Automation of determining the range of values for MEMS resistive parameters

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Abstract. This paper is devoted to the development of automating methods of the ranges determination process of the resistance values measurements for the investigated MEMS resistive parameters (strain gauges, piezoresistors, thermistors, magnetoresistors and photoresistors, etc.), electric resistance of which is changing during functioning of MEMS, in order to improve the accuracy of investigated resistive parameter value determining and optimization of the entire measuring process in general. The developed method for automation of values range determination of the MEMS resistive parameters measurand is based on the designed models and algorithm of automation for the process of an exemplary resistor value determination. A measurand of the investigated MEMS resistive parameter is located in a neighborhood of this exemplary resistor value. The abovementioned method is also based on the developed model and algorithm for automation of the values range determination of the MEMS resistive parameters measurand.

Key words: MEMS, resistor, range determination, automation.

INTRODUCTION

In recent years it becomes an increasingly distinct worldwide trend to actively implement the technologies of microelectromechanical systems (MEMS), components and devices [1-6] created by MEMS-technologies, into all areas of human activity. Such growth of popularity is caused, in particular, by a number of indisputable advantages, inherent to the devices, created by MEMS-technologies, unlike their macro analogues. Among those advantages are: micron size, low power consumption, high level of integration, functionality, reliability and others. However, the usage of MEMS leads to a number of problems, which are caused by peculiarities of these technologies. One of them is a problem of automation of the MEMS resistive parameters values determination, which involves the automation of electric resistance measurement process together with automation of a measured electric resistance value range determination process at a previous stage of working process in order to improve the accuracy of the measured value determination and optimization of the entire measuring process in general. Herewith an automation process of determination of the measurand value range of the investigated MEMS resistive parameter is preceded by automation of the process of determination of some exemplary resistor value, in neighborhood of which the measurand of the investigated MEMS resistive parameter is located.

PROBLEM OVERVIEW

There are many devices [7 - 15], which allows determining the measuring ranges of electric resistance automatically. By making the classification based on criteria of their applicability for solving the problem of automation for MEMS resistive parameters value ranges determination, the following basic types of deficiencies were identified:

➢ absence of narrow specialization and orientation of the devices in solving a wide class of problems (value ranges determination not only for resistive parameters, but also for inductive, capacitive ones, voltage, etc.),

➢ absence of narrow specialization of devices directly for the task of resistive parameters value ranges determination, and their orientation mainly on determination of the precise value of investiga-ted resistive parameter at one stage, that affects the accuracy of the measurand value, determined in such way,

➢ complexity (in some cases — impossibility) of realization (production) by MEMS technologies,

➢ complexity (impossibility) of extension the functionality,

➢ resistive parameters value ranges determination only in fixed value area, and complexity (in some cases — impossibility) of its extension.

Existence of at least one of the abovementioned deficiencies creates certain difficulties in using such approach for the given task accomplishment (and in some cases — makes their usage impossible).

Thus, there is a need for development of a new approach for automation of the investigated MEMS resistive parameters value ranges determination, which would maximally met all the criteria, the main of which are implementation simplicity and possibility of functionality expansion.

DEVELOPMENT OF THE ALGORITHM FOR AUTOMATION OF DETERMINATION OF AN EXEMPLARY RESISTOR VALUE, IN A NEIGHBORHOOD OF WHICH MEMS RESISTIVE PARAMETER MEASURAND IS LOCATED

Fig. 1 shows a flowchart of developed algorithm, which represents the process of determination of the exemplary resistor value, in a neighborhood of which MEMS resistive parameter measurand is located.

The developed algorithm works as follows. Index of electric resistance value range is established and it equals

1 (i:=1), thereafter the residual voltage ΔU of electric bridge imbalance is detected, its absolute value ($\Delta U:=|\Delta U|$) is calculated, which, in its turn, is stored into appropriate cell ΔU_i. After that an increasing of electric resistance value range index (i:=i+1) occurs together with detection, processing and saving of the residual voltage of current electric resistance value range until all ranges (i>=n) will be analyzed. Next step of the algorithm is the process of distribution of residual voltages ΔU_1–ΔU_n by appropriate channels in order to determine minimal residual voltage ΔU_j and the appropriate exemplary resistor R_j.
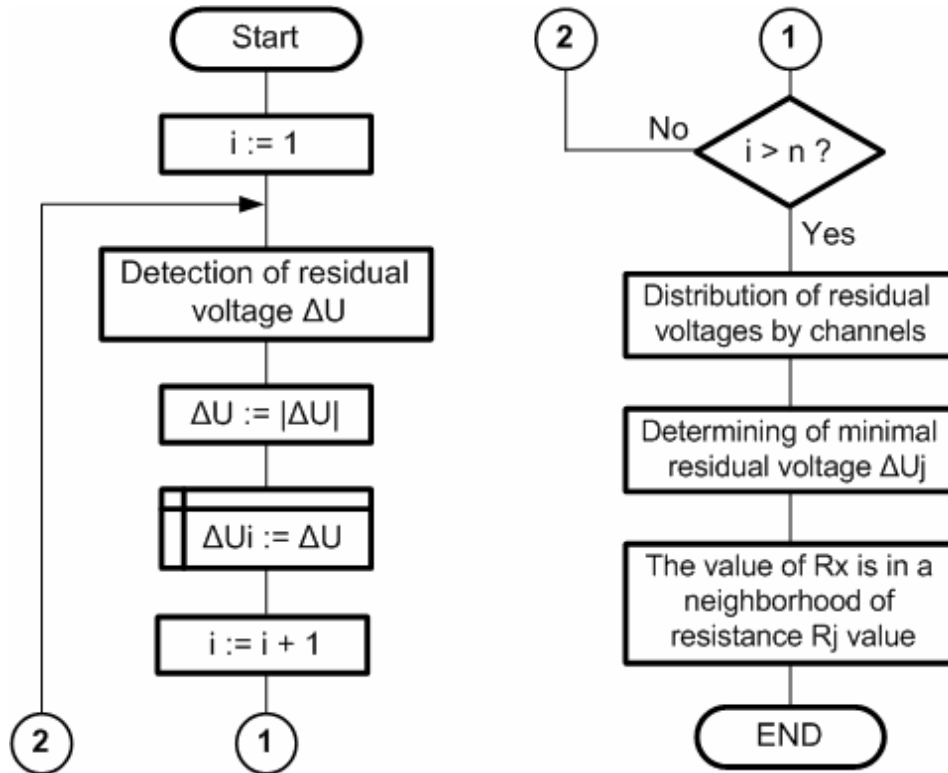

Fig. 1. Flowchart of the developed algorithm.

Thus, defining the minimal residual voltage ΔU_j, which corresponds to some exemplary resistor R_j, we can say that the measurand of investigated MEMS resistive parameter is in the neighborhood of given exemplary resistor R_j value.

DEVELOPMENT OF A MODEL FOR ANALYSIS OF A DYNAMICS OF THE PROCESS OF DETERMINATION OF THE VALUE OF EXEMPLARY RESISTOR, IN A NEIGHBORHOOD OF WHICH MEMS RESISTIVE PARAMETER MEASURAND IS LOCATED

Fig. 2 shows the developed model, based on colored Petri nets [16 – 20], for analysis the dynamics of the process of determination of the exemplary resistor value,

in a neighborhood of which MEMS resistive parameter measurand is located.

Developed model works as follows. Before an immediate start, the initial parameters are set, namely — a number of working ranges of electric resistance value in position p1 is assigned. If the number of ranges (n) is changed, the number of corresponding transitions of keys locking and individual positions of detected residual voltages has to be changed as well (see Fig. 2). After making all the necessary modifications in the developed model, a marker should be placed into work-starting position p2. In result of triggering of the transition t1, setting of the initial parameters of the model takes place, in particular the index of electric resistance value range is set to 'one' (i:=1), and marker moves to position p3.
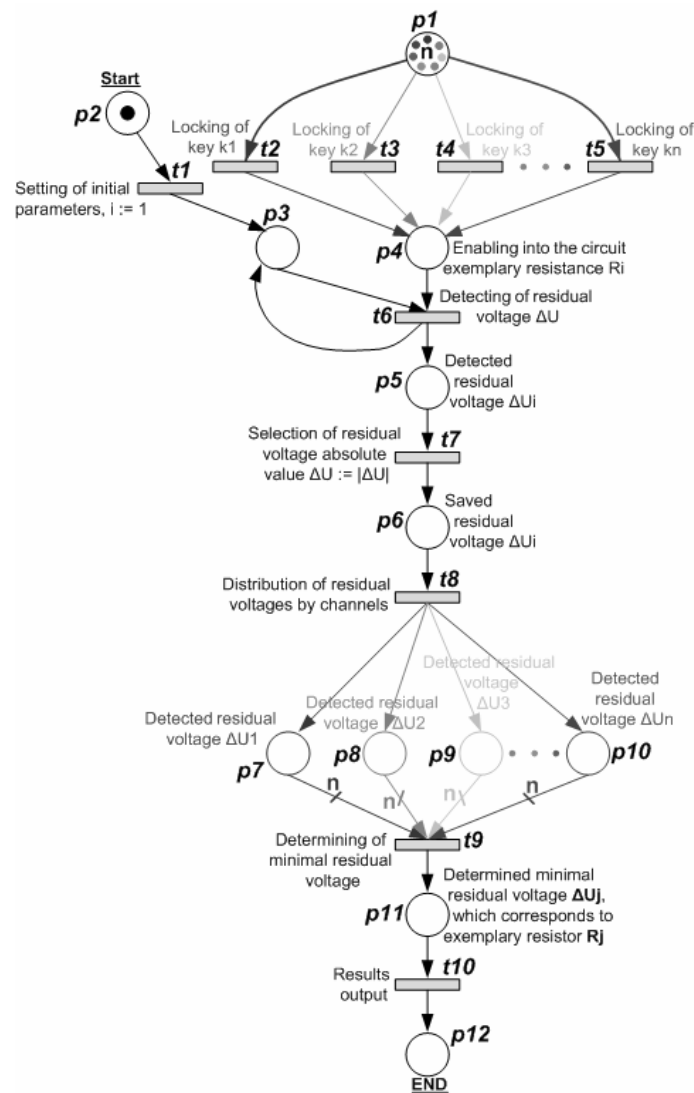
Fig. 2. Developed model, based on colored Petri nets, for the dynamics analysis.

After that the transition t2 is triggering, – the key k1 of the model is being locked, and the marker of first electric resistance value range moves from the position p1 into the position p4, which indicates the enabling into the model with exemplary resistance Ri an active electric resistance value range (in this case R1). Transition t6 is triggering and takes place the detection of residual voltage ΔU, which corresponds to the current exemplary resistor Ri, then marker moves into positions p3 and p5. Marker in position p5 activates the transition t7, which starts the process of evaluation of the residual voltage absolute value (ΔU=|ΔU|), and marker moves into position p6. By the marker from position p6 an activation of the transition t8 occurs and the mechanism of distribution throughout the channels of the residual voltages starts and also saving of current residual voltage ΔU in a corresponding cell ΔUi takes place as well. Marker moves into positions of detected residual voltages p7 – p10, increasing the number of markers in respective positions by 1 (the number of markers in these positions corresponds to the current range of electric resistance value), which indicates the completion of the analysis for the current working range of electric resistance value.

After that, analysis of the next electric resistance value working range occurs with activation of transition t3 by the second range marker of electric resistance value from position p1. Key k2 of the model is being locked, and enabling of the next exemplary resistor (in this case R2) into the model takes place, and analysis, processing and saving of the corresponding residual voltage ΔUi (in this case ΔU2), etc. occur until the last n-th working range of electric resistance value would be analyzed. In such case, positions p7 – p10 will be filled with n markers, so their number would be sufficient for triggering the transition t9, which launches the mechanism of determination of the minimal voltage. Marker moves into position p11, which indicates the determination of the value range of measured electric resistance. The transition t10 activates, and the output of model's working results is performed, and marker gets into the end position p12. The fig. 3 shows a state reachability graph of the above model, developed with colored Petri nets.

Constructed state reachability graph (see Fig. 3) shows sequential and parallel iterative working principle of the developed model, where markers of different types are processed by the same operations and only after all the markers will be processed, a transition to the final link of the tree would be carried out.
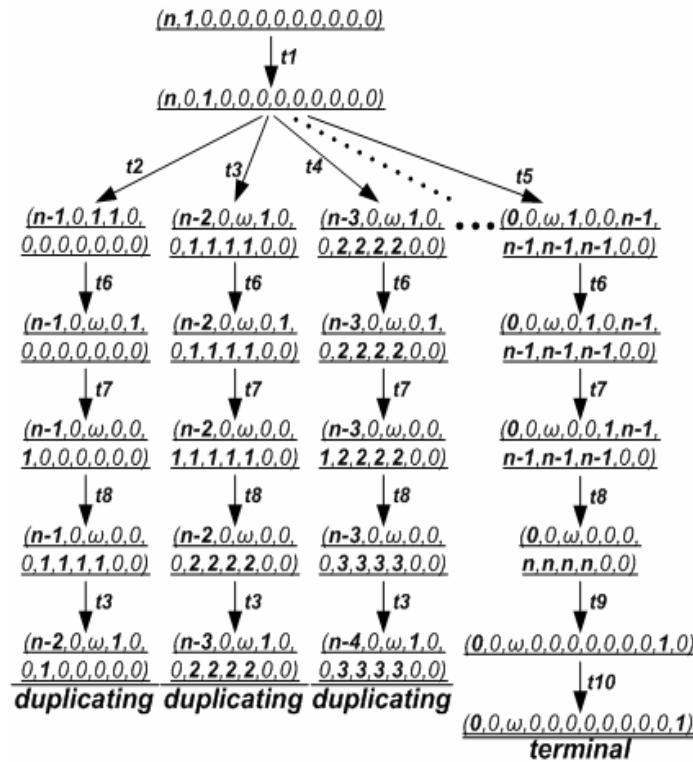
$(n,1,0,0,0,0,0,0,0,0,0)$

$\downarrow t1$

$(n,0,1,0,0,0,0,0,0,0,0)$

$t2$ $t3$ $t4$ $t5$

$(n-1,0,1,1,0,$ $(n-2,0,\omega,1,0,$ $(n-3,0,\omega,1,0,$ $\cdots$ $(0,0,\omega,1,0,0,n-1,$
$0,0,0,0,0,0)$ $0,1,1,1,1,0,0)$ $0,2,2,2,2,0,0)$ $n-1,n-1,n-1,0,0)$

$\downarrow t6$ $\downarrow t6$ $\downarrow t6$ $\downarrow t6$

$(n-1,0,\omega,0,1,$ $(n-2,0,\omega,0,1,$ $(n-3,0,\omega,0,1,$ $(0,0,\omega,0,1,0,n-1,$
$0,0,0,0,0,0)$ $0,1,1,1,1,0,0)$ $0,2,2,2,2,0,0)$ $n-1,n-1,n-1,0,0)$

$\downarrow t7$ $\downarrow t7$ $\downarrow t7$ $\downarrow t7$

$(n-1,0,\omega,0,0,$ $(n-2,0,\omega,0,0,$ $(n-3,0,\omega,0,0,$ $(0,0,\omega,0,0,1,n-1,$
$1,0,0,0,0,0)$ $1,1,1,1,1,0,0)$ $1,2,2,2,2,0,0)$ $n-1,n-1,n-1,0,0)$

$\downarrow t8$ $\downarrow t8$ $\downarrow t8$ $\downarrow t8$

$(n-1,0,\omega,0,0,$ $(n-2,0,\omega,0,0,$ $(n-3,0,\omega,0,0,$ $(0,0,\omega,0,0,0,$
$0,1,1,1,1,0,0)$ $0,2,2,2,2,0,0)$ $0,3,3,3,3,0,0)$ $n,n,n,n,0,0)$

$\downarrow t3$ $\downarrow t3$ $\downarrow t3$ $\downarrow t9$

$(n-2,0,\omega,1,0,$ $(n-3,0,\omega,1,0,$ $(n-4,0,\omega,1,0,$ $(0,0,\omega,0,0,0,0,0,0,1,0)$
$0,1,0,0,0,0)$ $0,2,2,2,2,0,0)$ $0,3,3,3,3,0,0)$

duplicating duplicating duplicating $\downarrow t10$

                                                 $(0,0,\omega,0,0,0,0,0,0,0,1)$

                                                 terminal

Fig. 3. The state reachability graph of the above model, developed with colored Petri nets.

Such structure of the graph is fully consistent with the developed model and method in general.

DEVELOPMENT OF A CIRCUIT MODEL FOR AUTOMATION OF DETERMINATION THE VALUE OF AN EXEMPLARY RESISTOR, IN A NEIGHBORHOOD OF WHICH THE INVESTIGATED MEMS RESISTIVE PARAMETER MEASURAND IS LOCATED

The fig. 4 below shows developed circuit model which realize the process of automation for determination the value of an exemplary resistor, in a neighborhood of which the investigated MEMS resistive parameter measurand is located.

Developed model contains the following main components (see Fig. 4): block of exemplary resistors R1–Rn, switching unit, based on keys k1–kn, measured electric resistance Rx (which represents investigated MEMS resistive parameter), two etalon electric resistances Rs1 and Rs2 (moreover, Rs1=Rs2), voltage absolute value selection unit, unit of distribution the residual voltages by channels, minimal voltage determining circuit and control unit.

In the results of sequential switching of keys k1-kn of the developed circuit model, some bridge circuit imbalance residual voltage ΔU appears in the neighborhood of equilibrium point of the electric bridge, formed by: 1) one of exemplary resistors Ri, 2) measured by electric resistance Rx (which represents investigated MEMS resistive parameter), 3) and sample resistors Rs1 and Rs2.

Thus, among all exemplary electric resistors R1–Rn the nearest (in magnitude) to measured value of investigated MEMS resistive parameter (represented by electric resistance Rx) will be that exemplary electric resistor Rj, during switching on of which into the bridge electric circuit of the model, the absolute value of residual voltage $|\Delta Uj|$ of bridge circuit imbalance would be minimal. Thus, the measured value of investigated MEMS resistive parameter, represented by electric resistance Rx, is located in the neighborhood of the value of an exemplary electric resistor Rj.

DEVELOPMENT OF CIRCUIT MODEL AND ALGORITHM FOR AUTOMATION OF THE VALUE RANGE DETERMINATION OF THE INVESTIGATED MEMS RESISTIVE PARAMETERS MEASURAND

To establish ranges of measured electric resistance value, which is represented by the investigated MEMS resistive parameter, let us use the property of the residual voltage of electric bridge imbalance to change its sign to the opposite when passing through the equilibrium point. The fig. 5 below shows the corresponding graph of the change of residual voltage value in the neighborhood of the electric bridge equilibrium point (data were get from the results of modeling of the developed circuit model for automation of determination the value of an exemplary resistor, in a neighborhood of which the investigated MEMS resistive parameter measurand is located).
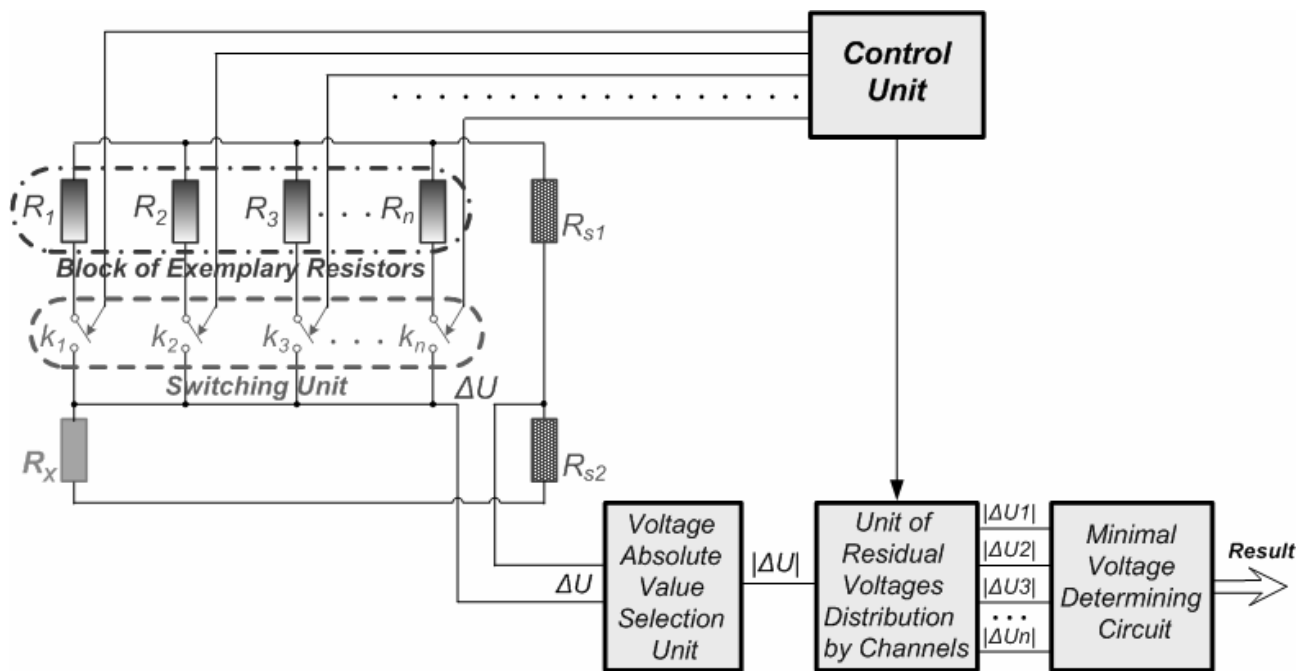
Fig. 4. Circuit model for automation of determination the value of an exemplary resistor, in a neighborhood of which the investigated MEMS resistive parameter measurand is located.
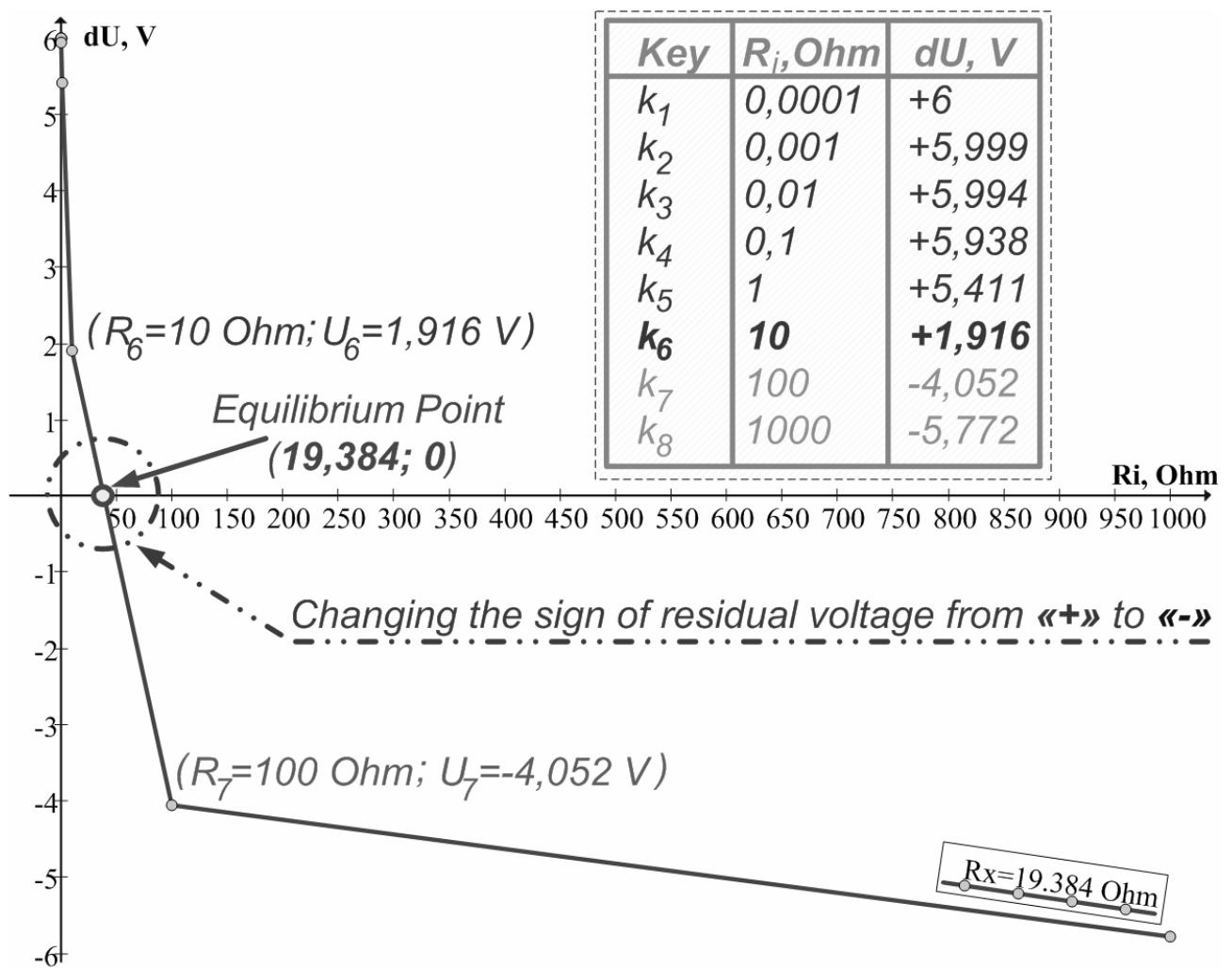

Key	R_i, Ohm	dU, V
k_1	0,0001	+6
k_2	0,001	+5,999
k_3	0,01	+5,994
k_4	0,1	+5,938
k_5	1	+5,411
k_6	10	+1,916
k_7	100	-4,052
k_8	1000	-5,772

Fig. 5. Graph of the change of residual voltage value.

Thus, for determination of measuring ranges it is necessary to identify the moment when model is passing through the electric bridge equilibrium point, or moment of changing the sign of imbalance residual voltage, appeared in the neighborhood of electric bridge equilibrium point, to the opposite one. In this case, the last value of an exemplary electric resistance will be the lower measuring range (when the sign of residual voltage was still unchanged), and the upper measuring range will be the first value of an exemplary electric resistance, in case of which the sign of residual voltage has changed to the opposite. So, for the considered case of determination of the value range of measured electric resistance $Rx=19,384 Ohm$ (see Fig. 5), the lower measuring range will be 10 Ohm, and the upper one will be 100 Ohm.

The figures below shows the developed circuit model (see Fig. 6) and flowchart of the developed algorithm (see Fig. 7) for automation of determination of the values range of electric resistance for investigated MEMS resistive parameters measurand.

Developed model works as follows (see Fig. 6, Fig. 7). At the beginning the resetting of first (T_1-T_N) and second ($T_{n+1}-T_{2*n}$) rows of triggers occurs by using a high-level logical signal, which enters the corresponding inputs R ("Reset") of the triggers control unit, moreover the signal enters one of the inputs of logical "AND" schemes ($\&_1-\&_n$) from the outputs of the first-row triggers T_1-T_n. After that locking of the first key k_1 occurs,— and thus enabling of the exemplary resistance R_1 into the circuit takes place together with the switching of appropriate (in this case first one, in general – i-th one) first-row trigger by using a high-level logical signal, which enters it's input S ("Set"). The trigger switching, in its turn, activates the appropriate logical "AND" scheme ($\&_i$).
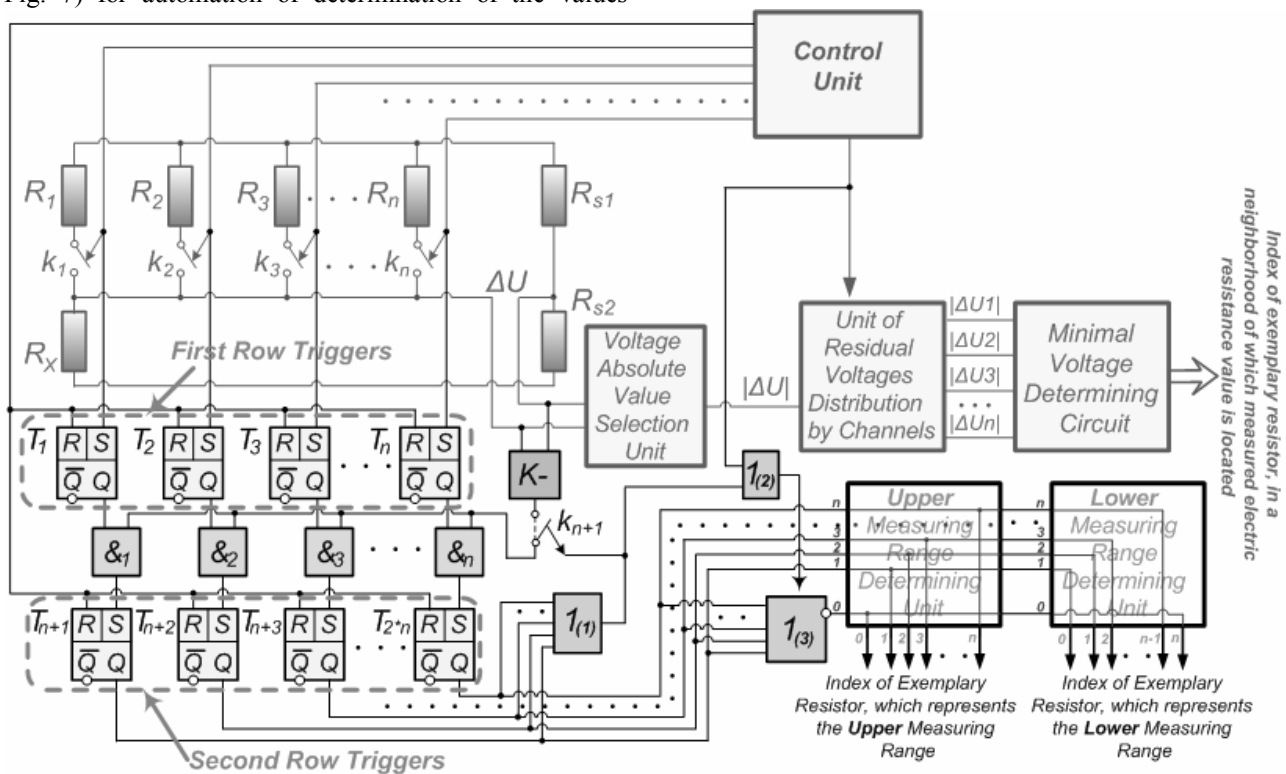

Fig. 6. Circuit model for automation of the values range determination of the investigated MEMS resistive parameters measurand.

A residual voltage ΔU appears in the neighborhood of equilibrium point of the formed electric bridge arises up because of locking of the electric circle. This residual voltage enters the input of negative-voltage comparator $K-$. Comparator works only when the residual voltage ΔU is negative at its entrance.

If the residual voltage ΔU is positive, then at the output of corresponding logical "AND" scheme ($\&_i$) we will have a low-level signal, or "logical zero", which enters the input of corresponding second-row trigger T_{n+i}. After that, the next working cycle takes place, which starts with enabling of the next exemplary resistor R_{i+1} into the circuit. If the residual voltage ΔU is negative, then a high-level logical signal from the output of negative-voltage comparator $K-$ enters the second inputs of all logical "AND" schemes $\&_1-\&_n$.

In result of triggering of comparator K–a high-level logical signal enters also the second input of logical-"AND" active scheme $\&_i$, leading to appearance of a high-level signal on its output. This signal immediately switches a corresponding second row trigger T_{n+i}, a high-level signal ("logical one") appears on its output, and this signal, in its turn, enters the input of the first logical "OR" scheme.

A high-level signal appearance at one of the inputs of the first logical-"OR" scheme generates at its output the same high-level signal, which unlocks the key k_{n+1}. Unlocking of the key is done to avoid the repetition of appearance of a high-level signals on outputs of all other logical-"AND" schemes ($\&_{i+1}$, $\&_{i+2}$, …, $\&_n$), because we are interested only in the moment when electric bridge circuit passes over its equilibrium point, which is

evidenced by changing of the sign of residual voltage to the opposite (in particular, with increasing of the controlled resistance value — from "+" to "−").

A high-level signal from the output of the first logical-"OR" scheme also enters one of the inputs of the second logical-"OR" scheme, which leads to launching of the third logical-"OR" scheme (with inversion at its output). In result of the abovementioned triggering upper- and lower-range determining units are starting their operation, and output of results occurs. The same happens after locking of the last key k_n by activation of the third logical-"OR" scheme (with inversion at its output) by a control-signal from the control unit.If the detected residual voltage ΔU wasn't negative in any of cases after sequential locking of all n keys of the model (at the outputs of all logical-"AND" schemes (&1–&n), we will have low-level logical signals at the outputs of all second-row triggers T_{n+1}–T_{2*n}), which enter the inputs of the third logical-"OR" scheme (with inversion at its output).

Thus, at the output of the third logical-"OR" scheme we will have a high-level signal, which enters the zero-th input of the upper-range determining unit. As a result, at one of the outputs of the upper-range determining unit we will have a high-level signal ("logical one"). Moreover, presence of a high-level signal at 0-th output of the upper-range determining unit indicates the «open» (undetermined) upper limit, and a high-level signal at the i-th output of the unit (i [1,n]) indicates that the upper measuring range is the i-th exemplary resistor Ri of the model. The upper measuring range is «open» (undetermined) in case, when the value of measured electric resistance Rx, which represents the investigated MEMS resistive parameter, is higher, than value of the largest exemplary resistor (for the developed model it is resistor Rn, see Fig. 6).
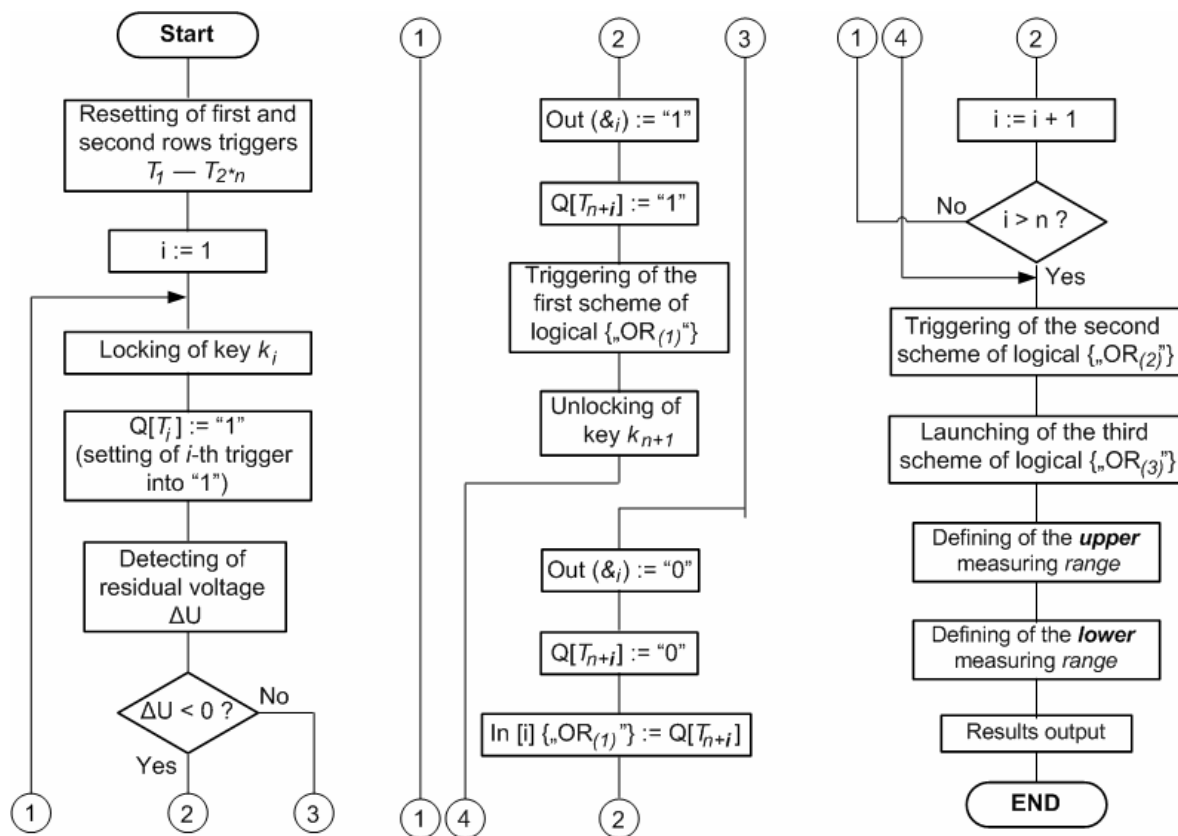

Fig. 7. Flowchart for the process of automation of determination the values range of the investigated MEMS resistive parameters measurand

At one of the outputs of the lower-range determining unit we will also have a high-level logical signal. Exactly the same like in the previous case, the "logical one" at i-th output of the lower-range determining unit (i [1,n]) indicates that the lower measuring range is the i-th exemplary resistor Ri of the model, and presence of a high-level signal at 0-th output of the lower-range determining unit indicates that lower limit is «open» (undetermined) — when the value of measured electric resistance Rx, which represents the investigated MEMS resistive parameter, is lower than value of the smallest exemplary resistor (for developed model it is resistor R1,

see Fig. 6). Determination of measuring ranges also allows to choose the optimal step of change of the value of controlled electric resistance, in order to achieve the equilibrium state of electric bridge more quickly at the stage of precise determination of the value of some investigated MEMS resistive parameter, and the value of this optimal step equals the value of determined lower measuring range.

So, for the considered case of determination the precise value of investigated resistive parameter with the value of electric resistance Rx=19,384 Ohm it has been found that its value is in the ranges from R6=10 Ohm

(lower measuring range) to R7=100 Ohm (upper measuring range) in the neighborhood of the value of exemplary resistor R6=10 Ohm. A further direction (in our case it's increasing) of change of the controlled electric resistance (which would be use later, on the stage of precise determination, to achieve the equilibrium state of the electric bridge), as well as the optimal step of change of the value of controlled electric resistance (which equals the determined lower measuring range R6=10 Ohm), were determined.

Thus, obtained results serve like an effective mechanism for increasing the speed of determining the precise value of investigated MEMS resistive parameter, since they remove the necessity of additional analysis of investigated object (MEMS resistive parameter, represented by measured electric resistance) on the stage of determination of its precise value.

CONCLUSIONS

The developed method for automation of determination the value range of investigated MEMS resistive parameters measurand is presented in this paper. This method is based on the developed models and algorithm for automation the process of determination of an exemplary resistor value, in a neighborhood of which MEMS resistive parameter measurand is located, as well as on the developed model and algorithm for automation of the value range determination.

Developed model, based on colored Petri nets, for analysis of a dynamics of the process of determination of the value of exemplary resistor, in a neighborhood of which MEMS resistive parameter measurand is located, was also presented in this article.

Developed circuit models (circuit model for automation of determination the value of an exemplary resistor, in a neighborhood of which the investigated MEMS resistive parameter measurand is located AND Circuit model for automation of the values range determination of the investigated MEMS resistive parameters measurand) give an opportunity to take into account the features and specifics of MEMS–technologies. Developed algorithms (the algorithm for automation of determination of an exemplary resistor value, in a neighborhood of which MEMS resistive parameter measurand is located AND the algorithm for automation of the value range determination of the investigated MEMS resistive parameters measurand) provide an opportunity to fully automate the process of determining and controlling of the values of investigated MEMS resistive parameters.

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