

## A method of self-testing of an analog circuit terminated by an ADC in electronic embedded systems controlled by microcontrollers

**Abstract.** A new self-testing method of analog parts terminated by an ADC in electronic embedded systems controlled by microcontrollers is presented. It is based on a new fault diagnosis method based on on-line (i.e. during measurement), transformations of voltage samples of the time response of a tested part to a square pulse - onto localization curves placed in the measurement space. The method can be used for fault detection and single soft fault localization.

**Streszczenie.** Przedstawiono nową metodę samotestowania toru analogowego zakończonym przetwornikiem A/C w elektronicznych systemach wbudowanych sterowanych mikrokontrolerami. Bazuje ona na nowej metodzie diagnostycznej opartej na przekształceniach transformujących na bieżąco, tj. w trakcie pomiarów, próbki odpowiedzi czasowej badanej części analogowej na pobudzenie impulsem prostokątnym na krzywe lokalizacyjne w przestrzeni pomiarowej. Metoda ta pozwala na detekcję i lokalizację pojedynczych uszkodzeń parametrycznych w układach analogowych (Metoda samotestowania toru analogowego zakończonym przetwornikiem A/C w elektronicznych systemach wbudowanych sterowanych mikrokontrolerami).

**Keywords:** self-testing, microcontrollers, Analog to Digital Converters.

**Słowa kluczowe:** samotestowanie, mikrokontrolery, przetworniki analogowo-cyfrowe.

### Introduction

An important group of electronic embedded systems, used among others in metrology and automation, are mixed-signal electronic microsystems. Mainly, but not only, they are more often smart sensors, which are components of wireless telemetry systems. These devices consist of a digital part responsible for the control, data processing and communication between the sensors, most often based on a microcontroller, and an analog part – an analog circuit – used for conditioning input signals, for example coming from the sensors, i.e. the amplification, filtering and adjusting these signals as required by the analog-to-digital conversion.

An important feature of these devices is their reliability. It should be as high as possible. It is achieved when their maintainability is assured [1]. This is accomplished, inter alia, by implementing in these devices self-testing procedures. These procedures are applied to the functional testing of the entire system [2] the control software [3,4], the functional blocks [5], and - in particular - the analog circuits [6-9].

As noted, the task of the analog circuits is conditioning analog signals in accordance with the requirements of ADCs. Therefore, incorrect operation of the analog circuits can "distort" the signals coming from e.g. the analog sensors, which are converted by the ADC (Analog-to-Digital Converter), and then processed and interpreted by the control system. In such a situation it can lead to incorrect interpretation of the results, which in turn may result even in damaging the controlled object.

Thus, many testing methods of analog circuits, e.g. [6-9], among them the self-testing methods of analog circuits terminated by external ADCs [8,9] in the systems controlled by the microcontrollers, were developed.

In these methods [8,9] the tested analog circuit is stimulated by a square pulse generated by the microcontroller controlling the system, and the time response of the analog circuit to this stimulation is repeatedly sampled at regular intervals by the ADC (Fig. 1). It should be emphasized that these methods do not introduce hardware redundancy, because we use for testing of analog circuits the devices already installed in the system: the microcontroller and the ADC.

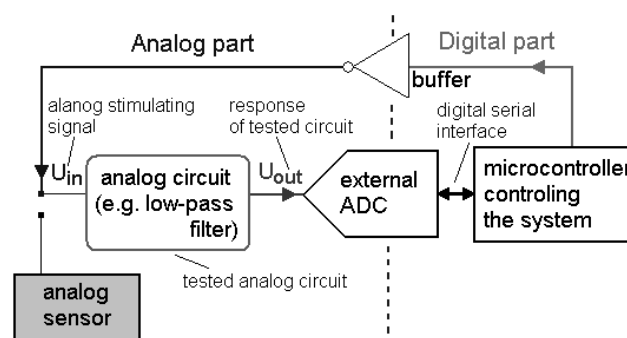


Fig.1. Configuration of the analog circuit in the self-testing mode of the analog part of an electronic embedded system

In the method proposed in [8] the measurement space is represented by coordinates, which are sub-totals of voltage samples calculated in real time during sampling the time response of the circuit under test. The advantage of the method is simple, quick calculation of  $K$  coordinates of a measurement point based solely on summing the sample values (e.g.  $K = 3$ ), whereas its disadvantage is a relatively long and fixed duration of the measurement procedure amounting to  $K \cdot T$ , where  $T$  – the duration of the stimulating pulse.

The method described in [9] is characterized by the best localization resolution. A multi-dimensional measurement space is obtained by converting the set of voltage samples of the time response of the tested circuit based on the modified discrete Fourier transform. Unfortunately, this results in a significant computational complexity of the method and a high volume of used microcontroller data memory. The duration of the measurement procedure compared with the previous solution is extended by the time spent to determine the coordinates of a measurement point.

Therefore, a new self-testing method (fault diagnosis of analog circuits) is presented in this paper. It is characterized by the simplest way of determining the coordinates of a measurement point, but - above all - also the shortest duration of the measurement procedure in comparison with all proposed methods. This is an important advantage of the new method, because the shorter duration of the measurement procedure, and thereby the self-testing

procedure, results in reduced energy consumption, which is important in battery-powered systems, e.g. smart sensors.

### The structure of the system in the self-testing mode

The self-testing method of the analog circuit terminated by an ADC is illustrated on an example of a microsystem shown in Fig. 2.

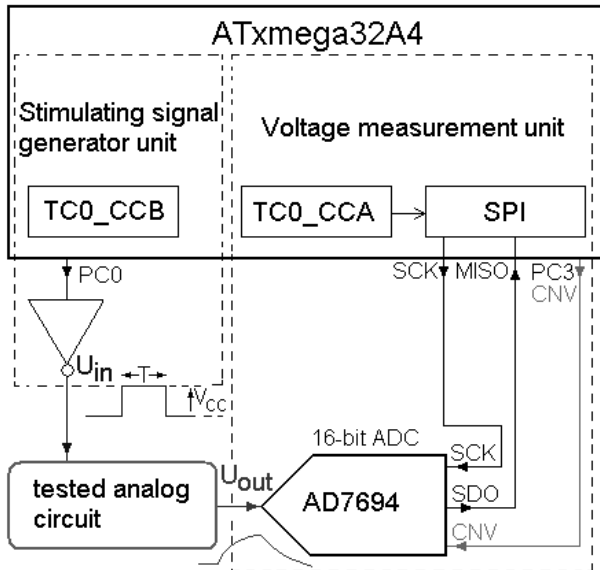


Fig.2. An example of an electronic system working in the self-testing mode of the analog part

The microsystem consists of an ATxmega32A4 microcontroller [10], a 16-bit ADC controlled by an AD7694 Serial Peripheral Interface (SPI) [11] and an inverting buffer built with the IRF7105 [12]. The chosen microcontroller has the following internal resources required by the method: five 16-bit Timer/Counters (TC) (three of them are equipped with four Compare or Capture (CC) channels), and two others - with two CC channels) and two SPIs.

Thanks to the extensive functionality of the TCs only one Timer/Counter TC0 is used to generate the stimulating pulse and to determine the moments of voltage sampling. The comparisons in the channel A (CCA) of TC0 determine the moments of voltage sample conversion and reading out from the AD7694 via the SPI on the port C, whereas the comparison in the channel B (CCB) defines the duration  $T$  of the stimulating pulse. The use of the buffer eliminates the negative effect of a varying impedance (load-dependent) of the output pin of the microcontroller influencing the shape of the stimulating pulse [13].

The tested analog circuit is a second order low-pass Sallen-Key filter with the bandwidth of up to 1 kHz (Fig. 3).

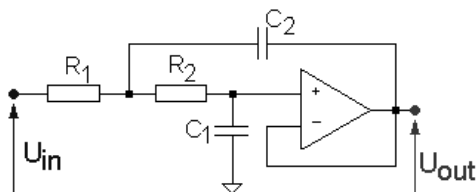


Fig.3. The tested analog circuit – a second-order low-pass Sallen-Key filter, where  $R1 = R2 = 10 \text{ k}\Omega$ ,  $C1 = 70.44 \text{ nF}$ ,  $C2 = 46.35 \text{ nF}$

The presented self-testing method belongs to the group of simulation-before-test (SBT) methods, i.e. it consists of simulation before the testing stage of creating the fault dictionary during system design and the testing stage

carried out by the microcontroller, e.g. after powering on, when the entire system is tested. The second stage is successively divided into the measurement procedure and the fault classification (fault detection and - next - localization of single soft faults).

### Definition of the measurement space

The short duration of the measurement procedure results from the established definitions of individual coordinates of the measurement space in which the set of localization curves (a family of localization curves) is placed – being a graphical illustration of the fault dictionary of the tested analog circuit (Fig. 4). These coordinates should represent the unique features of the waveforms (time responses of the tested circuit) which enable an unambiguous localization of a single soft fault, as described in [8].

Hence, a new measurement space (Fig. 4) with the coordinates  $(sum, u\_max, k)$  is proposed in the paper, where:

$$(1) \quad sum_n = (sum_{n-1} + u_n) / 2 \quad \text{from } n = 1 \text{ to } n = N,$$

where  $sum_0 = 0$

$$(2) \quad k = n \quad \text{when } u_n \geq u_{n+1}$$

starting from  $n = 1$  and finishing with  $n = k + 1$

$$(3) \quad u\_max = u_k$$

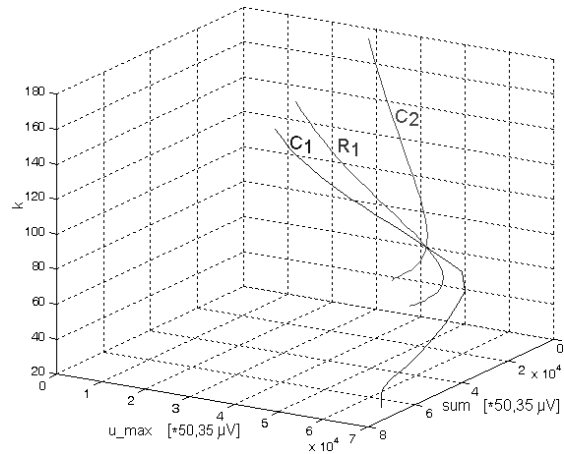


Fig.4. The localization curves of the tested circuit (from Fig. 3) in the measurement space  $(sum, u\_max, k)$

All coordinates are determined iteratively during sampling the time response of the tested circuit. The coordinate  $sum$  is the average value of  $N$  voltage samples  $u_n$  calculated according to (1), where  $N$  is a constant number of samples taken during the stimulating pulse. The values  $u_n$  are expressed as 16-bit results of the AD (Analog-to-Digital) conversion [11]. Using the formula (1) guarantees that the results of calculations for successive iterations are within a 16-bit variable  $sum_n$ , what simplifies calculations by 8-bit microcontrollers.

The coordinates  $u\_max$  and  $k$  are determined simultaneously. The coordinate  $u\_max$  is the greatest value of  $k + 1$  samples (3), because the algorithm keeps its work until the next sample  $u_{n+1}$  is less than the previous one  $u_n$ , then  $k = n$  and  $u\_max = u_k$  (2). Therefore, the coordinates  $u\_max$  and  $k$  describe the maximum value of the time response of the tested circuit. This approach shortens the duration of the measurement procedure to the range from  $T$ , for  $k < N$ , (because we need to calculate the coordinate  $sum$ ), to  $T + \tau(k - N + 1)$  for  $k \geq N$ , where  $\tau$  is the time interval between voltage samples  $u_n$  and  $u_{n+1}$  ( $\tau = T / N$ ). Obviously, the number  $k$  depends on the fault that occurred in the tested circuit.

### Determination of parameters of the method

The duration  $T$  of the stimulating pulse (its amplitude, a priori, is set to  $V_{cc} = 3.3\text{ V}$  – the supply voltage of the digital part of the microsystem) and the number  $N$  of voltage samples of the time response measured during the stimulating pulse should be chosen in such a way that the self-testing method will be characterized by the best possible localization resolution. However, one should remember to keep the optimal values of these parameters, paying particular attention to the duration of the measurement procedure.

Determination of the time  $T$  is performed by the sensitivity analysis as in [8,9], so as to obtain the greatest dynamics of changes of the time responses of the tested circuit for the assumed range of changes of values of individual components of this circuit, which defines a single soft fault. The established range is from 0.1 to 10 nominal values of the components. Thus,  $T = 2\text{ ms}$  is obtained.

For the most accurate measurement of the value  $u_{max}$  and determination of the value  $k$ , the number of voltage samples  $N$  should be as large as possible. However, the larger  $N$ , the higher the energy consumption of the ADC. Also, the following restrictions on the maximum number of samples  $N_{max}$  should be kept in mind. The first one is the assumption that  $k + 1 \leq 255$  – a byte variable. This is aimed to speed up and simplify calculations performed during the interrupt service. The second one is the minimum value of the time interval between samples  $\tau_{min} = T / N_{max}$ . It depends on hardware and computational capabilities of the microcontroller and the minimum AD conversion time plus the time required for reading out the result from the ADC. For the ATmega32U4 working with the system clock of 16 MHz and executing the code whose algorithm is shown in Fig. 6, this time is approximately  $\tau_{min} = 17\text{ }\mu\text{s}$  (it is based on analysis of the resulting file lss of the program executing the self-testing and written in the C language in the Atmel Studio 6.2 environment), what gives  $N_{max} = 117$ . Assuming in addition that  $N = 2^m$ , where  $m = 1, 2, \dots$ , in order to further simplify and accelerate the calculation, and considering the first constraint, it was obtained  $N = 64$ . The family of localization curves shown in Fig. 4 was generated for these values.

### The measurement procedure

The timing of the measurement procedure is shown in Fig. 5. The stimulating pulse  $U_{in}$ , the time response of the nominal tested circuit  $U_{out}$  with marked samples and the value  $u_{max}$  are also plotted in the figure. The algorithm of this procedure is partly implemented in the code of the main program of the microcontroller, and partly in the interrupt services of TC0 (Fig. 6).

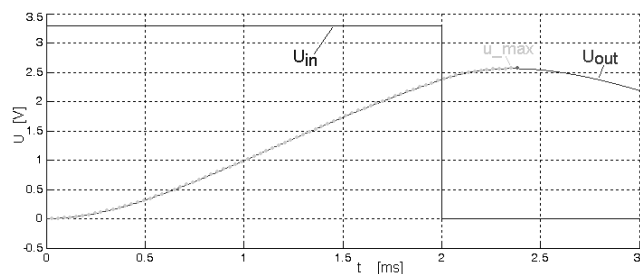


Fig.5. The timing of the measurement procedure during self-testing of the analog circuit (from Fig. 2)

At the beginning of the measurement procedure implemented in the *measurement* function (Fig. 6) the 16-bit counter register TCC0\_CNT of TC0 is cleared and the value corresponding to  $\tau = 62.5\text{ }\mu\text{s}$  taking into account the

correction  $t_{correct} = 1.1875\text{ }\mu\text{s}$  [10] resulting from the software delay is written to the 16-bit compare or capture register TCC0\_CCA (the value corresponding to the time  $T = 2\text{ ms}$  is entered in the register TCC0\_CCB, the function of which initializes the microsystem).

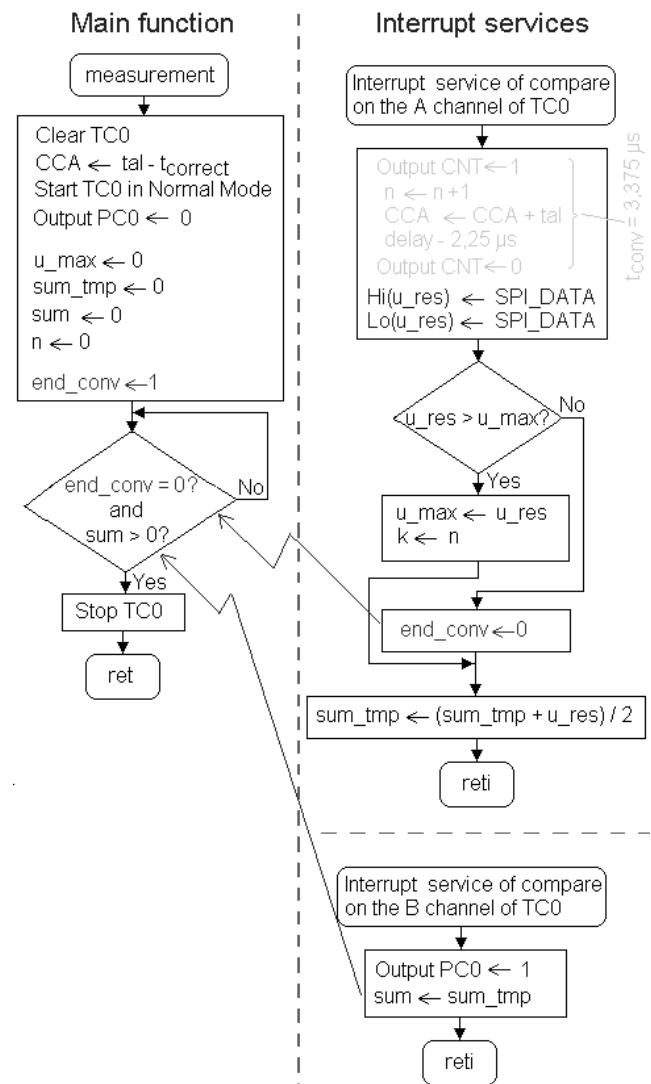


Fig.6. The flowchart of the algorithm of the measurement procedure implemented in the measurement function

After running the TC0 in the Normal Mode with the prescaler set to  $clk$ , (the frequency of the internal clock signal  $clk$  is equal to 16 MHz) and after beginning generation of the stimulating pulse (setting a low level at the PC0 output of the microcontroller – the stimulating signal passes through the inverting buffer – Fig. 2), variables used for calculation of the measurement point are reset and the variable  $end\_conv$  (used for synchronization of the *measurement* function executed in the main loop of the program and the interrupt service of a compare match in the compare or capture A channel of the TC0) is set. Next, the *measurement* function is waiting for determination of the value  $u_{max}$  ( $end\_conv = 0$ ) and completion of generation of the stimulating pulse ( $sum > 0$ ).

The events of a compare match between the register TCC0\_CNT and successive values of the register TCC0\_CCA, i.e. the ends of the countdown of time  $\tau$ , generate an interrupt, in which service the voltage measurement is served by the external ADC AD7694. This measurement consists of two stages. The first one is

conversion – setting a high level in the line CNT for 3.375  $\mu\text{s}$  and then reading out two bytes from the AD7694 through the SPI. During the pulse in the line CNT the content of the TCC0\_CCA register is updated, so that the next interrupt is generated after  $\tau = 62,5 \mu\text{s}$ . The conversion result is placed in the 16-bit variable  $u_{res}$ . In the second stage (after the voltage measurement) the current values  $u_{max}$  and  $k$  are determined and the average value  $sum_{tmp}$  is calculated from the current number of voltage samples. If in the next interrupt service the value  $u_{res}$  is less than the value  $u_{max}$ , the flag  $end_{conv}$  is cleared and the value  $sum_{tmp}$  is calculated.

The event of counting time  $T$  generates the compare match in the compare or capture B channel of the TC0 interrupt, during which service a high level in the line PC0 is set, what completes generation of the stimulating pulse, and the content of the variable  $sum_{tmp}$  is written to the variable  $sum$ . This solution simplifies the algorithm of determining the average value for  $N$  voltage samples, because it is no need to use conditional instructions and additional variables to check the condition  $n \leq N$ .

Determination of the values  $u_{max}$ ,  $k$  and  $sum$  by the interrupt services, i.e. determination of the measurement point coordinates, terminates the loop of waiting for these results, after which the TC0 is stopped.

### Classification of faults

The fault classification consists of two stages: the fault detection and - if a fault is detected in the circuit – the single soft fault localization of passive components of the tested circuit.

For both stages the measurement point "is placed" in the measurement space with a family of localization curves (Fig. 4) generated at the pre-testing stage for the tested circuit (Fig. 3). Then, it is checked [7] whether this point is disposed in the vicinity of the nominal point (the point where all localization curves intersect). If so, the circuit is faulty.

Otherwise, the location of the measurement point in the surroundings of a given curve localizes the faulty component. If the measurement point happens to be far away, according to the established criteria [7], from all curves, a multiple fault in the circuit is detected.

### Conclusions

A new self-testing method of an analog circuit terminated by an ADC in embedded electronic systems controlled by microcontrollers is presented in this paper. In this method, a tested analog circuit, e.g. an anti-aliasing filter, is stimulated by a square pulse with a predetermined duration generated by the microcontroller, and the time response of this circuit is sampled by the ADC. It should be emphasized that the whole measurement procedure (software and hardware) is executed by the microcontroller controlling this system already installed in the system, and the ADC. Such a solution does not introduce hardware redundancy into the system, i.e. it does not generate additional costs.

The new coordinates of the measurement space are defined as follows: the averages of voltage samples measured during the stimulating pulse, the maximum voltage value of the time response and the number of the sample with this value determined during the measurements. Thanks to this, the method is characterized by the simplest way of determination of coordinates of the measurement point and, especially, the shortest duration of

the measurement procedure in comparison with the previously proposed self-testing methods. This is an important advantage of the new method, because reducing the duration of the measurement procedure, which is a component of the self-testing procedure of the whole system, the power consumption is reduced. As already mentioned, this is a very important feature for battery-powered systems, e.g. for smart sensors.

Apart from the measurement procedure the microcontroller can perform the fault classification procedure, e.g. based on comparing the measurement point with the fault dictionary which is a set of coordinates representing the family of localization curves placed in the program memory of the microcontroller. It is characterized by a low computational complexity.

These advantages confirm that the proposed self-testing method can be used in practice for testing analog circuits of mixed-signal electronic embedded systems controlled even by simple 8-bit microcontrollers.

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