Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2016, № 1 (81)
ISSN 1727-7108. Web: ***visnyk.tntu.edu.ua***

UDC 004.08.01

ERROR OF METHODICAL STUDY AT MEASUREMENT OF AVERAGE ENERGY CONSUMPTION OF MICROCONTROLLERS

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Abstract. *The article deals with the comprehensive research of methodical error appearing during applying of new measurement method for average energy consumption of microcontrollers whole performing instructions, applications or their fragments. The author revealed that methodical error is rather insignificant, so the method provides high measurement accuracy and performance in terms of error probability.*

Key words: *microcontroller, measurement of power consumption, method.*

Received 29.12.15

Type Codes

MC – microcontroller;
CS – current stabilizer;
OB – operation booster;
VS – voltage stabilizer;
SCR – subsystem of current regulation;
SVM – subsystem of voltage measurement.

Problem setting. Built-in computer systems with autonomous power supply have been widely used lately. Usually, such systems are built on the base of those microcontrollers (MC) to provide the widest range of methods for economizing of battery and accumulator charge. One of the relevant tasks of elaboration of such systems is to increase the operation time without recharging of batteries that requires the corresponding optimization.

According to [1], there exist three main ways to solve the task of increasing of system operation time in autonomous mode: (i) to increase the capacity of power sources; (ii) to upgrade the production technology for integrated circuits; (iii) to optimize the power-consumption software. The two former ways require fundamental research. The third one needs only the equipment to measure power consumption.

The difficulty of power consumption measurement for MC (as well as for microprocessors) is evoked with the character of their power consumption. Modern MCs, made under CMOS (Complementary-symmetry/metal-oxide semiconductor) technology, consume the current in the form of peaks. These peaks are linked to impulses fronts of clock generator. Their amplitude exceeds the current constant in tens of times.

Analysis of the latest research and published works. The initial research [2] assumed the measurement of average energy consumption of MC. Therefore, the built models of MC power consumption have considerable error (10 per cent and more). Prof. Laopoulos' group from University of Salonika (Greece) [3] studied the power consumption of ARM7TDMI nucleus by means of measurement of instantaneous current of consumption with symmetric «current mirror». It allowed simultaneous grounding of the digital oscillograph during MC measurement [3]. The error analysis, made in [1], displayed low accuracy of «current mirror» due to the change in voltage drop on its transistors during change of MC consumption current. Into the bargain, the circuit capacitors are cut from MC with «current mirror» (MC power

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supply circuit is not standard). That is why the errors of elaborated models of consumption reach 7 per cent.

The method to measure MC instantaneous current of consumption [4, 5] uses a capacitor as a sensor of its consumption current. The elaborated in [6] methods to correct errors in measurement channel provide instrumental error of MC power consumption that is less than 0.75 per cent. The available capacitor in power supply circuit allows MC working in normal mode.

But suggested and studied in [4 – 6] method due to measurement of instantaneous voltage rates has insignificant performance in terms of error probability. This requires the special analysis of experimental research results. This method also piles up the errors at measurement of energy of programs or their fragments implementation.

Suggested in [7] method measures MC average consumption. It is based on scheme [4]. But it is reliable in terms of error probability (there are used integrated methods of analogue-to-number converting), does not accumulate errors and provides higher accuracy of power consumption measurement. However the method [7] has methodic errors.

Objectives are to research the character and rate of an error.

Task setting. The scheme to apply the suggested in [7] method to measure MC average power consumption is presented on Fig. 1. It includes the studied MC that is powered from current stabilizer CS. Its output is linked to capacitor C and stabilizer diode equivalent (on the base of operation booster OB and diode D). The scheme also assumes the bearing voltage stabilizer VS and resistor R. All listed elements of the methods' applying schemes [4] and [7] are analogical. Method's scheme [7] is different from [4] in the fact that digital oscillograph was replaced with subsystems of current measurement SCR of stabilizer CS and measurement of SVM integral of voltage drop on resistor R.

During the research they record the subsystem of MC's initiation into its program memory as well as the sequence of commands and their studied average power consumption (it can be both a multiply repeated command and entire studied program or its fragment). The system's operation faces two stages: setting and measuring. The first stage starts with the signal to launch the accomplishment of studied commands. At the very moment MC gives a launching impulse to SCR and SVM subsystems. SCR starts integrating of MC power supply voltage deviation from VS voltage (the latter is equal to MC nominal power supply voltage).

The measurement process is terminated when three following steps are made:

1. Interval T to measure voltage drop integral on resistor R should not be less of the rate due to which the elements of measuring schemes were calculated;

2. Interval T (the first clock at construction of SVM on the basis of existing analogue-to-number converter) should be divisible by period of power supply (the set of accomplished commands should be long respectfully), that is why the launch of MC program and termination of SVM measurement are to be synchronized ...ge transitions of power supply of the ...e via zero;

... During measurement of multiple ... energy one should keep record of ...ls' number to calculate the energy of ...nand.

...aving fulfilled these requirements ... is cut from MC and measures the ... of integral for MC power supply voltage from VS voltage. In case this integral exceeds admissible rate, SCR changes CS current in such way as to draw closer to zero

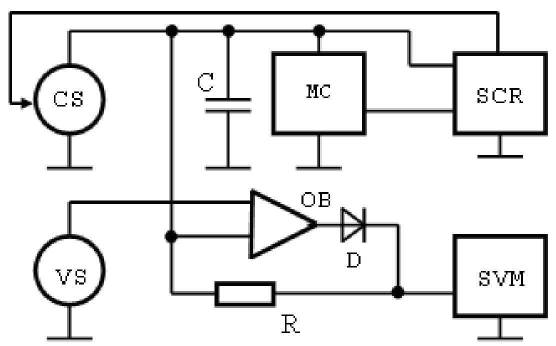

Figure 1. Subsystem to measure the average power consumption MC

the voltage change in MC circuit during measurement. After this SCR dumps VC and described setting process is repeated. During a couple of iterations the deviation of MC power supply voltage from nominal one will not exceed admissible rate. Then the regulation system records Cs current rate, launches SVM and dumps MC again. SVM starts integrating of voltage drop on resistor R. After measurement termination (fulfillment of three listed requirements) SCR again checks up the deviation of MC power supply voltage from VS voltage. If this deviation exceeds the admissible rate, SCR does not suspend the research process. It again draws CS current to necessary rate and initiates new measurement cycle. Unless this deviation exceeds the admissible rate, SCR suspends the research process and launches the calculation of average rate of energy for a command fulfillment.

The average energy is determined due to the following formula

$$E = \int_{t=0}^{T} u \cdot i \cdot dt \qquad (1)$$

where *u* and *i* are instantaneous MC voltage and current power rates MK; *t* – current time ratio; *T* – energy measurement period.

Energy balance in switch-board with plugged in CS, MC, C and stabilitron equivalent can be recorded in strict accordance with Kirchhoff 1st law. Having selected capacity C, one can succeed in obtaining maximum VC power supply voltage deviations that are rather low (0,5 – 1 per cent). Then the balance of generated and consumed energy will be recorded as follows

$$E_{CS} = E_{MC} + E_C + E_R \qquad (2)$$

where E_{CS}, E_{MC}, E_C and E_R – according to energy CS (generated, input to switch-board), MC (consumed, output from switch-board), capacitor C (output from switch-board when voltage on C grows and comes to switch-board-input, when voltage on C goes down), linked via OB at MC protection during voltage exceeding of admissible rate on C (consumed, on the switch-board output).

We neglect the energies consumed by measurement circuits. The change of capacitor energy конденсатора ΔE_C

$$\Delta E_C = (C \cdot \Delta U_C^2)/2 \qquad (3)$$

where ΔUC is voltage change on the capacitor.

As it was mentioned at the beginning they set current C at first in order to direct MC voltage deviation integral from initial rate during period *T* to zero $\int_0^T (u_i - U_{REF})dt \to 0$. Then energy change accumulated by C will go to zero $\Delta E_C \to 0$. That is why the capacitor, which creates standard work conditions for MC, does not really change the energy balance of generating / consuming (there are used ceramic capacitors with outflow current). That means E_C can be excluded from (2) and (2) can be re-written as

$$E_{MK} = E_{CC} - E_R \qquad (4)$$

E_{CC} in turn does not depend upon MC consuming energy, It can be defined as

$$E_{CC} = U_{CH} \cdot I_{CC} \cdot T \qquad (5)$$

When the commands' set is accomplished with relatively small energy then C voltage can grow higher than admissible one for this MC. Then OB through D and R «withdraws» excessive current from MC power supply switch-board. «Withdrawn» energy is taken into consideration through R by integration of voltage drop for the time period T.

$$E_R = \int_{t=0}^{T} u_{MK} \cdot i_R \cdot dt = \int_{t=0}^{T} u_{MK} \frac{u_R}{R} dt \qquad (6)$$

where u_{MK}, i_R are MC ongoing current and voltage rates through resistor R respectfully.

One has to emphasize that in case $u_{MK} \approx U_{REF}$, then (6) can be re-written as

$$E_R \approx \frac{U_{REF}}{R} \int_{t=0}^{T} u_R dt \qquad (7)$$

In this respect (4) can be re-written as

$$E_{MK} = U_{CH} \cdot I_{CC} \cdot T - \frac{U_{CH}}{R} \int_{t=0}^{T} u_R dt \qquad (8)$$

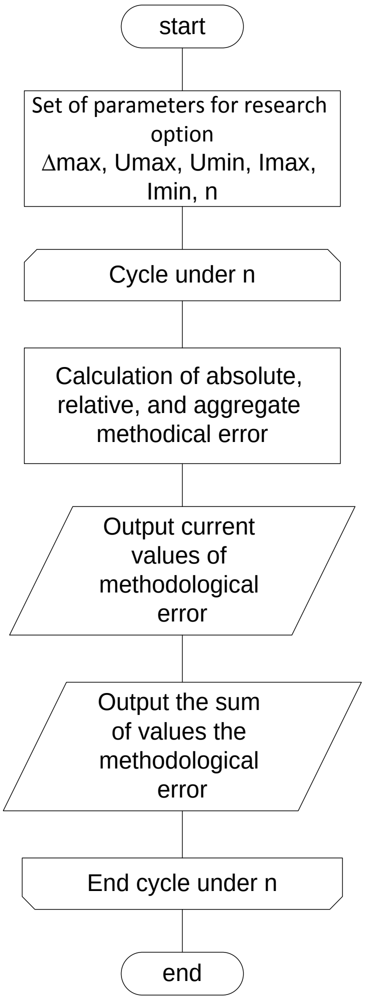

Figure 2. The general algorithm of simulation study

According to (8) the energy E_{MK} (consumed by MC) can be defined by means of voltage U_{CH} (it can be measured by precision digital volt-meter of direct current), current струмом I_{CC} (it can measured with precision digital ampere-meter of direct current) measurement time T (it can be measured with digital counter with incoming impulses from quartz generator with frequency identified by precision frequency-meter), electrical resistance R (it can be measured with precision digital ohmmeter of direct current) and voltage drop integral on R. Thus, during the experiment it is necessary to identify only mentioned integral. For this purpose it is worth to use the method of two-stroke integrating as one of the most precise and performing in terms of error probability during analogue-to-number transformation [8]. Besides, $U_{REF} \cdot I_{REFI} \cdot T_{VYM} >> \frac{U_{REF}}{R} \int_{t=0}^{T} u_R dt$, so measurement error for «withdrawn» excessive energy has the minor impact upon measurement result error during MC energy consumption.

Methodical errors and methods to study them. Methodical errors are intrinsic to suggested method of measurement of average power of MC energy consumption. The first one was caused by the change of product integral for instantaneous voltage and current according

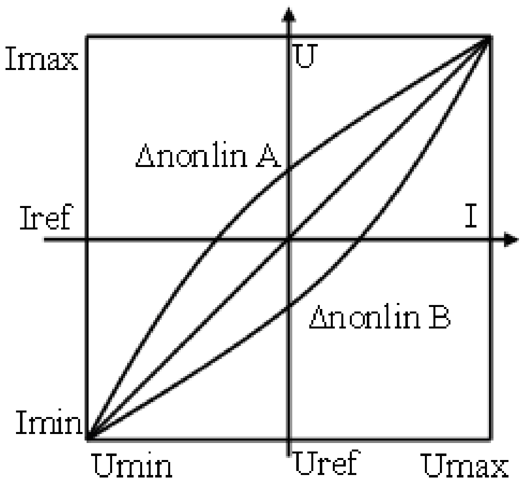

Figure 3. The generalized model of energy consumption of MC

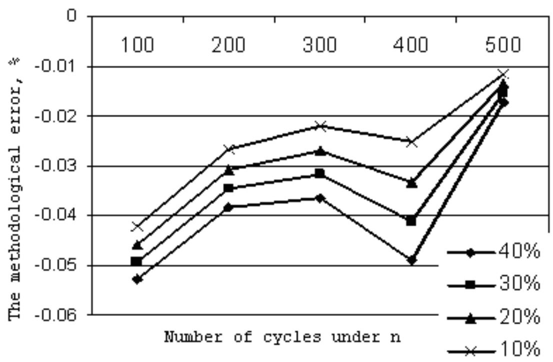

Figure 4. Dependence of the relative total average error of method on number of cycles n performed commands

to (1) on product of nominal values of voltage and current according to (5). This process can be described by the equation

$$E = \int_{t=0}^{T} (u \cdot i)dt \approx \sum_{j=0}^{T} u_j \cdot i_j \cdot t \approx U_{REF} \cdot I_{REF} \cdot T \qquad (9)$$

where u_j and i_j – instantaneous voltage and current rates on MC power supply contacts that were measured with system Fig. 1, t – period of one measurement, T – time of energy measure.

In case $\sum_{j=0}^{T} t = T$, the voltage changes on MC are inconsiderable, i.e. $\int_0^T (u_i - U_{REF})dt \to 0$ and studied device of energy consumption is linear, then there is no methodical error at changes according to (9). However, MC is semiconducting device so it has considerable non-linearity. Thus, there is methodical error due to approximate character of equation (9). The value of this error is to be studied.

Experimental research of error dependence from MC power consumption is not reasonable. Every studied MC will reflect only one option of methodical error. That is why t is necessary to apply the imitation modeling method. It will assist in implementation of all options of methodical error in given framework (even those practically impossible). General algorithm of the research is shown on Fig. 2.

It assumes determination of correlations between absolute and relative rates of methodical current and aggregate errors and number of command implementation cycles or program, non-linearity of energy consumption, maximum voltage and current rates of power supply in accordance with required research conditions. For its implementation it is necessary to build the model of MC power consumption

Model f MC non-linear consumption. The real character of different types MC energy consumption I defined by their technological characteristics. So it is necessary to build up aggregate model of consumption МК I_{MK} (Fig. 3). It includes the minimal consumption current I_{MIN} linear I_{LIN} and non-linear I_{NONLIN} current constituents of MC consumption.

$$I_{MK} = I_{MIN} + I_{LIN} + I_{NONLIN} \qquad (10)$$

I_{LIN} is defined as $I_{LIN}=k\cdot\Delta U_{MK}=k\cdot(U_{MK}-U_{MIN})$, where U_{MK} i ΔU_{MK} – current MC voltage and its change; k – coefficient, $k=(I_{MAX}-I_{MIN})/(U_{MK}-U_{MIN})$. I_{NONLIN} are defined as $I_{NONLIN} = A \cdot \Delta U_{MC}^2 + B \cdot \Delta U_{MC}$, where A, B – coefficients obtained as result of equation system solution.

$$\begin{cases} A(U_{MAX} - U_{MIN})^2 + B(U_{MAX} - U_{MIN}) = 0 \\ A((U_{MAX} - U_{MIN})/2)^2 + B(U_{MAX} - U_{MIN})/2 = \Delta_{MAX} \end{cases} \qquad (11)$$

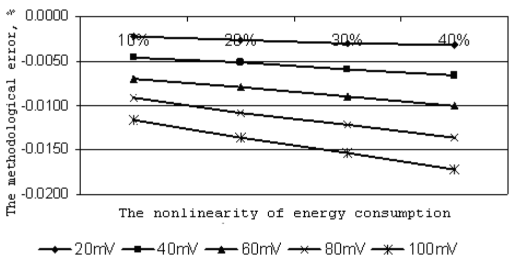

Figure 5. Dependence of the relative total average error of method on type A nonlinearity of energy consumption and maximum voltage change

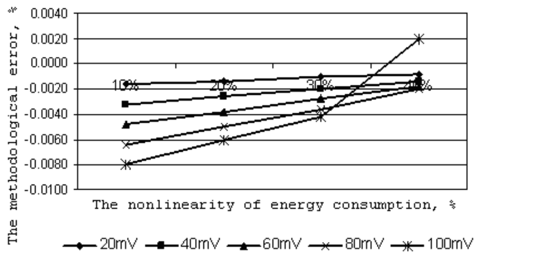

Figure 6. Dependence of the relative total average error of method on type B nonlinearity of energy consumption and maximum voltage change

where Δ_{MAX} – maximal absolute rate of methodical error.

It should be mentioned that for known MC types Δ_{MAX} and its marker are not fixed. Their research is also unknown. So, the model on Fig. 3 assumes Δ_{MAX} of both polarities. Its maximal value during imitation research is given within 10 … 40 per cent.

During the imitation modeling the value ΔU_{MC} is given at random. Thus, different energy consumption of MC is imitated. Methodical error Δ_{MET} grows simultaneously with deviation U_{MC} from U_{VS}. That is why there was selected the equable law of distribution ΔU_{MC}.

Results of methodical error research. Fig. 4 displays the correlation between aggregate average relative methodical error δ_{MET}^{Σ} and number of command cycles n (or number of rows in the program) as well as non-linearity of MC energy consumption (non-linearity is given to the right side from graphs). As Fig. 5 shows, δ_{MET}^{Σ} considerably drops simultaneously with n growth. It is explained with the fact that at initial setting of the system (see Fig. 1) the consumption current is set in such way that aggregate MC voltage deviation during given number of cycles n approaches zero. Then values of Δ_{MET} will be both positive and negative and compensate each other.

Fig. 5 displays the correlations between aggregate relative methodical error δ_{MET}^{Σ} for n = 500 and non-linear type A from non-linearity of MC energy consumption МК в межах 10…40% within 10 … 40 per cent and maximal voltage change on MC from ±10 до ± 50 megavolts (shown right side from graph).

As it show on Fig. 5, in case of non-linearity of consumption current at 40 per cent and voltage change ± 50 megavolts), $\delta_{MET}^{\Sigma} \le 0{,}018\%$. During decrease on non-linearity and voltage change on MC, δ_{MET}^{Σ} decreases considerably.

For non-linearity of B type and under the research conditions the relative methodical error δ_{MET}^{Σ}, as it displayed on Fig. 6, is less. In this case the mutual compensation of errors it acts more successfully.

Conclusions. The research of the methodical error of the proposed method for measuring the average energy consumption of MC (caused by replacing the integral of product of instantaneous values of voltage and current with the product of the nominal values of voltage and current supply of MC), have shown that it is quite small during multiple performance of an instruction or a program. One should investigate another methodological error that appears due to inequality voltage on the capacitor in the circuit of MC before and after studies (inability to ensure the accurate condition $\Delta E_C \rightarrow 0$) to solve the problem of designing of precision measuring system of MC energy consumption on the basis of the proposed method.

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УДК 004.08.01

ДОСЛІДЖЕННЯ МЕТОДИЧНОЇ ПОХИБКИ ПРИ ВИМІРЮВАННІ СЕРЕДНЬОГО ЕНЕРГОСПОЖИВАННЯ МІКРОКОНТРОЛЕРІВ

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Резюме. *Розглянуто методичну похибку, що виникає при використанні нового методу вимірювання середнього енергоспоживання мікроконтролерів під час виконання інструкцій, програм або їх фрагментів. Показано, що методична похибка є достатньо малою, тому метод забезпечує високу точність і завадостійкість вимірювань.*

Ключові слова: *мікроконтролер, вимірювання енергоспоживання, метод.*

Отримано 29.12.15