ANALOG-TO-DIGITAL CONVERTER BASED ON THE TRANSIENT PROCESS IN RC-CIRCUIT

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Abstract. ADC based on using the transient process in RC-circuit patented by the authors is presented. This ADC is conditionally called RC-ADC. The task was: to compare the conversion speed of RC-ADC and successive approximation ADC. An experimental sample of RC-ADC was built on the basis of ATmega16 AVR Microcontroller. As successive approximation ADC has been considered 10 bit ADC of AVR Microcontrollers.During the study of RC-ADC there were obtained results on the basis of which it could be affirmed, that the RC-ADC with the Microcontroller clock frequency of 10 MHz is not inferior in conversion speed of successive approximation ADC with the clock frequency of 100 kHz. RC-ADC absolute error is slightly higher than ADC AVR Microcontroller error. The article describes the sequence of time calculation needed for Microcontroller for one cycle of analog-to-digital conversion in RC-ADC. There are general Algorithm of RC-ADC work, timing Diagram for explaining the operation of RC-ADC and Oscillogram of capacitor voltage change in RC-circuit. This proposed RC-ADC can be implemented on the basis of the following elements: integrated circuits, programmable logic integrated circuits and Microcontrollers. Perhaps, the considered RC-ADC in comparison with the known ADC will be more versatile and simple for technical implementation.

Keywords: Microcontroller, RC-ADC, Analog Comparator, clock frequency, charge/discharge process.

Introduction

Analog-to-digital Converter (ADC) based on using the transient process in RC-circuit [1] patented by the authors. This ADC is named – RC-ADC. The task was: to compare the conversion speed of RC-ADC and 10-bit successive approximation ADC of AVR Microcontroller. AVR Microcontrollers in proportion of productivity-energy consumption-price are among the best in the world market of Microcontrollers.

Figure 1 shows the equivalent circuit of RC-ADC, implemented on the basis of Atmega16 AVR Microcontroller. Digital outputs of Microcontroller equipped with internal electronic switches $S1$ and $S2$, which will have output resistances R_{S1} and R_{S2}. It was established experimentally that $R_{S1} = R_{S2} = R_S \approx 26\ \Omega$, if Microcontroller temperature is 20 ºC and current through keys $S1$ and $S2$ is 1mA. When the output is low voltage (logic zero) or high (logic one), then the voltage drop in the resistors R_{S1} and R_{S2} is very small and they can be neglected. We assume that $V_L = 0\ V$ and $V_H = Vcc$, where Vcc – the supply voltage of Microcontroller.

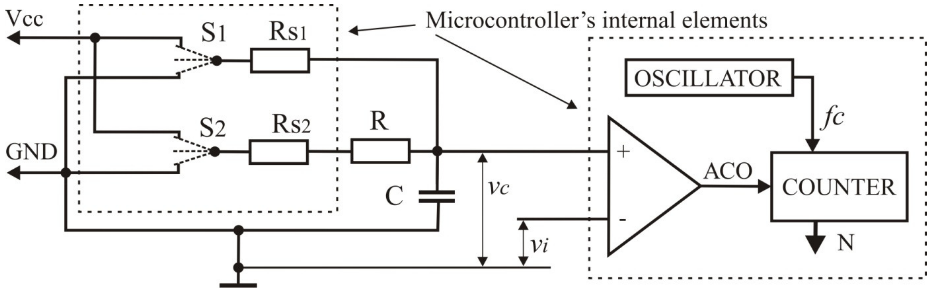

Fig. 1. **Equivalent circuit of RC-ADC**

The Analog Comparator Output (ACO) is connected to the special Input of Counter for realization of the Capture function, as shown in Figure 1. The Capture function is used to save the content of the Counter in the moment, when the logical state of ACO is reversed. Clock pulses of *fc* frequency come to Input of Counter from the Oscillator. The content of Counter – binary code N stored in Capture Register of Microcontroller, which in Figure 1 is not shown.

On Analog Comparator non-inverting Input from RC-circuit Output is applied voltage v_c, changing while charge (1) and discharge (2) of Capacitor C according to the known laws:

$$v_C = V_H \cdot (1 - e^{-t/RC}), \quad (1)$$

$$v_C = V_H \cdot e^{-t/RC}. \quad (2)$$

On Analog Comparator inverting Input the input voltage v_i is applied, which must be converted into binary code $N_{(RC\text{–}ADC)}$.

Binary code N stored in the Capture Register is the equivalent of time t, the value of which Microcontroller uses for calculating v_C in accordance with one of the expressions (1) or (2). Because the binary code N is stored at the time of equality $v_C = v_i$, then Microcontroller determines the value of v_i. Microcontroller keeps in its memory the value v_i in the form of the binary code $N_{(RC\text{–}ADC)}$ as a result of analog-to-digital conversion.

The structure of RC-ADC consists of the elements shown in Figure 2: Microcontroller (MCU); Resistor R and Capacitor C of RC-circuit; resistors R_1, R_2 and R_3, and wherein $R_3 >> R_1 = R_2$. Findings of Microcontroller port marked – PB0...PB4.

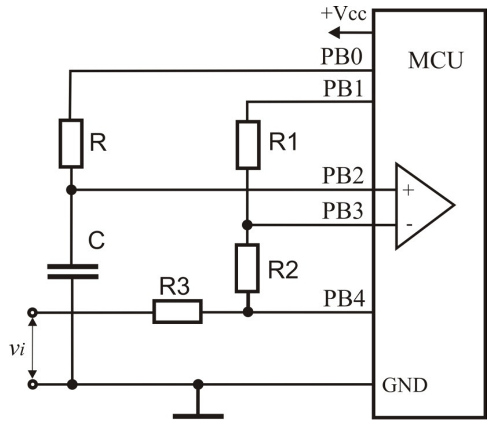

Fig. 2. **Functional scheme of RC-ADC-based Microcontroller**

RC-ADC work algorithm

Step 1. Microcontroller configures PB1 and RV4 to high-resistance level, PB2 and RV3 – to the input, i.e. PB2 Output connects to the non-inverting Input and PB3 Output – to Analog Comparator inverting Input. PB0 always leads to Output. Figure 3 shows a timing Diagram of RC-ADC operation.

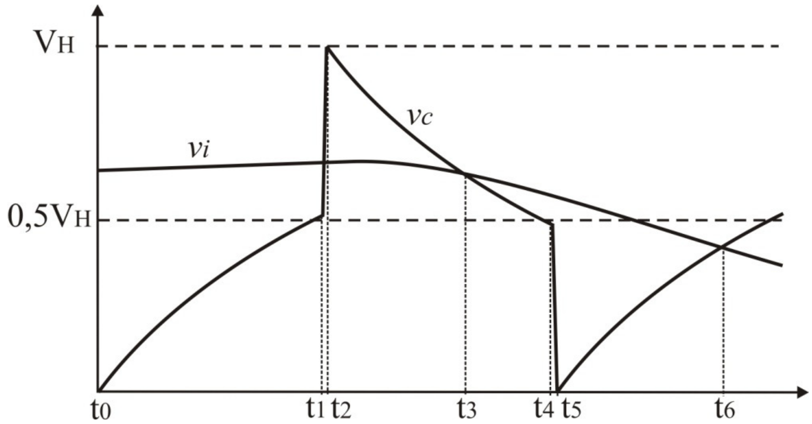

Fig. 3. **Operation of RC-ADC, Timing Diagram**

At the time moment t_0 Microcontroller is changing the level from low V_L to high V_H on its PB0 Output. Pre-discharged Capacitor C begins to charge through the Resistor R to 0.5 V_H voltage. We shall call this cycle stage "**basic charge process**". The time during which the process is implemented will be called "**basic charge process time**". This time is determined by the timing Diagram: $T_{Cb} = t_1 - t_0$, as well as by the equation:

$$T_{Cb} = -R \cdot C \cdot \ln\left(1 - \frac{0,5 \cdot V_H}{V_H}\right) = 0.693 \cdot R \cdot C. \tag{3}$$

Step 2. Microcontroller configures PB2 lead to the Output and outputs through it V_H. The Capacitor C is charged to V_H. We shall call this cycle stage "**preparatory charge process**". The time during which the process is implemented, will be called "**preparatory charge process time**". This time is determined by the timing Diagram: $T_{Cp} = t_2 - t_1$, as well as by the equation:

$$T_{Cp} = 5 \cdot R_S \cdot C, \tag{4}$$

where R_S – output resistance of the transistor switch PB2 Output, 26 Ω.

Step 3. Microcontroller configures PB2 lead to the Input and outputs V_L to PB0 Output. Capacitor C begins to discharge. We shall call this cycle stage "**basic discharge process**". The time during which the process is implemented, will be called "**basic discharge process time**". This time is determined by the timing Diagram: $T_{Db} = t_4 - t_2$, as well as by the equation: $T_{Db} = 0.693 \cdot R \cdot C$, analogously (3). At the time moment t_3 the voltage $Vc = Vi$ and Analog Comparator Output changes the logic level. The Counter contents, i.e. the binary code N_D is stored in the Capture Register. N_D is the equivalent of time interval $T_D = t_3 - t_2$. Capacitor C continues to discharge till $0.5V_H$ voltage, i.e. until the time moment t_4.

Step 4. Microcontroller configures PB2 lead to the Output and outputs through it V_L. In the time interval (t_4 ... t_5) the Capacitor C discharge to the voltage V_L is executed. We shall call this process "**preparatory discharge process**", and the time during which it is implemented – "**preparatory discharge process time**" $T_{Dp} = t_5 - t_4$.

Step 5. Microcontroller configures PB2 lead to the Input. At the time moment t_5 Microcontroller is starting off "**basic charge process**", similar to the process in the time interval (t_0 ... t_1). At the time moment t_6 voltage $Vc = Vi$ and Analog Comparator Output changes the logic level. The Counter contents – binary code N_C will be saved in the Capture Register. N_C is the equivalent of the time interval $T_C = t_6 - t_5$.

The time intervals of the basic charge and discharge processes are equal: $T_{Cb} = T_{Db}$. We shall call this time interval "**basic process time**" T_b. Then, in accordance with the expression (3):

$$T_b = 0.693 \cdot R \cdot C \tag{5}$$

The time intervals of the preparatory charge and discharge process are equal, too: $T_{Cp} = T_{Dp}$. Let us call this time interval "**preparatory process time**" T_p. Then, in accordance with the expression (4):

$$T_p = 5 \cdot R_S \cdot C \tag{6}$$

Comparative analysis conversion speed of RC-ADC and successive approximation ADC

For comparison 10-bit successive approximation ADC of the AVR Microcontroller was taken. We accept that the input voltage range change does not exceed the supply Microcontroller voltage $\Delta V_i = V_{cc} = 5$ V. Then, the resolution of 10-bit ADC provides sensitivity

$$S_V = \frac{\Delta V_i}{2^{10}} = \frac{5}{1024} \approx 4.883\,mV\ .$$

RC-ADC will reach the same sensitivity when performing the condition:

$$T_b = 2^9 \cdot T_C = 512 \cdot T_C, \tag{7}$$

where T_C – period of clock pulses of Microcontroller Oscillator, µs;
512 – decimal equivalent of 9-bit binary code.

Since the entire range of the input voltage ΔV_i in the RC-ADC is divided into two sub-bands $0.5 \cdot \Delta V_i$, then 9 bits are enough to get sensitivity

$$S_V = \frac{0.5 \cdot \Delta V_i}{2^9} = \frac{2.5}{512} \approx 4.883\,mV \ .$$

For example, we take the frequency time f_{clk} = 10 MHz. One clock pulse period $T_{clk} = 1/f_{clk} = 1 \cdot 10^{-7} = 0.1$µs. Then the time T_b in accordance with the expression (7) will be: T_b = 0.1·512 = 51.2 µs. The time constant of *RC*-circuit, at which will be achieved the required sensitivity S_V = 4.883mV, determined in accordance with expression (5): $\tau = R \cdot C = T_b$ / 0.693 = 51.2 / 0.693 ≈ 73.9 µs.

In the experiment elements with nominal values the following were used: capacitance of Capacitor C = 2000 pF and resistance of Resistor R = 43kΩ. Then, in accordance with the equation (6): $T_p = 5 \cdot 26 \cdot 2 \cdot 10^{-9} = 0.26$ µs.

The half-cycle time of RC-ADC conversion will be $T_p + T_b$ = 0.26 + 51.2 = 51.46 µs. Then, the whole cycle time of RC-ADC conversion will be $T_{RC\text{-}ADC} = 2 \cdot (Tp + T_b)$ = 2·51.46 ≈ 103 µs.

In the shown algorithm it does not consider the time spent by Microcontroller to perform the operations for v_i calculation in accordance with (1) and (2) under the condition $v_i = v_c$. Parallel work of the Microcontroller's Processor and Counter is possible. The processor may perform v_i calculation simultaneously with basic charge or discharge processes, i.e. when the Counter works. T_b time is enough to perform by the Processor the necessary calculations.

The time spent by 10-bit ADC of AVR Microcontroller for one conversion cycle is given by:

$$T_{ADC} = 14 \cdot \frac{1}{f_{ADC}} \ , \tag{8}$$

where 14 – number of ADC clock periods needed for one conversion;
f_{ADC} – ADC time frequency, kHz.

The highest conversion accuracy is achieved if the ADC clock frequency is in the range 50 ... 200 kHz [2; 3]. If the clock frequency f_{ADC} = 100 kHz, then according to expression (8) the cycle time of one conversion will be: T_{ADC} = 140 µs.

Thus, the conversion speed of RC-ADC is above the conversion speed of successive approximation ADC in T_{ADC} / $T_{RC\text{-}ADC}$ = 140 / 103 ≈ 1.4.

RC-ADC Experimental Study

The experiment was performed on the basis of ATmega16 Microcontroller with using a starter kit STK500 from Atmel Corporation. The functional scheme of device for RC-ADC study is submitted in Figure 4. The input voltage v_i is supplied on the Analog Comparator inverting Input. This voltage is formed by using two resistance boxes R_1 and R_2, forming the voltage Divider. The divider equivalent resistance is always $R_{eq} = R_1 + R_2$ = 5000 Ω. If the voltage V_{cc} = 5 V and $R_1 = R_2$ = 2500 Ω, then v_i = 2500 mV. When R_1 = 2000 Ω and R_2 = 3000 Ω, then v_i = 3000 mV etc.

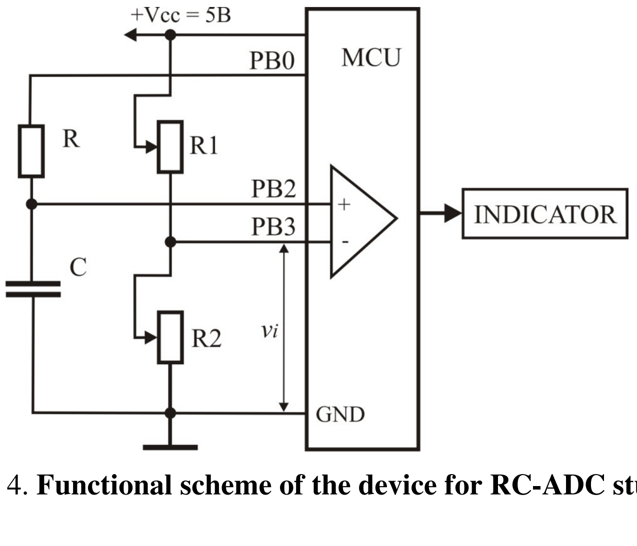

Fig. 4. **Functional scheme of the device for RC-ADC study**

For the experimental sample RC-ADC the program was designed. The conversion result – the number of clock cycles N_C or N_D – is output from the 8-bit Microcontroller's port into 8 LEDs (INDICATOR), which are available in the starter kit STK500. The 10-bit conversion result occupies two bytes. Its output on the INDICATOR is carried out sequentially: first the eldest, then the youngest byte.

The results of the experiment for study RC-ADC are shown in Table 1, where v_i – RC-ADC input voltage; $T_C = T_{clk} \cdot N_C$ and $T_D = T_{clk} \cdot N_D$; $v_{iC} = V_H \cdot (1 - e^{-T_C/\tau})$ and $v_{iD} = V_H \cdot e^{-T_D/\tau}$. The time constant τ of RC-circuit is known: $\tau = R \cdot C = 91\mu s$.

The input voltage Vi was controlled by a voltmeter with accuracy of ± 0.5%. For each account 5 measurements were performed from which 3 close values were chosen and their results were averaged.

Table 1

Results of RC-ADC experimental study

V_i, V	N_C	T_C, μs	v_{iC}, V	N_D	T_D, μs	v_{iD}, V
0.5	97	9.7	0.51			
1.0	201	20.1	0.99			
1.5	319	31.9	1.48			
2.0	457	45.7	**1.97**			
2.5	625	62.5	2.50	625	62.5	2.50
3.0				457	45.7	**3.03**
3.5				318	31.8	3.52
4.0				200	20.0	4.01
4.5				97	9.7	4.49

Table 1 shows that in the range of the input voltage 0.5 ... 4.5 V maximum absolute error of RC-ADC was $\Delta V_C = V_i - v_{iC} = 2 - 1.97 = 0.03$ V and $\Delta V_D = V_i - v_{iD} = 3 - 3.03 = -0.03$ V.

Figure 5 shows the Oscillogram of voltage change at the Capacitor of RC-circuit. Values of some variables were introduced by the authors at the Oscillogram for a visual display of processes in the RC-ADC. The Oscillogram is displaced along a vertical axis so that the horizontal axis divides in half the voltage of 5 V, i.e. $0.5V_H \approx 2.5$ V. At the Oscillogram the notations are given: $v_i \approx 3$ V – input voltage; v_c – voltage on the Capacitor of RC-circuit. The resolution of the oscilloscope for this case: along the horizontal axis – 20 μs/div; along the vertical axis – 1 V·div^{-1}.

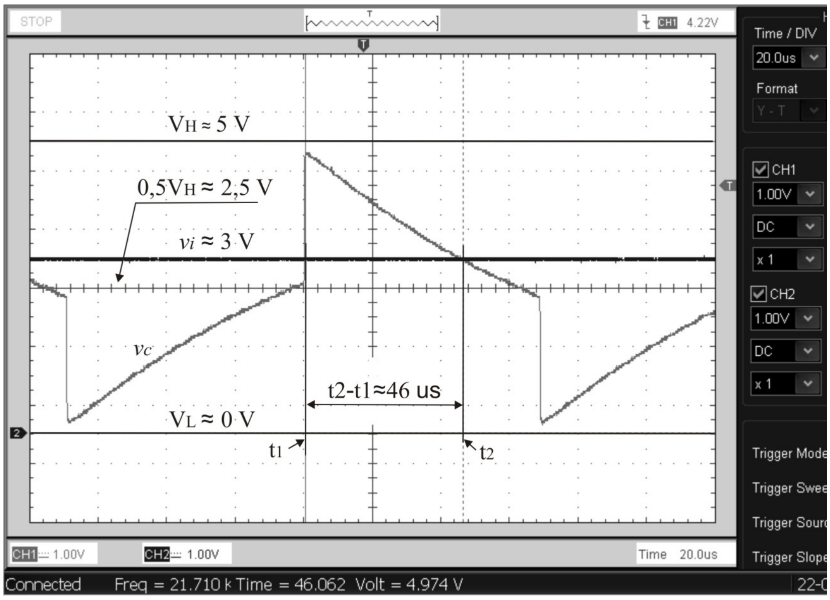

Fig. 5. **Oscillogram of Capacitor voltage v_c and input voltage v_i**

RC-ADC can be built on the basis of integrated circuits or programmable logic integrated circuits. In this approach, RC-ADC will have higher characteristics than if implemented on Microcontroller. Perhaps, the above considered RC-ADC in comparison with the known ADC will be more versatile and simple for technical implementation. The problems associated with the development of the new ADC are described in references [4; 5].

Conclusion

During the study of RC-ADC there were obtained results on the basis of which it could be affirmed that the RC-ADC with Microcontroller clock frequency of 10 MHz is not inferior in conversion speed successive approximation ADC with time frequency 100 kHz. RC-ADC conversion speed can be increased by several orders of magnitude by increasing of the Microcontroller clock frequency.

Absolute error of 10-bit RC-ADC at a clock frequency of 100 kHz is not more than 2,5 of the least significant bit (LSB). The result of RC-ADC error estimation was obtained by experimental methods. Technical realization of RC-ADC experimental sample can be improved to reduce the conversion error.

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