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Implementation of an input-output method of diagnosis of analog electronic circuits in embedded systems

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Abstract – In the paper an implementation of a new modified 2D bilinear method [1] of fault detection and localisation of analog electronic circuits, taking into consideration tolerances of elements in embedded systems based on microcontrollers is described. This approach consists of two stages. In the first stage a fault dictionary consisting of a nominal area representing a fault-free circuit and coefficients defining widths of localisation belts are created. In the second stage the measurement procedure and the algorithm of fault detection and localisation is made by the microcontroller mounted in an embedded system. A new procedure of measurements of a voltage and a time delay by the microcontroller, the new fault detection and localisation algorithm, the practical verification of the measurement procedure and the fault diagnosis procedure will be presented.

Keywords: fault diagnosis, embedded systems, microcontrollers.

1. INTRODUCTION

Nowadays simple embedded systems consist of not only a digital part, used for control and processing of data, but also of an analog part mostly used for adjustment of input signals e.g. from sensors. Moreover, in many cases microcontrollers control the operation of these embedded systems. Hence, methods of testing or automated testing of analog parts using microcontrollers already mounted in the system are needed

At present the microcontrollers generally used in practice have advanced timers/counters enabling the precise measurement of time, counting of external pulses, generating programmed square impulses, and they have 8, 10, 12-bits SAR-type A/D converters with sample & hold circuits which enable the measurement of temporary values of voltage.

ATmega16 made by Atmel [2] is one of these microcontrollers. It has one 16-bit and two 8-bit timers/counters, an analog comparator and 10-bit ADC. It will be used for building the exemplary embedded systems. The new modified 2D bilinear method [1] of fault detection and localisation of analog electronic circuits taking into consideration tolerances of elements will be implemented in this embedded system.

2. THE 2D MODIFIED BILINEAR METHOD

It was assumed that:

- The fault diagnosis method should not require excess hardware in the embedded system. Therefore, to exclude the hardware, the resources of microcontrollers accessible in the embedded systems should be used for measuring and processing data.
- The diagnosis procedure of the method should not be numerically complicated, because the computing power of typical microcontrolers is small and they have no floating-point instructions and often integer multiple and divide instructions.
- The size of the diagnosis procedure code and the fault dictionary should be as small as possible, because a whole main program controlled the embedded system is placed in the program memory of the microcontroller.

The above requirements are satisfied by the new version of the fault 2D bilinear diagnosis method [1]. It consists of two stages - see also [1]. In the first pre-testing stage, a fault dictionary of the tested analog part in the form of a family of localisation belts is generated in a simulated way on a PC computer. Next, it is compressed and placed in the microcontroller's program memory.

In the second stage, the measurement procedure of the amplitude and time delay of the output signal in the tested analog part (the 3-order lowpass Butterworth filter) is made by the microcontroller. Next the microcontroller runs the program with the diagnosis procedure and localises a faulty element in a similar way as described in [3,4].

2.1. The principle of the method

The modification of the 2D bilinear method bases on a change of the transfer function's real and imaginary parts to magnitudes which are easily measured and simply computed by the microcontroller: the voltage amplitude and the time delay of an output signal of the tested analog circuit. The voltage amplitude, a voltage offset and the frequency of a stimulating signal are known and determined. The voltage is measured by the ADC, and the time delay by the microcontroller's internal timer. The precision of voltage measurements is sufficient for the detection and in case faults' localisation.

So, the new version of the fault diagnosis method bases on transformation (1):

$$T_i(p_i) = U_{OUT\,i}(p_i)\mathbf{i} + \tau_i(p_i))\mathbf{j}, \qquad (1)$$

where: **i**, **j** - are versors, $U_{OUT\,i}$ - the output voltage amplitude, τ_i - time delay.

The transformation (1) maps changes of values of p_i elements into the identification curves on the plane U_{OUT},. τ_i. For all p_i elements of the tested circuit we obtain the family of identification curves (Fig. 1).

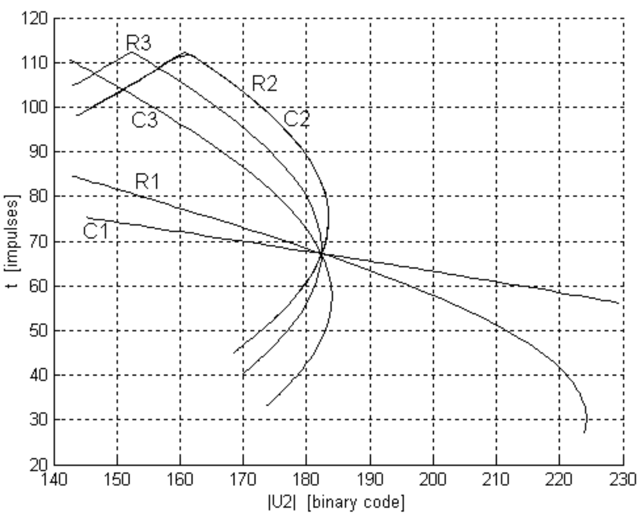

Fig 1. The family of identification curves of the tested analog part

In practice analog network (circuit) elements have tolerances. This causes fuzziness of the curves and they take the form of localisation belts, as shown in Fig. 2.

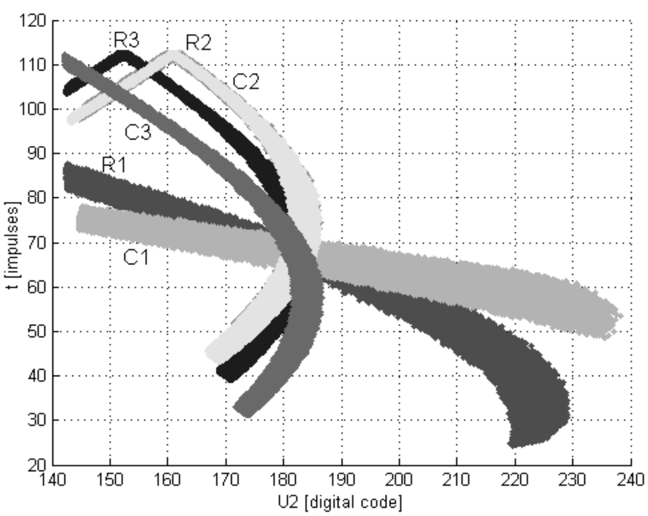

Fig 2. The family of localisation belts of the tested analog part (Fig. 3) for 5% tolerance of capacitors and 1% tolerance of resistors

It is seen (Fig. 2), that localisation belts overlap. It makes difficult to localise the fault correctly. Therefore in many cases the result of fault localisation can be not only one faulty element, but also a group of elements (a cluster), from which each can be potentially faulty.

2.2. The fault dictionary

The map of family of localisation belts (Fig. 2) describes properties of the tested circuit. So, it is used for the generation of a fault dictionary.

From assumptions dealing with features of the method presented at the beginning of this paragraph, the following assumptions were made:

- Measurements of the voltage and the time delay are made with 8-bit resolution.
- The *i*-th localisation belt of p_i elements is represented by a set of points $\{q_{ij}\}_{j=1,\ldots,J}$ with coordinates (u_{ij}, τ_{ij}), where J=32. The points are evenly located on the *i*-th identification curve, from which this belt was created. The width of the *i*-th belt is determined by a coefficient ξ_i [5].
- A nominal area is represented by a nominal point P_{nom} (u_{nom}, τ_{nom}), and its area is dependent on a coefficient ε_{nom} [5].

So, we can describe the fault dictionary in the following way: $S_{NJ} = \{(u_{ij}, \tau_{ij}), \xi_i, (u_{nom}, \tau_{nom}), \varepsilon_{nom}\}_{i=1,..,N,\ j=1,..,J}$. For the tested circuit (Fig. 3), which consists of I=6 elements, the fault dictionary takes only 393 bytes and it is small in relation to the 16kB program memory of Atmega16.

3. IMPLEMENTATION OF THE METHOD

The fault diagnosis method is parted into three stages. The first pre-testing stage of the fault dictionary creation is realized only once for the given analog part by a PC computer. Two remaining stages: the measurement stage and the fault detection and localisation stage are executed by the microcontroller.

3.1. Creation of the fault dictionary

The fault dictionary is generated by the PC computer using Matlab. For an assumption range of changes from 0.1 to 10 $p_{i\ nom}$ values of all elements, the values are chosen using a logspace function. It gives approximately even location of the approximate points on the identification curves. For chosen values of each element p_{ij} the response of the tested circuit is simulated. The coefficients ξ_i and ε_{nom} are calculated [5]. Next, the fault dictionary created in this way is written to a text file by a dlmwrite function, and a content of this file is copied and inserted to the file with the source code of the full main program for the microcontroller. At the end the code with the fault dictionary is assembled and loaded to the program memory of the microcontroller in an ISP mode.

3.2. The measurement procedure

In the second stage of the fault diagnosis method the measuring procedure is executed by the microcontroller. It measures the voltage amplitude and the time delay of the output signal of the tested circuit in the circuit shown in Fig. 3.

The part of the embedded system relating the fault diagnosis of the analog part consists of three elements: a sine-wave generator, the tested analog part and the microcontroller.

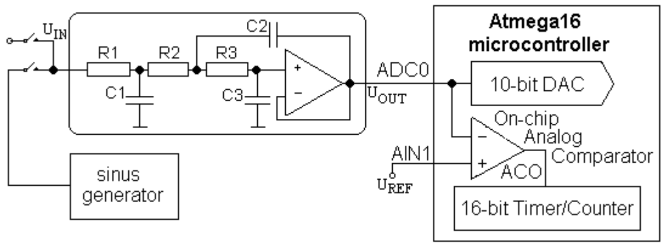

Fig. 3. The embedded system with the tested analog part (filter), where: R1=R2=R3=5kΩ, C1=44.5nF, C2=110nF, C3=6.42nF

The diagnosis procedure needs an extension of the embedded system by about one element maximum: the sinus generator. For instance, it can be realised as a chip (AD9833) or it can be built with discrete elements. Sometimes the generator can be an integrated part of the embedded system. In this case there is no need for an additional circuit.

This is the main advantage of our fault diagnosis method. All needed devices for the measurement (ADC, the analog comparator and the timer) are included in the microcontroller already mounted in the system.

The measurement procedure executed by the microcontroller runs in way shown in the Fig. 4.

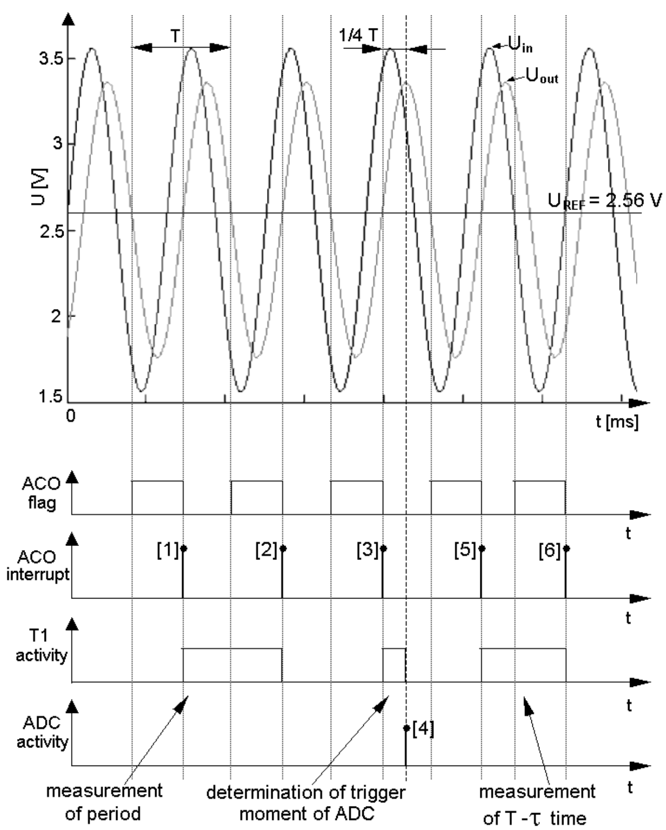

Fig 4. Timing of the measurement procedure

It is seen that the measurement procedure consists of three steps:

- The measurement of the period T of the stimulant signal by the Timer 1. This time will be used for calculation of $T/4$,
- Determination of the trigger moment of the ADC for which the output signal has a maximum value. It occurs $T/4$ after activation of the analog comparator. At this moment we measure $U = U_{OUT} + U_{REF}$, where U_{OUT} is the output signal amplitude.
- The measurement of the time delay T-τ between the input stimulating signal and the output response signal by Timer 1.

We set up, that the microcontroller operates with a 12 MHz clock. This clock is directly used by the Timer 1. Because the frequency $f = 1/T$ of the stimulating signal is equal to 830 Hz, the Timer 1 counts about 14458 impulses during the period T. This is the maximum value of the time delay τ. We use 8-bit resolution of the measurements. So, the result of the time delay is two times rotated to the left and only its 8 MSB bits are noted. It gives a maximum range of the time delay τ equal to 225.

Also, the voltage measurement 10-bit result is converted to an 8-bit value by its left adjustment.

The program for the microcontroller is written in C language. The measurement procedure is realised in three pipelines dependent on themselves. The central part of this procedure is included in the main program (Fig. 5), the second one in the routine of the analog converter interrupt service (Fig. 6), and the last one in the routine of the Timer 1 interrupt service (Fig. 7).

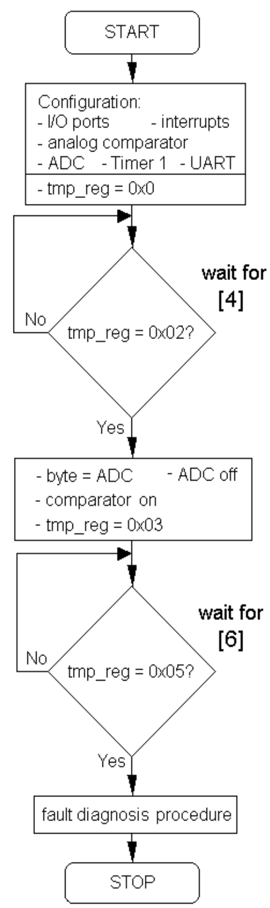

Fig. 5. The graph of the central routine of the measurement procedure

All routines are synchronised by a variable tmp_reg. It is used to determine an actually step of the measurement procedure (In the Figures 4, 5, 6 and 7 these steps are written in square brackets).

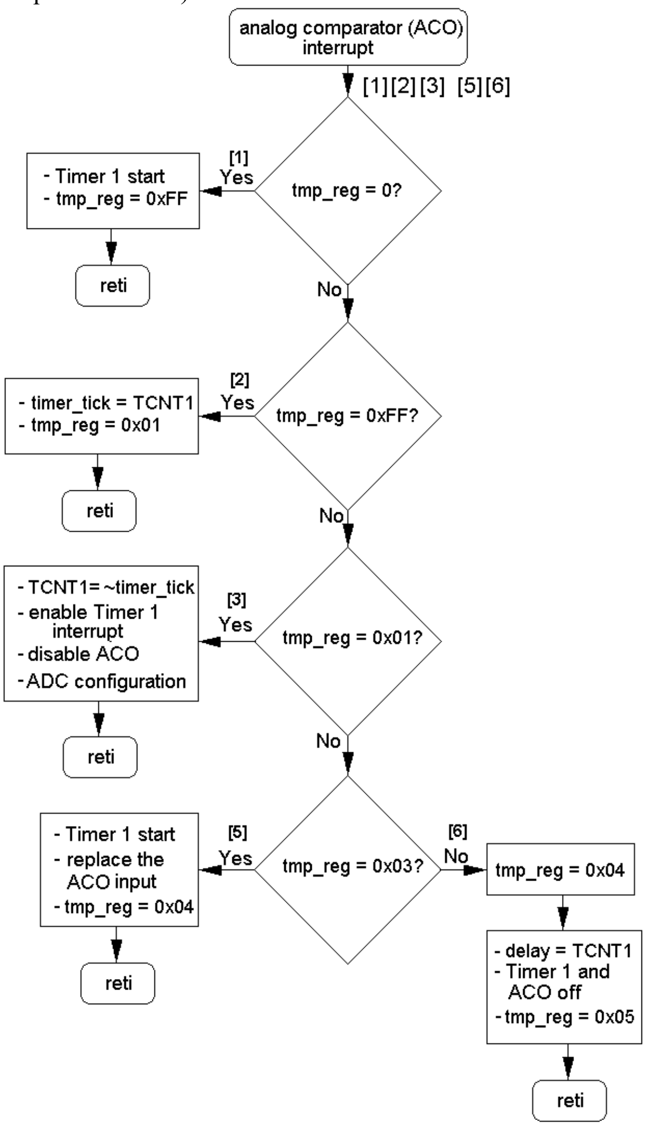

Fig. 6. The graph of the routine of the analog comparator (ACO) interrupt service

At the beginning of the measurement procedure internal resources of the microcontroller are configured (Fig. 4). Next the main routine waits for the measurement of the voltage of the output signal by the ADC (waits for the step [4]).

When the analog comparator (ACO) detects the first rising edge of the output signal (step [1]), the ACO routine is called out with temp_reg = 0 (Fig. 6). In this case the Timer 1 is triggered.

The second activation of the ACO routine (step [2]) reads the content of the Timer 1 and stops its. This value represents the period *T*.

In the third service interrupt of the ACO (step [3]) the calculated value of complement of time T/4 is loaded to the Timer 1. Next the Timer 1 is started up. The Timer 1 interrupt is enabled. The ACO is switched off, and the ADC is configured to use ADC0 input.

When the Timer 1 reaches the top (step [4]), the ADC is triggered and the Timer 1 overflow routine is executed (Fig. 7).

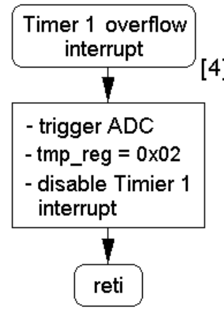

Fig. 7. The graph of the routine of the Timer 1 interrupt service

In this routine the Timer 1 is switched off and its interrupt is disabled. The variable tmp_reg is set to 4, what allows to the main routine to pass to the next instructions. At the end the CPU returns to the main routine.

The main routine (Fig. 5) waits for the measurement of the voltage of the output signal, next stores this result and switches off the ADC and switches on the ACO. This is the preparation to the measurement of the time delay. The variable tmp_reg is set to 3, and the routine waits for the end of the result of the time delay.

The fourth rising edge of the output signal generates the ACO interrupt (step [5]) (Fig. 6). Now, the ACO routine starts the Timer 1 and connects the input stimulating signal to the ACO input.

When the rising edge of the input signal appears (step [6]), the ACO routine is executed for the last time. The content of the Timer 1, contained T-τ time, is stored, the Timer 1 and the ACO are switched off. To the variable tmp_reg the value 5 is written, and the routine is abandoned, and the CPU goes to the main routine.

The main routine (Fig. 5) steps to the next part of the main program of the microcontroller with two 8-bit results: the voltage u_m (variable byte) and the time delay τ_m (variable delay). These results are utilized by the fault diagnosis procedure.

3.3. The fault diagnosis procedure

The microcontroller performs the fault detection and localisation of the analog part based on the measurement point P_m with co-ordinate (u_m, τ_m) and the fault dictionary S_{NJ} included in its program memory.

The code of the fault diagnosis procedure is contained in the function faultdiagnosis, the graph of which is shown in Fig. 8. This function consists of two parts. In the first part the fault detection is made. In the second one, if the a fault is detected, its localisation is made.

In the first fragment of the function, which deals with the fault detection, (Fig. 8) all variable $fault_i$ are cleared. The variable $fault_i$ represents a status of i-th element (zero signifies, that the i-th element is no-faulty).

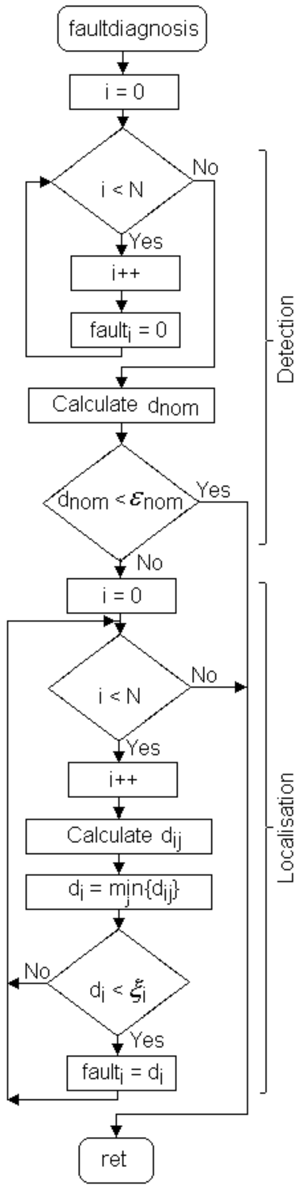

Fig. 8. The graph of the fault diagnosis procedure

Next the distance d_{nom} between the measurement point P_m and the nominal point P_{nom} is calculated. Because the microcontroller has a small computational power, we assumed the following definition of the distance between two points $P_1(u_1, \tau_1)$ and $P_2(u_2, \tau_2)$ [1]:

$$d = |u_1 - u_2| + |\tau_1 - \tau_2| \tag{2}$$

This calculation is realised by the function distance, which bases on this definition (2). This function is "fast" and consists of only 13 assembler instructions. These advantages are very important, because this function is called by function faultdiagnosis $I*J + 1 = 193$ times.

```
distance:
    sub   x1,x2
    brpl  plusx          ; if negative result
    com   x1
    inc   x1               ; change sign to plus
plusx:
    sub   y1,y2
    brpl  plusy          ; if negative result
    com   y1
    inc   y1               ; change sign to plus
plusy:
    add   x1,y1
    brcs  carry1           ; if carry
    ret
carry1:
    ser x1                 ; write to x1=0xFF
    ret
```

Listing. 1. The assembler code of the function distance

At the next step the microcontroller checks that the point P_m is inside the nominal area. It is made by verification that the distance d_{nom} is less than the coefficient ε_{nom}. If this condition is satisfied, the function faultdiagnosis is finished with cleared variables $fault_i$. Else, the fragment of the code with the localisation procedure is executed.

In this fragment for all elements p_i the distances d_{ij} among the point P_m and points q_{ij} are calculated. Next, the distances d_i among the point P_m and i-th identification curves are determined based on the relationship: $d_i = \min_j\{d_{ij}\}$. At the end of the localisation procedure it is checked that point P_m lies inside the i-th localisation belt (i.e. the distance d_i is less than the coefficient ξ_i defining the widths of the i-th localisation belts). If the condition is satisfied for a given distance d_i, the variable $fault_i$ admits the value d_i. Therefore the failure of i-th element is indicated by non zero value of the variable $fault_i$. This assignation can be useful, especially when the localisation result is a group (cluster) of elements, of which only one is in fact faulty. This inconvenience follows from tolerances of no-faulty elements. In this case values of variables $fault_i$ can be used for determination of probability of faults of respective elements from this group.

After the fault diagnosis procedure, the localisation results can be e.g. displayed on an 8 LED line connected to a port of the microcontroller (the simple way) or they can be transmitted via the UART interface to the PC.

3. EXPERIMENTAL VERIFICATION

The fault diagnosis method was experimentally verified in the laboratory circuit shown in Fig. 9. The figure presents only the digital part which consists of only the Atmega16 and the MAX232. The tested analog part is connected to the connector J1. The J3 connector is used for programming the microcontroller in ISP mode. The LEDs allow to show the operational status. The J2 connector enables to observe additional status signals on a port C.

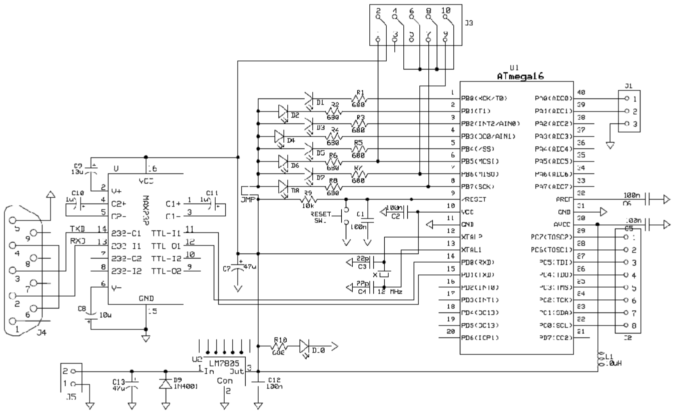

Fig. 9. The circuit for experimental verification of the fault diagnosis method

These signals were needed for test purposes of the measurement algorithm. They were realised by addition of instructions steering the port C. We assumed the following meaning of the lines of the port C (Fig. 10):

- PC0 – the measurement of the period of the output signal by the Timer 1 (line 0).
- PC1 – time of the *T*/4 minus initialisation time of the ADC (864 impulses) counted by the Timer 1 (line 1).
- PC2 – full conversion time of the ADC (line 2).
- PC3 – the measurement of the time delay (line 3).

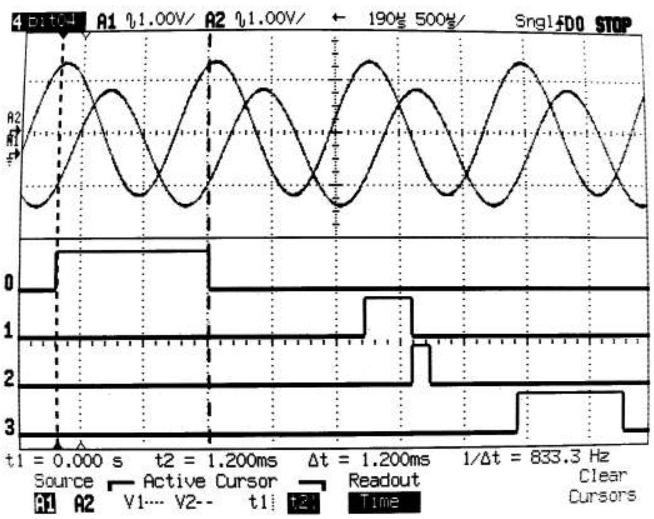

Fig. 10. The measurement procedure timing on the oscillograph

Measurements were carried out for each element p_i for its following values: 0.1, 0.14, 0.18, 0.25, 0.34, 0.46, 0.63, 0.86, 1, 1.17, 1.58, 2.15, 2.93, 3,98, 5.4, 7.36, 10 $p_{i\ nom}$. Different soft faults of each element were physically entered to the analog part of the embedded system and diagnosed on the level of fault detection and localisation.

The method for all parameter deviations gives correct results of fault detection and localisation. All the measurement results are conforming with theory. The assumed 8-bit result resolution is less then the 10-bit resolution of the ADC and the 16-bit resolution of the Timer1. Therefore the measurement results are stable and they are not dependent on measurement errors, what was elaborated. So, the measurement points lies on the proper localisation belts and they correctly localise faulty elements.

4. CONCLUSIONS

An advantage of the proposed fault diagnosis method is the possibility of its implementation in a simple microcontroller. All measurements and computations are realised only by the microcontroller. It is necessary to underline the fact that in spite of simplicity of the method, it enables fault detection and localisation in analog networks with component tolerances taken into consideration. Because these were elaborated for fault diagnosis of analog parts of mixed signal embedded systems based on microcontrollers, they have the following advantages:

- measurements of the analog parts can be made using only internal resources of popular microcontrollers,
- the diagnosis procedure does not require big computing power,
- the codes of the diagnosis procedure do not occupy much place in the program memory.

Thus, this method can be used in practice for self-testing or automated testing of mixed signal embedded systems or it can be also used for parametric identification of technical or biomedical objects modelled by electrical circuits.

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