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Optimal design of CMOS current mode instrumentation amplifier using bio-inspired method for biomedical applications

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ABSTRACT

Analog integrated circuits for biomedical applications require good performance. This paper presents an instrumentation amplifier (IA) design based on three complementary metal oxide semiconductor (CMOS) conveyors with an active resistor. This circuit offers the possibility to control the gain by voltage and current. We have designed the IA to minimize the parasitic resistance (Rx) with large bandwidth and high common mode rejection ratio (CMRR) using the artificial bee colony algorithm (ABC). The topology is simulated using 0.35µm CMOS technology parameters. The optimization problem is represented by an objective function that will be implemented using MATLAB script. The results were approved by the simulation using the advanced design system (ADS) tool. The simulation results were compared to the characteristics of some other instrumentation amplifiers exsisting in the literature. The circuit has a higher CMRR than other topologies.

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1. INTRODUCTION

An instrumentation amplifier (IA) is commonly used in industrial and medical applications with reduced power. A low voltage signal must be processed in the presence of common-mode voltages and considerable direct current (DC) potentials. The conventional instrumentation amplifier, as shown in Figure 1, consists of three operational amplifiers and the network of resistances.

Acquiring, transferring, and processing biopotential reliably are essential tasks in biomedical systems. These systems impose demanding specifications that usually increase the cost of the devices. The circuits used for processing biomedical signals must guarantee patient safety and the rejection or attenuation of any interfering signal [1]. Therefore, building high-performance blocks, such as low noise amplifiers and analog filters, are requirements for improving system performance [2]. For the implementation of biopotential acquisition systems, some of the most critical design considerations are low noise voltage and current levels, low harmonic distortion, reduced area, and low power consumption [3], [4]. A biomedical signal acquisition system, such as in Figure 2, consists of electrodes, amplifiers, low-pass filter (LPF), sample, socket (S/H), and analog-to-digital converter (ADC) [5], [6].

The detection of these signals is essential because they usually have very low amplitude with considerable noise levels. The majority of these signals have a very low-frequency range, generally less than 1 khz [7]. Instrumentation amplifiers are used to remove any unwanted noise and produce the amplification

adapted to the desired signal. Common mode rejection ratio (CMRR) is considered the main parameter of instrumentation amplifiers.

Currently, many of the physiological processes are continuous to sustain human life. The instrumentation amplifier is the basis of most electrocardiography (ECG), electroencephalography (EEG), and electromyography (EMG) acquisition systems [8], [9]. Voltage mode instrumentation amplifiers have high accuracy. In the current mode version, the CMRR is independent of the mismatching of the resistors.

Several documents show the topologies presented in the second-generation current conveyor (CCII). In 1989 [10], the current mode instrumentation amplifier based on current carriers was presented. The CCII is a device used to provide a wide operating frequency a bias current can electronically control it in numerous current mode applications [11], [12]. The disadvantage of electronic circuits based on the CCII is the parasitic resistance that polarization can control. This resistance is directly proportional to the mobility of the surface (μ), to the capacity of the oxide (Cox), and its relation to channel width and length (W/L) for complementary metal oxide semiconductor (CMOS) technology. The symbol of CCII is shown in Figure 3.

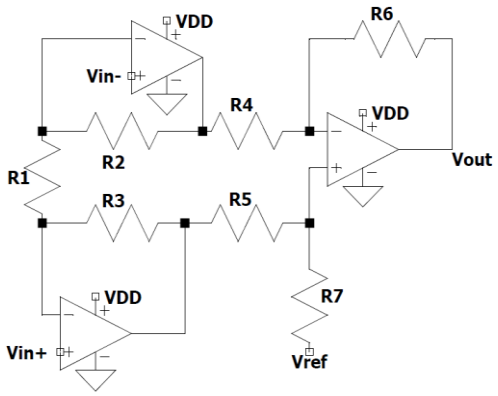


Figure 1. Conventional instrumentation amplifier

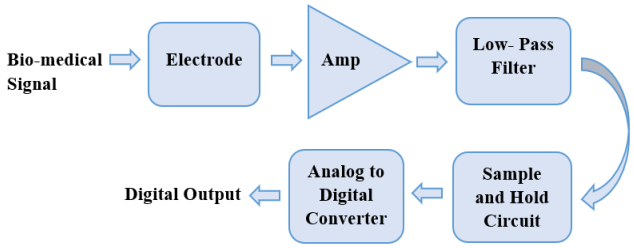


Figure 2. The electronic system for detecting physiological signal blocks

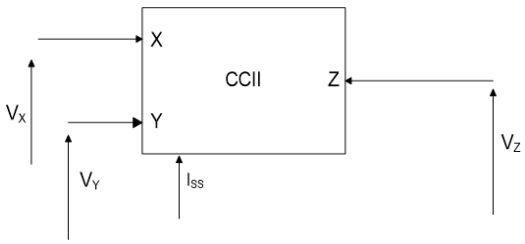


Figure 3. Second-generation current conveyor

However, nature is a vibrant field of inspiration for artificial intelligence by developing algorithms (metaheuristics) [13] with a great capacity to solve complex problems in which most traditional strategies have severe difficulties and limitations [14]. Optimization based on swarm intelligence (SI) is a very recent family of metaheuristic algorithms inspired by nature [15], [16]. Its principle is based on the intelligent comportment of the species during the search and exploitation of the food [17]. Thus, these species possessing a very high communication capacity by collaborating can solve very complex and challenging problems. Reliable, efficient, and robust optimization techniques are in high demand in all engineering

domains, especially in electronics applied to biomedical data processing. We focus in this article on the use of bio-inspired method, specifically artificial bee colony, for the optimal design of CMOS current-mode instrumentation amplifier using bio-inspired method for biomedical applications. This paper is structured as follows. An overview of artificial bee colony is highlighted in section 2. The proposed instrumentation amplifier is presented in section 3. Section 4 presents the results and discussion. Eventually, conclusion is given in section 5.

2. OVERVIEW OF ARTIFICIAL BEE COLONY ALGORITHM (ABC)

The artificial bee colony algorithm (ABC) was introduced by Karaboga in 2005 [18]. The ABC algorithm is formed by observing real bees' activities and behavior as they seek nectar resources and share the number of resources with other bees [19]. The ABC algorithm defines a set of operations that resemble some characteristics of the behavior of the bees. Each solution within the search space includes a set of parameters representing the positions of the food sources. The value of "affinity" (provided by the objective function) refers to the food source's quality. In general, the optimization process mimics the search for bees for important food sources resulting in a process analogous to finding optimal solutions [20], [21].

In the ABC, every food source is in the D-dimensional search area and represents a potential solution to the optimization problem. The quantity of nectar in the food source is assumed to be a food source's fitness value. In general, the number of bees employed and the number of bees as spectators is equal and is identical to the number of food sources. Each employed bee is a food source member and charged with the corresponding food source's operation. Then, the employed bees communicate the nectar information to the spectator bees in the "dance area". The spectator bees wait in the hive and decide which food source to exploit depending on the employed bees' information.

In this case, more beneficial food sources will have a more significant probability of being selected by the spectator bees. In the initial step of the ABC algorithm, the initial solutions are generated randomly in the specific range of variables $x_i(i = 1,2, \dots, w)$ [22]. Next, each employed bee identifies the new sources whose quantities are equal to half of the total sources. In (1) is used to determine a new source [23].

$$V_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj}) \quad (1)$$

In (1), $k \in \{1,2, \dots, N\}$ and $j \in \{1,2, \dots, D\}$ are randomly selected indices. While k it is randomly determined, it should be different to i and φ_{ij} random between 0 and1. This parameter controls the adjacent food sources production and visually compares two food positions x_{ij} by a bee. After each source position candidate V_{ij} is produced and then evaluated by the artificial bee, its performance is compared to the last one. If the new food has nectar equal to or superior to that of the ancient source, it is used to replace the old memory. In the opposite case, the ancient one is conserved in the memory. In the next step, the onlooker bees choose a food source with the probability mentioned in (2) [24].

$$P_i = \frac{fit_i}{\sum_{j=1}^{wN} fit_j} \quad (2)$$

The adequacy value fit_i of the solution i, which is proportional to the quantity of nectar from the food source in the position, is the number of food sources, which is the same as the number of bees employed. The scout bees are very responsible for the random searches in every colony. The scout bees do not use previous knowledge and facts when searching for nectar sources, so their searches are entirely random. The scout bees are selected from the bees employed according to the boundary parameters. If a solution that indicates a source is not achieved with a particular number of tests, then that source is rejected. The bee from this source selects the new head as the scout bee. The number of inputs/outputs of a source is determined by the "limit" parameter. The recognition of a new source of a scout bee is given in (3) [25].

$$X_{ij} = X_j^{min} + \left(X_j^{max} - X_j^{min}\right) * rand(0,1) \quad (3)$$

Where X_j^{min} and X_j^{max} are the minimum and maximum limits of the parameter to be optimized.

In the ABC algorithm, the termination criterion is generally based on the number of iterations. Usually, an optimization algorithm's stopping criteria are based on the maximum number of iterations or the maximum error between two successive iterations. Consequently, the stopping criterion for the proposed ABC is based solely on the maximum number of iterations. In general, the ABC algorithm process can be summarized, as shown in Figure 4 [26], [27].

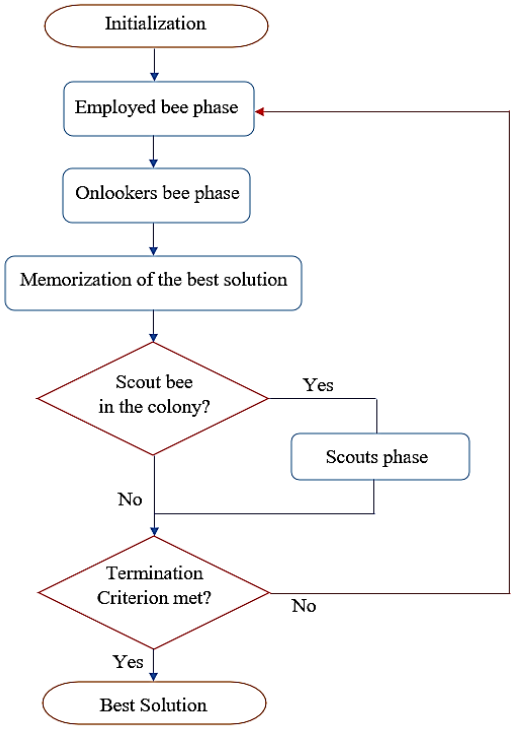


Figure 4. Flowchart of the basic model of the ABC algorithm

3. PROPOSED INSTRUMENTATION AMPLIFIER

3.1. CMOS second-generation current convoyors

Second generation current conveyors are among the best-known analog blocks in current mode [28]. The CCII composed of three blocks terminal active CMOS circuits. The matrix below presents the characteristic of CCII:

$$\begin{pmatrix} I_y \\ V_x \\ I_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 1 & R_X & 0 \\ 0 & 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} V_y \\ I_x \\ V_z \end{pmatrix} \quad (4)$$

As showing in the Figure 3, where the port X and Y of the CCII are the input of the circuit, the parasitic resistance R_X on this terminal is given by:

$$R_x = \frac{1}{2g_m} = \frac{1}{\sqrt{8K_n I_{SS}}} \quad (5)$$

where g_m is the transconductance of the CMOS transistor and K_n is the physical parameter of the metal-oxide semiconductor transistor. They can be expressed as:

$$g_m = \sqrt{2K_n I_{SS}} \quad (6)$$

$$K_n = \mu_n \, C_{ox} \left(\frac{W}{L}\right) \quad (7)$$

where C_{ox} is the gate capacity per unit area and μn is the electronic mobility of the PMOS transistor. The parasitic resistance R_x depends as well on the adaptation of the g_m values, but this parasitic resistance is available and adjustable even if the values do not correspond due to variations in the process.

3.2. Theoretical study

The diagram of the proposed instrumentation circuit is shown in the Figure 5. The instrumentation amplifier composed of three current conveyors and an active resistor structure based on MOS transistors. The active resistor format is realized by a parallel connected matched pair of MOS transistors, M1 and M2 as showing in the Figure 6.

Figure 6 illustrates the active resistor circuit. The voltage V_C is used to control the active resistance. The drain current for each transistor can be obtained from the circuit according to the following expressions:

$$I_{D1} = \mu_n C_{ox} \left(\frac{W}{L}\right)[(V_A - V_{th})V_A - \frac{V_A^2}{2}] \quad (8)$$

$$I_{D2} = \mu_n C_{ox} \left(\frac{W}{L}\right)\left[(V_C - V_{th})V_A - \frac{V_A^2}{2}\right] \quad (9)$$

Therefore, the resistance of the active resistor R_A [29] can be expressed as:

$$R_A = \frac{1}{\mu_n C_{ox}\left(\frac{W}{L}\right)(V_C - 2V_{th})} \quad (10)$$

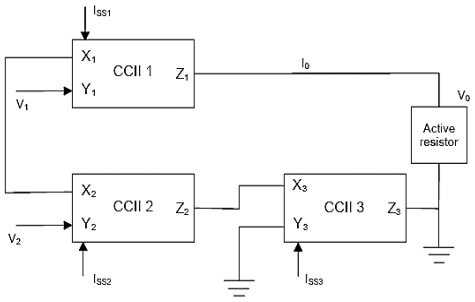


Figure 5. Proposed instrumentation amplifier

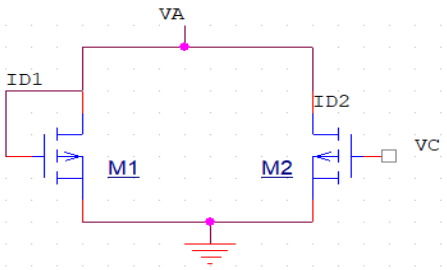


Figure 6. Active resistor circuit

The control voltage V_C makes it possible to adjust the active resistance R_A and as shown in the matrix (1) the current of port X is equal to the current of port Z which makes the proposed instrumentation amplifier provides a current with the following expression:

$$I_0 = \frac{V_1 - V_2}{R_{x1} + R_{x2} + R_{x3}} \quad (11)$$

The voltage at port X, as shown in Figure 7, can be expressed as:

$$Vx_1 = K_1 V_1 \quad (12)$$

$$Vx_2 = K_2 V_2 \quad (13)$$

$$Vx_3 = K_3 V_3 \quad (14)$$

By varying the bias current of the conveyors and the control voltage of the active resistance, the differential gain of the IA can be controlled. The parasitic resistance can be adjusted by a bias current and that the active resistance can also be adjusted by the control voltage. The current and voltage tracking error between ports X-Z and ports X-Y can be expressed as follows:

$$\alpha = 1 - \varepsilon_I \quad (15)$$

$$K = 1 - \varepsilon_V \quad (16)$$

Where α and K are the current and voltage transfer gains and ε_I and ε_V are the current and voltage transfer errors of the conveyors, respectively. At port Z, the current can be expressed as:

$$I_Z = \alpha I_X \quad (17)$$

The output voltage will be:

$$V_0 = \frac{R_A}{R_{x1} + R_{x2} + R_{x3}}(V_1 - V_2) \quad (18)$$

3.3. Real instrumentation amplifier

Figure 8 shows the real model of the proposed instrumentation amplifier. We can calculate the resulting current i_x as follows:

$$I_X = \frac{Vx_1 - Vx_2 - Vx_3}{3R_x} \quad (19)$$

From (12), (13), (14) and (19) we obtain:

$$I_0 = \alpha I_X = \alpha \frac{K_1 V_1 - K_2 V_2}{3R_x} \quad (20)$$

The output voltage V_0 (s) can be written as follows:

$$V_0(s) = I_0 (R_A \,//\, \frac{1}{sC_b}) \quad (21)$$

where $C_b = C_Z + C_A$ are the capacity of the output node, which is parallel to the resistance R_A as showing in the Figure 7 thus:

$$V_0(s) = \alpha \frac{(K_1 V_1 - K_2 V_2) R_A}{3R_x\ (1 + sC_b R_A)} \quad (22)$$

We assume that $V_1=V_2=V_3=V_{Cm}$, the gain in common mode can be obtained as follows:

$$A_{Cm} = \frac{V_0}{V_{Cm}} = \alpha \frac{(K_1 - K_2) R_A}{3R_x\ (1 + sC_b R_A)} \quad (23)$$

For ideal current conveyors, $\alpha = K_1 = K_2 = 1$, the differential output gain A_{dm} can be written:

$$A_{dm} = \frac{R_A}{3R_x} \frac{1}{(1 + sC_b R_A)} \quad (24)$$

From the (24), the voltage gain is controllable by $R_A\ /3R_x$.

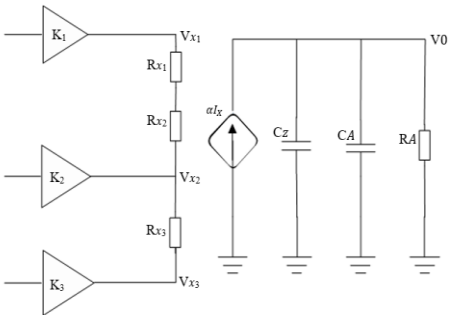


Figure 7. Error equivalent circuit of instrumentation amplifier

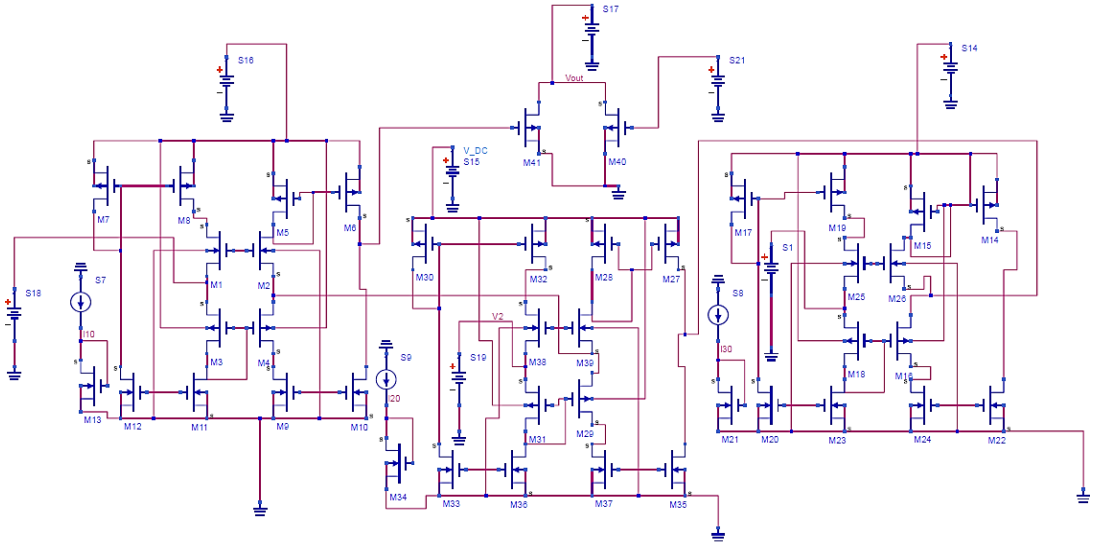


Figure 8. Real model of instrumentation amplifier

4. RESULTS AND DISCUSSION

Our problem is to minimize the resistance and maximize the cutoff frequency. We will consider our optimization problem as a minimization problem, where our objective function will be written as follows:

$$OF = \alpha Rx + \beta tci \quad (25)$$

where $t_{ci}=1/f_{ci}$ and $\alpha+\beta=1$.

A factor $\alpha=\beta=0.5$ means that there will be no favoritism when optimizing our objective function. Neither of the two parameters will be considered more important than the other. Using MATLAB, we can draw our objective function $OF=0.5*(R_x+t_{ci})$. The factor 0.5 means that we want to optimize each of the resistance and the frequency of power failure by giving them the same importance. When we talk about optimizing the FO function, we are talking about minimization, hence the convergence of the function towards 0. In this case, the function could reach a power *-10* as showing in Figure 9. We note that our parasitic resistance, during the optimization of the OF, as showing in the Figure 10 Rxmin converges to stabilize on a value of 457.745Ω. Table 1 summarizes the optimization of parasitic resistance and cutoff frequency, the values of our parameters Wp and Wn for the MOS transistors' channel lengths (Ln and Lp) fixed.

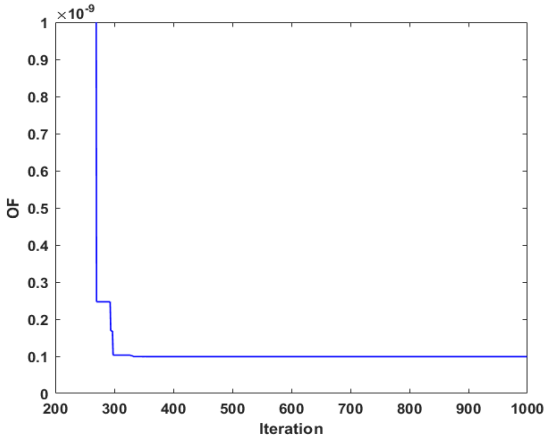


Figure 9. Objectif function

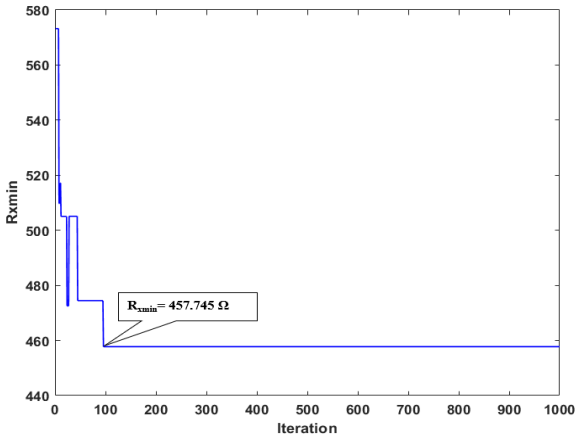


Figure 10. Optimal result of R_x

Table 1. Optimal sizes of transistor dimensions

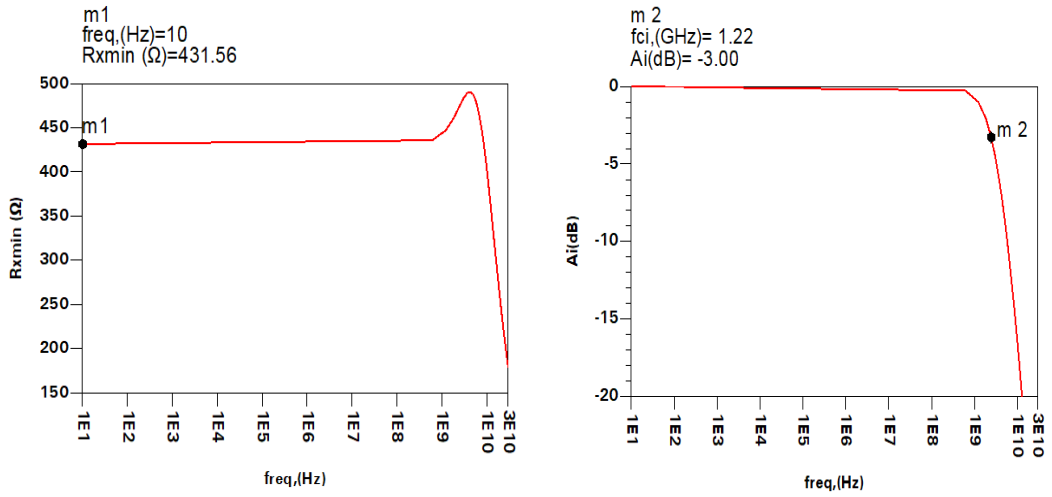
L_n(µm)	L_p(µm)	W_p(µm)	W_n(µm)
0.58	0.35	36	19.77

To confirm the results obtained, we will simulate the design using the advanced design system (ADS) software. The circuit in Figure 8 simulated with the parameters of 0.35µm CMOS technology to verify the proposed circuit's performance with a supply voltage of 3.8V. The ISS chose at 90µA because the amplifier's gain is practically constant with ISS values higher than 90µA. As showing in Figure 11(a), Rxmin stabilizes on a value of 431.56Ω. The bandwidth is showing in Figure 11(b) with a 1.22GHz value of cutoff frequency. The CMRR of the proposed circuit has been examined and found that it is dependent on both the voltage transfer error ε_V and current transfer error ε_I.

The CMRR frequency response of the instrumentation amplifier is shown in Figure 12. We observe that the CMRR value of the instrumentation amplifier is very significant. The CMRR obtained by the simulation was 182.070dB at 10Hz, which shows the importance of the circuit in biomedical applications, especially in the acquisition of physiological signals. A comparison between the proposed circuit and those of different studies is given in Table 2.

Table 2. Comparison between same instrumentation amplifier characteristics

Ref.	Supply Voltage	CMRR (dB)	Control Function	Techno.	Passive Component
[29]	2.5V	147	Current	BJT	No
[30]	2.8V	76	Passive resistor	BJT	Yes
[11]	3.3V	142	Voltage or current	CMOS	No
This work	3.8V	182.070	Voltage or current	CMOS	No



(a) (b)

Figure 11. Simulation of (a) Rx using ADS tools and (b) Ai using ADS tools

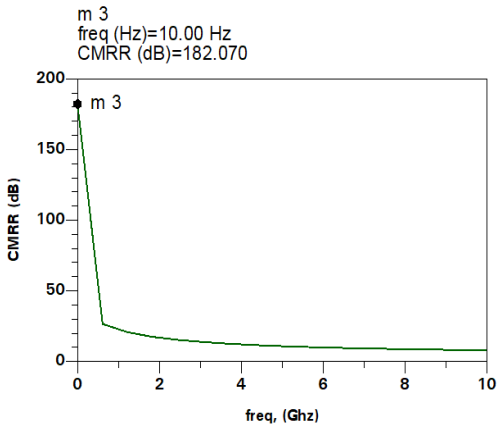


Figure 12. Result of CMRR simulation

5. CONCLUSION

In this study, an optimum design for an instrumentation amplifier is used, which consists of three current conveyors and has no passive components, which is attractive for medical applications. The proposed circuit was simulated using an ADS simulation program. The simulation results were compared to the properties of some other instrumentation amplifiers existing in the published papers. The circuit has an important CMRR than other works.

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