MEANS FOR MEASURING THE ELECTRIC AND MAGNETIC QUANTITIES

STUDY OF THE METROLOGICAL CHARACTERISTICS OF CONDUCTIVITY SENSORS

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Abstract. Conductivity measurement is a universal method of process control. Measurement is fast and straightforward, and most modern sensors only require little maintenance. The measured conductivity value is applied to obtain different assumptions about what happens in the substance, so such measurements are relevant when controlling technological processes and products in various industries (e.g., food, pharmaceutical).

The main metrological characteristics of sensors for measuring conductivity LDL100, LDL200 are analyzed in the article. Studies have been carried out for various objects: non-carbonated mineral water, fruit juice, and tap water.

Keywords: Conductivity, Tap water, Sensor, Uncertainty budget, Metrological characteristics.

1. Introduction

Rapid technological progress is pushing out obsolete equipment every day. Today, electromechanical systems have been replaced by electronic sensors, which are one of the brightest examples of digitalization. A lot of conductivity sensors (Fig. 1) on the market are large and bulky [1] or consist of two elements - a probe and an assessment processing unit, which must be calibrated in working conditions. The compact size of the LDL series sensors ensures easy deployment of sensors in enterprises/systems and reduces the mechanical load on the piping system. The standard 4-pin connector eliminates the need to connect terminal blocks. Since the LDL sensor is universal, calibration is not required under operating conditions. Moisture can penetrate the cable connections and cable entries of sensors from individual manufacturers [2]. This is often the weak point of sensors installed in wet areas. A series of LDL sensors reduces the number of failures by the universal transmitter IP68/IP69K. The sensors contain a solid stainless-steel housing probe and do not require a cable terminal box or cable entry. Application of the IO-Link software makes the opportunity to calibrate sensors in the workplace using a calibration factor (CGA) and a standard or reference solution.

There are two methods of measuring conductivity: galvanic and induction. The choice depends on the conductivity of the surrounding, the aggressiveness of the object under study, and the content of solid particles [3]. The LDL100 sensor is designed to measure liquids' electrical conductivity and temperature by the galvanic method (Fig. 2). The device is designed for direct contact with the environment (Fig. 1) [4].

The LDL200 sensor works on the inductive principle of measurement (Fig. 3).

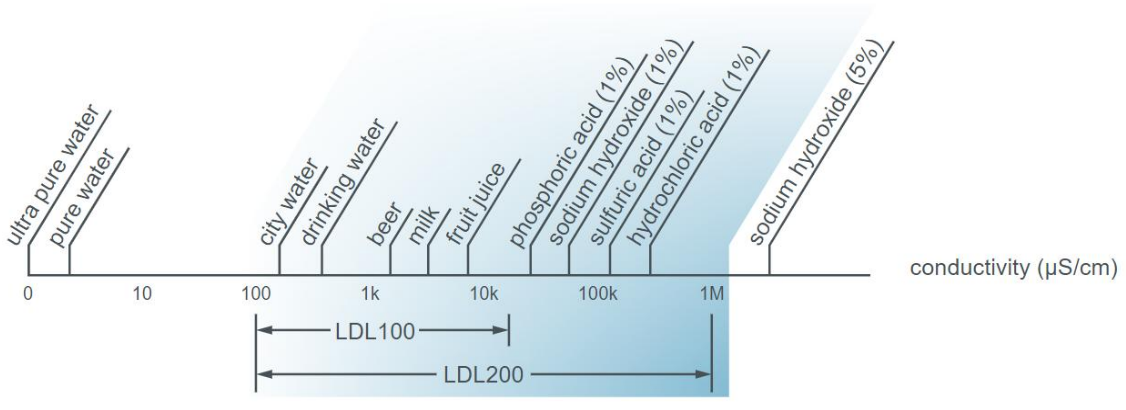
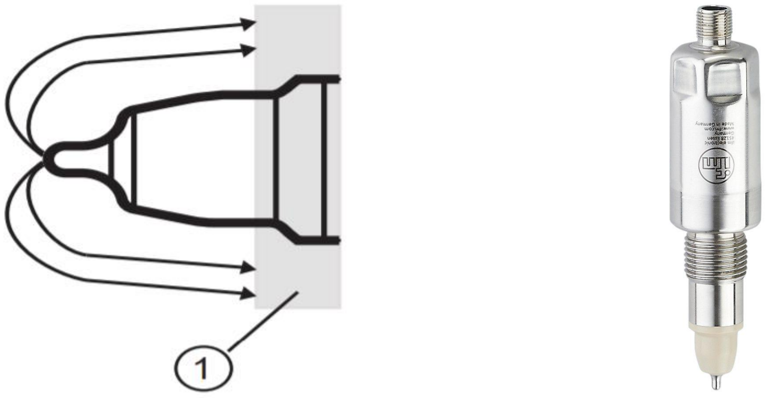
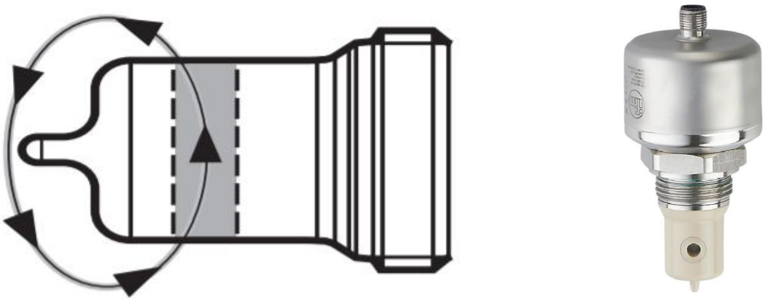


Fig. 1. Distribution of objects by conductivity



a) b)

Fig. 2. LDL100 sensor: a) block diagram; b) general appearance



a) b)

Fig. 3. LDL1200 sensor: a) block diagram; b) general appearance

LDL100 with measuring range 100 μS / cm… 15 μS / cm. Objects with a conductivity level above 15 μS / cm cannot be measured. LDL200 sensor with measuring range 100 μS / cm… 1S / cm.

2. Drawbacks

The information provided in the literature does not contain specific data on the metrological characteristics of conductivity sensors in the study of various objects and does not recommend their application.

3. The Goal of the Paper

The work investigates metrological characteristics and performs their comparative analysis for conductivity sensors LDL100, LDL200, built on different principles. To establish the sensitivity of the conductivity drift of such sensors to changes in temperature, investigate their stability, and compute the budget of the measurement uncertainty. To identify the trend of drift depending on the object under study.

4. Study of the Parameters of Conductivity Sensors

4.1 Research methods and analytical comparison of sensor characteristics

Conductivity was measured with two sensors LDL100, LDL200 for such objects as non-carbonated mineral water, fruit juice, tap water. Temperature sensitivity was studied from 38 ^{0}C to 18 ^{0}C by preheating the object and its natural cooling.

It should be noted that the conductivity sensors are mainly designed for use in the food industry. They determine the conductivity and concentration of different media and can distinguish, for example, detergents, wash water, and food. Thanks to them, it is possible to monitor the state of matter constantly and reduce the cost of resources and water. Accurate, fast, and reliable process measurements help improve the operational readiness of equipment and optimize control processes.

LDL 100 and LDL 200 sensors differ not only in the principle of operation but also in size and technical characteristics (Table 1).

The studied sensors generate an analog signal proportional to the value of electrical conductivity or ambient temperature. The setting of the analog output signal is to choose the scale of the resulting curve of the dependence of the output current on the conductivity or temperature. Examples of the application of sensors are given in Table 2.

Both sensors are equipped with an IO-Link communication interface, which allows sensor settings and direct access to the measured data. This requires either a personal computer with a USB IO-Link wizard or a USB drive programmed to adjust the sensor settings. In-service settings can also be performed using an IO-Link-compatible controller-based module.

Table 1

Sensors' performance

Characteristics	LDL 100	LDL 200
Accuracy (in the measuring range)	10 % MW ± 25 µS/cm	2% MW ±25µS/cm
Drift [%/K]	0.2 %/K MW ± 25 µS/cm	0,1 %/K MW ± 25 µS/cm
Temperature measurement	20...50 °C: < ± 0.5 K; -25...150 °C: < ± 1.5 K	20...50 °C: < ± 0.2 K; -25...150 °C: < ± 1.5 K
Measuring range [µS/cm]	100…15000	100…10000000
Measuring range [°C]	-25…150	-25…150

Table 2

Application of sensors

Application	LDL 100	LDL 200
Media transition measurement (e.g. rinse water/product)	✓	✓
Product differentiation / verification	✓	✓
Leak detection (ex. heat exchangers)	✓	✓
Water quality (above 100 µS / cm)	✓	✓
CIP chemical concentration		✓
Salinity		✓

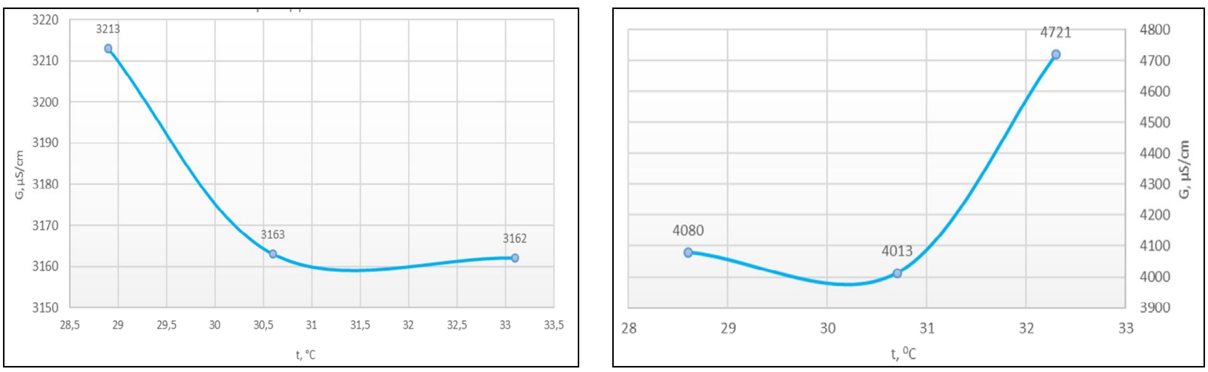
4.2 Assessment of temporal and temperature stability

Studies of temperature dependences of conductivity were performed for fruit juice (Table 3, Fig. 4). From the analysis of the obtained results, it can be concluded that the readings are unstable over time, and drift in the temperature is not observed. There are noticed jumps in conductivity. This can be explained by the nature of the object. Here, the chemical and biological processes happen over time and temperature alters, which leads to conductivity instability.

Table 3

The results of measurements of the conductivity of fruit juice depending on temperature

LDL 100		LDL 200	
Temperature, t, ^{0}C	Conductivity, G, µS/cm	Temperature, t, ^{0}C	Conductivity, G, µS/cm
33.1	3162	32.3	4721
30.6	3163	30.7	4013
28.9	3213	28.6	4080



a) b)

Fig. 4. Dependence of conductivity of fruit juice on temperature a) LDL-100 sensor, b) LDL-200 sensor

The next chosen object of study was mineral water, for which were obtained the results (Table 4, Fig. 4). The analysis of obtained results demonstrates that the readings are unstable; it was noticed a non-uniformity of conductivity with temperature. Natural mineralization of the studied objects causes the instability of the readings due to the certain transformations under heat impact.

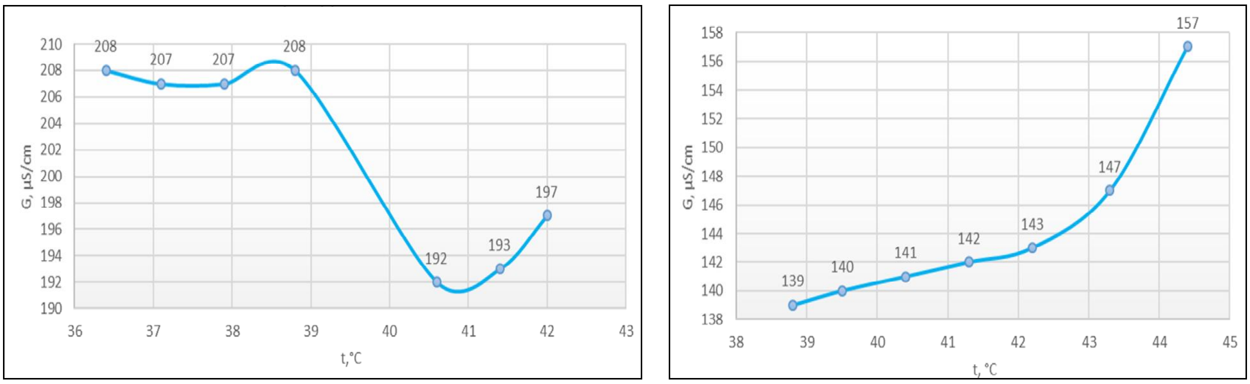
The most natural indications of the dependence of conductivity on temperature change were obtained for two sensors LDL-100 and LDL-200, for tap water of immutable composition (Table 5, Fig. 6).

To study the readings of sensors at higher conduction ranges, the concentration of minerals in water was changed by adding NaCl in portions. After the salt was completely dissolved, the sensors were immersed in water, and measurements were performed. By the same principle, add another 0.3 mg of salt to the solution. The measurement results are shown in Table 6.

Table 4

The results of measurements of the conductivity of still mineral water depending on temperature

LDL-200		LDL-100	
Temperature , t, ^{0}C	Conductivity, G, μS/cm	Temperature , t, ^{0}C	Conductivity, G, μS/cm
42	197	44,4	157
41.4	193	43,3	147
40.6	192	42,2	143
38.8	208	41,3	142
37.9	207	40,4	141
37.1	207	39,5	140
36.4	208	38,8	139



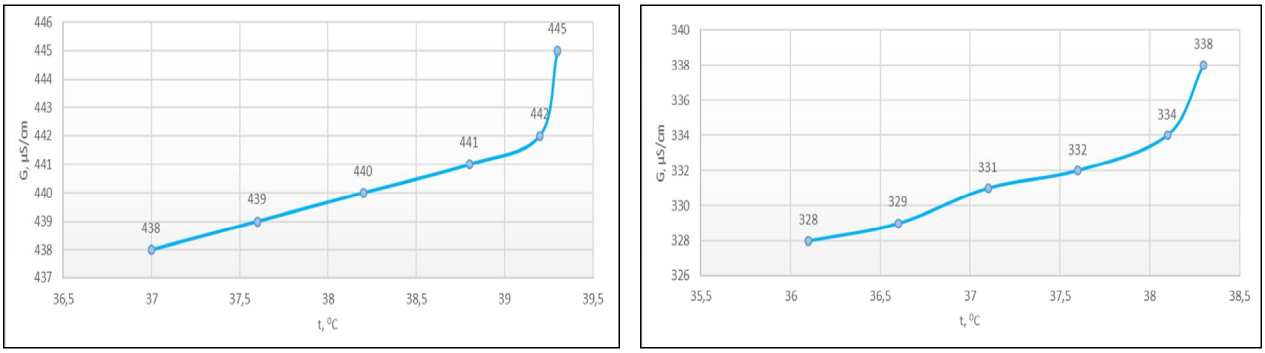
a) b)

Fig. 5. Dependence of non-carbonated mineral water conductivity on temperature
a) LDL-200 sensor, b) LDL-100 sensor

Table 5

The dependence of tap water conductivity on temperature

LDL-200		LDL-100	
Temperature, t, ^{0}C	Conductivity, G, μS/cm	Temperature, t, ^{0}C	Conductivity, G, μS/cm
39.3	445	38.3	338
39.2	442	38.1	334
38.8	441	37.6	332
38.2	440	37.1	331
37.6	439	36.6	329
37.0	438	36.1	328



a) b)

Fig. 6. Dependence of conductivity of tap water on temperature a) LDL-200 sensor, b) LDL-100 sensor.

Table 6

The conductivity of tap water after adding salt

LDL 100		LDL 200	
Temperature, t, ^{0}C	Conductivity, G, µS/cm	Temperature, t, ^{0}C	Conductivity, G, µS/cm
29.,3	2609 (+NaCl, c= 0.2 mg)	28.5	2714 (+NaCl, c= 0.2 mg)
28.3	6769 (+NaCl, c= 0.5 mg)	27.9	6253 (+NaCl, c= 0.5 mg)

Comparison of the sensitivity of the sensors to changes in concentration, taking into account the temperature, allowed us to conclude that at low values of conductivity, the difference in sensor readings is bigger (24 %) than at high values (8 %). This can be explained by the different principles of their construction and operation. In addition, they should be used for the research of low-impedance objects.

4.3 Calculation of the uncertainty budget of conductivity measurements

Uncertainty of type B assumes the error of each sensor, and uncertainty of type A was investigated by conducting 10-fold equivalent observations (Table 7) at a constant temperature of 16.3 ^{0}C of the studied object [5].

The calculated budget of uncertainties of conductivity measurement is given in Table 8.

Total standard measurement uncertainty (relative):

$$U_c(X) = \sqrt{U_A^2(X) + U_B^2(X)} = 4.35\ \%.$$

Effective degrees of freedom:

$$\nu_{eff} = (n-1)\cdot\left[\frac{u(y)}{u_A}\right]^4, \qquad (1)$$

Table 7

Results of multiple observations of conductivity

LDL-200, G, µS/cm	LDL-100, G, µS/cm
363	290
364	290
363	290
363	290
363	290
362	290
362	290
362	290
361	290
362	290

Table 8

The uncertainty budget of conductivity

Name quantities	The value of estimating quantities	±Δ	Type of uncertainty	Type of distribution probability	Absolute Standard uncertainty / Relative Standard uncertainty. %	Sensitivity index
Conductivity, G, µS/cm	362.5	± 25	B	Rectangular	14.4 µS/cm or 3.97%	1
Temperature, t, ^{0}C	16.3	± 0.5	B	Rectangular	0.29 ^{0}C or 1.78%	1
G, µS/cm	362.5	-	A	Normal	0.305 µS/cm / 0.08%	-
Name quantities	**The value of estimating quantities**	**Total standard uncertainty type B, %**	**Total standard uncertaint y, %**	**Coverage ratio**	**Extended uncertainty. %**	
G, µS/cm	362.5	$u_B(G) = \sqrt{U_G^2 + U_T^2} =$ =4.35%	4.35 %	2.1604	9.4%	

Since the parameters of the distributions of the components that cause uncertainty of the measurement result are known only approximately, the calculated standard uncertainties are also approximate. Assume that the relative uncertainty of the parameters of the distribution of components is approximately ¼ (because the exemplary (reference) tools used to determine the actual parameters of the measuring instrument, preferably only 3-5 times more accurate). Then the equivalent number of degrees of freedom of each of the components:

$$\nu_{екв,i} \approx \frac{1}{2\times(1/4)^2} = 8, \qquad (2)$$

The adequate number of degrees of freedom w:

$$\nu_{ef} = 13$$

Using the Student's distribution approximation for ν_{eff} = 4 and the confidence level P = 0.95, we find the coverage factor:

$$k_p = t_p(\nu_{ef}) = t_{0.95}(13) = 2.1604$$

Extended uncertainty at P=0.95:

$$U_p(X) = K \times U_c(X), \qquad (3)$$

Relative expanded uncertainty of the conductivity measurement result

$$U_{0.95}(G) = 2.1604 \times 4.35 = 9.4\%$$

5. Conclusions

1. The analysis of temperature dependences of conductivity performed for fruit juice and non-carbonated mineral water proved that sensor readings are volatile over time. The general trend is not observed; there are jumps in conductivity. The latter can be explained by the nature of the object in which chemical and biological processes, change the properties of the object with time. Non-stability in temperature can also lead to a similar conductivity. The most consistent indications of the dependence of conductivity on temperature change were obtained using two sensors LDL-100 and LDL-200, for tap water, which is characterized by an invariable composition unchangeable with temperature. 2. Comparison of the sensitivity of the sensors allowed us to conclude that at the measurement of low values of conductivity, the difference in sensor readings is higher (24 %) than at high values (8 %). This can be explained by the different principles of their construction and operation. Therefore, it is advisable to use sensors to study high-conductivity objects.

3. The budget for the uncertainties of conductivity measurements was calculated. The expanded relative uncertainty of the conductivity measurement was estimated as 9.4 % for the confidence level 0.95.

6. Gratitude

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7. Conflict of interest

The authors state that there are no financial or other potential conflicts regarding this work.

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