore, it is proposed to apply the rule of rejecting measurements of very high error (outliers such as -100% < e(C_p) or e(C_p) < 200%). Results using the outlier rejection rule are shown using datasets SET1 (Fig. 18) and SET2 (Fig. 19).

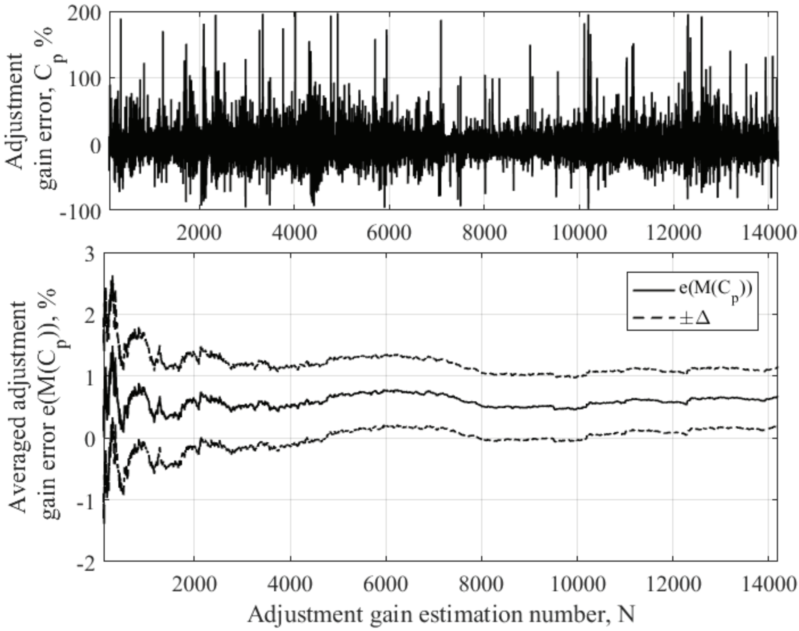

Fig. 18. Adjustment gain error (above) and adjustment gain error dependent on the number of averaged adjustment gain values (SET1).

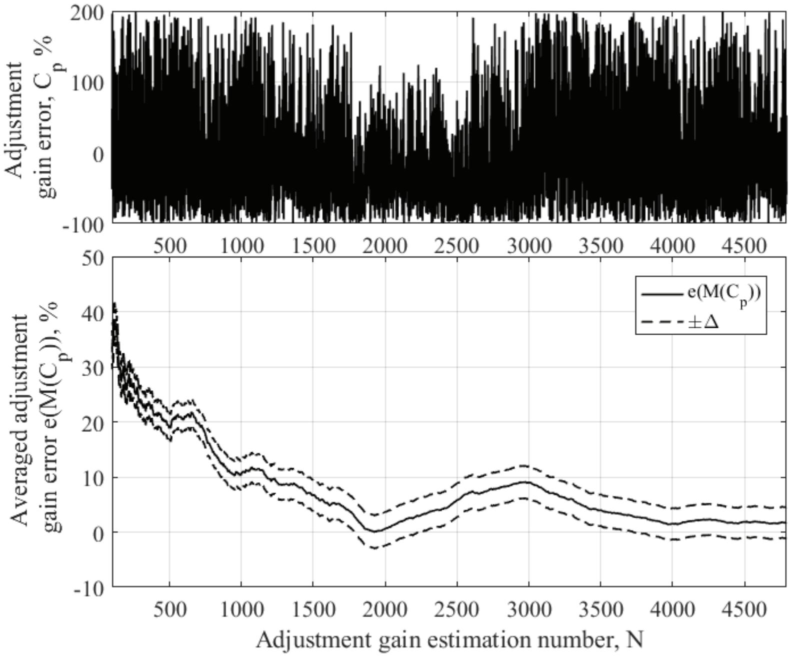

Fig. 19. Adjustment gain error (above) and adjustment gain error dependent on the number of averaged adjustment gain values (SET2).

The error of the 24 h averaging adjustment gain for SET2 was 2.21%. Once all adjustment gains have been selected, using the outlier rejection rule presented above, we can see that (9571/14400) = 66.47% of all transactions per day have been rejected, which means that only 33.57% of all transactions were used for adjustment gain calculation. Such low efficiency does not make it economically worthwhile to use this method only on a round-the-clock basis. If there was a wide variety of electrical loads on the distribution network, it would be helpful to wait until consumer activity is reduced (for example, during the night). Reduced consumer activity can be seen by selecting a 100-minute interval during the night (selected from Fig. 14, starting at hour nine of monitoring). When the outlier rejection condition is applied, the estimates of adjustment gain and the error rate average change are shown in Fig. 20.

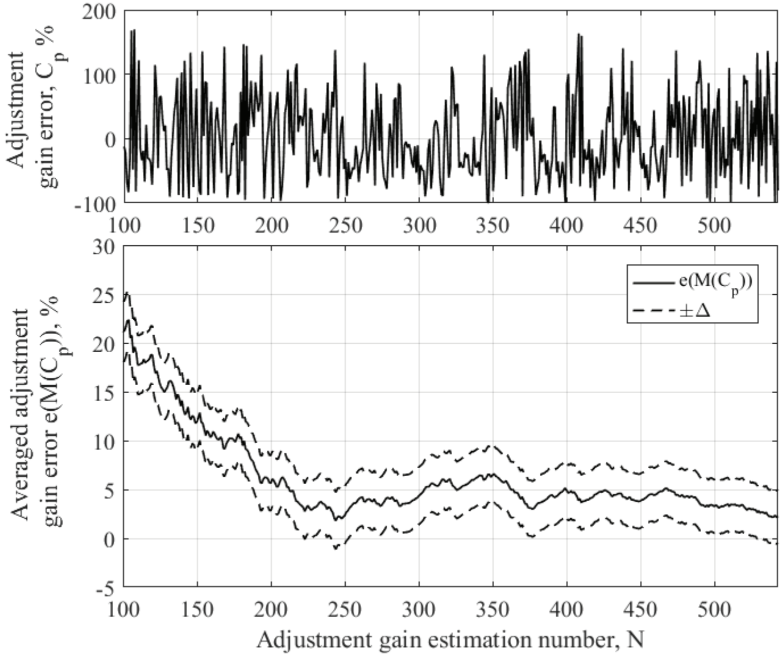

Fig. 20. Adjustment gain error (above) and adjustment gain error dependent on the number of averaged adjustment gain values (SET2).

Analysis of the uncertainty of the active power adjustment gain

Following GUM recommendations, the standard uncertainty of the calculated MUT adjustment gain mean $\overline{C_p}$ can be expressed as follows:

$$u^2(\overline{C_p}) = w_{RM1}^2 u^2(\overline{P_{RM1}}) + w_{RM3}^2 u^2(\overline{P_{RM3}}) + 2r(\overline{P_{RM1}}, \overline{P_{RM3}}) w_{RM1} w_{RM3} u(\overline{P_{RM1}}) u(\overline{P_{RM3}}) + w_{MUT2}^2 u^2(\overline{P_{MUT2}}) + w_{MUT1}^2 u^2(\overline{P_{MUT1}}) + 2r(\overline{P_{MUT1}}, \overline{P_{MUT2}}) w_{MUT2} w_{MUT1} u(\overline{P_{MUT2}}) u(\overline{P_{MUT1}}) + 2r(\overline{P_{RM1}}, \overline{P_{MUT1}}) w_{RM1} w_{MUT1} u(\overline{P_{RM1}}) u(\overline{P_{MUT1}}) + u^2(\overline{c_E}), \quad (7)$$

here $w_{RM1}, w_{RM3}, w_{MUT1}$, and w_{MUT2} are sensitivity coefficients calculated as partial derivatives of (6) in respect of $\overline{P_{RM1}}$, $\overline{P_{RM3}}$, $\overline{P_{MUT1}}$, and $\overline{P_{MUT2}}$ respectively; $u(\overline{P_{RM1}})$ and $u(\overline{P_{RM3}})$ are standard uncertainties of measurements acquired by the RM, $u(\overline{P_{MUT2}})$ and $u(\overline{P_{MUT1}})$ are standard uncertainties of measurements acquired by the MUT, $r(\overline{P_{RM1}}, \overline{P_{RM3}})$, $r(\overline{P_{MUT1}}, \overline{P_{MUT2}})$, and $r(\overline{P_{RM1}}, \overline{P_{MUT1}})$ are correlation coefficients between measurements of quantities shown in brackets, and $u(c_E)$ is the standard uncertainty due to the assumptions made while deriving the indirect measurement equation (5). The standard uncertainty for the average active power measurements collected by the RM is

$$u^2(\overline{P_{RM}}) = u^2_{RMRes} + u^2_{Var}(\overline{P_{RM}}) \quad (8)$$

here P_{RM} stands for P_{RM1} or P_{RM3}. RM resolution and variance-related uncertainty constituents are correspondingly

$$u^2_{RMRes} = \frac{\Delta^2_{RM}}{12} \quad (9)$$

and

$$u^2_{Var}(\overline{P_{RM}}) = \frac{\sigma^2_{VarRM} + \sigma^2_{fRM}}{N}, \quad (10)$$

here Δ_{RM} is the resolution of RM in watts, σ_{VarRM} is the variance of measurement results caused by the RM error, σ_{fRM} is the standard uncertainty term induced by power consumption fluctuations in the distribution grid measured at RM. N is the number of measurements used to estimate average power measurements.

Similarly, the uncertainty of the average power measurement obtained by the MUT is

$$u^2(\overline{P_{MUT}}) = u^2_{MUTRes} + u^2_{Var}(\overline{P_{MUT}}), \quad (11)$$

where P_M stands for P_{M2} or P_{M3}. MUT resolution and variance-related uncertainties are correspondingly

$$u^2_{MUTRes} = \frac{\Delta^2_{MUT}}{12} \quad (12)$$

and

$$u^2_{Var}(\overline{P_{MUT}}) = \frac{\sigma^2_{VarMUT} + \sigma^2_{fMUT}}{N}, \quad (13)$$

here Δ_{MUT} is the resolution of MUT in watts, σ_{VarMUT} is the variance of measurement results caused by the MUT error, σ_{fMUT} is the power consumption fluctuation variance measured at the MUT.

Variances $u^2_{Var}(\overline{P_M})$ could be estimated from the measurement data. However, it would be much more convenient if measurement instrument specification could be used instead of collecting data experimentally at this research stage. Therefore, seeking to avoid underestimation of the variance-related uncertainty (19), the error from the instrument specification assuming a uniform distribution is used for the characterization of meter variances

$$\sigma_{VarRM} = \frac{e_{RM}}{\sqrt{3}} \quad (14)$$

$$\sigma_{VarMUT} = \frac{e_{MUT}}{\sqrt{3}} \quad (15)$$

where specified error of the RM expressed using the accuracy class of the meter is

$$\mathrm{e}_{RM} = \frac{RM\ Accuracy\ Class}{100\%} P_{RM} \quad (16)$$

and the specified error of the MUT is

$$e_{MUT} = \frac{MUT\ Accuracy\ Class}{100\%} P_{MUT.} \quad (17)$$

If the RM or the MUT was calibrated (industrial metrology), then the power measurement variances of the meter (25) and (26) would be estimated using information about variance (data scattering) from its calibration certificate.

The relative standard uncertainty of C_p expressed in percent from the average value of estimated adjustment gain is

$$u(C_{pr}) = \frac{u(C_p)}{C_p} \cdot 100\ \%. \quad (18)$$

In Table 6, ten cases are shown to provide an insight into the achievable relative uncertainty of C_p relating to the standard values of quantities and parameters affecting uncertainty under (18)–(28). For the numerical estimation of typical uncertainties, a realistic energy consumption level in the residential premise P_L and power consumption in the sub-grid that delivers energy to a group of consumers in a multi-apartment building or a small group of private houses P_{grid} are selected. Since relative uncertainty depends on the magnitude of the adjustment gain, its values for the most common adjustment gain ($C_p = 1$) are given in Table 6.

Table 6. Cases of standard uncertainty of meter adjustment gain and the influencing factors

Parameter	Case number									
P_{grid}, kW	1	2	3	4	5	6	7	8	9	10
P_L, kW	1	1	1	5	5	1	5	5	7.5	10
P_S, W	0.1	0.5	0.1	0.1	0.5	0.1	0.5	1	1	1
N (averaged power samples)	2,160	2,160	2,160	2,160	2,160	1,800	1,800	1,800	1,800	1,800
RM accuracy class	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Δ_{RM}, W	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
σ_{fRM}, W	0.2	0.2	0.2	0.6	0.6	0.2	0.2	0.6	0.2	0.2
$\frac{\sigma_{fRM}}{P_S} 100\ \%$	2%	2%	2%	6%	6%	2%	2%	2%	2%	2%
MUT accuracy class	1	1	1	2	2	1	1	2	1	1
Δ_{MUT}, W	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
σ_{fMUT}, W	0.2	0.2	0.2	0.2	0.2	0.05	0.05	0.05	0.05	0.05
$\frac{\sigma_{fMUT}}{P_S} 100\ \%$	2%	2%	2%	2%	2%	0.5%	0.5%	2%	0.5%	0.5%
$u(k_E)$, %	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$r(\overline{P_{RM1}}, \overline{P_{RM3}})$	0	0	0,5	0	0	0	0	0	0	0
$r(\overline{P_{MUT1}}, \overline{P_{MUT2}})$	0	0	0,5	0	0	0	0	0	0	0
$r(\overline{P_{RM1}}, \overline{P_{MUT1}})$	0	0	0,5	0	0	0	0	0	0	0
$\boldsymbol{u}(c_{pr})$, %	**4.2**	**4.2**	**3.6**	**9.3**	**9.4**	**3.2**	**3.9**	**4.9**	**5.9**	**6.8**

Table 6shows cases 4 and 5 with the higher uncertainty $u(C_{pr})$, mainly due to higher power fluctuations.

CONCLUSIONS

1. The dissertation presents a new method of remote error monitoring of electricity meters, which allows to remotely estimate the active power errors of the meters under test without disconnecting them from the electricity grid and without interrupting the electricity supply to the consumer.
2. The possibilities of application of the analysed method of remote metrological condition verification are as follows: 1) in the field of legal metrology, in order to establish the moment of extraordinary inspection of a meter or a group of meters; 2) in the field of industrial metrology, in order to correct meter readings or establish the need to replace a meter.
3. When computer-modelling the proposed method, a typical model of the electricity distribution network was used, and it has been found that the systematic error of estimating the adjustment gain does not exceed 0.31%.
4. The impact on the accuracy of the method in the power fluctuation distribution network was examined experimentally and using synthesized

power profiles. Applying the adjacent power samples exceeding the 20 W rejection threshold and averaging the samples in six-minute intervals, the standard deviation of the experimentally measured active power fluctuations in a typical low-voltage distribution network did not exceed 0.1 W. When processing the synthesized active power profiles with a sampling period of 1 s, a standard deviation of 0.2 W for adjacent power measurements at 2 s intervals was established with the use of averaging in a 3-hour interval and a 20 W filtering threshold. The standard deviation of power fluctuations impacts the uncertainty of the estimation of the adjustment gain of the active power.

5. Having implemented the system layout and performed experimental tests in typical electrical distribution networks of buildings, it was found that by applying multiple estimations of the adjustment gain and the averaging over a 1-day interval and using the correction factor estimation filtering, the method made it possible to obtain a random error component of the estimation of the adjustment gain which does not exceed 2%.
6. With the use of the tested meters with the accuracy class 1 and 2, the readings of the active power of which do not exceed 0.5 kW, and with the use of reference meters of accuracy class 1 and 2, the readings of the active power of which do not exceed 5 kW, it was found that the uncertainty of the estimated adjustment gain does not exceed 9.4%.

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LIST OF SCIENTIFIC AND OTHER PUBLICATIONS

ARTICLES IN PEER-REVIEWED SCIENTIFIC PUBLICATIONS

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(1) NAKUTIS, Žilvinas; KAŠKONAS, Paulius; SAUNORIS, Marius; **DAUNORAS, Vytautas**; JURČEVIĆ, Marko. A framework for remote in-service metrological surveillance of energy meters // Measurement. Oxford: Elsevier. ISSN 0263-2241. 2021, vol. 168, art. no. 108438, p. 1-10. DOI: 10.1016/j.measurement.2020.108438.

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Tyrimo aktualumas

Elektros energijos skaitikliai yra plačiai naudojami elektros energijos suvartojimo vartotojų ūkiuose, gamybos cechuose, bendrosioms paslaugoms, tokioms kaip apšvietimas bei oro kondicionavimas apskaitai ir energetinių auditų tikslams. Be tradicinių komercinės elektros energijos apskaitos priemonių, vis labiau plinta išankstinio apmokėjimo, subapskaitos ir suminės apskaitos skaitiklių, bei tinklo būsenos stebėsenos matuoklių naudojimas [1]–[4]). Įvairūs išmanieji lizdai, išmanieji kištukai, išmanieji matuokliai, kaip priedai prie atsinaujinančios energijos inverterių, ir kt. sudaro besiplečiantį elektros energijos matuoklių (EEM) parką. Komercinės apskaitos matuokliai patenka į teisinės metrologijos reguliavimo sritį, o jų matavimo rezultatai naudojami vartotojų apmokestinimui. Taip pat, atsižvelgdamas į elektros energijos matuoklių rodmenis, vartotojas sprendžia apie patalpų, gamybos vietos ar kt. elektros energijos vartojimo efektyvumą. Tikimasi, kad išmaniųjų elektros energijos skaitiklių plėtra Europos Sąjungoje leis 3 % sumažinti elektros energijos suvartojimą dėl atisrandančių galimybių vartotojams koreguoti savo energetinę elgseną [5]. Taigi, pasitikėjimas energijos matuoklių matavimo tikslumu yra aktualus ne tik komercinėje apskaitoje teisingiems atsiskaitymams už pateiktą ir suvartotą energiją, bet ir priimant sprendimus bei vertinant energetinio efektyvumo gerinimo priemones. Dėl didelio rinkoje naudojamų komercinių ir nekomercinių energijos apskaitos priemonių jų metrologinės priežiūros kaštai yra dideli, įvertinant skaitiklio išmontavimo, transportavimo, pakaitinio skaitiklio instaliavimo ir patikros ar kalibravimo paslaugų įkainius. Todėl metrologinės priežiūros kaštų sumažinimui yra naudojami statistinės (atrankinės) patikros metodai, kurie leidžia priimti sprendimą apie homogeniškos skaitiklių grupės atitiktį standartų reikalavimams, remiantis tik nedidelės dalies skaitiklių metrologine patikra. Statistinės patikros intervalai elektros skaitikliams įvairiose pasaulio šalyse yra gana ilgi, pvz., Lietuvoje 12 metų, o skaitiklių metrologinės charakteristikos netikrinamos iki šio intervalo pabaigos. Tiesa, matuokliai gali būti iš anksto tikrinami gavus vartotojo nusiskundimą. Tačiau, jeigu paklaidos padidėjimas nėra akivaizdus, tai net ir netenkinantis metrologinių reikalavimų skaitiklis gali būti eksploatuojamas daugelį metų, taip lemdamas finansinius nuostolius tiekėjui arba vartotojui. Išmaniųjų EEM energijos matavimo paklaidos tolygus didėjimas nėra pagrindinė neatitikties specifikuotiems reikalavimams priežastis [6], kadangi matuoklių vidinių komponentų gedimai gali sąlygoti staigų paklaidos pasikeitimą ir nulemti ženklius ekonominius nuostolius tiekėjui arba vartotojui [7]. Dėl šių priežasčių pastaruoju metu vis intensyviau yra ieškoma naujų būdu, kaip būtų galima atlikti nuotolinę EEM paklaidų stebėseną ir jos rezultatus panaudoti metrologinei priežiūrai eksploatacijos metu. Sprendžiant minimas problemas kyla darbo **mokslinė problema**: trūksta žinių, kaip nuotoliniu būdu stebėti elektros energijos matuoklių paklaidas, nepertraukiant elektros tiekimo elektros vartotojui, bei kaip nustatyti tokiais stebėsenos metodais pasiekiamą paklaidos įvertinimo neapibrėžtį.

Įvairiose mokslinėse publikacijose bei techninėse ataskaitose yra svarstoma apie galimybę atlikti EEM paklaidų stebėseną be transportavimo į sertifikuotą laboratoriją. Šiems metodams bendra tai, kad tikrinamasis elektros energijos matuoklis (TM) nėra išmontuojamas iš savo eksploatacijos vietos. Pagal pamatinio (etaloninio) matuoklio (PM) arba etaloninio matuojamo dydžio, pvz., etaloninės apkrovos prijungimą prie TM, gali būti išskiriami du nuotolinės stebėsenos tipai:

- stebėsena matuoklio eksploatacijos vietoje (angl. *on-site verification*), kuriai reikalingas PM transportavimas į TM eksploatavimo vietą;
- nuotolinė matuoklių stebėsena kai PM ir TM yra vienas nuo kito nutolę, bet sujungti duomenų perdavimo ryšio kanalu.

Darbo mokslinė hipotezė formuluojama taip: EEM aktyviosios galios matavimo paklaidą galima praktikoje priimtinu tikslumu įvertinti nuotoliniu būdu ir jo neišmontuojant iš eksploatacijos vietos bei nenutraukiant energijos tiekimo vartotojui, panaudojant pamatinį energijos matuoklį, prijungtą tame pačiame skirstomojo tinklo potinklyje kaip ir tikrinamasis matuoklis. Prielaidos, kurių laikomasi iškeliant hipotezę yra: matavimo vienetą perduodančios terpės (elektros tinklo) įnešamos sistemingosios paklaidos įtaka nuotolinės stebėsenos tikslumui yra paneigtina, o atsitiktinių paklaidų įtaka gali būti sumažinta iki pageidaujamos ribos, taikant daugkartinius matavimus ir jų rezultatų apdorojimą.

Nors teisinėje metrologijoje EEM paklaidų nuotolinės stebėsenos metodai kol kas nėra numatomi ar standartizuoti, bet jie galėtų būti išbandomi asmeninės ar pramoninės apskaitos (subapskaita) srityse Tikimasi, kad teisinės metrologijos reguliuojamoje srityje nuotolinių paklaidos stebėsenos metodų rezultatai galėtų vaidinti pagalbinę rolę, pasirenkant neeilinės patikros laiko intervalus.

Kuriant nuotolinės EEM paklaidų stebėsenos metodus ir juos realizuojančius techninius sprendimus, patrauklumo vartotojui ir metrologinės priežiūros kaštų mažinimo požiūriu yra tikslinga siekti tokių savybių:

1) nebereikia EEM išmontavimo ir gabenimo į akredituotą laboratoriją,

2) EEM paklaidų stebėsenos metu vartotojo nereikia atjungti nuo elektros tinklo,

3) individualaus EMM paklaidos nustatymą galima užsisakyti kaip vienkartinę arba periodinę paslaugą.

Tyrimo tikslas ir uždaviniai

Daktaro **disertacijos tikslas** – sukurti ir ištirti nuotolinį žemos įtampos elektros skirstomųjų tinklų elektros energijos apskaitos prietaisų paklaidų stebėsenos metodą, panaudojant sinchronizuotą pamatinę matavimo priemonę, įjungtą elektros potinklio įvade.

Darbo tikslui pasiekti suformuluoti **uždaviniai**:

1. Pasiūlyti nuotolinį elektros energijos matuoklių paklaidų stebėsenos metodą, sudarantį sąlygas paklaidų stebėseną vykdyti

nuotoliniu būdu nenutraukiant elektros energijos tiekimo vartotojui.
2. Atlikti metodo panaudojimo galimybių teisinės ir pramoninės metrologijos srityse analizę.
3. Atlikti nuotolinio TM paklaidos stebėsenos metodo verifikavimą matematinio modeliavimo būdu, nustatant sistemingosios matavimo paklaidos ribas tipiniame žemosios įtampos elektros skirstomajame tinkle.
4. Atlikti tinklo ir apkrovų įtakos TM paklaidos įvertinimo nuotoliniu būdu neapibrėžčiai analizę.
5. Sukurti metodą realizuojančią eksperimentinę sistemą ir ja naudojantis atlikti nuotolinio TM paklaidos stebėsenos metodo verifikavimą eksperimentiniu būdu tipiniame žemosios įtampos skirstomajame elektros tinkle, nustatant TM paklaidos įvertinimo neapibrėžtį.

Darbo mokslinis naujumas:

Rengiant disertaciją buvo gauti šie nauji elektros ir elektronikos inžinerijos mokslui rezultatai:

1. Pasiūlytas naujas nuotolinės EEM paklaidų stebėsenos metodas, nepertraukiant elektros tiekimo elektros vartotojui panaudojant sinchronizuotą pamatinę matavimo priemonę įjungtą potinklio įvade.
2. Nustatytos pasiūlyto metodu pasiekiamos paklaidos tipiniuose žemosios įtampos elektros skirstomuosiuose tinkluose.

Praktinė darbo reikšmė

Disertacijoje gauti rezultatai panaudoti sukuriant nuotolinį aktyviosios galios paklaidų stebėsenos metodą bei apskaičiuojant juo pasiekiamą multiplikatyvinio aktyviosios galios pataisos koeficiento įvertinimo neapibrėžtį. Sukurto metodo įdiegimo atveju numatoma vertė yra geresnė elektros energijos vartotojų ir tiekėjų ekonominių interesų apsauga, įgalinant nuolatinę matavimo skaitiklių parko būsenos stebėseną, nesiunčiant aptarnaujančio personalo į skaitiklio įdiegimo vietą, jo neišmontuojant ir netransportuojant į metrologijos laboratoriją. Sukurtasis stebėsenos metodas nėra skirtas pakeisti galiojančios metrologinės priežiūros procedūrų, įteisintų nacionaliniuose teisės aktuose, tačiau jis įgalina kiekvienos elektros energijos matavimo priemonės būklės stebėseną intervaluose tarp metrologinių patikrų, o jo rezultatai gali būti panaudoti identifikuoti pavienius skaitiklius, kurių metrologinės charakteristikos netenkina atitinkamų standartų reikalavimų.

Disertacijos tyrimų rezultatai buvo panaudoti vykdant:

− KTU tarpsritinį / tarpkryptinį mokslo projektą „Nuotolinio elektros apskaitos prietaisų kalibravimo ir diagnostikos metodas (ELENOT)“ 2017.

– KTU MTEPI fondo finansuotą mokslo projektą „Žemos įtampos elektros tinklų parametrų stebėsenos sinchronizavimo būdų tyrimas paskirstytomis matavimo priemonėmis“ 2018.

Rezultatų aprobacija

Disertacijos metu gauti moksliniai rezultatai buvo pateikti 8 publikacijose: 3 iš jų straipsniai leidiniuose, įrašytuose į mokslinės informacijos instituto (ISI Web of Science) referuojamų leidinių, turinčių citavimo indeksą, sąrašą,

5 publikacijos tarptautinių konferencijų, vykusių Splite (Kroatija), Bolonijoje (Italija), Liverpulyje (Didžioji Britanija), Turine (Italija), medžiagos rinkiniuose. Rezultatai taip pat pristatyti Lietuvoje (Pabariukų k. Kelmės r.) vykusioje konferencijoje bei mokslinių darbų konkurse Vilniuje.

Ginti pateikiami rezultatai

1. Sukurtas naujas nuotolinis EEM paklaidų stebėsenos metodas, paremtas tikrinamojo matuoklio aktyviosios galios rodmenų palyginimu su PM rodmenimis. Šis metodas leidžia pasiekti ne didesnę negu 0,31 % sistemingąją tikrinamojo matuoklio matavimo multiplikatyvinio pataisos koeficiento paklaidą, nepriklausomai nuo kitų tame pačiame žemos įtampos skirstomajame tinkle energiją vartojančių apkrovų.
2. Pasiūlytą metodą teisinės metrologijos srityje galima taikyti, siekiant greičiau aptikti EEM, kurių paklaida viršija leistiną ribą dar prieš pasibaigiant patikros intervalui, o pramoninės metrologijos srityje, siekiant aptikti EEM paklaidos padidėjimą ir esant poreikiui koreguoti rodmenis.
3. Nutolusio matuoklio aktyviosios galios multiplikatyviojo pataisos koeficiento nustatymo atsitiktinę paklaidą įtakoja skirstomajame tinkle veikiančių elektros apkrovų trumpalaikės galios fluktuacijos ir vartojamos galios pokyčiai, kurių poveikį galima efektyviai mažinti, atliekant daugkartinius matavimus ir taikant vidurkinimo bei filtravimo procedūras.
4. Taikant pasiūlytąjį nuotolinės stebėsenos metodą, galima pasiekti tikrinamojo matuoklio multiplikatyviojo pataisos koeficiento standartinę santykinę neapibrėžtį, ne didesnę negu 9,4 %, kai pamatinio matuoklio instaliavimo vietoje matuojamai galiai neviršijant 5 kW, tikrinamojo matuoklio instaliavimo vietoje galia neviršija 0,5 kW, TM tikslumo klasė yra 1 arba 2, o PM tikslumo klasė yra 0,2 arba 0,5.

Disertacijos struktūra

Daktaro disertaciją sudaro įvadas, 4 skyriai, išvados, literatūros sąrašas ir mokslinių publikacijų disertacijos tema sąrašas. Darbo apimtis – 114 puslapių, kuriuose pateikiami 77 paveikslai, 15 lentelių, 55 matematinių išraiškų ir 101 pavadinimų literatūros sąrašas.

I skyrius: Pirmajame skyriuje apžvelgti vietiniai bei nuotoliniai elektros energijos skaitiklių (matuoklių) paklaidos įvertinimo metodai.

II skyrius: Antrajame skyriuje aprašytas siūlomas nuotolinės elektros energijos skaitiklių paklaidų stebėsenos metodas.

III skyrius: Trečiajame skyriuje pateiktas pasiūlyto metodo sistemingosios paklaidos tyrimas ir gauti rezultatai, modeliuojant metodo taikymą tipiniame žemos įtampos skirstomajame tinkle. Taip pat skyriuje yra nagrinėjama galios fluktuacijų elektros tinkle įtaka momentinės aktyviosios galios matavimo atsitiktinėms paklaidoms, pasiūlyti šių paklaidų mažinimo būdai bei apibūdintas jų efektyvumas.

IV skyrius: Ketvirtajame skyriuje aprašytas nuotolinio EEM klaidų stebėsenos metodo patikrinimas, atliekant eksperimentinius tyrimus, bei aktyviosios galios matavimo pataisos koeficiento nustatymo neapibrėžties analizė.

BENDROSIOS IŠVADOS

1. Disertacijoje pristatytas naujas nuotolinės elektros energijos matuoklių paklaidų stebėsenos metodas, leidžiantis nuotoliniu būdu įvertinti tikrinamojo elektros energijos matuoklio aktyviosios galios paklaidas, jo neatjungiant nuo elektros tinklo bei nepertraukiant elektros tiekimo vartotojui.
2. Nagrinėjamo nuotolinės metrologinės būklės stebėsenos metodo taikymo galimybės yra: 1) teisinės metrologijos srityje, siekiant nustatyti matuoklio ar jų grupės neeilinės patikros momentą; 2) pramoninės metrologijos srityje, siekiant atlikti matuoklio rodmenų pataisą arba nustatyti matuoklio pakeitimo poreikį.
3. Pasiūlytą metodą modeliuojant kompiuteriniu būdu, taikytas tipinis elektros skirstomojo tinklo modelis ir buvo nustatyta, kad sistemingoji multiplikatyvinio pataisos koeficiento įvertinimo paklaida neviršija 0,3 %.
4. Galios fluktuacijų skirstomajame tinkle įtaka metodo tikslumui buvo ištirta eksperimentiškai bei naudojant sintezuotus galios profilius. Taikant gretimų galios imčių, viršijančių 20 W atmetimo slenkstį ir imčių vidurkinimą 6 min. intervale, eksperimentiniu būdu išmatuotų aktyviosios galios fluktuacijų tipiniame žemos įtampos skirstomajame tinkle standartinis nuokrypis neviršijo 0,1 W. Apdorojant sintezuotus aktyviosios galios profilius, kurių diskretizavimo periodas 1 s, buvo

nustatytas 0,2 W gretimų galios matavimų 2 s intervaluose standartinis nuokrypis, taikant vidurkinimą 3 val. intervale ir 20 W filtravimo slenkstį. Galios fluktuacijų standartinis nuokrypis įtakoja multiplikatyvinio aktyviosios galios pataisos koeficiento įvertinimo neapibrėžtį.

5. Realizavus sistemos maketą ir atliktus eksperimentinius bandymus tipiniuose pastatų elektros skirstomuosiuose tinkluose nustatyta, kad taikant daugkartinį multiplikatyvinio pataisos koeficiento įvertinimą ir vidurkinimą vienos paros intervale bei naudojant pataisos koeficiento įverčių filtravimą, metodas leido pasiekti pataisos koeficiento įvertinimo atsitiktinę paklaidos dedamąją, neviršijančią 2 %.
6. Naudojant 1 ir 2 tikslumo klasės tikrinamuosius matuoklius, kurių aktyviosios galios rodmenys neviršija 0,5 kW, bei 0,2 ir 0,5 tikslumo klasės pamatinius matuoklius, kurių galios rodmenys neviršija 5 kW, nustatyta įvertinto multiplikatyvinio pataisos koeficiento neapibrėžtis neviršija 9,4 %.

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