ENHANCING MEASUREMENT ACCURACY UNDER NONLINEAR SENSORS

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Abstract: The paper solves a physical quantity measurement enhancement problem under a shifted power sensor-transfer function with known and unknown values of its power exponent n. The problem is solved on the basis of a functional-algorithmic method, used to linearize a general transfer function, existing for a digital meter, as well as of a redundant measurements method, used for automatic correction of systematic errors. It is shown, that the distinctive feature of the former method is application of respective quantities substitution formulas. The essence of the proposed methods is described. The redundant measurements equations are derived.

Keywords: redundant measurements, errors, correction

1 INTRODUCTION

When technological process parameters or quantities of different physical nature are measured, digital meters (DM) with those sensors, which have a nonlinear transfer function (NTF), are widely applied due to the fact, that such sensors are highly sensitive under a low production cost price. The majority of sensor NTFs are elementary nonlinear, power, exponential, linear-fractional, nonlinear-fractional and some other functions [1-5]. The main drawback of NTF sensors is that an individual approach is needed for each applied sensor, since there are large variations of sensor characteristics. And when sensors, based on sensing semiconductor elements, are created, this circumstance entails some certain difficulties, associated with interchangeability of such sensors in DMs, with variations in characteristics, practically reaching 5% ... 15%, and with additional costs, needed for device adjustment and regulation.

On the other hand, when the conditions, under which the mentioned sensors are operated with, change, then sensor NTF parameters and, therefore, parameters of a general transfer function (GTF) of DMs (DM GTF), vary. Due to an effect, exerted by different destabilizing factors onto a sensor, and because of sensor ageing, observed, when sensors are operated with for long time, a real sensor transfer function (TF) differs from a nominal TF. In this case, a real sensor TF is described by the quantities equation

$$y_{nl} = S'_{nl}\, x^{n} + \Delta y_{nl}\ ,\tag{1}$$

where $S'_{nl} = S_{nl}(1+\gamma_{nl})$ is a current conversion conductance with a size $\{S'_{nl}\}$, which becomes different from a nominal size $\{S_{nl}\}$ due to destabilizing factors; $\Delta y_{nl} = \Delta y + \Delta_a$ is a resulting NTF shift; Δy is an initial TF shift; Δ_a is an additive error component or zero drift of a sensor; $x^{n}\gamma_{nl} = \Delta_{mp}$ is a nonlinear component of a multiplicative error; and γ_{nl} is a relative deviation of a conversion conductance from a nominal value.

Hence, all this causes an urgency and a necessity for resolution of the problems, concerned with GTF linearization and with automatic correction of systematic errors, introduced by a sensor, when it is operated with and when sensors are replaced after operation time expiration.

2 DM GTF LINEARIZATION

To solve the mentioned problems, the existing linearization methods were analyzed in [6-8]. But they cannot be applied for DM GTF linearization in a proper way. Therefore, some new functional-algorithmic (FAL) methods [9] are elaborated for this purpose. The FAL methods are based on

application of the formulas, illustrating substitution of sensor input and output quantities, and this is done in order to obtain linearization algorithms.

Under a power sensor TF, the DM GTF linearization problem can be solved for two special cases, when: a) a value of n is known and constant; and b) a value of n is not known.

2.1 DM GTF Linearization under a known value of n

Consider the linearization problem solution for the case, when a power exponent value is known and constant. To solve this problem, use the quantities substitution formulas $X = x^n$ and $Y = y_i$ [10]. The quantities X and Y are transformed, and the quantities x, y_{nl} and Δy_{nl} are initial or transformable. Substitute the transformed quantities $X = x^n$ and $Y = y_i$ into quantities equation (1), and the linear equation of transformed quantities (or the linearization algorithm) is obtained as follows:

$$Y_i = S'_{nl} X_i + \Delta Y_{nl} . \tag{2}$$

The unknown parameters S'_{nl} and ΔY_{nl} in equation (2) and the quantity X_i can be determined, if additional quantities equations are made up and when an obtained quantities equation system is solved with respect to unknown parameters. In particular, a formula, used to determine the value of $S'_{nl,}$ may be derived in the following way. When proceeding from expression (2), make up two additional equations with respect to the quantities X_1 and X_2, which have their specified sizes, the difference of their right and left sides is taken and then solved for S'_{nl} In this case, as for their sizes, the transformed quantities X_1 and X_2 are to differ from each other K_l times, while this value is known, i.e. $\{X_2\} = K_ë \{X_1\}$. Hence, the sizes of the initial physical quantities (PhQ) x_2 and x_1 are interrelated by the equation $x_2 = k_ë x_1$ (under $K_ë = (k_ë)^n$).

The coefficient $k_ë$, which characterizes a normalized deviation of a size of one quantity with respect to some other quantity and which provides the solution for the considered problem, is dealt with as the first linearization coefficient. A numerical value of $k_ë$ should be selected as such one, which is close, but not equal to one, i.e.: $k_l = 0,8…0,99$, or $k_l = 1,01…1,2$, and it should be also such one, that a deviation of X_1 from X_2 (or of x_2 from x_1) is a small-size quantity, but, at the same time, a meter should be able to make out this quantity [10].

If the relation $\{X_2\} = K_l \{X_1\}$ is taken into account, then the additional quantities equations are described by the expressions

$$Y_1 = X_1 S'_{nl} + \Delta Y_{nl,} \tag{3}$$

and

$$Y_2 = K_l X_1 S'_{nl} + \Delta Y_{nl} . \tag{4}$$

The unknown parameter S'_{nl} can be calculated by solution of equations(3) and (4) relative to this parameter. Take equations (3) and (4) into account, and the final form of quantities equation (2) is

$$Y_i = X_i \frac{Y_2 - Y_1}{X_1(K_l - 1)} + \Delta Y_{nl} . \tag{5}$$

Linear quantities equation (5) contains the unknown quantity $\Delta Y_{nl,}$ which can be determined, when the system of three additional equations of transformed quantities is solved with respect to ΔY_{nl} . To derive these equations, any three PhQs should be used [10], which have specified sizes and which are chosen within a domain of possible values of a quantity X_i , and a size of one of them is to be equal to the square root of the product of sizes of two other PhQs. To meet this condition, it is proposed to use the quantities X_1 , X_2 and X_3 , which satisfy the equality $\{X_2\} = \sqrt{\{X_1\}\{X_3\}}$, viz. $\{X_2\} = K_ë \{X_1\}$ and $\{X_3\} = K_l \{X_2\} = K^2_l \{X_1\}$. Therefore, the main GTF linearization condition is to select such PhQs x_1, x_2, and x_3 , the sizes of which are in their geometric progression

$$\{x_1\}, k_l \{ x_1 \}, k^2_l \{ x_1 \}. \tag{6}$$

Take this condition into account, and the third equation

$$Y_3 = K^2_ë X_1 S'_{nl} + \Delta Y_{nl} . \tag{7}$$

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is added to equations of transformed quantities (3) and (4). Solve the system of three equations (3), (4) and (7) with respect to ΔY_{nl}, and the following equation is obtained:

$$\Delta Y_i = (Y_1 \, Y_3 - Y_2^{\,2}) / (Y_1 + Y_3 - 2Y_2) \tag{8}$$

Take equation (8) into account, and the final form of equation (5) is

$$Y_i = X_i \frac{Y_2 - Y_1}{X_1(K_{\ddot{e}} - 1)} + \frac{Y_1 Y_3 - Y_2^2}{Y_1 + Y_3 - 2Y_2} \, . \tag{9}$$

2.2 DM GTF Linearization under an unknown value of n

When a sensor TF power exponent is not known, then, if a GTF is to be linearized, it is expedient to apply the isomorphism, under which new and initial variables are interrelated, in particular, by logarithmic transformations. In this case, it is possible to use simple natural and decimal logarithmic operations. For the considered shifted power TF, the quantities substitution formulas [10] $X' = ln \, x$, and $Y' = ln \, (y_{nl} - \Delta y_{nl})$, or $X'' = lg\,x$ and $Y'' = lg \, (y_{nl} - \Delta y_{nl})$ are used under linearization with reference to a specified NTF graph point A $[0, \Delta y_{nl}]$.

Place the quantity Δy_{nl} into the right side of expression (1) and take the logarithm of both sides of the equation:

$$ln \, (y_{nl} - \Delta y_{nl}) = ln S'_{nl} + n \, ln x \, . \tag{10}$$

Take expressions $X' = ln \, x$ and $Y' = ln \, (y_{nl} - \Delta y_{nl})$ into consideration, and the linear equation of transformed quantities (the linearization algorithm) is obtained in the following form:

$$Y_i = nX_i + ln S'_{nl} \, . \tag{11}$$

The unknown parameters S'_{nl} and n of power TF (1) and linear TF (11) can be determined, if additional quantities equations are made up on the basis of equation (11) and solved with respect to unknown parameters.

As it is shown above, one condition of GTF linearization, performed when it is impossible for a zero-sized PhQ to be created, consists in selection of PhQs of specified sizes, while these are in their geometric progression. Hence, suppose, that, in accordance with quantities equation (11), those quantities X_1 and X_2 are transformed, the sizes of which are k_l times different. Then,

$$Y_1 = nX_1 + ln S'_{nl} \, , \tag{12}$$

and

$$Y_2 = nX_2 + ln S'_{nl} \, . \tag{13}$$

Solve system (12)-(13) with respect to the unknown parameter n, and

$$n = \frac{Y_2 - Y_1}{X_2 - X_1} \tag{14}$$

is obtained. Take expression (14) into account, and linear equation of transformed quantities (11) has the following form:

$$Y_i = X_i \frac{Y_2 - Y_1}{X_2 - X_1} + ln S'_{nl} \, . \tag{15}$$

The parameter S'_{nl} of equation (15) can be determined, when equations (12) and (13) are solved. As a result, the unknown parameter $ln S'_{nl}$ is described by the quantities equation

$$ln S'_{nl} = 0,5(Y_1 + Y_2) - 0,5(X_1 + X_2)\frac{Y_2 - Y_1}{X_2 - X_1} \, . \tag{16}$$

Finally, the equation of transformed quantities for an unknown sensor TF power exponent value has the form

$$Y_i = 0{,}5(Y_1 + Y_2) + [X_i - 0{,}5(X_1 + X_2)]\frac{Y_2 - Y_1}{X_2 - X_1} \; . \tag{17}$$

This is the essence of the FAL methods, used for DM GTF linearization under known and unknown values of n. Under a power sensor TF, the following main linearization condition is to be met: to make up three additional quantities equations, it is necessary to select such three PhQs, the specified sizes of which are in their geometric progression.

3   REDUNDANT MEASUREMENTS METHODS WITH AUTOMATIC CORRECTION OF SYSTEMATIC ERRORS

To solve measurement accuracy enhancement problems under a sensor NTF, some methods of redundant measurements of PhQs with automatic correction of systematic errors are developed. The paper considers two redundant measurements methods, used for the case with power sensor TF (1).

3.1   Error correction under a known and constant value of n

Solve equation of transformed quantities (9) with respect to X_i and write this expression, when proceeding from initial quantities. Due to $\Delta y_{nl} = [y_{nl1}\, y_{nl3} - (y_{nl2})^2\,]\,/\,(y_{nl1} + y_{nl3} - 2y_{nl2})$ for these initial values,

$$x_i = x_1 \sqrt[n]{(k_{\ddot{e}}^{\,n} - 1)\frac{y_{nli}(y_{nl1} + y_{nl3} - 2y_{nl2}) - (y_{nl1}\, y_{nl3} - y_{nl2}^2)}{(y_{nl2} - y_{nl1})(y_{nl1} + y_{nl3} - 2y_{nl2})}} \; , \tag{18}$$

is derived, where

$$y_{nl\,i} = S_{nl}\,(1 + g_{nl})\,x_i^n + \Delta y + \Delta_{\grave{a}} \; , \tag{19}$$

$$y_{nl\,1} = S_{nl}\,(1 + g_{nl})\,x_1^n + \Delta y + \Delta_{\grave{a}} \; , \tag{20}$$

$$y_{nl\,2} = S_{nl}\,(1 + g_{nl})\,x_2^{\,n} + \Delta y + \Delta_{\grave{a}} \tag{21}$$

and

$$y_{nl\,3} = S_{nl}\,(1 + g_{nl})\,x_3^{\,n} + \Delta y + \Delta_{\grave{a}} \tag{22}$$

are the quantities equations, which exist for the case, when deviations of sensor NTF parameter values from nominal values are taken into consideration. And here, the condition $\{x_2\} = \sqrt{\{x_1\}\{x_3\}}$ is also to be met for the PhQs x_1, x_2 and x_3 of the specified sizes, and, at the same time, this condition is true only when the sizes of these PhQs are in their geometric progression.

In accordance with redundant measurements equation (18), when a real value of the controlled PhQ x_i is determined under a power sensor TF, it is necessary to measure homogeneous PhQs in four steps and to process obtained values (of a controlled PhQ and of correcting PhQs) in one step.

3.2   Error correction under an unknown value of n

Solve linear equation of transformed quantities (17) with respect to X_i and write the obtained equation as for initial quantities. As a result, the logarithmic equation of redundant measurements is

$$lnx_i = 0{,}5(lnx_1 + lnx_2) + \Big[ln(y_i - \Delta y_i) - 0{,}5\,ln(y_2 - \Delta y_i) - 0{,}5\,ln(y_1 - \Delta y_i)\Big]\frac{ln(x_2 / x_1)}{ln(y_2 - \Delta y_i) - ln(y_1 - \Delta y_i)} \tag{23}$$

The final redundant measurements equation for the case with the power sensor NTF and with an unknown value of n is obtained after taking of antilogarithm of expression (23), i.e.

$$x_i = \sqrt{x_1 x_2} \left[\frac{y_{nli} - \Delta y_{nl}}{\sqrt{(y_{nl1} - \Delta y_{nl})(y_{nl2} - \Delta y_{nl})}} \right]^{\ln (x_2 / x_1) \Big/ \ln \frac{y_{nl2} - \Delta y_{nl}}{y_{nl1} - \Delta y_{nl}}} \tag{24}$$

where y_{nli}, y_{nl1} and y_{nl2}, described, respectively, by expressions (19), (20) and (21), are the main quantities equation and the additional quantities equations, written for the case, in which deviations of power sensor TF parameters from nominal values are considered.

Expression (24) contains the unknown quantity Δy_{nl}. Its calculation and the derivation of the corresponding redundant measurements equation is associated with creation of three additional quantities equations and with their solution with respect to Δy_{nl}. The following main linearization condition is to be met here: to make up three additional quantities equations, it is necessary to select such PhQs x_1, x_2 and x_3 of the specified sizes, which are in their geometric progression

$$\{x_1\}, \ k_l\{x_1\}, \ k^2_l\{x_1\} \ ... \tag{25}$$

with the common ratio, equal to the linearization coefficient k_l. The solution of three additional quantities equations results in the following equation of redundant measurements of a real power TF shift value:

$$\Delta y_{nl} = \frac{y_{nl1} y_{nl3} - y_{nl2}^2}{y_{nl1} + y_{nl3} - 2 y_{nl2}} \tag{26}$$

in which

$$y_{nl3} = S_{nl} (1 + g_{nl}) \, x_3^{\,n} + \Delta y + \Delta_à \tag{27}$$

In accordance with expressions (24) and (26), when a real value of the controlled PhQ x_i is calculated under a power sensor TF and under an unknown power exponent value, it is necessary to execute four steps of measurements of homogeneous PhQs and one step of processing of intermediate PhQ measurement results.

The analysis shows, that the result of determination of a real value of the PhQ x_i is beyond an influence, exerted onto it by an absolute value and nonstability of the parameter S_{nl}, possessed by the power TF, by absolute values of the additive component of the measurement error $\Delta_à$ and by the TF shift Δy_{nl}. The errors of regeneration of the PhQs x_2 and x_3, which have their specified sizes, as well as the errors of AD conversion of output sensor quantities remain not eliminated. The possible ways to decrease them are: 1) to regenerate the PhQs x_2 and x_3 of specified sizes with the same absolute error, i.e. under $\{\Delta_{x\,2}\} = \{\Delta_{x3}\} = \{\Delta_x\}$; 2) to provide an equal precision of AD conversion of PhQs, especially of x_2 and x_3, which have their specified sizes, since this circumstance leads to a decreased resulting relative error; and 3) to introduce certain respective corrections, for instance, to change a sensor TF shift or an output sensor signal level.

4   CONCLUSION

A measurement accuracy of DMs, possessing those sensors, which have a shifted power TF with a known or an unknown value of power exponent n, is enhanced, when the above-mentioned redundant measurements methods and equations, associated with automatic correction of systematic errors, are implemented.

It is shown, that it is possible for the DM GTF linearization problem to be solved, if the FAL methods, used to linearize a sensor NTF, are the basis. The formulas of substitution of only one sensor input quantity is proposed for application. The redundant measurements equations are derived, which describe the sequence of the measurement operations, providing, in their turn, the solution for the GTF linearization problem under power sensor TF (1), as well as enhancement of an accuracy of calculation of a real value for the controlled PhQ x_i.

The paper states, that the main GTF linearization condition consists in execution of a redundant measurement of the controlled PhQ and of the correcting PhQs, having the specified sizes in their geometric progression.

The described redundant measurements methods and redundant quantities equations provide elimination of the influences, exerted by those constant components of a systematic error, which take place due to an absolute value and nonstability of the parameter S_{nl}, as well as to absolute values of an additive component of the measurement error $\Delta_à$ and of the TF shift Δy_{nl}.

The problem of automatic correction of systematic errors under power TF (1) with an unknown power exponent value is solved, when mutually-inverse logarithmic transformations of quantities are applied. This circumstance makes it possible to derive the linear equation for transformed quantities, on the basis of which the redundant measurements equation is obtained.

The described method of automatic error correction provides elimination of the influence, exerted by nonstability of the NTF parameters S_{nl}, and Δy and the power exponent $n,$ as well as of their values onto a final result of calculation of a real value of the controlled PhQ x_i .

The paper also states, that the zero value of a relative methodological error is achieved, when an NTF shift calculation accuracy is enhanced. The other condition, under which a high accuracy of the measurements, performed by the described method, is obtained, consists in provision of an equal accuracy of regeneration of PhQs with their specified sizes, as well as of an equally exact AD conversion of sensor output quantities.

The described methods, concerned with automatic correction of systematic errors under an unknown sensor TF power exponent value, provide the resolution for the problem, concerned, in its turn, with interchangeability of semiconductor sensors, and which arises, since there are large variations of sensor characteristics, observed for different technical reasons and as a result of rejection of products.

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