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DESIGN ILLUSTRATION OF AN EKG ANALOG INTERFACE USING GENETIC ALGORITHMS

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Abstract: Electrocardiography (EKG) systems provide a solution for the recording of the heart activity and are indispensable in patient monitoring. Interfacing the EKG system with the human body is done with analog signal processing and operates towards proper signal conditioning. The EKG analog interface consists of an instrumentation amplifier, a notch filter and a highpass filter. This paper proposes an approach to design the EKG interface using genetic algorithms. Two design strategies are used: coefficient equation for amplifier and notch filter design, and curve fitting for highpass filter design. The validity of the evolutionary design results is demonstrated with transistor-level simulation.

Keywords: *EKG analog interface, genetic algorithms, coefficient equation, curve fitting.*

I. INTRODUCTION

Biomedical electronics has enabled a wide range of applications for bio-potential monitoring and tissue stimulation, in order to aid diagnostics and disease treatment [1].

Biomedical monitoring systems operate towards the acquisition of the bio-potentials and perform some pre-processing in order to remove a number of artifacts, e.g. noise due to patient movement, improper electrode connection, etc. Thus, necessary information can be extracted from the biomedical signal, aiding a proper interpretation of the biological phenomenon and a correct diagnosis. For this purpose, electronic instrumentation and computers have widely been used for the investigation of physiological activity, e.g. the electrical activity of the cardiovascular system, the brain, the neuromuscular system, the variation in pressure in the cardiovascular system [2].

The first step in the investigation of physiological systems is the application of dedicated sensors to the area of interest. Next, proper instrumentation for interfacing converts the bio-potential into a measurable electrical signal, i.e. voltage or current. Pre-processing of the electrical signal is mandatory for noise and artifact removal [2]. Thus, a careful design of the interfacing and signal pre-processing blocks ensures a qualitative acquisition of the bio-potential.

One example of a very common electronic biomedical system for bio-potential monitoring is electrocardiography. Electrocardiography was introduced to medical practice at the beginning of the 20th century, and has marked a new era in clinical diagnostics.

The electrocardiogram (EKG) is the graphical representation of potential differences during the electric activity of the heart. The electric potentials are produced in the hearth as a sum of the potentials resulting from the heart muscle cells during depolarization and re-polarization [1, 3].

While the EKG signal processing is digital, interfacing the EKG monitoring system with the human body is analog. The block diagram of an EKG system acquisition board is illustrated in figure 1 and is explained as follows [4].

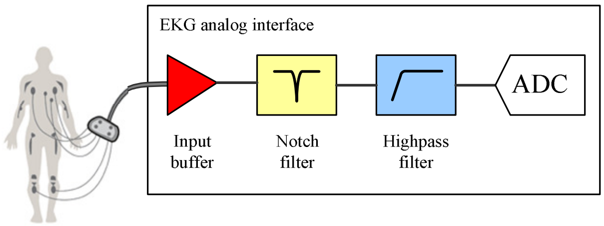

Figure 1. Block diagram of the EKG analog interface

The main functional blocks of the EKG acquisition board illustrated in figure 1 are the instrumentation amplifier, a 50Hz notch filter and a high-pass filter. The cardiac bio-potentials sensed by the electrodes, ranging from 100 µV to 4 mV [5], are amplified and applied to a high-pass filter for the removal of the DC component and to a 50Hz notch filter for rejection of the mains frequency. Next, the filtered signal is converted to digital for further digital processing.

This article presents a novel approach to designing the analog interface of an EKG monitoring systems using genetic algorithms (GA). This paper is organized as follows. Section 2 describes the EKG analog interface building blocks along with the transistor-level implementation. Section 3 provides an overview on GAs and illustrates their employment to solve the EKG interface design problem.

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Section 4 illustrates the simulation results for the EKG analog interface design with GAs. The designed circuits are then validated with transistor-level simulation. Finally, some conclusions are drawn.

II. THE EKG ANALOG INTERFACE

The analog interface of the EKG monitoring system consists of three main building blocks: instrumentation amplifier, notch filter and highpass filter. The three building blocks are described as follows, along with the transistor-level implementation.

THE INSTRUMENTATION AMPLIFIER

The first stage in the analog interface is the instrumentation amplifier (IA). The requirements for the IA are a high common mode rejection ratio (CMRR), high precision gain, low power consumption and small residual current [6]. The electrical schematic of the IA is illustrated in figure 2.

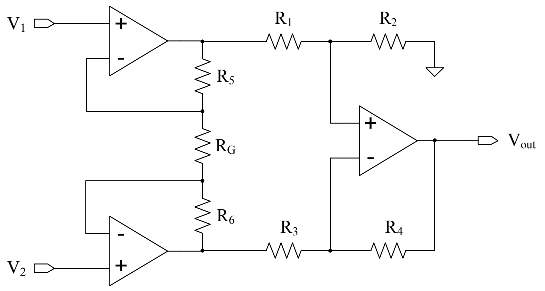

Figure 2. Instrumentation amplifier with 3 OpAMPs [1]

The operation of the IA is described as follows. The common mode and differential gains are expressed with resistance ratios as:

$$Acm = \left(\frac{R_5}{2R_G} - \frac{R_6}{2R_G}\right)\frac{R4}{2R3}\left(\frac{1+\frac{R3}{R4}}{1+\frac{R1}{R2}}+1\right) \quad (1)$$

$$Ad = \left(2 + \frac{R_5}{2R_G} + \frac{R_6}{2R_G}\right)\frac{R_4}{2R3}\left(\frac{1+\frac{R_3}{R4}}{1+\frac{R1}{R2}}+1\right) \quad (2)$$

The aim of the IA is to only amplify the differential signal, i.e. the imbalance between the two input pins, while suppressing the common mode signal. Then, a common mode rejection ratio (CMRR) is defined as:

$$CMRR = 20\log_{10}\left(\frac{Ad}{Acm}\right) \quad (3)$$

which gives a quantitative measure of the degree in which common mode signal is suppressed while differential signal is amplified [1].

In order to balance the IA, the following equalities are imposed

$$\begin{aligned} R_5 &= R_6 \\ R_2 &= R_4 \\ R_1 &= R_3 \end{aligned} \quad (4)$$

which reduce the IA gain to

$$G = \frac{R_2}{R_1}\left(1+2\frac{R_5}{RG}\right) \quad (5)$$

THE NOTCH FILTER

The second block in the EKG analog front-end is the 50 Hz notch filter which operates towards the suppression of the common mode mains frequency [1]. We have chosen to implement the notch filter with a twin-T structure illustrated in figure 3.

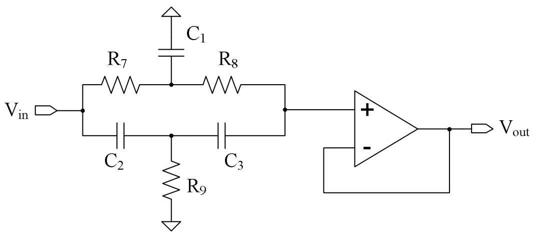

Figure 3. The twin-T notch filter [6]

The notch filter is implemented with a band-stop filter characteristics with overlapping cutoff frequencies. The two cutoff frequencies of the notch filer are expressed as

$$\begin{aligned} fc1 &= \frac{1}{2\Pi\sqrt{C_2C_3R_9(R_7+R_8)}} \\ fc2 &= \frac{\sqrt{C_2+C_3}}{2\Pi\sqrt{C_1C_2C_3R_7R_8}} \end{aligned} \quad (6)$$

Two equality constraints are defined as follows in order to balance the notch filter.

$$\begin{cases} R_7 = R_8 \\ C_2 = C_3 \end{cases} \quad (7)$$

THE HIGHPASS FILTER

The third stage in the EKG analog interface is a high-pass filter with a 0.05Hz cutoff frequency, which operates towards the rejection of the DC component and low-frequency noise[6].

We have chosen an active-RC approach to implement the high-pass filter, using the Sallen-Key biquad illustrated in figure 4.

The cutoff frequency of the Sallen-Key high-pass biquad is expressed as

$$f_0 = \frac{1}{2\Pi\sqrt{C_4 C_5 R_{10} R_{11}}} \tag{8}$$

Additionally, the passive resistances R_{13} and R_{12} enable the fine-tuning of the DC gain value.

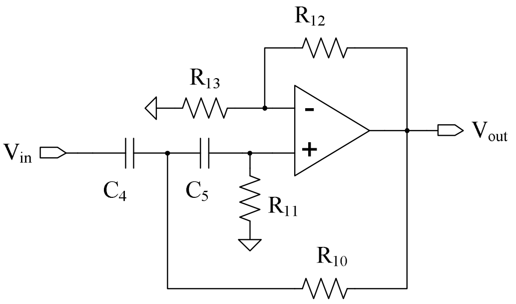

Figure 4. The Sallen-Key highpass biquad [6]

TRANSISTOR-LEVEL IMPLEMENTATION

The building blocks of the EKG analog interface are built around operational amplifiers. For the transistor-level implementation, we have chosen the folded-cascode operational amplifier (OpAMP) with PMOS input transistors illustrated in figure 5.

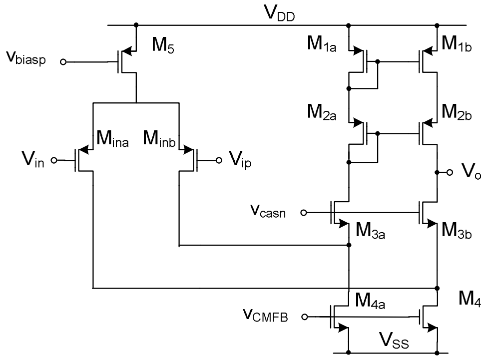

Figure 5. Transistor-level schematic of the folded-cascode OpAMP

In order to comply with the specifications in medical instrumentation electronics, the OpAMP was designed for a 1MHz gain bandwidth product (GBW) and a 4 V/µs slew-rate (SR) [7]. The transistor sizes are listed in table 1.

Table 1. Folded-cascode OpAMP transistor sizes

Transistor	Aspect ratio (W/L)
M_{ina}, M_{inb}	9.8µ / 1µ
M_{1a}, M_{1b}	14.9µ / 1µ
M_{2a}, M_{2b}	14.9µ / 1µ
M_{3a}, M_{3b}	4.3µ / 1µ
M_{4a}, M_{4b}	7.2µ / 1µ
M_5	19.8µ / 1µ

III. EKG ANALOG INTERFACE DESIGN WITH GENETIC ALGORITHM

This section illustrates the employment of Genetic Algorithms (GA) to solve the different stages in the EKG analog interface design problem. Two design methods are employed: coefficient equation and curve fitting. Each design method was customized to solve the different stages of the EKG analog interface design procedure: instrumentation amplifier, notch filter and high-pass filter respectively. The GA will determine the proper values of the passive elements in each of the three building blocks, in order the implement the desired circuit behavior.

GENETIC ALGORITHMS

Genetic algorithms (GA) are stochastic search methods which mimic natural evolution. GAs operate on a population of solution candidates, rather than on individual solutions, and apply the principle of "survival of the fittest" in order to produce individuals better and better fitted to the solving the optimization problem. Thus, the population is iteratively evolved along the evolutionary process. The GA block diagram is illustrated in figure 6 and is explained as follows[8].

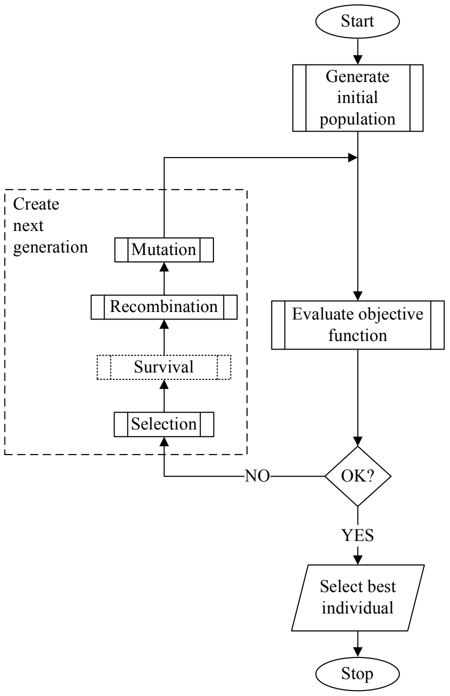

Figure 6. Genetic Algorithms block diagram [8]

A randomly generated initial population is evaluated in order to compute the fitness function for each individual. Should the optimization criteria not be satisfied, the evolutionary loop is entered. Based on the fitness value, pairs of individuals are probabilistically selected for reproduction, such that better fitted individuals have a higher chance to create offspring. Nature-inspired cross-over operator creates two offspring from every selected pair of parents. A mutation operator then randomly affects individuals from the new population pool. To be noticed is that, while cross-over operates towards transmitting the promising genetic information from one generation to the next, mutation operates towards maintaining population diversity. Optionally, a survival operator copies the best individuals from one generation to the next, in order to keep the most promising individuals in the search pool [8].

Genetic algorithms are a rather non-conventional approach to solving analog circuit optimization problems. They are an attractive alternative to the traditional circuit design methods, in order to partially automate the design procedure and minimize human intervention and design effort. Moreover, a proper choice of the genetic operators and algorithm parameters achieves very good performance in terms of runtime, solution accuracy and computational effort.

COEFFICIENT EQUATION

The coefficient equation method operates towards equating the coefficients of the mathematical expression of two characteristics [9, 10]. The coefficient equation method is used for both the IA and notch filter design problems. The IA is defined by a vector

$$[R_1\ R_2\ R_3\ R_4\ R_5\ R_6\ R_G] \tag{9}$$

which determines the IA performance in terms of differential gain and CMRR as expressed in equations (1) and (2). The notch filter is defined by a vector

$$[R_7\ R_8\ R_9\ C_1\ C_2\ C_3] \tag{10}$$

which determines the rejected frequency according to equations (6). Since the two circuit blocks are independent, they can be designed in the same GA run. If equality constraints (4) and (7) are considered, the GA chromosome is defined as

$$[R_1\ R_2\ R_5\ R_G\ R_7\ R_9\ C_1\ C_2] \tag{11}$$

A set of absolute errors is defined in order to measure the in-satisfaction of the design specifications for differential gain – A_d, common mode rejection ratio – *CMRR*, and lower and upper cutoff frequency of the notch filter – f_{c1} and f_{c2} respectively, as follows:

$$\begin{cases} err_1 = | A_d^{(spec)} - A_d | \\ err_2 = | CMRR_d^{(spec)} - CMRR_d | \\ err_3 = f_{c1}^{(spec)} - f_{c1} | \\ err_4 = | f_{c2}^{(spec)} - f_{c2} | \end{cases} \tag{12}$$

where $A_d^{(spec)}$, $CMRR^{(spec)}$, $f_{c1}^{(spec)}$ and $f_{c2}^{(spec)}$ are the design specifications and A_d, $CMRR$, f_{c1} and f_{c2} are the performance measures. Error measure err_1 measures the IA differential gain error, err_2 measures the *CMRR* error and err_3 and err_4 measure the lower and upper bandstop cutoff frequency errors respectively. To be noticed in expressions (12) is that the absolute value is used to measure the error magnitude, with no consideration being paid to the relation between specified and implemented performance parameters.

Finally, the GA objective function to solve the IA and notch filter design problems using the coefficient equation method is expressed as the sum of the individual absolute error values:

$$OF = err_1 + err_2 + err_3 + err_4 \tag{13}$$

CURVE FITTING

The curve fitting method basically operates towards optimizing the circuit parameter set in order to overlap two characteristics [9, 11]. In this work, the curve fitting method is used to design the highpass filter in the EKG analog interface according to a set of design specifications. The design specifications for the highpass filter define the allowable areas for the filter characteristics as illustrated in figure 7 in terms of:

- f_0 – cutoff frequency
- A_0 – attenuation @ f_0

Then, the GA aims to design the analog filter in order to fit its characteristics within the non-shaded areas in figure 7.

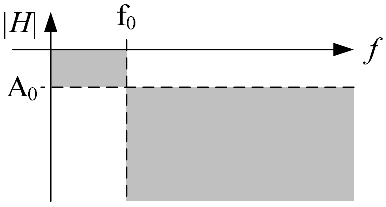

Figure 7. Highpass filter design specifications

The chromosome used to represent the highpass filter is defined as

$$[R_{10}\ R_{11}\ R_{12}\ R_{13}\ C_4\ C_5] \tag{14}$$

and consists of the passive elements which determine the filter cutoff frequency according to equation (8).

The GA objective function for highpass filter design measures the non-overlapping of the desired and the implemented frequency characteristics. The non-overlapping error is defined in two sub-bands: stop-band and pass band respectively.

The non-overlapping error is computed on a frequency sweep basis and is expressed as the absolute value of the difference between the desired and the implemented frequency characteristics. The flow diagram for the computation of the characteristics' non-overlapping error at each point in the frequency sweep is illustrated in figure 8 and is explained as follows. In the stop-band, i.e. $f<f_0$, the magnitude response $G(f)$ should be below A_0. Therefore, an

error value is computed if the magnitude response *G(f)* is higher than A_0. In the pass-band, i.e. $f>f_0$, the magnitude response *G(f)* should exhibit unity gain, i.e. 0dB. However, the transition band from attenuation $A_0@f_0$ to 0dB also has to be considered. Therefore, an error value is computed if the magnitude response is below A_0, or higher than 0dB. At the cutoff frequency, i.e. $f=f_0$, an error value is computed if the magnitude response of the filter differs from A_0. To be noticed is that the cutoff frequency error value is weighted with factor 1000 to amplify its contribution to the curve fitting error.

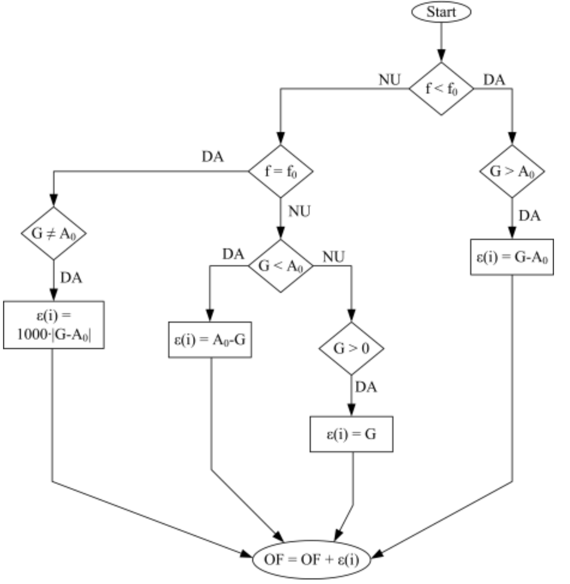

Figure 8. Flow diagram of the evaluation of the curve-fitting error

IV. SIMULATION RESULTS

The GA for the evolutionary design of the EKG analog interface is implemented using the Matlab Genetic Algorithms and Direct Search Toolbox.

The GA for the IA and the notch filter design problem, using the coefficient equation method, was implemented as follows. The chromosome and the objective function are expressed in equations (11) and (12) respectively. The population size was set to 20 individuals. Selection was done using a stochastic selection scheme. For reproduction, a scattered cross-over operator was used with a cross-over fraction of 80%. The stopping criteria were set to a maximum 180 generations, and 50 stall generations with a function tolerance of 10^{-6}.

The IA was designed for unity gain and CMRR maximization. The notch filter was designed for a 50Hz rejection frequency. The evolution lasted for 161 generations. The evolution of the objective function vs. generations is plotted in figure 9 illustrating algorithm convergence. The results after the GA run are listed in table 2.

The GA for the highpass filter design problem, using the curve fitting method, was implemented as follows. The chromosome and the objective function are expressed in equation (14) and figure 8 respectively. The population size was set to 20 individuals. Selection was done using a stochastic selection scheme. For reproduction, a single-point cross-over operator was used with a cross-over fraction of 80%. The stopping criteria were set to a maximum 250 generations, and 50 stall generations with a function tolerance of 10^{-6}.

The highpass filter was designed for a 0.05 cutoff frequency for DC component rejection. The evolution lasted for 174 generations. The evolution of the objective function vs. generations is plotted in figure 10, illustrating algorithm convergence. The results after the GA run are listed in table 3.

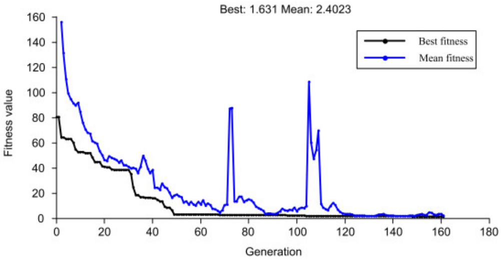

Figure 9. Evolution of the fitness vs. generations for the coefficient equation method

Table 2. Parameter values resulting after the GA run

EKG interface block	Circuit parameter	Parameter value
Instrumentation amplifier	$R_1 = R_3$	57.3 kΩ
	$R_2 = R_4$	18.6 kΩ
	$R_5 = R_6$	99.5 kΩ
	R_G	88.3 kΩ
Notch filter	$R_7 = R_8$	2.95 MΩ
	R_9	1.9 MΩ
	C_1	2.5 nF
	$C_2 = C_3$	0.95 nF

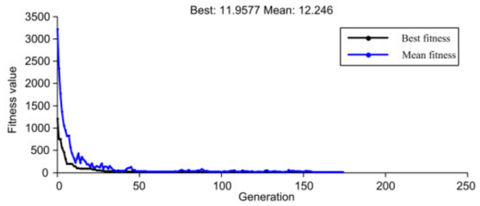

Figure 10. Evolution of the fitness vs. generations for the curve fitting method

Table 3. Parameter values resulting after the GA run

EKG interface block	Circuit parameter	Parameter value
Highpass filter	R_{10}	1.51 MΩ
	R_{11}	4.35 MΩ
	R_{12}	17.2 MΩ
	R_{13}	100 kΩ
	C_4	1.37 µF
	C_5	1.13 µF

In order to validate the evolutionary design, the EKG analog interface was implemented and simulated at transistor level in LTSpice using a 180nm CMOS process.

The IA differential gain and CMRR are plotted against frequency in figure 11, illustrating the fulfillment of the design specifications.

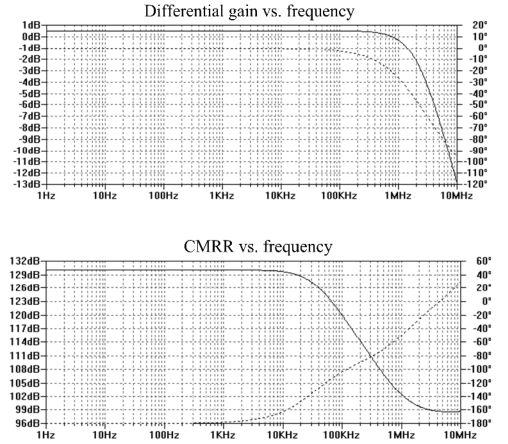

Figure 11. Instrumentation amplifier differential gain and CMRR, plotted against frequency

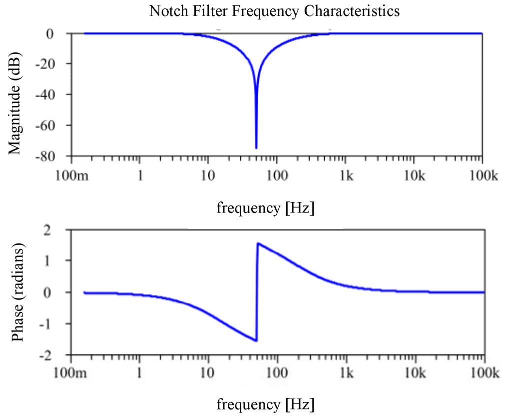

Figure 12. Frequency characteristics of the notch filter

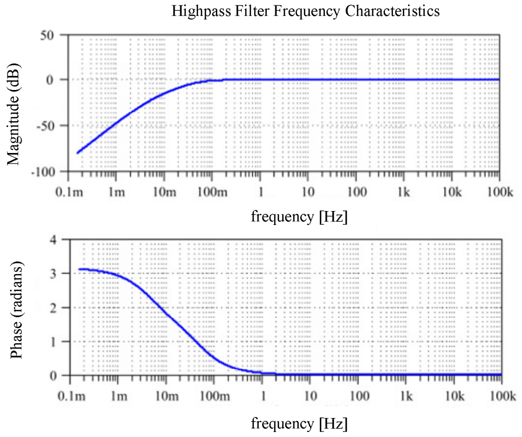

Figure 13. Frequency characteristics of the highpass filter

The frequency characteristics of the notch filter are illustrated in figure 12, accounting for a 50Hz rejection frequency. The frequency characteristics of the highpass filter are illustrated in figure 13, accounting for a 0.05Hz cutoff frequency.

CONCLUSIONS

This article illustrated the evolutionary design of an EKG system analog interface. Two design methods have been employed: coefficient equation for instrumentation amplifier and notch filter design, and curve fitting for highpass filter design respectively. The genetic algorithms determine the passive component values in the analog interface building blocks in order optimize their performance to comply with the design specifications. Fulfillment of the design specifications was illustrated with extensive simulation of the evolutionary design algorithm. The validity of the designed EKG analog interface building blocks was demonstrated with transistor-level simulation.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Rahul Sarpeshkar, *Ultra Low Power Bioelectronics Fundamentals, Biomedical Applications, and Bio-Inspired Systems*, Cambridge University Press, 2010.

[2] Robert-Gabriel Lupu, *Tehnici noi de prelucrare şi transmitere eficientă a informaţiilor în aplicaţii de telemonitorizare în medicină*, PhD Thesis, „Gheorghe Asachi” Technical University of Iaşi, 2011.

[3] Alexandra Râza, *Proiectarea interfeţei analogice a echipamentului EKG folosing metode evoluţioniste*, Diploma Thesys, Technical University of Cluj-Napoca, 2014.

[4] Electrocardiogram Solution from Texas Instruments, [Online], Available: www.ti.com/solution/ecg_electrocardiogram [Accessed July 15, 2014].

[5] *Specificaţii generale hardware şi software* [Online], Available: http://tc.unitbv.ro/biomed/sites/default/files/specificatii_biomed.pdf [Accessed July 15, 2014]

[6] Richard M. Millis, *Advances in Electrocardiograms - Methods and Analysis*, InTech, January 25, pp. 297-308, 2012.

[7] Charles Kitchin and Lew Counts, *A Designer's Guide to Instrumentation Amplifiers*, 3rd edition, Analog Devices, 2006.

[8] S. Hintea, G Csipkes, D. Csipkes, L. Festila, R. Groza, P. Farago, M.Cirlugea, *Reconfigurable Analog Circuits for Mobile Communications - Variable topology filters and design automation*, Editura Casa cărtii de ştiinţa, 2011.

[9] Bogdana Râza, *Metode evoluţioniste de proiectare a filtrelor analogice*, Diploma Thesys, Technical University of Cluj-Napoca, 2014.

[10] P. Farago, L. Feştilă, P. Söser, S. Hintea, “Automatic Filter Synthesis Based on Tree Generation and Evolutionary Optimization”, *Knowledge-Based And Intelligent Information And Engineering Systems*, *Lecture Notes in Computer Science*, vol. 6884, pp. 455-464, 2011.

[11] Umut Engin Ayten, Revna Acar Vural and Tulay Yildirim, ”Low-pass Filter Approximation with Evolutionary Techniques”, *ELECO 2011 7th International Conference on Electrical and Electronics Engineering*, 1-4 December, Bursa, TURKEY, pp. 115-119, 2011.