Model of Low-Noise, Small-Current-Measurement System Using MATLAB/Simulink Tools

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***Abstract*—In this paper the model of a system for measuring small currents, which generates the digital signal proportional to the input current, was designed. The analysed measuring system is the part of a larger microelectronic mixed-signal integrated chip (SoC – System on Chip), and it is located between the input sensor and the external digital device. Since the part that mostly contributes to the noise inside the whole measuring chain is at the input of the chain, the measurement method is analyzed to minimize the impact of noise. Because the noise is not definite, the simulation of measurement by the model was made using statistical principles. Performing multiple measurements of the input value (in our example it is current I_d) it is possible to calculate its mean value and standard deviation. It was shown that the measured quantity can be calculated from the mean value and that the standard deviation represents an amount of noise. Depending on the standard deviation it is needed to do either less or more sequential measurements to determine the reliable measured output digital value.**

Keywords: Small-currents measurement system, Low-noise systems, Sensors, Conversions into electrical quantity, Analog IC design, MATLAB/Simulink tools.

I. INTRODUCTION

Information processing devices that are placed between the sensor and the external circuit are often used in the practice. In this paper we present a model of one such system. The model is used for the functional analysis of a sub-circuit of a microelectronic integrated circuit, which is located between an input sensor and an external device for further digital data processing or value representing (e.g. microcontroller, LCD screen). The circuit under consideration generates a digital value proportional to the input analogue small current, considerably exposed to the noise (highly-sensitive, digital, integrated ampermeter) [1].

The considered circuit is convenient for a broad area of measurements and further analysis, using sensors where a non-electrical quantity (e.g. light, physical, chemical or electrochemical) has been transformed to electrical quantity (voltage or current). The application is very broad: bioindustry, medicine, ecology (water and air pollution), agriculture, food production, aviation, instrumentation, military and automobile industry, etc.

The MATLAB/Simulink model shows a principle to measure small input values. Using the model, we analyse the impact of the noise at the integrated measurement chain (realized as microelectronic integrated circuits on 180nm TSMC technology shown in Fig. 1) at the final output values [2].

II. NOISE

The main challenge in the system for measuring small input currents is noise. Noise is produced by random fluctuations of voltages and currents in the physical elements of electrical circuits, and as such represents a fundamental limitation in the precision of the measurements. In microelectronic systems there are several noise categories: internal noise (thermal, 1/f, shot, etc.), external noise (environment impact, interference etc.). Other effects include offset, finite open-loop gain and slew-rate of operational amplifiers, signal lines crosstalk, etc. [3].

Since in microelectronic devices and circuits it is very difficult to treat, quantize and measure the noise, an equivalent input RMS noise (root mean square noise) is used [4]. Basically, the equivalent input noise is a measure how much noise is added to the input current signal. Such representation of the noise at the input of the model does not have any impact on the functional or operational behaviour of the model and it is also independent of gain and current range settings. The value of all noise contributors in the system (all operational amplifiers, switches, sample & hold, current/voltage converter, etc.) is obtained from laboratory measurement as total RMS value at the output of the processed microelectronic chip. This combined RMS output noise value, also incorporating system's frequency behaviour, is then referred to the input of the model as the equivalent input noise. The effect of offsets of operational amplifiers is reduced by offset cancelation circuits.

Furthermore, this all gives ability using the model to run simulations of the integrated, complex microelectronic system.

III. MODEL IN MATLAB / SIMULINK

In the analysis of the model we will study the parts of the modelled measuring chain. As shown in Fig. 1, the integrated microelectronic measurement system consists of current-voltage converter (I/V converter), differential amplifier (diff. builder), programmable-gain amplifiers (gain chain), sample and hold circuit (S&H circuit) and analogue-to-digital converter (A/D converter).

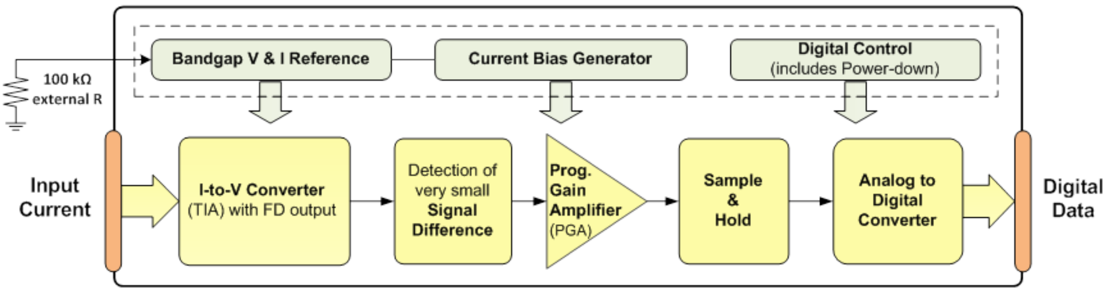

Figure 1. Block scheme of the measuring chain of low-noise, small-current-measurement system.

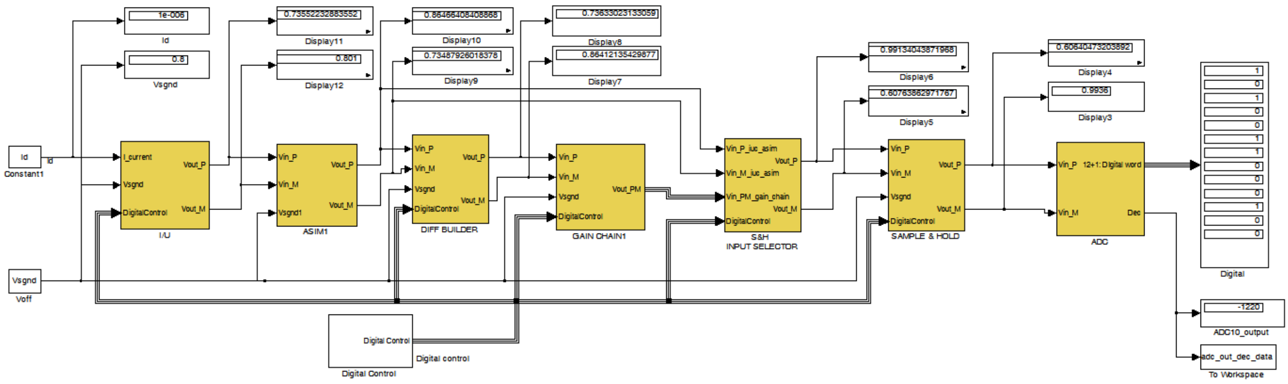

Figure 2. Model of the complete low-noise, small-current-measurement system in MATLAB/Simulink.

All blocks, except the A/D convert, are modelled with their own frequency behaviour. The model is built in MATLAB / Simulink tool [5] and is shown in Fig. 2. It is realized by 8 blocks, and additional blocks for measuring and displaying the output value. At the input there is a current source I_d, and a reference voltage V_{sgnd}. Each part of the system is described as follows.

A. Current-to-voltage converter

Current-to-voltage converter is the first block in the MATLAB/Simulink model and is shown in Fig. 3. Its purpose is to convert input current to voltage. It has three control signals: *az* (auto-zero), *cr_select* and *noise_select*.

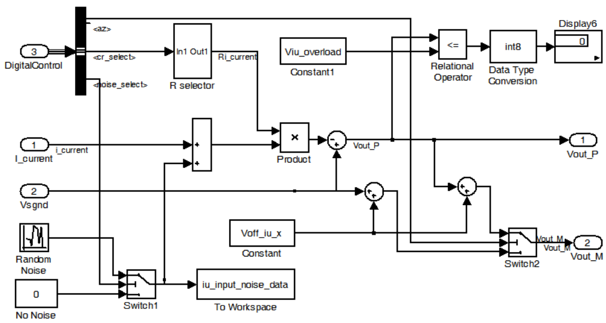

Figure 3. Model of the current-to-voltage converter.

The auto-zero signal controls the auto-zeroing process in order to eliminate offsets of operational amplifiers. When *az*=1, the block samples the combined voltage offset since this mode configures the circuit in the way it is equivalent to input current being zero (I_d =0). When *az*=0, the output has the voltage offset superposed to the useful signal. When those two output signals are subtracted, only the value of useful signal remains. The signal *cr_select* has 3 bits and controls the input current range by selecting the transresistance of the I/V converter, modelled as shown in Fig. 4. When *noise_select* is 1, the random noise is added to the input current. Once the noise is added, it propagates through the signal chain to the output of the model, so it is possible to perform simulations of measurements.

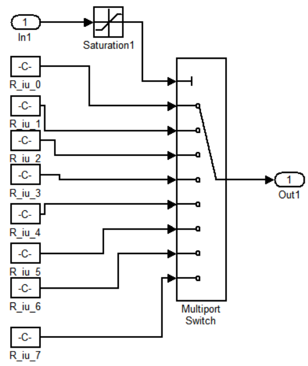

Figure 4. Reistance selector model in current-to-voltage converter.

B. Symmetric converter

The symmetric converter is shown in Fig. 5. The I/V converter and the symmetric converter operate as one block. The main purpose of the symmetric converter is to produce differential symmetrical signal. Thus, the current-to-voltage converter and the symmetric converter together convert measured input current to a symmetric differential voltage signal since it is more robust to interference. As shown below, it is very important to reduce noise in the input stages, because they mostly contribute to the output total noise (see [6]).

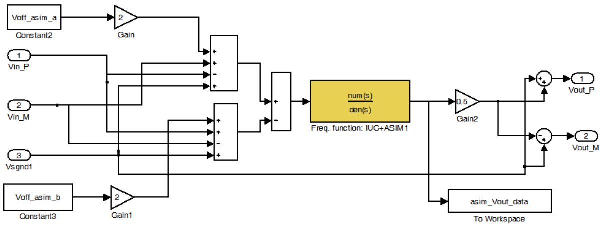

Figure 5. Model of the symmetric converter.

C. Differentiator

The next block in the chain is a differentiator and is shown in Fig. 6. The differentiator is the block where subtraction of the offset from useful signal from the I/V converter is done.

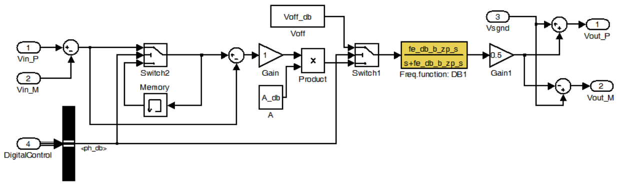

Figure 6. Model of the differentiator.

It operates in two phases, which are controlled by the signal *ph_db*, which serves to make a difference between the two input current sampling (I_d and I_d =0), i.e. the difference between the previous (t–1) state and current state (t).

$$\begin{aligned} &ph\_db = 1, \quad \Delta V_{out} = V_{off} \\ &ph\_db = 0, \quad \Delta V_{out} = -A[\Delta V_{in}(t-1) - \Delta V_{in}(t)] \end{aligned} \tag{1}$$

D. Cascade amplifier

The fourth block is a cascade amplifier, which consists of four-amplifier stage with bypass and gain control shown in Fig. 7. It determines the overall gain of the chain. Four amplifiers (instead of one) are used for practical reasons of circuit realization and also because of stability and impedance reduction. Since the overall gain of the integrated measurement system is specified before the designing and modelling the measurement system, the number of the gain stages is determined by achieving the gain and to have appropriate gain linearity.

The amplification of every amplifier can be programmed to be 3 or 6 and the maximum gain of the whole block is 6^4 = 1296. The multiplexer with bypass path is used if the desired stage gain is one. Therefore, it is possible to realize only the amplification which is the product of gains 1, 3 and 6 in 4 amplifiers. The final gain of the gain chain is gain multiplication of each stage, given by:

$$G_{final} = G_1 \cdot G_2 \cdot G_3 \cdot G_4 \,. \tag{2}$$

By setting the gains of the stages in the cascade amplifier, it is possible to optimize the quality of the measurements of small input currents.

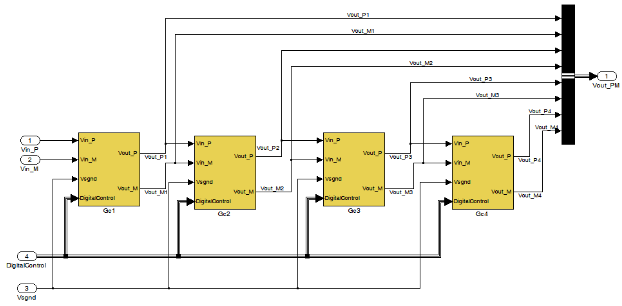

Figure 7. Model of the cascade amplifier.

As shown in Fig. 10 below, showing model of every amplifier in the cascade, each of these 4 amplifiers is controlled by 3 control signals *ph_gc*, *gain* and *ByPass* in the following way: when *ByPass*=0 and *gain*=1 then the gain is 6, when *gain*=0 then the gain is 3; when *ByPass*=1 then the gain is 1.

Each gain stage operates in two phases defined by the control signal *ph_gc*:

$$\begin{aligned} &A)\,\text{For } ByPass = 0 \\ &1)\, ph\_gc = 1 \text{ [phase of samplig input signal } \Delta V_{in}(t)] \\ &\qquad \Delta V_{out} = V_{off} \\ &2)\, ph\_gc = 0 \\ &\qquad \Delta V_{out} = -Gain[\Delta V_{in}(t-1) - \Delta V_{in}(t)] \\ &B)\,\text{For } ByPass = 1 \\ &\qquad \Delta V_{out} = \Delta V_{in}(t) \end{aligned} \tag{3}$$

The *noise factor* is a figure-of-merit for a circuit with respect to noise (see [6]–[8]), defined by:

$$F = \frac{S_i / N_i}{S_o / N_o} = \frac{N_o}{N_i} \cdot \frac{1}{A_a} \,, \tag{4}$$

where S_i and N_i are signal and noise powers at the input, respectively, while S_o and N_o are the same quantities at the output. A_a is system power gain.

If we consider a multistage amplifier (e.g. gain chain), where each stage has its corresponding noise factor F_1, F_2, etc., then the overall noise factor F of the cascade is given by the Friis formula (see [7], [8])

$$F = F_1 + \frac{F_2 - 1}{A_1} + \frac{F_3 - 1}{A_1 A_2} + \ldots + \frac{F_N - 1}{A_1 A_2 \cdot \ldots \cdot A_N} \,, \tag{5}$$

where A_1, A_2, …, A_N are the maximal power gains of each stage. From (5) and A_i>1; (i=1, 2, …, N) it follows that to minimize the noise factor F of the whole cascade structure, it is most important to have the first block with minimum noise factor F_1.

E. Sample and Hold and Multiplexer block

The sample and hold circuit is shown in Fig. 8. There is one control signal *ph_sh* that controls when the circuit takes the sample and when the circuit will let that sample propagate to the next block.

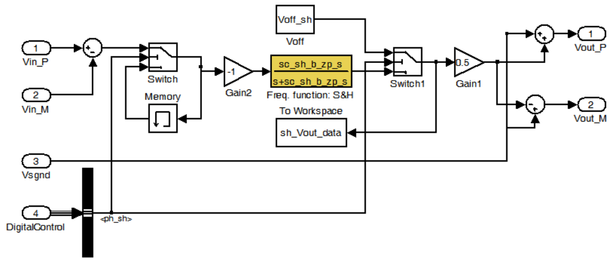

Figure 8. Sample and hold circuit.

The memory elements are capacitors that are charged and discharged, accordingly.

The multiplexer block, shown in Fig. 9, is controlled automatically depending on the state of bypass control bits, so user is not able to change or control block's functionality. The purpose of multiplexer block is to minimize impact of the amplifiers noise in the gain chain blocks in the case when gain = 1 by bypassing the particular gain stage or whole gain chain.

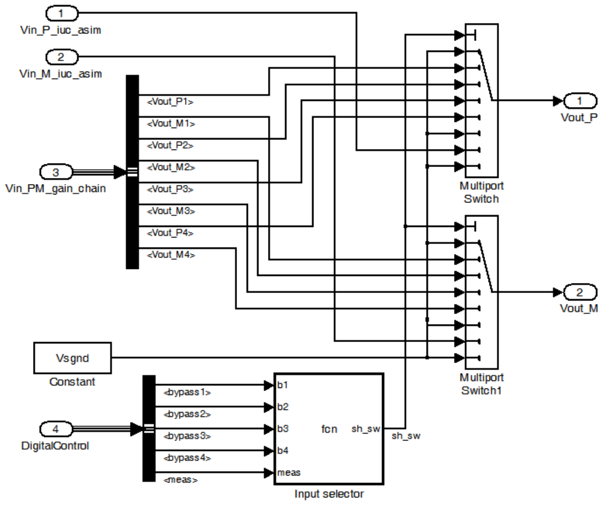

Figure 9. Multiplexer blok (Sample and Hold input selector).

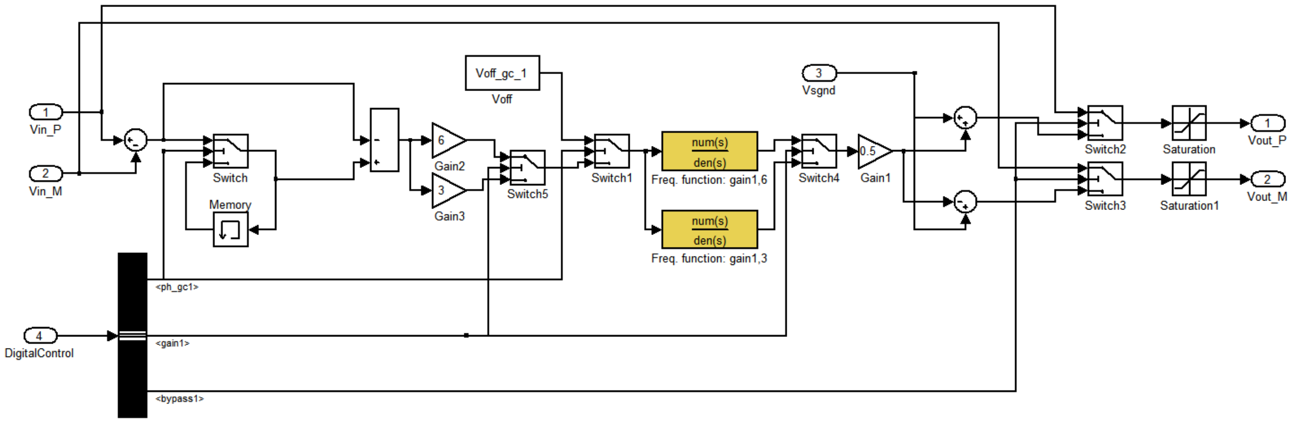

Figure 10. Model of every amplifier in the cascade.

TABLE I. SIMULATION RESULTS OF THE MODEL WITH VARIOUS NUMBER OF SAMPLES.

N	G=1 / I_d = 5.125E-6			G=54 / I_d = 9.4907E-8			G=324 / I_d = 1.5818E-8			G=648 / I_d = 7.909E-9			G=1296 / I_d = 3.9545E-9		
	StdDev	**Error**	**Mean**	**StdDev**	**Error**	**Mean**	**StdDev**	**Error**	**Mean**	**StdDev**	**Error**	**Mean**	**StdDev**	**Error**	**Mean**
5	2.191	0.048	–2081.6	131.354	2.873	–2089.6	825.152	18.874	1911.4	443.892	8.638	2640.8	2498.934	68.460	1332.4
10	1.581	0.035	–2081.5	139.828	3.044	–2110.3	558.366	11.038	2558.8	1039.873	22.731	2092.8	1950.097	44.260	1941.3
20	1.943	0.043	–2080.8	148.467	3.260	–2073.6	659.474	14.366	2107.3	1212.146	27.614	1926.8	2128.244	48.306	1941.1
50	2.143	0.047	–2081.2	133.334	2.930	–2071.3	678.909	15.133	2012.5	1417.575	30.998	2091.3	2203.085	49.143	1987.6
100	2.340	0.051	–2081.0	122.757	2.679	–2099.4	706.122	15.297	2130.8	1266.276	27.881	2062.8	2026.784	43.808	2140.4

F. Analog to digital converter

The last block in the chain is ideal analogue-to-digital converter and is shown in Fig. 11. It takes the voltage values stored in S/H circuit and converts them to a digital word. The digital word at the output has 13 bits, of which one bit defines the sign. The conversion is performed according to the formula

$$D_{Integer} = \frac{\Delta V_{in}}{V_{range}} \times 2^{N-1}, \tag{6}$$

where V_{range} is the output voltage range, and N is the number of the bits (excluding the sign bit), and $D_{Integer}$ is integer value of binary output. Using MATLAB functions we convert measured values from the decimal to the binary system. Thus, we finally obtain a binary word displayed using 13 bits. Using a display in the model, the decimal value is shown too.

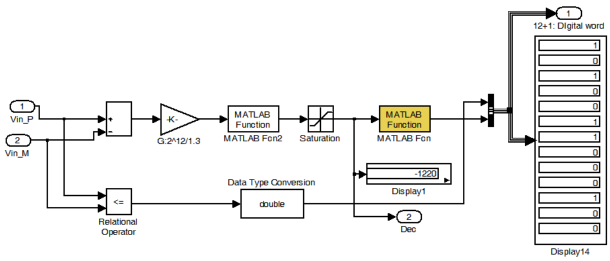

Figure 11. Analog to digital converter.

Finally, there also exist *digital control block* in the model, which contains all the signals with respective wave forms that control other blocks. The control waveforms are shown in Fig. 12.

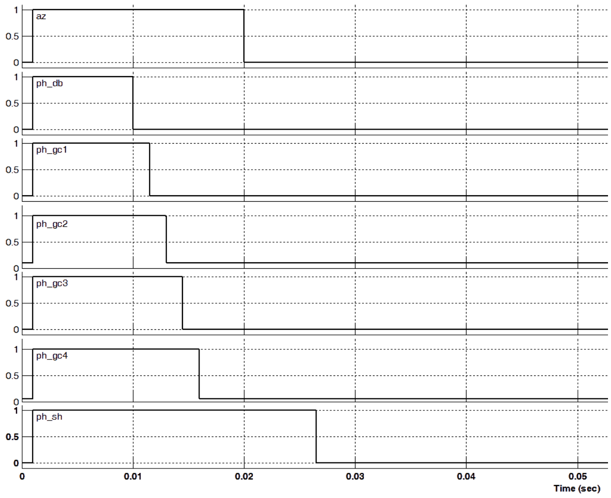

Figure 12. AZ and PH signals at control block.

IV. OPERATION OF THE MODEL

Running the simulation of the system for small input currents measurement using the MATLAB/Simulink model is performed with *statistical* method of measurement, i.e. the statistical method will make the final calculation of measured quantity [4]. Small input current I_d is not uniquely determined because of the influence of the noise, but it is possible to calculate the mean value and deviation of a set of values obtained from multiple measurements (i.e. samples).

The optimized measurement means to determine the sufficiently large number of multiple measurements. By that, the method of measuring the output quantity with noise is to eliminate the noise by calculating the mean value and standard deviation. The measurement error and the quality of the resulting quantity (value of the mean) are determined by the number of measurements (*sample_size*), and the value of standard deviation. The standard deviation of the output quantity represents the value of RMS noise.

In the simulation of measurements, the automated multiple measurements are performed using a script in MATLAB [5]. As explained in the model description above, using signals *gain* and *ByPass* the gains in cascaded amplifier are determined. The simulations have been run for the gains of the whole system as G=1, 54, 324, 648 and the highest gain G=1296. The input current amount is used for simulation: I_d=5.124[μA]. The random noise generator is set at the input of the model adding the noise to the measured input current I_d.

The numbers (*sample_size*) of sequential running the simulation of the measurement are 5, 10, 20, 50 and 100 (the results are given in Table I). The mean values and standard deviations of the measurements are calculated using a script in MATLAB.

The mean value represents the measured value of the input current, whereas the standard deviation represents the value of the noise (RMS noise). This conclusion comes from the noise nature of a random signal with the normal (Gaussian) distribution of amplitudes and zero mean.

Consider the obtained mean values and standard deviations of the simulated measurements in Table I that vary as a function of gain and the number of measurements. In the case of higher gains (G=54, 325, etc.), the simulated input current at the input is divided by the total gain, in order to produce the same output digital value. In the columns “StdDev” standard deviations of the measurements are displayed and they represent the RMS value of the output noise. In the columns “Mean” the measured / simulated value of the signal (input current) is displayed in the digital form and is within the voltage range V_{range} defined by (6). The ± sign is dependent on the positive or negative gains of the amplifier stages, and it can be neglected (absolute value is used). It is shown that for higher gain the output RMS noise is also higher (higher standard deviation). With higher number of sequential measurements the obtained “Mean” values are nearer to the correct value of measured input current I_d.

V. CONLUSION

In this paper we presented the model of a system for measuring small input currents. The model is built using MATLAB / Simulink and it is shown that it is possible to use such model to perform the simulation of the circuit solution that is the part of a mixed-signal IC chip. It is also shown that the noise is the limiting factor in measuring small input currents. The increased noise for higher gains produces the higher standard deviation. Given that the gains are large, and noise is also large, it is necessary to perform a larger number of sequential measurements of the same input value. According to the final value theorem (Gauss distribution), the calculated mean value (as the representative of measured input value) is reliable only after a sufficient number of measurements (see [4], [9]). The expected measurement error δ is given as:

$$\delta = \frac{\sigma}{\sqrt{N}}, \tag{7}$$

where σ is the standard deviation and N the number of performed sequential measurement.

Therefore, if the standard deviation as a measure of noise is lower, the required number N of sequential measurements (sampling) is also lower. Conversely, if the standard deviation is higher (higher level of noise that comes with higher gain), to have the same level of measurement error, more measurements are needed to be performed and finally the correct mean value can be calculated, reliably representing the measured value (trusted value) [4].

ACKNOWLEDGMENT

This “diploma in industry” work has been possible by the cooperation between the Economic Council of the

Department of Electronic Systems and Information Processing, Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia and the industry represented by the company Systemcom Ltd. Zagreb, Croatia that developed the sensor interface chip described in the paper.

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