EQUILIBRATION OF THE WHEATSTONE BRIDGE BY THE PULSE-WIDTH MODULATION METHOD

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ABSTRACT

Possibility of an equilibration of the resistive sensor bridge scheme (the Wheatstone bridge) is investigated by the Pulse-Width Modulation method. On the basis of imitating modeling and experiment the transformation process of the resistive sensor resistance into binary code by Microcontroller Measurement Converter is considered. The equilibration process of the Wheatstone bridge circuit is realized with using Pulse-Width Modulator and the Analogue Comparator built in the microcontroller. The offered method allows combining functions of Analog-to-Digital Conversion with the Wheatstone bridge equilibration that is very important at creation of intellectual sensors.

Keywords: Wheatstone bridge, microcontroller measuring converter, resistance, pulse-width modulator, resistive sensor, binary code.

1. INTRODUCTION

The bridge scheme of inclusion of the resistive sensor, known as the Wheatstone bridge, is the basic circuit decision necessary for maintenance of the high accuracy measurement. Its lack is sensitivity decreasing while increasing of the bridge disbalance. The material about the problems appearing in using of the resistive bridge schemes and ways of their overcoming is stated in the works [1, 2] in enough clear form.

The task decision of the increase accuracy measurement by the Wheatstone bridge is in the support its balance status. For this purpose Programmable Resistors [3] are using. We offer to apply the Pulse-Width Modulation method for control by resistance, realized by Microcontroller Measuring Converter (MMC). MMC is the basis of any intellectual sensor.

2. THE MICROCONTROLLER MEASUREMENT CONVERTER (MMC) SCHEME

MMC is the microcontroller system intended for conversion of the measured physical size into the binary code. Scheme MMC with equilibration of the resistive bridge by the Pulse-Width Modulation method is presented on Figure-1.

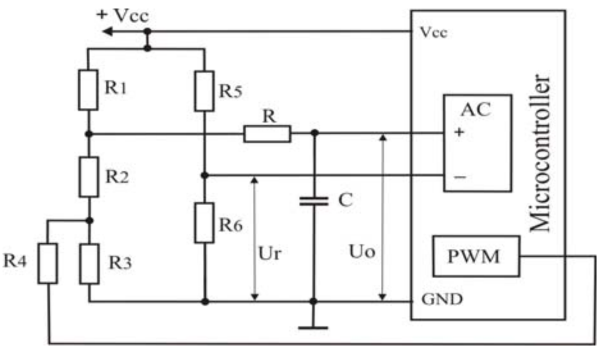


Figure-1. MMC with equilibration of the Wheatstone bridge by the pulse-width Modulation method, scheme.

MMC (Figure-1) contains the following elements: the microcontroller; exemplary resistors R_1, R_3, R_4 and resistive sensor R_2 - the elements of controlled resistive divider, and it is possible another variant, when $R_1 = R_3 = R_4$; resistors R_5 и R_6 - the elements of reference resistive divider intended for formation of voltage reference *Ur*, and, $R_5 = R_6$; resistor R and condenser C - elements of the smoothing RC-filter on which output voltage *Uo* is formed, and $R >> R_1,...,R_4$. When the modeling we will accept $R = 100k\Omega$ and $C = 0{,}1\,\mu F$. The microcontroller contains the Pulse-Width Modulator (PWM) и Analogue Comparator (AC).

The RC-filter output is connected to AC non-inverting input; the average point of reference resistive divider is connected to AC inverting input. Bridge and microcontroller power supply is carried out from one source, which voltage $V\tilde{n}\tilde{n}$.

The microcontroller watches for the voltage *Uo*, which is formed on an output of the RC-filter and depends on resistance R_2 of the resistive sensor, and also coefficient of filling *G* of the pulse-width modulated signal (PWM-signal) formed by means of PWM. If, voltage *Uo* becomes less then voltage *Ur*, for example, due resistance R_2 reduction, then AC will change the logic level for the opposite on its output. After this event the microcontroller starts gradually increasing the coefficient of filling *G* that leads to increase the equivalent resistance forming by the resistors R_3 and R_4, and consequently to increase voltage *Uo*. *AC* will change logic level for the opposite, as soon as voltage *Uo* becomes more than voltage *Ur*. When this event happens the microcontroller starts gradually reducing *G* etc. Value of voltage *Uo* fluctuates near to value of reference voltage *Ur*, i.e., $Uo \approx Ur$. Analog-to-Digital Conversion with using the Pulse-Width Modulation method is considered in works [4-6].

Thus, by the change of the filling coefficient *G* it can control equivalent resistance, forming by resistors R_3 and R_4, and consequently voltage *Uo*. It is possible to confirm, that the coefficient of filling *G* is function R_2, i.e., $G = f(R_2)$. Deviation value *Uo* from *Ur,* and consequently, also resistance sensitivity, depend from PWM resolution.

3. CONVERSION'S PROCESS

For the maximum and constant sensitivity achievement of the Bridge in all range of resistance R_2 change, it is necessary to keep this condition: $R_1 = R_2 + R_{M34}$, where $R_{M34} = (R_3 \cdot R_{M4})/(R_3 + R_{M4})$ - the equivalent resistance of resistors R_3 and $R_{M4} = R_4/(1-G)$ connected in parallel. Let's consider, that condition $R_5 = R_6$ is always carried out, and therefore reference voltage $Ur = const$.

The scheme explaining of the process of voltage formation *Uo* is represented on Figure-2. The Equivalent circuit of output cascade PWM is designated by a shaped line. Key S is operated by PWM.

It is necessary to note feature the particular PWM work. In a standard mode any PWM periodically deduces on an output or logic «1» (high level of voltage) or logic «0» (low level of voltage). In this case, instead of conclusion logic «1» output of PWM (Pn) is switched by the microcontroller in a high-resistance status (Z - position).

Key S can be in three positions L, Z and H. L-position is characterized by that key S connects output Pn to the plug «–» of the microcontroller power supply (key S is in the bottom position, Figure-2). Z-position is characterized by that key S is in a high-resistance status (key S is on the average position, Figure-2). H-position is characterized by that key S connects Pn to the plug «+» of the microcontroller power supply (key S is in the top position, Figure-2).

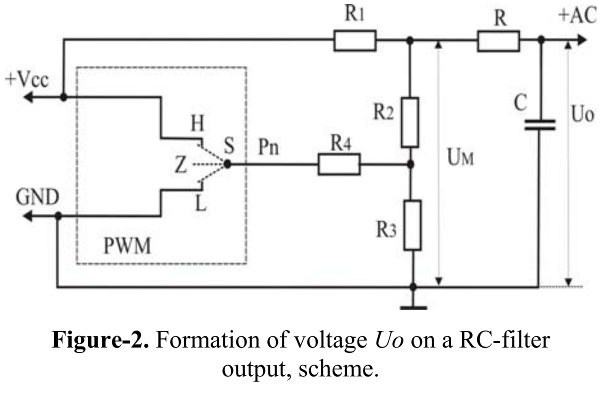


Figure-2. Formation of voltage *Uo* on a RC-filter output, scheme.

If key S is in a Z-position that on RC-filter input high level of the voltage which value is defined by formula will be generated:

$$U_H = \frac{Vcc \cdot (R_2 + R_3)}{R_1 + R_2 + R_3} \tag{1}$$

If key S is in a L-position that on RC-filter input low level of the voltage which value is defined by formula will be generated:

$$U_L = \frac{Vcc \cdot \left(R_2 + \dfrac{R_4 \cdot R_3}{R_4 + R_3} \right)}{R_1 + R_2 + \dfrac{R_4 \cdot R_3}{R_4 + R_3}} \tag{2}$$

Average value of PWM-signal voltage on the RC-filter input is defined by expression:

$$U_M = (U_H - U_L) \cdot G + U_L, \tag{3}$$

where $G = t_Z / T_M$ - the coefficient of filling of PWM-signal; $T_M = t_Z + t_L$ - the period of PWM-signal; t_Z и t_L - accordingly, duration of statuses in Z- and L-positions (Figure-3) of key S.

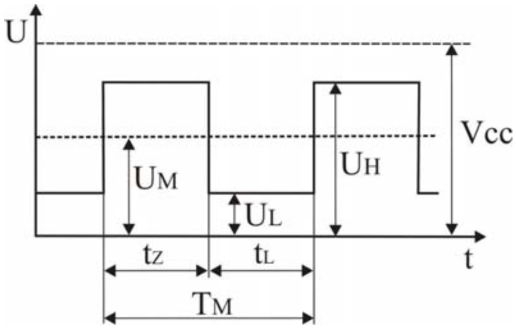


Figure-3. Voltage change on the RC-filter input, timing diagram.

Filling's coefficient G character of dependence from resistance R_2 change has interest. On the basis of expression (3) we will receive:

$$G = (U_M - U_L)/(U_H - U_L) \tag{4}$$

4. CONVERSION'S PROCESS MODELING

4.1. Analytical model

Analytical model for research of MMC, realizing expression (4) with using expressions (1) and (2), is constructed in the system Matlab/Simulink (Figure-4).

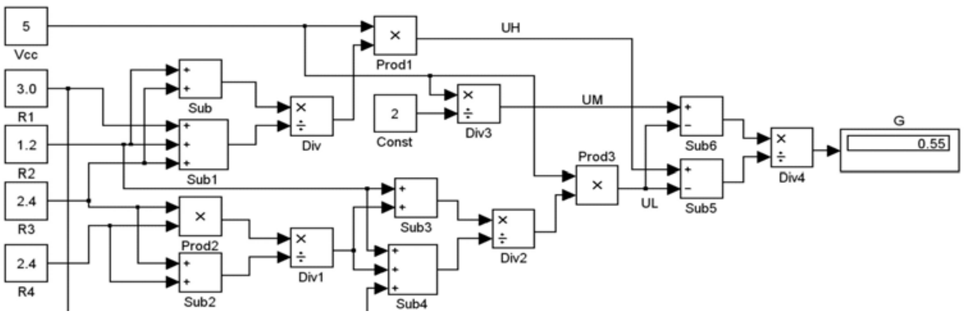


Figure-4. Analytical model for research of MMC.

In analytical model (Figure-4) values of resistance R_1 ... R_4 are set in kiloohms (kΩ), voltage *Vcc* of the power supply - in volts (V). As $R_5 = R_6$, that $Ur = Vcc/2$. The indicator reflects value of filling's coefficient $G = 0, 55$, for the case, when $R_2 = 1, 2\ k\Omega$ (in Table-1 these values are assigned). The dependence $G=f\ (R_2)$ (Table-1.) is received with using of analytical model (Figure-4), which adequacy is confirmed by imitation model (Figure-5), constructed in the system Matlab/Simulink.

Table-1. The dependence $G=f\ (R_2)$.

R_2, kΩ	0, 7	0, 8	0, 9	1, 0	1, 1	1, 2	1, 3	1, 4	1, 5	1, 6	1, 7
G	0, 93	0, 86	0, 79	0, 71	0, 63	0, 55	0, 47	0, 38	0, 29	0, 19	0, 10

The range of resistance's change R_2 from 0, 7 to 1, 7 kΩ is equal to the range of resistance's change of the semi-conductor temperature KTY81/110 sensor. At the change of sensor's temperature KTY81/110 from 0 to $100^{\circ}C$ its resistance changes taking into account technological scattering from 802 Ω to 1733 Ω [7].

4.2. Imitating model

In imitating model (Figure-5) of the measuring converter's module, realizing the process of the bridge scheme equilibration by a method PWM, the following blocks are used:

Block G is intended for the task of value of filling's coefficient G, is referred to the blocks Simulink library and has designation Constant.

Block PWM is controlled by PWM, which filling coefficient proportionally changes at signal change on the input +ref. The given block is referred to the electronic devices SimElectronics library and has a designation - Controlled PWM Voltage 1 [8].

The blocks Subsystem … Subsystem 3 are applied for connection of the blocks used from different libraries of subsystem Simulink.

Block Voltaqe-Controlled Switch represents a key controlled by voltage. When on output of block PWM the high level of voltage the given key is open, when the low level is close.

Oscillographs Scope … Scope 2 is intended for display of voltage change in the corresponding points of the measuring converter's model.

Block Solver Configuration is intended for the task of modeling parameters. Other elements of the model have designations which do not demand explanations.

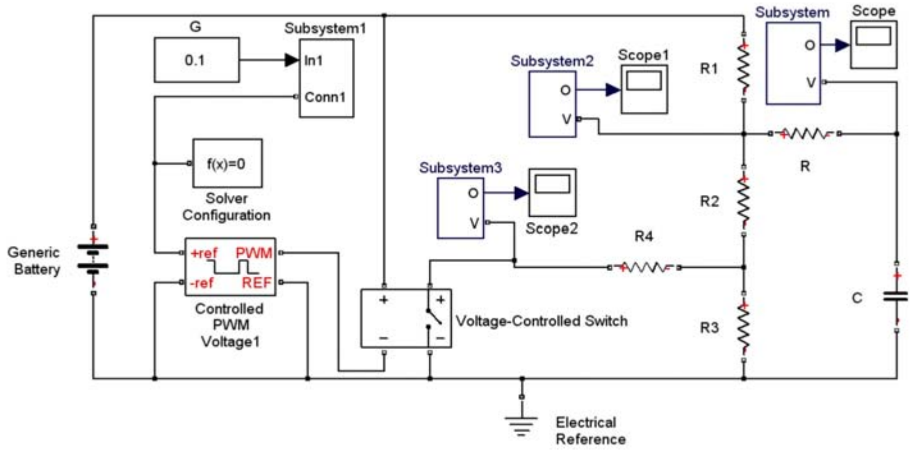


Figure-5. Imitating model for research of MMC.

For check of adequacy of imitating model the experiment with using Starter Kit of microcontroller devices STK500 is made. The experimental sample of MMC is constructed on the basis of microcontroller ATmega16, its program [9] is developed in Assembler language.

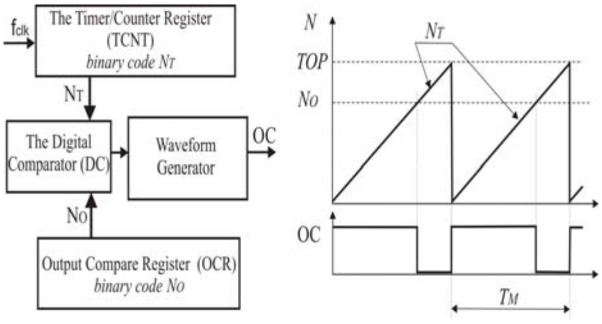
The resistance box P33 is used as variable resistor R_2. Frequency of the microcontroller clock generator makes $f_{clk} = 4\ MHz$ thus frequency of the PWM-signal - $f_M = 1960\ Hz$ (prescaler divider - 8). The description of microcontroller architecture ATmega16 is resulted in the textbook [10]. We will shortly consider typical process of the PWM-signal formation on the microcontroller output.

5. PWM MODE IN EXPERIMENTAL RESEARCHES MMC

The binary code proportional to filling coefficient is formed by the counter built into the microcontroller, working in PWM mode. It is appropriate to use «Fast PWM» mode at which on PWM output the impulses sequence of the highest frequency is formed, that allows to receive on the RC-filter output the smoothed voltage with smaller coefficient of pulsations for realization MMC.

Counter's functioning in the regime «Fast PWM» consists in the following. The Timer/Counter Register TCNT (Figure-6) sums up the clock pulses, becoming with frequency f_{clk}, for example, from the internal clock generator of the microcontroller. As soon as binary code *NT* of the Timer/Counter Register TCNT will be equalize to binary code *NO* of Output Compare Register OCR, on the output OC PWM of the microcontroller low logic level is formed. The Timer/Counter Register TCNT continues the count until reaches the TOP when it becomes equal to the highest value in the count sequence. The counter throws off into zero, and on the OC PWM output high logic level is formed. The moment of equality $NT = NO$ fixes the digital comparator. In this case we have considered the non-inverting PWM.

The PWM-signal frequency is defined $f_M = 1/T_M = f_{clk} / (TOP + 1)$. TOP value can be any in range 3 … 65535, that corresponds to the resolution of 2 … 16 digits. TOP's value registers in the capture register (on Figure-6 it is not shown). Filling's coefficient, if don't consider displacement $1/(TOP+1)$, is directly proportional to contents *NO* of the Output Compare Register (OCR) and it is defined by expression $G = (NO + 1) / (TOP + 1)$, for $0 \le NO \le TOP$.



a) b)

Figure-6. PWM-signal formation on OC output in mode «Fast PWM»: a) PWM Unit, block diagram; b) Formation of PWM-signal on OC output, timing diagram.

Values of filling's coefficient in depending from change of resistance R_2, received as the result: experiment - G_e, analytical modeling - G_a and imitating modeling - G_i are resulted in Table-2. Also values of decimal equivalent of binary code N, which is an equivalent of filling's coefficient G_e are resulted. Change of the binary code increment, defined by expression $\Delta N = N_i - N_{i+1}$ changes from 23 to 29, at constant increment $\Delta R_2 = 0,\ 1\ k\Omega$ in range $1,\ 1\ \ldots\ 2,\ 0\ k\Omega$. The conclusion follows from here - at increasing of resistance R_2 the MMC sensitivity is increased.

The insignificant average divergence between $G\text{э} - Ga = 0,\ 039$ (Table-2), is obviously connected with voltage drop across the transistor key, which has been not considered in analytical model. There is experimentally established, that at $Vcc = 5\ B$, and H-, L-positions of key S the voltage on the Pn output (Figure-2), are accordingly equal $U_H \approx 4{,}975\,B$ and $U_L \approx 0{,}026\,B$. Thus the current in the Pn output's circuit of PWM is equal 1мA.

Table-2. Results of experiment, analytical and imitating modeling.

R_2, kΩ	N	$N_i - N_{i+1}$	G_e	G_a	G_i	$G_e - G_a$
1, 1	245		0, 961	0, 915	0, 916	0, 046
1, 2	222	23	0, 871	0, 827	0, 828	0, 044
1, 3	198	24	0, 776	0, 735	0, 736	0, 041
1, 4	174	24	0, 682	0, 64	0, 641	0, 042
1, 5	149	25	0, 584	0, 542	0, 543	0, 042
1, 6	122	27	0, 478	0, 44	0, 441	0, 038
1, 7	95	27	0, 372	0, 335	0, 336	0, 037
1, 8	66	29	0, 259	0, 227	0, 228	0, 032
1, 9	37	29	0, 145	0, 115	0, 116	0, 030
2, 0	8	29	0, 031	0, 0	0, 001	0, 031

PWM resolution is 8 bits that allows to output result in any 8-digit port of the microcontroller on 8 light - emitting diodes of general appointment of device STK500.

Thus, we have received enough good converting characteristic, that will probably serve as the reason for the further development of the given equilibration method of the Wheatstone bridge with use microcontroller's PWM. The nearest analogue MMC for resistive sensors is considered in the works [11, 12], and MMC for capacitive sensors are considered also in the articles [13-15].

6. ALGORITHMS EXPLAINING A PRINCIPLE OF FUNCTIONING MMC

Algorithms explaining a principle of functioning MMC with the Wheatstone bridge equilibration by the Pulse-Width Modulation method are presented on Figure-7. The same algorithms can be used for developing MMC software, constructed on the basis of other microcontrollers.

Last block of the program algorithm (Figure-7(a)) specifies transition in this place to the subprogram of calculation R_2 over known values of resistances R_1, R_3, R_4 and filling's coefficient G received as a result of transformation. This subroutine should realize computing operations according to expression (5), which is received as a result of transformations given lower.

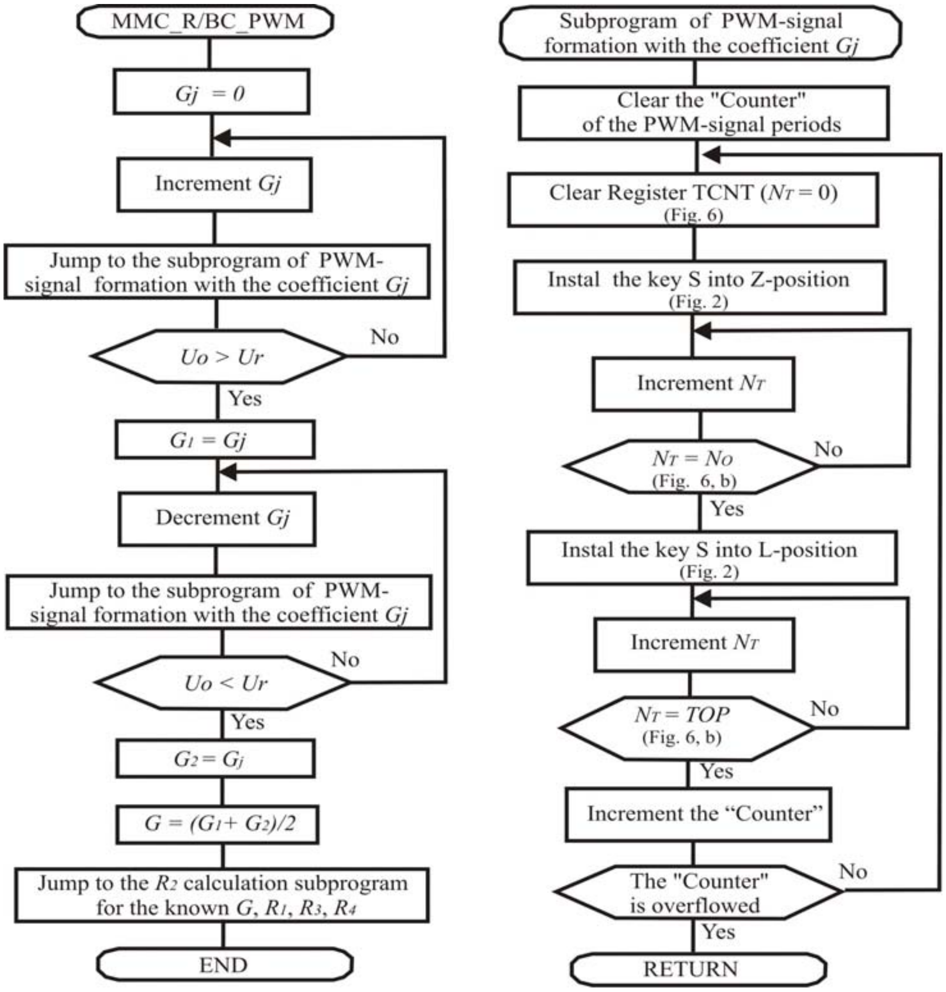


Figure-7. Algorithms: a) MMC Program; b) Subprogram of PWM-signal formation with the coefficient *Gj*.

Let's solve the equation (3) concerning R_2, using expressions (1), (2) and accepting $U_M = Vcc/2 = 0{,}5V_{cc}$

$$0{,}5V_{cc} = (U_H - U_L)\cdot G + U_L = U_H\cdot G - U_L\cdot G + U_L = U_H\cdot G + U_L\cdot(1-G)$$

$$0{,}5\,V_{cc} = \frac{V_{cc}\cdot(R_2+R_3)}{R_1+R_2+R_3}\cdot G + \frac{V_{cc}\cdot\left(R_2+\dfrac{R_4\cdot R_3}{R_4+R_3}\right)}{R_1+R_2+\dfrac{R_4\cdot R_3}{R_4+R_3}}\cdot(1-G)$$

As a result of transformations we obtain the quadratic equation:

$$aR_2^2 + bR_2 + c = 0,$$

where $a = 0{,}5$;

$$b = 0{,}5 \cdot \left(R_3 + \frac{R_4 \cdot R_3}{R_4 + R_3} \right);$$

$$c = G \cdot R_1 \cdot \left(R_3 - \frac{R_4 \cdot R_3}{R_4 + R_3} \right) + 0{,}5 \cdot (R_1 + R_3) \cdot \left(\frac{R_4 \cdot R_3}{R_4 + R_3} - R_1 \right)$$

As is known

$$R_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{5}$$

The solution of the quadratic equation gives two values for R_2 - positive and the negative, the latter is discarded, because it does not satisfy the condition $R_2 > 0$.

7. CONCLUSIONS

Received results testify, that on the basis of the microcontroller it is possible to realize the method of equilibration of the resistive Wheatstone bridge enough effectively. This method is used for the decision of the tasks, where high accuracy of measurement is required. Adequacy of the developed imitating and analytical models, allowing investigating processes of conversion of the resistive sensor resistance into binary code equivalent to filling coefficient of the PWM-signal is experimentally confirmed. The given models can be used for the decision of the tasks of the intellectual resistive sensors designing constructed on the basis of microcontrollers with use of equilibration of the resistive Wheatstone bridge by the method of Pulse-Width Modulation.

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