1. Roman HOLYAKA, 2. Mykola KHILCHUK, 3. Oksana BOYKO,
4. Roman KUKHTA, 5. Yevhen HALUSHKA, 6. Tetyana KOLACH

ORCID: 1. 0000-0002-7720-0372, 2. 0009-0002-4445-236X, 3. 0000-0002-8810-8969,
4. 0009-0003-2060-4004, 5. 0009-0001-5137-2213, 6. 0000-0002-4114-5519

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Power supply optimization in energy-efficient sensors devices

Optymalizacja zużycia energii w energooszczędnych sygnałowych urządzeniach czujnikowych

***Abstract**. An important requirement for up-to-day sensor devices is minimization their power consumption. An effective method of reducing power consumption is cyclic switching of signal chains of sensor devices between active mode and sleep mode. There are two main algorithms for automatic Wake-up transition between these modes – based on the duration of the measurement process and based on the signal level. This study demonstrates the possibility of optimizing pulse power supply modes in energy-efficient sensor devices using the Wake-up transition algorithm with a software-controlled duration of the measurement process. The implementation of signal circuits of such energy-efficient sensor devices is based on the Programmable System on a Chip (PSoC). Criteria for selecting the optimal duration of power pulses are presented. The optimization methodology is based on parametric analysis of the dependence of dynamic characteristics of signal circuits on the amplitude of power pulses. In the process of such parametric analysis, the results from both experimental and model studies are used.*

***Streszczenie.** Ważnym wymogiem dla nowoczesnych urządzeń czujnikowych jest zapewnienie minimalnego zużycia energii. Skuteczną metodą zmniejszenia zużycia energii jest cykliczne przełączanie łańcuchów sygnałowych urządzeń czujnikowych między trybem aktywnym a trybem uśpienia. Istnieją dwa główne algorytmy automatycznego przejścia budzenia między tymi trybami – na podstawie czasu trwania procesu pomiarowego i na podstawie poziomu sygnału. Badanie to pokazuje możliwość optymalizacji trybów zasilania impulsowego w energooszczędnych urządzeniach czujnikowych za pomocą algorytmu przejścia Wake-up z kontrolowanym programowo czasem trwania procesu pomiarowego. Implementacja obwodów sygnałowych takich energooszczędnych urządzeń czujnikowych oparta jest na programowalnym systemie na chipie (PSoC). Przedstawiono kryteria wyboru optymalnego czasu trwania impulsów mocy. Metodologia optymalizacji opiera się na analizie parametrycznej zależności charakterystyk dynamicznych obwodów sygnałowych od amplitudy impulsów mocy. W procesie takiej analizy parametrycznej wykorzystywane są wyniki badań eksperymentalnych i modelowych.*

Keywords: sensor, energy efficiency, mixed signal, embedded system
Słowa kluczowe: czujnik, efektywność energetyczna, sygnał mieszany, system wbudowany

Introduction

With the development of information technology, in particular sensor devices in the IoT (Internet of Things) concept [1], the requirements for their embedded systems are increasing significantly. The critical parameters of embedded signal conversion systems in modern sensor devices are the ability to be programmatically reconfigured, miniaturization, stable operation with low-voltage power supplies, and micro-power consumption. In sensor electronics, the concept of Mixed Signal Front-end has been formed [2, 3] with the implementation in the basis of System on Chip (SoC) [4], in particular, Programmable System on a Chip PSoC 5 (Cypress Semiconductor, Infineon Technologies) [5]. Such PSoCs contain a wide range of mixed signal conversion nodes with the possibility of their reconfiguration and programmatic control.

This paper solves the problem of minimizing the power consumption of embedded mixed signal conversion systems for IoT sensor devices. Most of these sensor devices operate in pulse modes. Therefore, the problem of minimizing power consumption is solved by optimizing the switching power supply modes of sensor device components and generating informative signals, taking into account the dynamic parameters of the SoC signal paths.

Pulse modes of operation of electronic devices are well known and widely used, in particular, in computer equipment, communication systems, navigation aids, medical diagnostics, etc. [6-8]. In recent years, the direction of minimizing the power consumption of microprocessor-controlled devices using a cyclic Wake-up transition between active mode and sleep mode has been intensively developing [9].

There are two main algorithms for automatic Wake-up transition between these modes - by the duration of the measurement process and by the signal level. To implement the first of them, a microprocessor with a built-in timer is used to provide a Wake-up transition from the power-saving mode to the operating mode, and in the power-saving mode, the vast majority of microcontroller nodes are turned off [10]. To implement the second algorithm, a threshold device is used that turns on the power supply circuits of energy-consuming signal converter nodes at a certain level of the measured signal and turns off these nodes with a certain delay when the signal level drops below the threshold. An example of a device based on the first algorithm is a pulse-acting radio beacon or radio frequency identification equipment, and the second is a microphone, the input signal amplification and comparison stage is constantly turned on, and the output powerful radio frequency generation stage is activated only at a certain power of sound vibrations [11]. It is obvious that for the implementation of sensor devices with a wide measurement range that do not allow the signal converter to be turned off at low levels of the measured value, the Wake-up transition by signal level is unacceptable. Therefore, within the framework of this work, we consider only the algorithm of Wake-up transition by the duration of the measurement process, in which short-term measurement pulses alternate with long pauses of the energy-saving sleep mode.

The problem of energy efficiency is particularly relevant in distributed sensor networks, the latest trend in the development of the information environment. Such sensor networks consist of autonomous electronic devices, in particular, for measuring temperature, humidity, magnetic and electromagnetic fields, environmental pollution, etc., and, similar to modern cellular communication systems, transmit the measurement results to a centralized information system. Examples of recent articles describing state-of-the-art solutions for embedded systems of energy-efficient sensor devices include: embedded system integrated into a wireless sensor network for online dynamic torque and efficiency monitoring [12], low-cost embedded real-time handheld vibration smart sensor for industrial equipment [13], embedded module for 3-D mechanical strain measurement [14], electronic embedded system for stair recognition based on probabilistic modelling of ultrasonic signal [15], reconfigurable smart sensor interface for IoT environment [16]. The materials of these articles confirm the relevance of the issues of further development of embedded systems of energy-efficient sensor devices considered in this paper.

Structural diagram of the sensor device

In a generalized form, the structural diagram of the Mixed Signal SoC of sensor devices is shown in Fig. 1. The formation of informative signals is realized by primary transducers (sensors of physical, chemical or biochemical quantities). It should be borne in mind that the functionality and parameters of the primary transformation are determined not only by sensors (Sensor, S) but also by actuators (Actuator, A) that activate the first process of the measurement transformation.

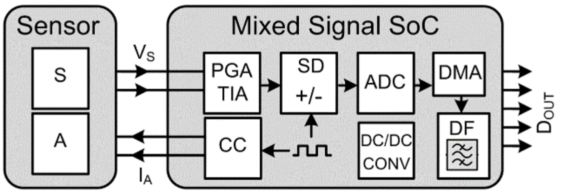

Fig. 1. Generalized structural diagram of the sensor device

In addition to the primary conversion unit, the new generation of sensor devices based on the Mixed Signal SoC concept contain a programmable gain amplifier PGA, pulse power supply controller for the actuator CC (Current Controller), synchronous detector SD, analog-to-digital converter ADC, digital filter DF, Direct Memory Access DMA controller, photovoltaic energy converter and power stabilizer (DC-DC CONV) and other nodes. In particular, these are communication units (wired, optical or radio frequency), indication units, etc. For simplicity, these nodes are not shown in the generalized diagram.

In photoelectronic sensors, light-emitting diodes (LEDs, Fig. 2, a) or lasers can serve as actuators. From the energy point of view, the activation (formation) of light radiation involves the expenditure of certain energy, which, in particular, can be represented as the product of power P by time interval t_P. In turn, the power of the activation circuit can be described by the current I_A. In the process of such a measurement transformation, an informative signal is generated, which can be represented by the I_{PH} current of the photosensitive sensor (D_{PH} photodiode). In a broader sense, the energy of the primary transducer of sensor devices can be represented by the supply current I_A of resistive type transducers (R_B, Fig. 2, b) or transducers of functional electronics, in particular, Hall sensors (HG, Fig. 2, c).

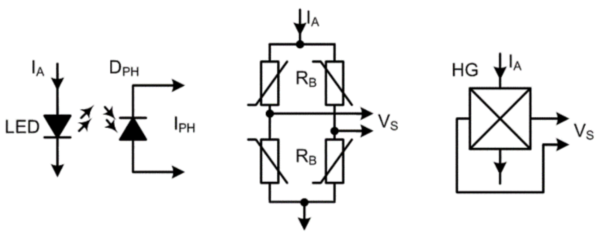

Fig. 2. Primary transducers of the sensor device

All of these primary transducers are characterized by a functional dependence of the amplitude of the informative signals of the current I_{PH} or voltage V_S on the activation current I_A. The higher the current value, the greater the amplitude of the pulses of the informative signal. For the most part, within the range of real values of the activation current (from several tens of microamperes to several tens of milliamperes), this functional relationship is linear.

Therefore, increasing the activation current I_A also increases the amplitude of output signals I_{PH} or V_S (within the linear range of the measurement transformation), which reduces the requirements for signal conversion (in particular, the signal gain). In addition, this increase in the current I_A increases the signal-to-noise ratio of the measuring circuit. The fact that the signal rise and stabilization time is characterized by a direct proportionality to the signal circuit gain and an inverse proportionality to the signal circuit supply current (amplifier, synchronous detector, analog-to-digital converter, etc.) is fundamentally decisive from the point of view of the task being solved.

For the purpose of investigating the solutions proposed in this work, a reconfigurable prototyping platform was developed and fabricated (Fig. 3). It comprises the following components: 1, 3 – photovoltaic power supply batteries; 2 – an energy-efficient flexible display based on electronic ink technology (Waveshare E-Ink 2.13inch e-Paper HAT); 4 – a set of photodiodes; 5 – a module based on the PSoC 5LP platform; 6, 8 – specialized analog front-end units with ultra-low power consumption and Rail-to-Rail operation; 7 – a Wi-Fi radio frequency module; 9 – STM32 and AVR microcontroller module designed to implement extended software control functionality via peripheral interfaces.

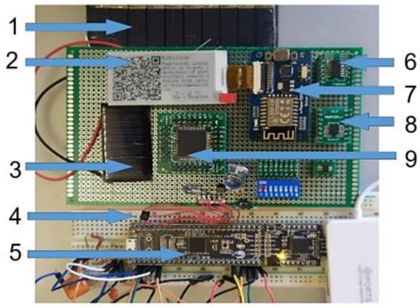

Fig. 3. Reconfigurable prototyping platform

Analysis of pulse operating modes

Most energy-efficient sensor devices operate in pulse modes with a certain repetition period T_P (Fig. 4). In each T_P period, there is a time interval t_P of active measurement (Active Mode) and a time interval t_Z of the passive state (Sleep Mode). At a constant supply voltage, the power supply during the active measurement interval is determined by two main components - the activation current I_A of the sensor (primary transducer) and the supply current I_S of the signal (secondary) conversion circuit. The power supply current in the passive state interval I_Z is significantly less than the current $I_A + I_S$ of the active measurement.

The analysis of the functioning of sensor devices with a pulse mode of operation shows that the same informational capacity can be provided both by increasing the activation current I_A and the supply current I_S of the signal converter while shortening the interval t_P of active time measurement (Case A, upper diagram of Fig. 3) and by reducing the activation current I_A and the supply current I_S of the signal converter while extending the interval t_P of active time measurement (Case B, lower diagram of Fig. 4).

Analyzing the speed of signal converters, we note that the signal settling time, in particular at the amplifier output, is determined by a number of parameters. The performance parameters of such amplifiers are the product of the gain coefficient by the bandwidth GBP (Gain Bandwidth Product) in frequency units (Hz), the slew rate (SR) in Volts/seconds (V/s), and the output voltage setting time (ST) in time units (s). It should also be noted that the product of the gain by the frequency bandwidth GBP in a number of specifications and SPICE models of amplifiers is represented by the unity gain bandwidth product GBW. SPICE models also specify the maximum positive slew rate SRP (V/s) and maximum negative slew rate SRN (V/s) of the output voltage pulses.

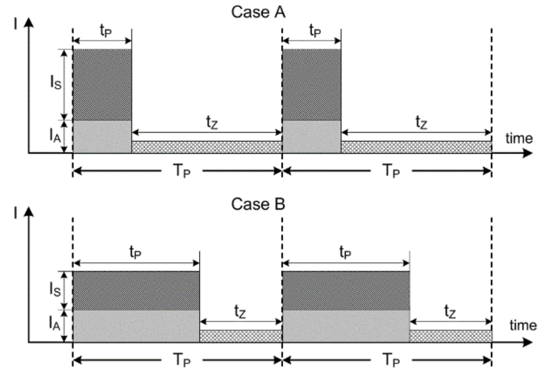

Fig. 4. Illustration of pulse operating modes

The performance parameters are determined by the supply current of the IS circuit - the higher the value of the IS current, the faster the output voltage is established. In modern components of mixed signal conversion with programmable functioning parameters, in particular, as shown in the Operational Amplifier (Opamp, Fig. 5) specification of the PSoC 5 programmable system on a chip, a choice of Programmable Power and Bandwidth power modes is provided - Low Power, Med Power, High Power [17].

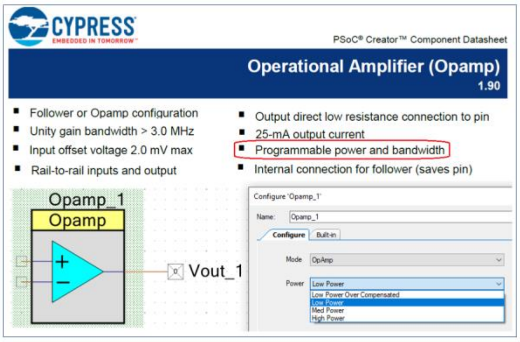

Fig. 5. Specification and Opamp PSoC configuration window

Therefore, in the process of optimizing the power supply modes of signal converters, the parameters of specifications and the results of experimental studies of transient processes are used. In particular, Fig. 6 shows a typical example of such experimental studies of the transient processes of an inverting PGA in High Power mode and in Low Power mode. These data are used to determine the characteristic dependencies of the output signal settling time on the power or current supply of the components.

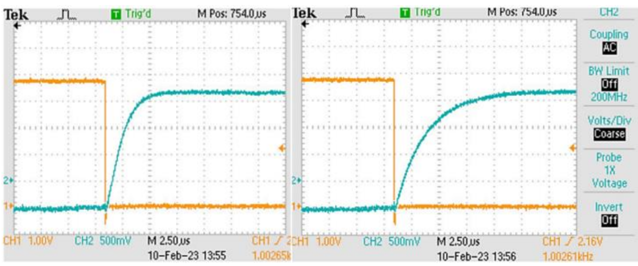

Fig. 6. Oscillogram of PGA output voltage increase in High Power mode (left) and Low Power mode (right)

Further, SPICE models are synthesized, which are used to study the effect of power supply modes on the dynamic characteristics of signal circuits. An example of a SPICE scheme of the inverting amplifier model based on the operational amplifier XOA, the input signal of which is formed by a pulse voltage source $Vinp$, is shown in Fig. 7, and the result of model studies of the increase in the output voltage $Vout$ at the given values of unity gain bandwidth GBW = 1E6 (1), 2E6 (2), 5E6 (3) is shown in Fig.8. With a decrease in power consumption of operational amplifiers, the GBW coefficient decreases and the setting time of output voltage pulses increases.

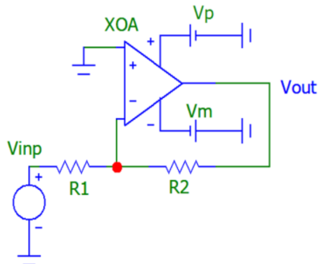

Fig. 7. SPICE scheme of the inverting amplifier model

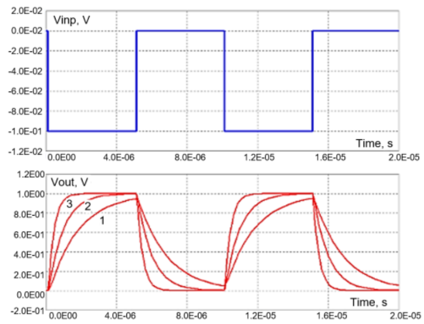

Fig. 8. Shapes of input V_{inp} and output V_{out} voltages

Optimization methodology

The methodology for optimizing the power supply modes of signal converters of sensor devices with pulsed modes of operation developed in this paper involves the following steps.

First, the energy E of consumption is defined by the product

(1) $$E = P \cdot t = V \cdot I \cdot t\,,$$

where P is the power, V and I are the voltage and current, t is the time interval.

Next, we introduce the concept of normalized by the supply voltage V_E energy E_N of the signal conversion

(2) $$E_N = \frac{E}{V_E}$$

Such normalization is typical in the specifications of autonomous power sources (in particular, Power Bank accumulators), where the main parameter is energy in units of the product of current I for time t, in particular in [Amps Hours].

Therefore, the E_N value will be determined by the sum of normalized energies in each of the time intervals t_i

(3) $$E_N = \sum_{i=1}^{n} I_i \cdot t_i$$

In particular, in accordance with the above mentioned illustration of pulsed modes of operation (Fig. 4), the normalized energy for one period is determined by the expression

(4) $$E_N = (I_A + I_S)t_p + I_z(T_p - t_p)$$

The delay time for establishing the output signal t_{DELAY} is represented by the sum of the time t_0 independent of the power supply and the time dependent (inversely proportional) to the power supply current I_{POWER}

(5) $$t_{DELAY} = t_0 + \frac{K_I}{I_{POWER}}$$

where K_I is the proportionality coefficient with dimension $[K_I]$=*A s*

Examples of characteristic dependencies of the delay time on the supply current in conventional units a.u. (Arbitrary Unit) are shown in Fig. 9.

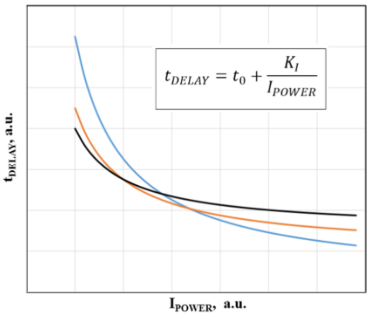

Fig. 9. Dependence of the delay time on the supply current

The power supply efficiency can be analyzed by the activation current I_A or the supply current of the signal converter I_S. For example, consider the dependence of the minimum duration of the interval t_P of active measurement, which is determined by the time of the output signal establishment, and the normalized energy E_N of the signal conversion for the period T

(6) $$t_p = t_0 + \frac{K_I}{I_S},$$

(7) $$E_N = (I_A + I_S)\left(t_0 + \frac{K_I}{I_S}\right) + I_Z\left(T_p - t_0 - \frac{K_I}{I_S}\right),$$

(8) $$E_N = I_S t_0 + \frac{(I_A - I_Z)K_I}{I_S} + (I_A - I_S)t_0 + I_Z T_p + K_I .$$

It can be seen that the mathematical expression of normalized energy consumption E_N is represented by the following function (Fig. 10)

(9) $$E_N(I_S) \to f(x),$$

(10) $$f(x) = ax + \frac{b}{x} + c .$$

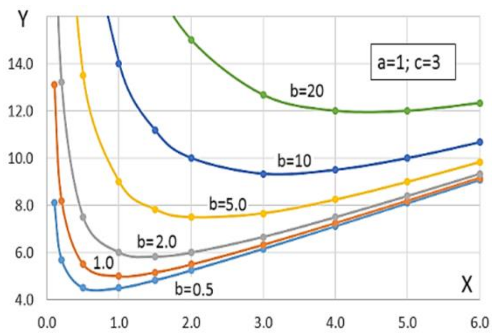

Fig. 10. The extreme values of the function *f(x)*

Derivative of this function

(11) $$\frac{df(x)}{dx} = a - \frac{b}{x^2}$$

has an extremum at the point $x = \sqrt{b/a}$.

Similarly, the derivative of the normalized energy consumption function and its extremum are calculated using the formulas

(12) $$\frac{dE_N(I_s)}{dI_S} = t_0 - \frac{(I_A - I_Z)K_I}{I_S^2},$$

(13) $$\frac{dE_N(I_s)}{dI_S} = 0 \; at \; I_S = \sqrt{\frac{(I_A - I_Z)K_I}{t_0}} .$$

Examples of calculating the normalized power consumption E_N from the current I_S for certain sets of values I_A, I_Z, K_I, t_0, T_P are shown in Fig. 11 - Fig. 13.

	E_1	E_2	E_3
I_A, A	1E-4	1E-3	1E-2
I_Z, A	1E-5	1E-5	1E-5
K_I, A·s	1E-8	1E-8	1E-8
t_0, s	1E-5	1E-5	1E-5
T_P, s	1E-1	1E-1	1E-1

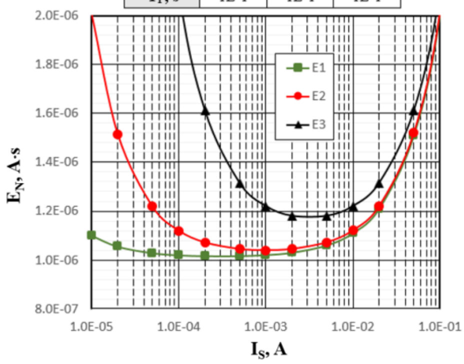

Fig. 11. Dependencies $E_N = f(I_S)$ (Case 1)

	E_1	E_2	E_3
I_A, A	1E-3	1E-3	1E-3
I_Z, A	1E-6	3E-6	1E-5
K_I, A·s	1E-8	1E-8	1E-8
t_0, s	1E-5	1E-5	1E-5
T_P, s	1E-1	1E-1	1E-1

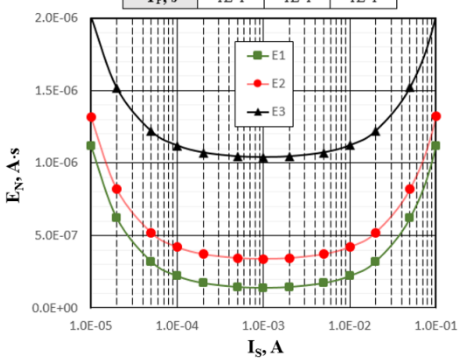

Fig. 12. Dependencies $E_N = f(I_S)$ (Case 2)

The presented examples demonstrate the existence of extrema of the power consumption function E_N and the characteristic dependencies of these extrema on the values of the sensor activation current I_A, the sensor supply current in sleep mode I_Z, the proportionality coefficient K_I, and the delay time t_0. Therefore, in the process of optimizing the power supply modes and signal conversion parameters, it is possible to determine the supply current I_S of the signal converter at which the energy consumption by the sensor device will be minimized. A similar analysis of the power consumption function can be performed by the activation current I_A or the sum of $I_S + I_A$.

	E_1	E_2	E_3
I_A, A	1E-3	1E-3	1E-3
I_Z, A	1E-6	1E-6	1E-6
K_I, A·s	**1E-8**	**1E-7**	**1E-6**
t_0, s	1E-5	1E-5	1E-5
T_P, s	1E-1	1E-1	1E-1

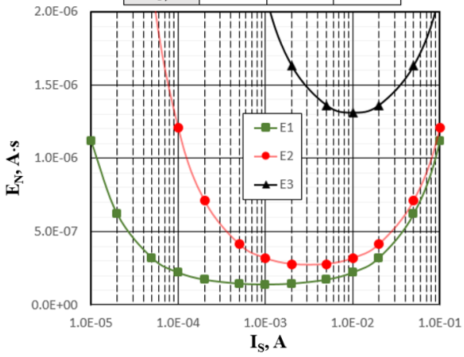

Fig. 13. Dependencies $E_N = f(I_S)$ (Case 3)

The obtained results are used in the design and optimization of the operating modes of embedded mixed signal conversion systems for sensor devices, in particular, based on programmable systems on a chip PSoC 5. The above-mentioned SPICE models are used in the process of such optimization. Therefore, the methodology for optimizing the power supply modes of signal converters of sensor devices presented in this paper serves as the basis for selecting their operating modes.

Conclusions

An analysis of the possibility of optimizing the power consumption of sensor devices using the cyclic switching of their signal circuits between the active mode of operation and the sleep mode was carried out. In each period T_P of signal formation, there is a time interval t_P of active measurement (Active Mode) and a time interval t_Z of the passive state (Sleep Mode). The power supply during the active measurement interval is determined by two main components - the activation current I_A of the sensor and the supply current I_S of the signal conversion circuit. The power supply current in the passive state interval I_Z is significantly less than the current of the active measurement $I_A + I_S$. It is shown that the same informational capacity can be provided both by increasing the activation current I_A and the supply current I_S of the signal converter while reducing the interval t_P of the active time measurement, and by reducing the activation current I_A and the supply current I_S of the signal converter while extending the interval t_P of the active time measurement.

A method for optimizing the duration of sensor activation pulses and the power supply of the signal conversion circuit has been developed. This method is based on identifying the regularities of the dynamic characteristics of signal circuits depending on the amplitude of the power supply pulses. In the process of parametric analysis, the results of experimental and model studies are used. The presented examples demonstrate the existence of extrema in the power consumption function and the characteristic dependencies of these extrema on the dynamic parameters of the signal circuits. The implementation of signal circuits for such energy-efficient sensor devices is carried out using a Programmable System on a Chip, specifically PSoC 5 (Fig.3), which features an extended set of mixed-signal conversion components.

***Authors**: prof. DSc, Roman Holyaka, Lviv Polytechnic National University, Department of Electronics and Information Technology, 12 Bandery str., Lviv, Ukraine, E-mail: roman.l.holiaka@lpnu.ua; Ph.D., Mykola Khilchuk, Lviv Polytechnic National University, 12 Bandery str., Lviv, Ukraine, E-mail: mykola.o.khilchuk@lpnu.ua; prof. DSc, Oksana Boyko, Danylo Halytsky Lviv National Medical University, Medical informatics department, 69 Pekarska str., Lviv, Ukraine, E-mail: oxana_bojko@ukr.net; Ph.D. student, Roman Kukhta, Lviv Polytechnic National University, 12 Bandery str., Lviv, Ukraine, E-mail: roman.a.kukhta@lpnu.ua; Ph.D. student, Yevhen Halushka, Lviv Polytechnic National University, 12 Bandery str., Lviv, Ukraine, E-mail: yevhen.o.halushka@lpnu.ua, Sen.Lec. Tetyana Kolach, Danylo Halytsky Lviv National Medical University, Medical informatics department, 69 Pekarska str., Lviv, Ukraine, E-mail: kolach_tanya@meduniv.lviv.ua*

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