ISSN 0002-306X. Proc. of the RA NAS and NPUA Ser. of tech. sc. 2024. V. LXXVII, N2

UDC 621.374.3 MICROELECTRONICS

DOI: 10.53297/0002306X-2024.v77.2-190

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CALCULATION OF SCHMITT TRIGGERS DEPENDING ON INPUT THRESHOLD VOLTAGES, THE INVERSE PROBLEM

The way and features of solving the inverse problem of calculating inverting and non-inverting classical Schmitt triggers are presented. Equations have been derived in which the input threshold voltages are known as the **main and constant** parameters, while the other parameters are secondary to the threshold voltages. All the other unknown parameters of the trigger circuit are calculated. The dependences of these errors on the output voltages of the triggers and on their relative errors are shown. The equations for calculating the relative errors of the threshold voltages are derived. It has been proved that each of these equations is a linear function depending on the output voltages when the difference between these voltages is constant. A methodological guideline for relative error calculation of threshold voltages has been developed. The graphs of dependence of relative errors of the input threshold voltages on output voltages are constructed. It is shown that for the construction of each curve, it is sufficient to select only one pair of output voltages. A guideline to using the graphs has been developed. A moving ruler has been proposed, by which, without preliminary calculations a pair of output voltages that will ensure accuracy meeting the requirements of the problem is chosen. Solutions have been proposed to reduce the relative errors for both thresholds simultaneously in the conditions of the existing errors of the output voltages. With the proposed methods, it is possible to calculate a new Schmitt trigger, avoiding errors that may occur during the calculation of the direct problem, when the choices of reference voltage, output voltages and feedback factor are not justified. The proposed methods justify the choice of technical parameters of the triggers, which will increase their quality.

Keywords: Schmitt trigger, inverse problem, comparator, threshold voltage, reference voltage, output voltage, relative errors of voltages.

Introduction. One of the most common schematic solutions in radio engineering is the Schmitt trigger. It is an inverting or non-inverting comparator that converts the input analog signal into a logic one (analog-digital converter ADC) depending on the direction of overcoming two pre-selected high (higher) or low (lower) threshold voltages. The accuracy of the phase synchronization of digital signals in the ADC and, as a result, the accuracy of information transmission depends on the stability of the threshold voltage. In the studied literature, formulas for calculations of the input threshold voltages triggers are presented in different forms

[1-7]. In [1], the need to use the formula of only one general form is justified. For a trigger running on any device, this kind of computation is considered a **direct problem**. That is, the parameters of all the active and passive elements of the trigger, the supply voltages are known, and the threshold voltages are unknown, which must be calculated. More often, when developing a new device, it is necessary to solve **the inverse problem**: to develop a new Schmitt trigger to convert the analog signal to digital. In this case, the parameters of the input signal and the values of the **two threshold voltages** (high and low) are known, at the moment of overcoming, which the analog signal is converted to digital. It is required to calculate all the remaining unknown magnitudes of the trigger circuit. The formulas for calculating the inverse problem are not mentioned in the studied literature, the choices of parameters are not justified, the issues of improving the quality of the technical parameters of the triggers are not discussed either, expected errors are not estimated. [2-7]. In [2-4], only the calculations of threshold voltages (direct problem) are given, using voltage dividers to obtain the reference voltage. In [5-8], the solution to the inverse problem is given, where the threshold voltages are given, but the supply voltages, the reference voltage and the calculation of the passive elements are not justified.

Problem setting. Our investigation aims at finding a clear way to solve the inverse problem, to highlight the features. For that, it is necessary:

1) to derive formulas for solving the inverse problem of calculating triggers;

2) to find the dependence of the relative errors of the input threshold voltages on the output high or low voltages of the trigger and their relative errors, separately;

3) to develop a methodological guide for the calculation of the increase in the accuracy of the threshold voltages;

4) to propose justified solutions to increase the quality of parameters of the trigger.

As a basis, we adopted the general formulas derived in [1] for calculating the threshold voltages. We used all designations of [1]: supply- *VCC* and *VEE*, output- ${U^1}_{out}$ and U_{out}^0, reference-U_z, and thresholds-$U_{in}\downarrow$ and $U_{in}\uparrow$. The arrows show the directions of jumps in output voltages when the input analog voltage exceeds a given threshold. As a feedback coefficient, we accepted *K=R2/R1*, where *R1* and *R2* are the positive feedback resistances, through which the threshold voltages are formed from the output voltages U_{out}^1 and U_{out}^0 of the comparator (Fig. 1.1). The voltages *VCC* and *VEE* can have positive, negative and zero values. The trigger output voltages **must satisfy the condition $\boldsymbol{U_{out}^1 > U_{out}^0}$** to ensure positive feedback. Depending on the choice of the microchip, it is possible to satisfy the conditions $VCC = U_{out}^1$ and $VEE = U_{out}^0$. In the inverse problem, the input threshold voltages are given as the **main** and **constant parameters**, all other parameters are secondary and can be changed.

1. Inverting Schmitt trigger. In *Fig.1.1,* the classical Schmitt trigger with an inverting comparator tested with *Multisim* program is shown. In *Fig.1.2,* the dependence of $U_{out} = f(U_{in})$ (the curve of hysteresis) is shown. Threshold values $U_{in}\downarrow$ and $U_{in}\uparrow$ are indicated on the input voltage U_{in} axis:

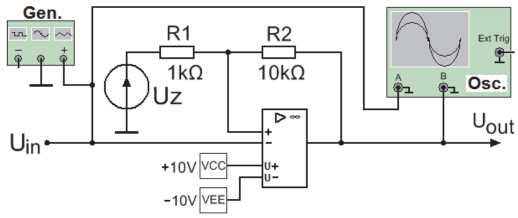

Fig.1.1. The circuit with inverting Schmitt trigger

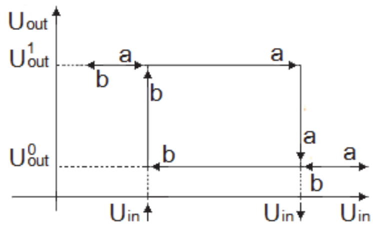

Fig.1.2. The dependence of $U_{out} = f(U_{in})$

From *Fig.1.2* it can be seen that $U_{in}\uparrow < U_{in}\downarrow$. To solve the inverse problem of calculating the inverting trigger, let's use the equation for determining the threshold voltages given in [1]. To solve the inverse problem, let's write the threshold voltage equation from [1].

$$U_{in} = U_z \frac{R2}{R1+R2} + U_{out} \frac{R1}{R1+R2}. \qquad (1.1)$$

Putting the feedback factor $K = R2/R1$ in (1.1), we get:

$$U_{in} = U_z \frac{K}{1+K} + U_{out} \frac{1}{1+K}. \qquad (1.2)$$

For high and low thresholds we will have:

$$U_{in}\downarrow = U_z \frac{K}{1+K} + U_{out}^1 \frac{1}{1+K} \text{ (high)}, \; U_{in}\uparrow = U_z \frac{K}{1+K} + U_{out}^0 \frac{1}{1+K} \text{ (low)}. \qquad (1.3)$$

From equations (1.3), it can be seen that the voltage $U_{in}\downarrow$ (high threshold) depends on the voltage U_{out}^1, and the voltage $U_{in}\uparrow$ (low threshold) depends on the voltage U_{out}^0. For simplicity, we can choose: $U_{out}^1 = VCC$ and $U_{out}^0 = VEE$. In equations (1.3) two unknowns remain: K and U_z. In (1.3), by subtracting the low threshold voltage from the high threshold voltage, we get *K*:

$$K = \frac{U_{out}^1 - U_{out}^0}{U_{in}\downarrow - U_{in}\uparrow} - 1. \qquad (1.4)$$

In fact, the (vertical) height of the hysteresis rectangular curve is written in the numerator, and the (horizontal) width in the denominator. In (1.3), by adding the low threshold voltage to the high threshold voltage, we get U_z:

$$U_z = \frac{U_{in}\downarrow + U_{in}\uparrow}{2} \frac{1+K}{K} - \frac{U_{out}^1 + U_{out}^0}{2} \frac{1}{K}. \quad (1.5)$$

Choosing a certain pair $\boldsymbol{U_{out}^1}$ and $\boldsymbol{U_{out}^0}$, only the values $\boldsymbol{U_z}$ and $\boldsymbol{K}$ the respective to that pair can be calculated. Since the number of this pairs and the number of K-is unlimited, it is necessary to find criteria to limit their number. That's why it should be taken into account that:

1) the voltages $U_{in}\uparrow$ and $U_{in}\downarrow$ are given as the main and constant;
2) K-is a calculated quantity for trigger circuit;
3) the output voltages are selected, they depend on the supply voltages.

If we consider the height of the hysteresis curve to be constant: $U_{out}^1 - U_{out}^0 = C$, then it can be seen from (1.4) that for a given C, for a large group of output voltages, K will also be constant. In that case, choosing the pairs of voltages U_{out}^1 and U_{out}^0 in the ranges we need, we can calculate for each pair its U_z voltage using equation (1.5). By choosing another C, we will have another K and nother groups of output voltages. To limit the number of groups, there is a need find another criterion. We choose such output voltages, whose influence of instability (aging of parts, thermal effects, supply voltage fluctuations, etc.) on the input threshold voltages is smaller than the amount allowed by the technical requirements. Let's find the dependence of the threshold voltage change (error) on the output voltage change (instability or error). Using equation (1.2), for the input threshold voltage we can write:

$$\Delta U_{in} = \Delta U_{out} \frac{1}{1+K}. \quad (1.6)$$

Now let's find the dependence of the relative error of the input threshold voltage $\frac{\Delta U_{in}}{U_{in}}$ on the relative error of the output voltage. From (1.6) and (1.2), we will get:

$$\frac{\Delta U_{in}}{U_{in}} = \frac{\frac{\Delta U_{out}}{U_{out}}}{\frac{U_z K}{U_{out}}+1}, \frac{\Delta U_{in}}{U_{in}\downarrow} = \frac{\frac{\Delta U_{out}}{U_{out}}}{\frac{U_z K}{U_{out}^1}+1} \text{ (high)}, \frac{\Delta U_{in}}{U_{in}\uparrow} = \frac{\frac{\Delta U_{out}}{U_{out}}}{\frac{U_z K}{U_{out}^0}+1} \text{ (low)}. \quad (1.7)$$

It can be seen from (1.2) and (1.6), that if $U_{out} = 0$, then $\Delta U_{out} = 0$, $\Delta U_{in} = 0$ and $\frac{\Delta U_{in}}{U_{in}} = 0$. If $U_z = 0$, we get: $\frac{\Delta U_{in}}{U_{in}} = \frac{\Delta U_{out}}{U_{out}}$, as in [1]. In (1.7), we see that the relative error of the input threshold voltage depends on three variables: U_z, K and U_{out}. To show that, we conditionally choose any reasonable constant value of the relative error of the output voltage: $A_1 = \frac{\Delta U_{out}}{U_{out}}$. Recalculating the result for other values is not difficult. In the equation (1.5), let's denote the term independent of U_{out} by the constant A_2: $A_2 = \frac{U_{in}\downarrow + U_{in}\uparrow}{2} \frac{1+K}{K}$. If we put the designations in equations (1.7), then the relative errors of the input threshold voltages will be:

$$\frac{\Delta U_{in}}{U_{in}\downarrow} = \frac{2A_1}{2KA_2+C} U_{out}^1, \frac{\Delta U_{in}}{U_{in}\uparrow} = \frac{2A_1}{2KA_2-C} U_{out}^0. \quad (1.8)$$

These equations are linear equations depending on the output voltages. This allows to construct dependence graphs (1.7) for any C, using several (2÷5) values.

1.1. The methodical guideline to calculating the relative error of the input threshold voltage. In modern operational amplifiers, the entire range of allowable positive and negative voltages can be used from *VCC* to *VEE*. For calculation it is necessery:

1) to select the value of the vertical gap of the hysteresis curve in equation (1.5) and consider it constant in this example: $U_{out}^1 - U_{out}^0 = C$. In this case, K will have one constant value for different pairs of U_{out}^1 and U_{out}^0;

2) to select several pairs of voltages U_{out}^1 and U_{out}^0 that satisfy the condition $U_{out}^1 - U_{out}^0 = Cn$ (n=1, 2, …). For this, the window of the given hysteresis curve should be shifted along the vertical axis, from the highest value of VCC to the lowest value of VEE, keeping the coordinates of the threshold voltages $U_{in}\uparrow$ and $U_{in}\downarrow$. For simplicity, assume that $VCC = U_{out}^1$ and $VEE = U_{out}^0$;

3) calculate *K* from (1.5) for the selected *C*, select *R1*, calculate *R2* ($R2 = KR1$);

4) for each pair of voltages U_{out}^1 and U_{out}^0, calculate U_z-by (1.6);

5) having any pair of U_{out}^1 and U_{out}^0, and the respective U_z, K, test the circuit shown in Fig.1.1 as a direct problem [1] by *Multisim* program. Compare the obtained threshold voltage values with the required values. In our examples, the measurement error of threshold voltages is less than 1%, which is acceptable;

6) choose some constant value of output voltage relative error, for example:0,1 (10%), or a smaller are based on the requirements of the problem;

7) for $C1$, calculate the relative errors of threshold voltages using (1.8);

8) select another value of $C(C2, C3, ...)$, and repeat the calculation steps 1÷7;

9) construct the graph of equation (1.7) for each C.

1.2. Calculations according to the guide. Calculations of unipolar, asymmetric bipolar, symmetric bipolar input threshold voltages are performed. We have chosen a microchip LT1366 and $-25V \div +25V$ voltage range. The values of U_z are given as a fraction with the same denominator. It is convenient to choose such values of C-s that their curves do not cover each other on the graph.

1.2.1. Unipolar input threshold voltage:

Table 1.1

Calculation results when $U_{in} \downarrow = +1V$, $U_{in} \uparrow = +0{,}5V$

$C1 = 5V; K = 9$					$C2 = 12V$; K= 23			
Data	Data 1	Data 2	Data 3	Data 4	Data 5	Data 6	Data 7	Data 8
$U^1_{out}; U^0_{out}$[V]	15; 10	10; 5	5; 0	0; -5	24; 12	12; 0	8; -4	0; -12
U_z [V]	-5/9	0	5/9	10/9	0	12/23	16/23	24/23
$\Delta U_{in}/U_{in} \downarrow$	15	10	5	0	10	5	3,33	0
$\Delta U_{in}/U_{in} \uparrow$	20	10	0	-10	10	0	-3,33	-10

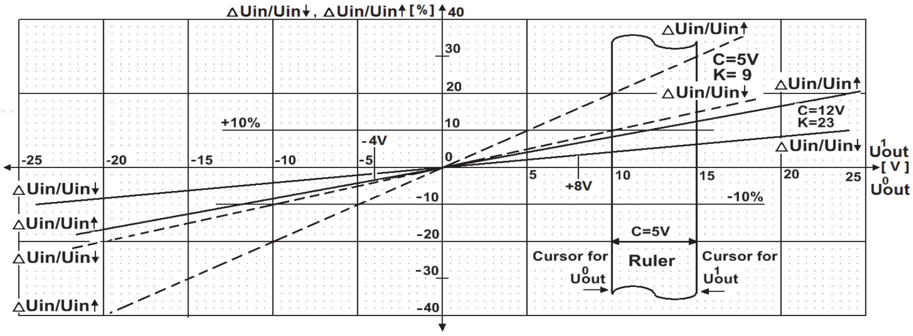

Fig.1.3. The graphs for unipolar input threshold voltage: $U_{in} \downarrow = 1V$, $U_{in} \uparrow = 0{,}5V$

In *Table 1.1*, the graphs of *Fig.1.3* are constructed, which are straight lines passing through the point 0;0 of coordinate axis: the horizontal axis shows U_{out}, and the vertical one the relative errors of the input threshold voltages in %. Curves with parameters $\mathrm{C1} = 5\mathrm{V}$ and $\mathrm{K} = 9$ are shown by dashed lines, curves with parameters $\mathrm{C2} = 12\mathrm{V}$ and $\mathrm{K} = 23$-by solid lines.

1.2.2. Bipolar asymmetric input threshold voltage

Table 1.2

Calculation results when $U_{in} \downarrow = +1{,}5V$, $U_{in} \uparrow = -0{,}5V$

$C1 = 5V; K = 1{,}5$					$C2 = 10V$; K= 4			
Data	Data1	Data2	Data3	Data4	Data5	Data6	Data7	Data8
$U^1_{out}; U^0_{out}$[V]	10; 5	5; 0	3,75; -1,25	2,5; -2,5	15; 5	7,5; -2,5	5; -5	0; -10
U_z [V]	-12,5/3	-2,5/3	0	2,5/3	-15/8	0	5/8	15/8
$\Delta U_{in}/U_{in} \downarrow$	26,66	13,3	10	6,66	20	10	6,66	0
$\Delta U_{in}/U_{in} \uparrow$	-40	0	10	20	-20	10	20	40

In Fig. 1.4, the graphs are constructed based on. the *Table 1.2.*

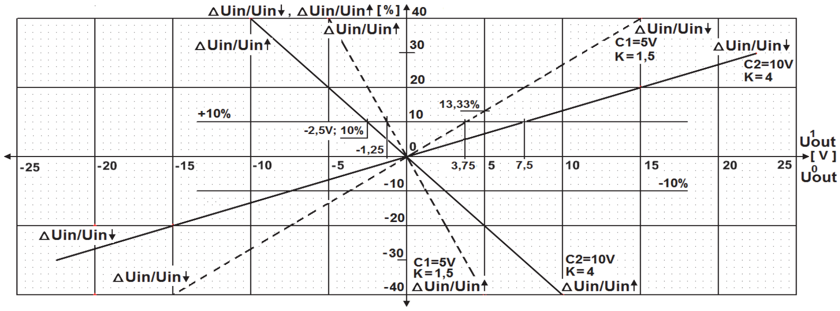

Fig.1.4. The graphs for bipolar asymmetric input threshold voltage: $U_{in} \downarrow = +1{,}5V$, $U_{in} \uparrow = -0{,}5V$

In *Fig.1.4,* curves with parameters $\text{C1} = 5V$ and $\text{K} = 1{,}5$ are shown by dashed lines, and curves with parameters $\text{C2} = 10V$ and $K = 4$-by solid lines.

1.2.3. Bipolar symmetric input threshold voltage

Table 1.3

Calculation results when $U_{in} \downarrow = +0{,}5V$, $U_{in} \uparrow = -0{,}5V$

	$C1 = 5V; K = 4$				$C2 = 10V; = 9$			
Data	Data1	Data2	Data3	Data4	Data5	Data6	Data7	Data8
$U_{out}^1; U_{out}^0$[V]	10; 5	5; 0	2,5; -2,5	-5; -10	10; 0	5; -5	0; -10	-5; -15
U_z [V]	-15/8	-5/8	0	15/8	-5/9	0	5/9	10/9
$\Delta U_{in}/U_{in} \downarrow$	40	20	10	-20	20	10	0	-10
$\Delta U_{in}/U_{in} \uparrow$	-20	0	10	40	0	10	20	30

In *Fig.1.5* the graphs are constructed based on *Table 1.3*. Curves with parameters $\text{C1} = 5V$ and $\text{K} = 4$ are shown by dashed lines and curves with parameters $\text{C2} = 10V$ and K= 9-by solid lines.

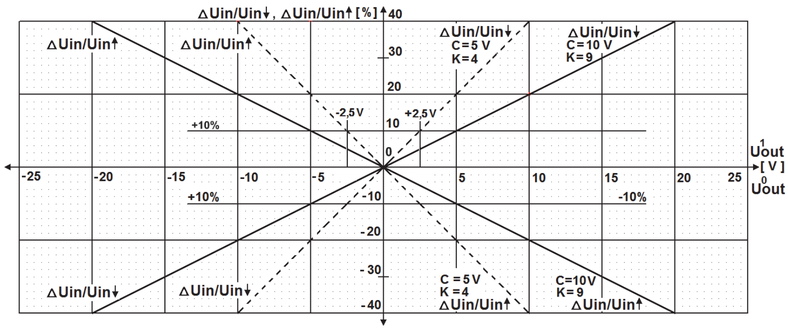

Fig. 1.5. The graphs for bipolar aymmetric input threshold voltage: $U_{in} \downarrow = +0{,}5V$, $U_{in} \uparrow = -0{,}5V$

It can be seen from all the graphs that as *C* increases, *K* also increases and the angle formed by the U_{out} axis and the the respective curves of the graph decreases. The range of output voltages with error of less than 10% increases.

1.3. A guide to using graphs. The Graphs make it possible to replace complex mathematical calculations with the results obtained by construction methods characteristic of nomograms. The Graphs are constructed by computer software or on A4 (or larger) *mm* paper to ensure relatively high accuracy in use. That's why:

1) for each C, we prepare a movable vertical ruler, the width of which is equal to the linear size of the selected C on the graph, expressed in *mm*, and the other dimension is equal to the vertical height of the graph;

2) based on the technical requirements of the problem, we select the necessary range of relative errors of any C ($C1$, $C2$ or $C3$);

3) The right edge of the ruler (U_{out}^{1} cursor) should coincide with any U_{out}^{1} voltage on the U_{out} axis (for example, the maximum). At that position, the left border (U_{out}^{0} cursor) will show the U_{out}^{0} value corresponding to the given U_{out}^{1} on the graph. In this case, the vertical edge lines (cursors) of the ruler intersect with the $\frac{\Delta U_{in}}{U_{in}}$ curves and show the respective relative errors: $\frac{\Delta U_{in}}{U_{in}\downarrow}$ and $\frac{\Delta U_{in}}{U_{in}\uparrow}$, expressed as percentages (take into account point 9 of 1.1).

For any C, it is necessary to move its ruler parallel to itself, corresponding to the selected pair U_{out}^{1} and U_{out}^{0}, and record the relative error new values on the vertical axis at the point of intersection of the cursor and graph curves. For example, at the unipolar threshold voltage, for $C1 = 5V$, if we set the right edge of the ruler on $U_{out}^{1} = 15V$, then the left edge will coincide with $U_{out}^{0} = 10V$. The corresponding relative error values at the points of intersection with the graph curves will be: $\frac{\Delta U_{in}}{U_{in}\downarrow} = 15\%$ և $\frac{\Delta U_{in}}{U_{in}\uparrow} = 20\%$ (*Table 1.1*, Data1; *Fig.1.3*): By moving the ruler along the U_{out} axis to the left, it is possible to select pairs of voltages any U_{out}^{1} and U_{out}^{0}, in which case the relative error is smaller than |±10%|. If we choose another pair of voltages, we need to calculate the voltage U_z corresponding to it (1.5).

1.3.1. Some features of the graph curves. It can be seen from the Tables and the graphs, that:

1) For **unipolar threshold voltages**, for example, when $C1 = 5V$, the range of relative error $\Delta U_{in}/U_{in} \leq |\pm 10\%|$ includes from the pair $U_{out}^{1} = +10V$, $U_{out}^{0} = +5V$ (***Table 1.1*, Data1**) to the pair of voltages $U_{out}^{1} = 0V$, $U_{out}^{0} = -5V$ (***Table 1.1*, Data4**). When moving the ruler to the left or the right from this range, the relative error increases from |±10%| **for at least one threshold**. Within this range, with the help of a ruler, we can already select a pair of supply voltages for a

given *C* that will provide the accuracy required by the problem. In the case of unipolar threshold voltages, it is possible to **simultaneously** reduce the relative errors of both thresholds. In the direct problem of classical trigger calculation, the relative error was reduced to the necessary extent for the first time in [1] for only one threshold. When choosing a larger *C* and larger output voltage pairs, the range, where the relative errors are smaller than |±10%|, increases. From *Table 1.1*, Data7, it can be seen that at $C2 = 12V$, $U_{out}^1 = 8V$ and $U_{out}^0 = -4V$, the respective relative errors are the smallest: $\frac{\Delta U_{in}}{U_{in}\downarrow}$ =3,33%, $\Delta U_{in}/U_{in}$ ↑=-3,33%, ensuring a 3-fold diminution in threshold voltage errors, under conditions of 10% error of output voltages (*Fig.1.3).*

2) For **bipolar input threshold voltages,** when $U_z = 0V$, the minimum relative error for both thresholds **simultaneously** is 10% only, for example, in the case of **asymmetric** input threshold voltages, for the voltages pairs Data3 ($U_{out}^1 = 3{,}75V$ and $U_{out}^0 = -1{,}25V$) and Data6 ($U_{out}^1 = 7{,}5V$ and $U_{out}^0 = -2{,}5V$) of *Table 1.2 (*see *Fig.1.4).* And when $U_z \neq$ 0V, then when choosing another pair of voltages U_{out}^1 and U_{out}^0, the error of one of the thresholds increases by |±10%|, and the other decreases. If we move the ruler the respective to the movable $C1 = 5V$ from its original position to the right, select the pair of voltages $U_{out}^1 =$ 5V and $U_{out}^0 = 0V$ (*Table 1.2*, Data2), then the error of the low threshold decreases, becomes equal to $\frac{\Delta U_{in}}{U_{in}\uparrow} = 0\%$, and the high threshold error exceeds the allowable amount: $\frac{\Delta U_{in}}{U_{in}\downarrow} =$ 13,3% (see also *Fig.1.4*). This is a consequence of influence of all parameters (*K, C,* U_{out}, U_z) on the formation of the relative error. For both threshold voltages, in order to simultaneously provide a relative error smaller than |±10%|, a change in the technical solutions of the problem should be made. For this there is a need to use a *VCC* power supply with a smaller error. If we use a supply voltage with an error of 3% instead of 10%, then the relative error of the corresponding threshold voltage will be $\frac{13{,}3*3}{10} \approx$ 4%. Thus, using only one *VCC=5V* power supply with smaller error, and $U_z = -2.5/3 = -0.83$V reference voltage (Table 1.2, Data2), we provide smaller relative error **for both thresholds**: $\frac{\Delta U_{in}}{U_{in}\uparrow} = 0\%$, $\frac{\Delta U_{in}}{U_{in}\downarrow} \approx 4\%$. And using a higher precision stabilizer (for example LM4041) and a voltage polarity converter (to have a negative reference voltage, for example TC1220) will ensure higher accuracy and smaller error.

3) In the case of **bipolar symmetrical threshold voltages**, we proceed in the same way.

2. Non-inverting Schmitt trigger. *Fig. 2.1* shows the non-inverting trigger. In *Fig.2.2* the dependence of $U_{out} = f(U_{in})$ (the hysteresis curve), where $U_{in}\downarrow < U_{in}\uparrow$ are shown.

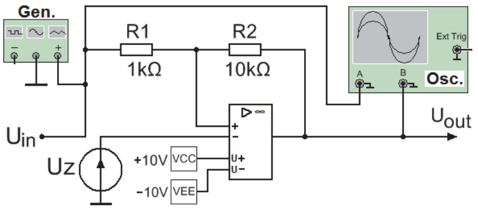

Fig.2.1. The circuit with non-inv. Schmitt trigger

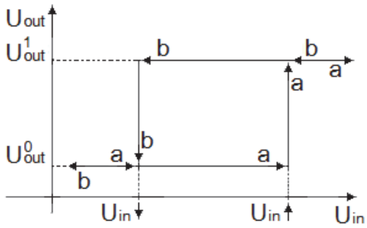

Fig.2.2. The dependence of $U_{out} = f(U_{in})$

The general equations are taken from [1]. Due to size limitations in the article, the equations for non-inverting triggers are given without comments, and only the graphs are presented:

$$U_{in} = U_z \frac{\mathrm{R1+R2}}{\mathrm{R2}} - U_{out} \frac{R1}{R2}, \tag{2.1}$$

$$U_{in} = U_z \frac{1+\mathrm{K}}{\mathrm{K}} - U_{out} \frac{1}{K}, \tag{2.2}$$

$$U_{in} \uparrow = U_z \frac{1+\mathrm{K}}{\mathrm{K}} - U_{out}^0 \frac{1}{K} \text{(high)}; U_{in} \downarrow = U_z \frac{1+\mathrm{K}}{\mathrm{K}} - U_{out}^1 \frac{1}{K} \text{(low)}, \tag{2.3}$$

$$K = \frac{U_{out}^1 - U_{out}^0}{U_{in}\uparrow - U_{in}\downarrow}, \tag{2.4}$$

$$U_z = \frac{U_{in}\uparrow + U_{in}\downarrow}{2} \frac{K}{1+K} + \frac{U_{out}^1 + U_{out}^0}{2} \frac{1}{1+K}, \tag{2.5}$$

$$\Delta U_{in} = -\Delta U_{out} \frac{1}{K}, \tag{2.6}$$

$$\frac{\Delta U_{in}}{U_{in}} = \frac{-\frac{\Delta U_{out}}{U_{out}}}{\frac{U_z(1+K)}{U_{out}} - 1}; \frac{\Delta U_{in}}{U_{in}\uparrow} = \frac{-\frac{\Delta U_{out}}{U_{out}}}{\frac{U_z(1+K)}{U_{out}^0} - 1} \text{(high)}; \frac{\Delta U_{in}}{U_{in}\downarrow} = \frac{-\frac{\Delta U_{out}}{U_{out}}}{\frac{U_z(1+K)}{U_{out}^1} - 1} \text{(low)}, \tag{2.7}$$

$$\frac{\Delta U_{in}}{U_{in}\uparrow} = \frac{-2A_1}{2A_2\,(1+K)+C} U_{out}^0; \frac{\Delta U_{in}}{U_{in}\downarrow} = \frac{-2A_1}{2A_2\,(1+K)-C} U_{out}^1 . \tag{2.8}$$

Unlike an inverting trigger, here $U_{in}\uparrow$ (high threshold) voltage depends on U_{out}^0 voltage, and $U_{in}\downarrow$ (low threshold) depends on U_{out}^1 .We calculated and constructed the corresponding graphs of the relative errors of the threshold voltages, as was the case with the inverting trigger, taking into account that $U_{out}^1 > U_{out}^0$. For each voltage pair, we calculate the unknown voltage U_z using formula (2.5).

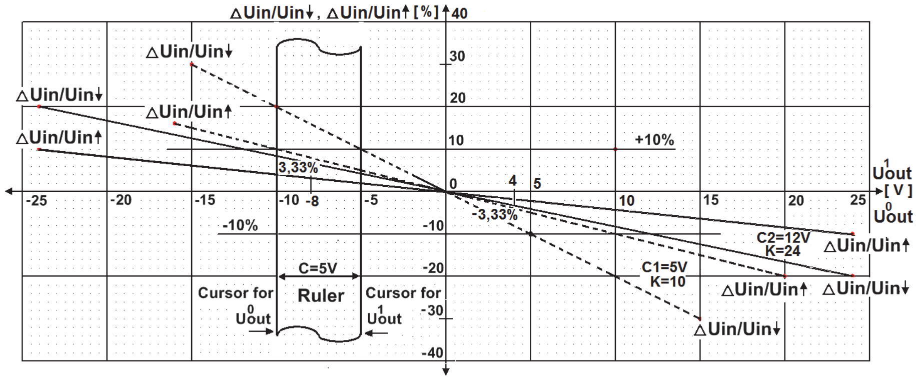

Fig.2.3. The graphs for unipolar input threshold voltage: $U_{in}\uparrow = +1V$, $U_{in}\downarrow = +0{,}5V$

In *Fig.2.3,* curves with parameters $\text{C1} = 5V$ and $\text{K} = 10$ are shown by dashed lines, and curves with parameters $\text{C2} = 12V$ and $\text{K} = 24$-by solid lines.

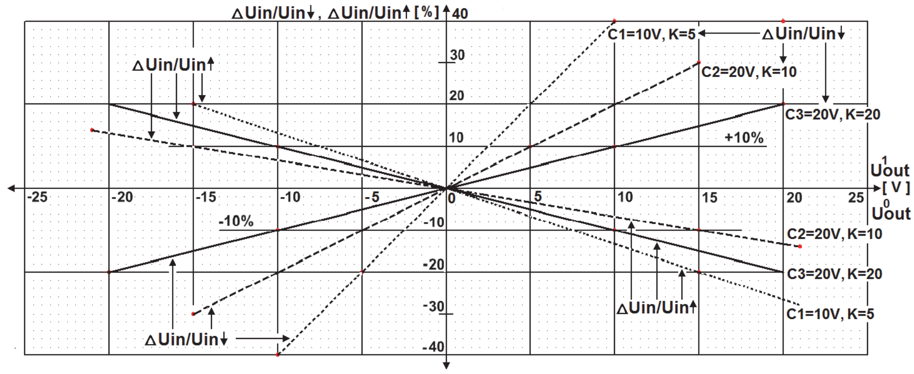

Fig.2.4. The graphs for bipolar asymmetric input threshold voltage: $U_{in}\uparrow = 1{,}5V$, $U_{in}\downarrow = -0{,}5V$, for symmetric input threshold voltage: $U_{in}\uparrow = +0{,}5V$, $U_{in}\downarrow = -0{,}5V$

In *Fig.2.4,* for bipolar asymmetric input threshold voltage, curves with parameters $\text{C1} = 10V$ and $\text{K} = 5$ are shown by dotted-dashed, curves with parameters $\text{C2} = 20V$ and $\text{K} = 10$-by dashed lines. For symmetric input threshold voltage, curves with parameters $\text{C2} = 20V$; K= 20 are shown by solid lines.

2.1. Some features of the graph curves:

1) for **unipolar threshold voltages**, similarly to an inverting trigger, place the movable ruler in the position of voltages: $U^1_{out} = -5V$ and $U^0_{out} = -10V$. In that position, the lines $\frac{\Delta U_{in}}{U_{in}\downarrow}$ and $\frac{\Delta U_{in}}{U_{in}\uparrow}$ intersect with the horizontal +10% line simultaneously. If we move the ruler to the right and place it in the position corresponding to the pair $U^1_{out} = 5V$ and $U^0_{out} = 0V$, we will see that $\frac{\Delta U_{in}}{U_{in}\downarrow} = -10\%$, $\frac{\Delta U_{in}}{U_{in}\uparrow} = 0\%$ (see *Fig2.3.*, curves with parameters $C1 = 5V$ and

$K = 10$). In the range of these two pairs of output voltages, the relative errors of the threshold pair voltages are simultaneously smaller than |±10%|, as in the inverting trigger. When moving the ruler to the left or the right from this range, the relative error increases from |±10%| **for at least one threshold**;

2) for **bipolar input threshold** voltages, the minimum relative error for both thresholds simultaneously is 10% only when $U_z = 0V$, just like in the inverting trigger. And when $U_z \neq 0V$ choosing another pair of voltages U_{out}^1 and U_{out}^0, the error of at least one of the thresholds increases from |±10%|, and the other one decreases. In order to ensure a relative error smaller than |±10%| for two threshold voltages simultaneously, we make a change in the technical solutions of the task, similar to an inverting trigger.

Conclusion: For solving the inverse problem of calculating Schmitt inverting and non-inverting triggers:

1) we derived equations in which the input threshold voltages are known as the main and constant parameters, and all other parameters are secondary;

2) we have shown that if K and U_z are constant, then the relative errors of threshold voltages depending on output voltages are linear functions passing through the point of intersection of the coordinate axes, for the construction of which it is sufficient to choose only one pair of output voltages for each *C*.

1. In the case of **unipolar input threshold voltages**:

1) when $U_z \neq 0V$, we can **always** choose such pairs of output voltages, in which the relative errors of threshold voltages are smaller than |±10%|;

2) in case of a certain error of the output voltages, we simultaneously reduce the errors of both threshold voltages by the necessary amount.

2. In the case of **bipolar input threshold voltages**:

1) the minimum relative error for both thresholds is 10% simultaneously, when $U_z = 0V$, and when $U_z \neq 0V$, the relative error of at least one of thresholds can always be ensured in the range of 0÷|±10%|;

2) in order to reduce simultaneously the relative error values below |±10%|, we have proposed new solutions using **only one power supply** with a smaller error.

When calculating a Schmitt trigger with our proposed methods, we avoid the errors that occur of the direct problem, when the choices of parameters U_z, U_{out}^1, U_{out}^0 and K are not justified. With our methods, the choices of the technical parameters of the triggers are justified, by which their quality standards can be improved. We have proposed solutions, to reduce the relative errors for **both thresholds simultaneously** to the necessary extent, in the conditions of the existing errors of the output voltages.

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Institute of Radiophysics & Electronics National Academy of Sciences of RA. The material is received on 10.06.2024.

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ՇՄԻՏՏԻ ՏՐԻԳԵՐԻ ՀԱՇՎԱՐԿԸ՝ ԿԱԽՎԱԾ ՄՈՒՏՔԱՅԻՆ ՇԵՄԱՅԻՆ ԼԱՐՈՒՄՆԵՐԻՑ, ՀԱԿԱԴԱՐՁ ԽՆԴԻՐ

Ներկայացված են Շմիտտի շրջող և չշրջող դասական տրիգերների հաշվարկի հակադարձ խնդրի լուծման ճանապարհը և առանձնահատկությունները: Արտածվել են նոր հավասարումներ, որոնցում հայտնի են մուտքային շեմային լարումները՝որպես **գլխավոր և անփոփոխ** պարամետրեր, իսկ մյուս պարամետրերը երկրորդական են շեմային լարումների համեմատ: Հաշվարկվել են տրիգերի սխեմայի մնացած բոլոր անհայտ պարամետրերը: Արտածվել են հավասարումներ՝ շեմային լարումների հարաբերական սխալների հաշվարկի համար: Գնահատվել է ելքային լարումների սխալների ազդեցությունը շեմային լարումների սխալների վրա: Հաշվարկվել են մուտքային շեմային լարումների (վերնի, ներքնի) հարաբերական սխալների կախվածությունները տրիգերի ելքային լարումների հարաբերական սխալներից: Ապացուցվել է, որ այդ հավասարումներից յուրաքանչյուրը, ելքային լարումներից կախված, գծային ֆունկցիա է այն դեպքում, երբ այդ լարումների տարբերությունը հաստատուն է: Մշակվել է մեթոդական ուղեցույց մուտքային շեմային լարումների հարաբերական սխալների հաշվարկների համար: Նրա միջոցով կատարվել են հաշվարկներ շեմային լարումների երեք տարբերակների դեպքում՝ միաբևեռ, երկբևեռ ասիմետրիկ և երկբևեռ սիմետրիկ: Հաշվարկային աղյուսակների հիման վրա կառուցվել են ելքային լարումներից մուտքային շեմային լարումների հարաբերական սխալների կախվածության գրաֆիկները: Ցույց է տրվել, որ ամեն մի կորի կառուցման համար բավարար է ընտրել ելքային լարումների միայն մեկ զույգ: Մշակվել է գրաֆիկներից օգտվելու ուղեցույց: Առաջարկվել է շարժական քանոն, որով հեշտությամբ (առանց հաշվարկների) կարելի է ընտրել ելքային լարումների այնպիսի զույգ, որը կապահովի խնդրի պահանջներին բավարարող ճշտություն: Լուծումներ են առաջարկվել երկու շեմերի համար միաժամանակ նվազեցնելու հարաբերական սխալները՝ ելքային լարումների առկա սխալների պայմաններում: Առաջարկված մեթոդներով կարելի է հաշվարկել Շմիտտի նոր տրիգեր՝ զերծ մնալով այն սխալներից, որոնք կարող են առաջանալ ուղիղ խնդրի հաշվարկի ժամանակ, երբ հենակային լարման, ելքային լարումների և հետադարձ կապի գործակցի մեծության ընտրությունները հիմնավորված չեն: Առաջարկած մեթոդները հիմնավորում են տրիգերների տեխնիկական պարամետրերի ընտրությունը, ինչը կբարելավի դրանց որակը:

Առանցքային բառեր. Շմիտտի տրիգեր, հակադարձ խնդիր, կոմպարատոր, շեմային լարում, հենակային լարում, ելքային լարում, լարումների հարաբերական սխալներ:

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РАСЧЕТ ТРИГГЕРА ШМИТТА В ЗАВИСИМОСТИ ОТ ПОРОГОВЫХ НАПРЯЖЕНИЙ. ОБРАТНАЯ ЗАДАЧА

Представлены путь и особенности решения обратной задачи расчета инвертирующих и неинвертирующих классических триггеров Шмитта. Получены уравнения, в которых входные пороговые напряжения известны как **основные и постоянные** параметры, а остальные параметры являются вторичными по отношению к пороговым напряжениям. Рассчитаны все остальные неизвестные параметры триггерной схемы. Выведены уравнения для расчета относительных погрешностей пороговых напряжений. Показаны зависимости этих погрешностей от выходных напряжений триггеров и их относительных погрешностей. Доказано, что эти уравнения в отдельности являются линейными функциями от выходных напряжений в том случае, когда разность этих напряжений постоянна. Разработаны методические указания по расчетам относительных погрешностей пороговых напряжений. Построены графики зависимости относительных погрешностей входных пороговых напряжений от выходных напряжений. Показано, что для построения каждой кривой достаточно выбрать только одну пару выходных напряжений. Разработано руководство по использованию графиков. Предложена подвижная линейка, с помощью которой без предварительных расчетов можно подобрать такую пару выходных напряжений, которая обеспечит удовлетворяющую требованиям задачи точность. Предложены решения, позволяющие одновременно снизить относительные погрешности для обоих порогов в условиях существующих погрешностей выходных напряжений. С помощью предложенных методов можно рассчитать новый триггер Шмитта, избежав ошибок, которые могут возникнуть при расчете прямой задачи, когда выборы значений опорного напряжения, выходных напряжений и коэффициента обратной связи не обоснованы. Предложенными методами обосновывается выбор технических параметров триггеров, что позволит повысить их качество.

Ключевые слова: триггер Шмитта, обратная задача, компаратор, пороговое напряжение, опорное напряжение, выходное напряжение, относительные погрешности напряжений.