The experimental verification of metrological properties of direct current Watt-hour meter

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Abstract. The paper presents a method for evaluating the accuracy of indications of the direct current Watt-hour meters in a designed and constructed measuring system. Such measuring system is composed of two multi-function calibrators, and a specialised high-voltage attachment dedicated for this system, which makes it possible to generate direct voltages in a required range up to 4 kV with a suitably high precision. The authors described in detail particular elements of the measuring system together with the results of its calibration. They showed the results of experiments carried out on a large and representative number of LE3000plus Watt-hour meter items.

1. Introduction

The evaluation of metrological parameters of devices dedicated for settlements among enterprises and market contributors is a complex measurement problem. In practice, calibration is frequently assumed as the proper form of such evaluation. The values obtained as result of calibration, associated with the uncertainty of determining them, should be defined in specified measuring points, according to respective standards and other supplementary documents. The paper presents a method for evaluating the parameters of DC energy meter LE3000plus. Meters of that type find application in measuring the power and energy of direct current in the railway traction network. The currently used meters are modern measurement devices, usually microprocessors, equipped with an additional measurement interface that allows the remote transmission of registered measurement results.

The evaluation of meter will be in this paper focused on the determination of the accuracy of measuring the voltage, current, and import/export energy of the supply network.

The evaluated Watt-hour meter of type LE3000plus consists of: high-voltage, measuring part LE3000plus_HVM, low-voltage, communication part - LE3000plus_KOM, measuring shunt, fiber optic cable connecting the high-voltage and low-voltage parts, GSM/GPS antenna, together with antenna wires. A detailed description of all the functions and potential of this meter is included in [1].

2. Measuring system for the evaluation of the metrological properties of Watt-hour meters

A measuring system was prepared for calibrating the evaluated meter whose construction was described in the previous chapter. It has a direct current supply in a range of 0 V - 4 kV, and a signal

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of current shunt corresponding to the flow of a current with values between a few hundred and over a thousand amperes.

The measuring system consists of two multi-function calibrators, and a specialised high-voltage attachment dedicated for this system, which allows the generation of direct voltages in a demanded range of up to 4 kV with suitably high precision.

Fig. 1 presents a diagram of the prepared measuring system for the testing of direct current Watt-hour meters.

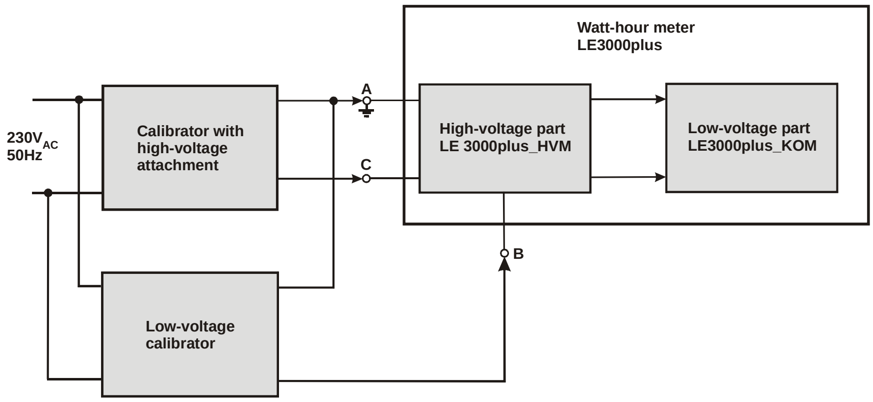

Figure 1. Diagram of measuring system for testing the direct current Watt-hour meters.

The signal between terminals A and B corresponds, in working conditions, to the voltage drop on the external measurement shunt, and the signal between terminals A and C is the voltage corresponding actually to a high voltage in electrical traction. In the developed measuring system voltage U_{AB} attained small values, and therefore the costs of insulation between internal blocks of the measuring system were minimized. Terminal C of the developed measuring system is located on a high minus potential, of the order of 4 kV. Proper configuration and insulation of this terminal guaranteed safe operation of the whole measuring system. The developed measuring system provides appropriate metrological parameters, minimum energy consumption from the supply network, which is relevant in view of the research costs, as well as adequate separation of components.

The determined relative value of expanded uncertainty of this part of the measuring system equals 0.06 % and it is stated in the current calibration certificate. In the original version of the system, during the determining of electrical energy values, time was measured with mechanical stopwatch. At the measurement of time of the order of 30 min. with such stopwatch, the value of expanded uncertainty at a level of 0.12 s was achieved. A detailed description of these problems can be found in work [2].

Essential modifications were introduced in the present version of measuring system, which enabled the energy measurement inaccuracies to be significantly limited. The modifications allowed the error related to the reaction time of the person conducting the measurements to be eliminated. High voltage obtained from the voltage calibrator with attachment is connected to the investigated meter for the whole duration of measurements. During normal work of a meter in railway traction network the load current is measured by the meter indirectly, through a voltage drop on the external shunt. In the measuring system the load current measured by the meter is simulated by the low-voltage calibrator, the output signal of which simulates the voltage drop from the shunt. The calibrator is equipped with a precise time distributor with a range of settings 1 ÷ 85 min. It generates a signal during a strictly specified time interval; in standard version it is a 15-minute interval. The construction of this calibrator makes it possible to generate an impulse with the longest possible rise time, which is identical to the shortest possible time of switching the impulse on and off. This calibrator, together with the time distributor that is its integral part, was calibrated in order to evaluate the inaccuracies of time and voltage measurement.

The results of calibrating the time distributor were compared to the state standard of units of time and frequency measurement. For this purpose, a digital frequency-time meter of type 53132A was used as the control device, synchronized with the model frequency from the state standard of units of time and frequency measurement. The low-voltage calibrator was tested in lab with an ambient temperature of (21.9 ÷ 23.0) °C and relative humidity (38.3 ÷ 41.3) %. The calibration results were compared to the state standard of units of direct electrical voltage measurement by using a digital multimeter. The measurement uncertainties were determined according to the recommendations in document [3].
The calibrator with high-voltage attachment as well as the low-voltage calibrator work with an inner feedback loop. Therefore, the output signals of both devices are stable in time. The value of expanded uncertainty of time measurement in this measuring system, compared to the measuring method with a mechanical stopwatch, is over fifty times smaller.
A detailed description of these problems can be found in work [4].

3. Experimental research

In the measuring system presented in Fig. 1, the Watt-hour meters of direct current LE 3000plus were calibrated. During this process, the indications of the same meter were compared with the settings on control devices. The readings were made from the display of the very meter, with resolution equal to 0.1 kWh. Because, in case of meters installed in electrical locomotives, the energy imported from and exported to the network is in standard version registered in 15-minute records, it is purpose-full and essential that also the measurement time of the meter's parameters equals 15 minutes. Therefore, it is possible to compare the results displayed on the meter with the values set on the measuring devices.

3.1. Voltage measurements

The meter under evaluation was installed in the measuring system – its diagram is shown in Fig. 1. The tests were carried out for nominal voltage U_n = 3300 V, and also for voltages differing from the nominal voltage by ± 10 %. For each of these voltages the measurements were repeated many times. The measurements were carried out in lab with an ambient temperature of (22.5 ÷ 22.9) °C and relative humidity (41.1 ÷ 45.3) %. Examples of the results achieved are shown in Table 1.

Table 1. Results of calibrating LE3000plus meter at voltage measurements

U_n = 3300 V								
Test point U = 2970 V			Test point U = 3300 V			Test point U = 3630 V		
W_{wsk}	W_{zad}	Δ	W_{wsk}	W_{zad}	Δ	W_{wsk}	W_{zad}	Δ
V	V	V	V	V	V	V	V	V
2970	-2971.00	-1.00	3300	-3300.80	-0.80	3630	-3630.80	-0.80
2970	-2971.20	-1.20	3300	-3301.00	-1.00	3630	-3631.00	-1.00
2970	-2971.00	-1.00	3300	-3300.60	-0.60	3630	-3630.60	-0.60
2970	-2971.20	-1.20	3300	-3301.00	-1.00	3630	-3631.00	-1.00
2970	-2971.00	-1.00	3300	-3300.60	-0.60	3630	-3630.80	-0.80
2970	-2971.20	-1.20	3300	-3301.00	-1.00	3630	-3630.80	-0.80
2970	-2971.00	-1.00	3300	-3300.60	-0.60	3630	-3630.60	-0.60
2970	-2971.20	-1.20	3300	-3301.00	-1.00	3630	-3630.80	-0.80
2970	-2971.00	-1.00	3300	-3300.60	-0.60	3630	-3630.60	-0.60
2970	-2971.20	-1.20	3300	-3300.80	-0.80	3630	-3630.80	-0.80

Correct values W_{zad} of voltage measurement were given according to the setting adopted on the control equipment. Because according to the diagram shown in Fig. 1, the system works with the so-called "inverted mass", in this case the indication error Δ takes a form according to equation (1):

$$\Delta = W_{wsk} - (W_{zad}) \tag{1}$$

where W_{wsk} is the value indicated by the evaluated meter.

3.2. Current measurements
Similar meter evaluation was carried out with regard to current changes. The measurements were done in seven test points for the following current values: 50 A, 100 A, 250 A, 500 A, 800 A, 1000 A, and 1500 A, and the value of nominal current for this meter was I_n = 1000 A. For each of these currents, the measurements were repeated many times. The measurements were carried out in lab at the same values of temperature and humidity variation as in the case of voltage measurements. Examples of test results achieved during the measurements for 3 test points are presented in Table 2. Similarly as for the voltage measurements, the value of current indication error Δ was determined according to equation (1).

Table 2. Results of calibrating LE3000plus meter at current measurements

I_n = 1000 A								
Test point I = 50 A			Test point I = 1000 A			Test point I = 1500 A		
W_{wsk}	W_{zad}	Δ	W_{wsk}	W_{zad}	Δ	W_{wsk}	W_{zad}	Δ
A	A	A	A	A	A	A	A	A
49.9	-50.0	-0.1	999.4	-1000.0	-0.6	1498.9	-1500.0	-1.1
49.9	-50.0	-0.1	999.5	-1000.0	-0.5	1498.8	-1500.0	-1.2
49.9	-50.0	-0.1	999.4	-1000.0	-0.6	1498.9	-1500.0	-1.1
49.9	-50.0	-0.1	999.4	-1000.0	-0.6	1498.9	-1500.0	-1.1
49.9	-50.0	-0.1	999.5	-1000.0	-0.5	1498.9	-1500.0	-1.1
49.8	-50.0	-0.2	999.4	-1000.0	-0.6	1498.8	-1500.0	-1.2
49.9	-50.0	-0.1	999.4	-1000.0	-0.6	1498.9	-1500.0	-1.1
49.8	-50.0	-0.2	999.5	-1000.0	-0.5	1498.9	-1500.0	-1.1
49.9	-50.0	-0.1	999.4	-1000.0	-0.6	1498.9	-1500.0	-1.1
50.0	-50.0	0.0	999.5	-1000.0	-0.5	1498.8	-1500.0	-1.2

4. Uncertainty budget
Final measurement result is complete only when it contains both the measurand value and the measurement uncertainty attributed to that value. According to document [5], measurement uncertainty is a non-negative parameter characterizing the dispersion of the quantity values, being attributed to the measurand, calculated on the basis of information used. Such parameter may be e.g. standard deviation, called standard measurement uncertainty (or its specified multiple), or a half of the width of an interval, having a specified extension probability. Usually measurement uncertainty comprises a lot of components. The values of some of them can be determined with Type A evaluation of measurement uncertainty, which consists in determining the value of a component of measurement uncertainty by means of the statistical analysis of the measurand values, obtained in defined measurement conditions.

According to document [6] – with the assumption that the best estimation of the measurand value, defined on the basis of a series of n observations, is arithmetic mean $\bar{x}$ – the value of the standard deviation estimator for the mean is equal to the standard uncertainty determined with Type A evaluation and given with equation (2):

$$s(\bar{x}) = u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}\,. \tag{2}$$

Other components, with values determined with Type B evaluation of measurement uncertainty, can also be characterized by means of standard deviation, determined with the probability density function

based on experience or other information. It consists in determining the value of a component of measurement uncertainty by means of instruments different from those applied in Type A evaluation [5]. There is not one stated algorithm for calculating standard uncertainty with Type B evaluation. A typical situation encountered in metrological practice is when we know only the variation limits of the values around a given result, e.g. the limiting error of measuring equipment Δ_g . It is possible to assume, then, that a value unbiased with the rounding error in each point of the rounding interval is equally probable, i.e. uniform distribution can be assigned to this interval. The above assumption on uniform distribution is rather safe because for such distribution, we obtain the biggest uncertainty value from among all symmetrical, limited, unimodal distributions, with the probability density function decreasing at the ends of the domain.
Statement of all identified component standard uncertainties estimated with A and B Type methods is called uncertainty budget. The aim of creating the uncertainty budget is to prove that the combined uncertainty of measurement result u_c, was estimated in a matter-of-fact, penetrating and verifiable way. With a correctly constructed budget, we can prove that all elements of uncertainty have been analysed, also those that were not the greatest parts of the combined uncertainty. It means that no element was rejected arbitrarily, based on believes or traditional manner of conduct. Moreover, no assumption was made that some element was negligibly small. Thanks to the analysis of uncertainty budget, we can answer the question: which component uncertainties are the greatest parts of the combined uncertainty? We can also indicate directions for improving the measurement, which could lead to significant decrease in the combined uncertainty. On that account, all the component uncertainties taken into consideration, also those with the value estimated as zero, should be listed in the budget. It is essential to assign a suitable type of probability distribution to particular component uncertainties in the uncertainty budget.
For the measurement results presented in Tables 1 and 2, the uncertainty budgets were prepared according to the rule described above.
Below, in Table 3, the uncertainty budget at the voltage measurement for test point U = 3300 V is presented.

Table 3. Uncertainty budget of LE3000plus meter for evaluation of selected voltage measurement

Quantity symbol	Quantity estimate	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Part of combined uncertainty
U_{wsk}-U_{zad}	-1.1	3.33E-02	Normal	1	3.33E-02
$\Delta\delta_U$	2.13 E-01	2.00E-02	Normal	- 1	2.00E-02
$\delta\Delta_{rU}$	0	2.89E-01	Rectangular	1	2.89E-01
Δ_U	-1.313	-	-	-	2.91E-01

The quantities influencing the value of combined uncertainty, put in the above table, denote respectively:

- U_{wsk}-U_{zad} – difference of indicated value and given value. Because for this factor normal distribution was assumed, uncertainty was determined with A Type method,
- $\Delta\delta_U$ – control device error, read out from a current calibration certificate of calibrator with high-voltage attachment. To this factor also normal probability distribution was assigned,
- $\delta\Delta_{rU}$ – correction resulting from the calibrated meter's resolution. To this factor rectangular distribution was assigned, therefore uncertainty was determined with B Type method,
- Δ_U – factor determined according to equation (U_{wsk} - U_{zad}) - $\Delta\delta_U$ + $\delta\Delta_{rU}$.

Table 4 shows the determined values of expanded uncertainty U, for the results of voltage measurements in Table 1.

Table 4. Results of calibrating voltage measurements for nominal voltage U_n = 3300 V

Voltage measurement (U_n = 3300 V)			
Indicated value U_{wsk}	Correct value	Indication error Δ_U	Measurement uncertainty U
V	V	V	V
2970	-2971.31	-1.3	0.6
3300	-3301.34	-1.3	0.6
3630	-3631.72	-1.7	0.6

For the current measurements contained in Table 2, the uncertainty budget was prepared in a way similar as for voltage measurements. The results for all test points are shown in Table 5.

Table 5. Results of calibrating current measurements for nominal current I_n = 1000 A

Current measurement (I_n = 1000 A)			
Indicated value I_{wsk}	Correct value	Indication error Δ_I	Measurement uncertainty U
A	A	A	A
49.9	-50.00	-0.11	0.09
99.8	-100.00	-0.16	0.09
249.7	-250.00	-0.34	0.11
499.8	-500.00	-0.18	0.11
799.5	-800.00	-0.47	0.12
999.4	-1000.00	-0.56	0.12
1498.9	-1500.00	-1.13	0.14

5. Conclusion

The authors of the paper attempted to discuss complex problems of experimental research on Watt-hour meters for voltage of the order of 4 kV. A designed and constructed measuring system was presented, consisting of two multi-function calibrators, a specialised high-voltage attachment dedicated for this system, in order to generate direct voltages in a range of up to 4 kV. The publication contains the results of experiments carried out on a numerous and representative set of direct current Watt-hour meters LE3000plus items, in the conditions of accredited laboratory. The testing of so large population of devices permitted the authors to draw reliable and objective conclusions. When selecting the measurement points of a meter tested in the measuring system, the authors took into account the conclusions drawn from the testing of meters in working conditions, during their normal work.

6. References

[1] Operational and Maintenance Manual 2011 Direct current Watt-hour meter 3 kV LE3000plus
[2] Otomański P Zazula P 2008 Metrological characteristics of measuring position for direct current Watt-hour meter research in range to 4 kV Electrical Review 2008 315-317
[3] EA-4/02 1999 Expression of the Uncertainty of Measurement in Calibration European co-operation for Accreditation
[4] Otomański P Zazula P The measuring system for the evaluation of the metrological properties of direct current Watt-hour meters Measurement Automation and Monitoring 2012 764-766
[5] JCGM 2008 *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)* JCGM 200:2008
[6] JCGM 2008 *Evaluation of measurement data – Guide to the expression of uncertainty in measurement* JCGM 100:2008