Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics
Multidisciplinary : Rapid Review : Open Access Journal Vol. 4, No. 4, November 2022, pp.174-181 e-ISSN: 2656-8624

RESEARCH ARTICLE OPEN ACCESS

Manuscript received June 03, 2022; revised September 01, 2022; accepted September 01, 2022; date of publication November 28, 2022
Digital Object Identifier (**DOI**): https://doi.org/10.35882/ijeeemi.v4i4.248

How to cite: Anita Miftahul Maghfiroh, Syevana Dita Musvika, "Performance Comparison of ECG Bio-Amplifier Between Single and Bi-Polar Supply Using Spectrum Analysis Based on Fast Fourier Transform", Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics, vol. 4, no. 4, pp. 174–181, November. 2022.

Performance Comparison of ECG Bio-Amplifier Between Single and Bi-Polar Supply Using Spectrum Analysis Based on Fast Fourier Transform

Anita Miftahul Maghfiroh[1], Syevana Dita Musvika[1], and Vugar Abdullayev[2]
[1] Department of Electromedical Engineering, Poltekkes Kemenkes Surabaya, Jl. Pucang Jajar Timur No. 10, Surabaya, 60245, Indonesia
[2] Azerbaijan State Oil and Industry University, Azerbaijan

Corresponding author: syevana dita musvika (e-mail: syevana@poltekkesdepkes-sby.ac.id).

ABSTRACT Heart performance is one of the vital signs that cannot be ignored and must be monitored periodically. In this case, the measuring range of the human heart rate is between 60-100 BPM, in which the measurement unit is expressed as Beat per Minute (BPM). Therefore, it is very important to use Electrocardiograph equipment to tap the electrical signals of the heart with correct readings and minimal interference such as frequency of electric lines and noise. The purpose of this study was to compare the instrumentation amplifier using a single supply with a bi-polar supply in the ECG design to select the best instrumentation amplifier, which is expected to contribute to other researchers in choosing the right type of instrumentation amplifier that is efficient and qualified. In this case, the research was carried out by comparing two single supply instrumentation amplifiers using the AD623 IC and the bi-polar supply using the AD620 IC, continued by the use of Fast Fourier Transform (FFT) to determine the frequency spectrum of the ECG signal. The test results further showed that the use of single power instrumentation could reduce more noise compared to the Bi-Polar instrumentation amplifier by strengthening 60 dB Low pass filter circuit. Meanwhile, the FFT results in finding the frequency spectrum explained that the FFT results on the ECG signal provided information that the ECG signal had a frequency range between 0.05 Hz and 100 Hz. When the frequency is more than 100 Hz, the frequency started to be suppressed and when the frequency is less than 100 Hz, the frequency is passed. This research could be further used as a reference by other researchers to determine which type of instrumentation amplifier is better.

INDEX TERMS Electrocardiography, high pass filter, low pass filter, notch filter

I. Introduction

Electrocardiography (ECG) is a commonly used method to measure the performance of the human heart through the electrical activity of the heart. Heart performance is one of the vital signs that cannot be ignored and must be monitored periodically [1]. In this case, the measuring range of the human heart rate is between 60-100 BPM, in which the measurement unit is expressed in Beat per Minute (BPM). The ECG signal is obtained by tapping using electrodes attached to the skin surface and recorded at a frequency range of 0.05-150Hz [2]. Therefore, it is very important to use Electrocardiograph equipment to tap the electrical signals of the heart with correct readings and minimal interference such as frequency of electric lines and noise. In several recent studies, the design of an ECG amplifier instrumentation has been carried out using a single supply type to suppress the noise interference from 50Hz power lines on an adaptive filter with low power, low cost, and portable ECG design. There are two techniques applied for reducing noise, namely by filtering noise using an analog filter circuit or a digital filter [3]. Enrique M. Spinelli et al., implemented a low-powered scheme using a single battery to input a biopotential amplifier with a gain of 60 dB and a DC input range of ± 200 mV. The system was implemented using a low-power operational amplifier for detecting the biopotential signals with a single supply [4]. However, because it only uses one battery, the performance of the ECG cannot be carried out for long time. Hsiu-Cheng Lee et al, made a chip as an instrumentation amplifier to get a low-power ECG signal using a single supply [5]. This system actually obtained a very good performance but this chip is still not available in the market. Furthermore, in order to eliminate the 50Hz frequency interference on the Bashar s power lines, Mohamad-Ali applied an adaptive filter using a single supply, so that the parasitic current or 50Hz frequency that enters the patient's body can be suppressed [6]. In addition, Ali S. AlMejrad designed an ECG using a single supply of a Standard 8051 Microcontroller based on K-Grade medical isolation [7]. Some of the researchers above explained that the advantages of using a single supply are low power, low cost, and smaller size. Meanwhile, the disadvantage of using a single supply is that it cannot be used for a long time because it only uses battery power. Furthermore, ECG design using a Bi-polar supply is still being developed [8]–[14], such as the research that was conducted by Sugondo Hadiyoso et al, in designing a wearable ECG using the Einthoven triangle method using a bi-polar supply, where the research had a weakness in the presence of noise interference [15]. Low power is also used to design ECG instrumentation s using Bi-Polar system [16], [17].

Some researchers in the development of ECG also used instrumentation amplifier with bi-polar supply [18]–[24] because it has advantages in the forms of low power and the system is more stable. However, the disadvantage of using a bi-polar supply is that there is still interference with the frequency signal of the power lines and noise, so a filter that can remove noise and other disturbances is needed.

Based on the literature review above, researchers have not found a discussion on the comparison of the advantages of each instrumentation. Therefore, the purpose of this study was to compare the instrumentation amplifier using a single supply and a bi-polar supply in the ECG design to select the best instrumentation amplifier. This research was further expected to contribute to other researchers in choosing the best type of instrumentation amplifier that is efficient and qualified as well as to know the frequency spectrum of the dynamics of the heart signal using FFT.

II. Materials and Methods

A. Experimental Setup

In this study, the instrumentation amplifier used were two types of ICs, namely AD620 which was used for designing Bi-polar supply instrumentation amplifiers and IC AD623 which was used for designing single-supply instrumentation amplifiers. Furthermore, the shape of the signal was compared using the output of the oscilloscope.

1) Materials And Tools

The material used in this research was to make two types of instrumentation amplifiers and then continued by making a filter to remove noise. In this case, the output signal was then displayed on the oscilloscope. The input voltage used on the AD623 was positive and grounding, while the input voltage used on the AD620 IC was positive, negative, and grounding. The analog filter system used in both instrumentation was the same, the only difference was the input voltage.

2) Experiment

In this study, two ECG instrumentations with different systems were designed using a single supply and a bi-polar supply on each instrumentation amplifier. In this case, the output of the instrumentation amplifier was filtered with an analog filter circuit design with a cut-off frequency between 0.05 Hz to 100 Hz. Data acquisition was done by displaying the data on an oscilloscope and then stored to an SD-card or flash drive where the data were further analyzed off-line. In this case, each test of the instrumentation amplifier and filter will be measured five times to determine the average gain and standard deviation. To determine the level of accuracy or error from this research, statistical analysis is carried out by calculating the value, error, and standard deviation according to the calibration uncertainty formula [25].

3) Methods

In this study, the Fast Fourier Transform (FFT) method was used to determine the frequency spectrum of each ECG instrumentation using a single supply and a bi-polar supply. FFT is an algorithm used to calculate Discrete Fourier Transform (DFT) quickly and efficiently [26]. DFT calculations directly require arithmetic operations of 0 (N2) or have the order of N2, while calculations with FFT will require operations of 0 (NlogN). DFT is expressed in Eq. (1) and Eq. (2) [27].

$$\begin{aligned}X(k) &= \sum_{n=0}^{N-1} x(n)W_N^{nk} = \sum_{r=0}^{N/4-1} x(4r)W_N^{k(4r)} + \sum_{r=0}^{N/4-1} x(4r+1)W_N^{k(4r+1)} \\ &+ \sum_{r=0}^{N/4-1} x(4r+2)W_N^{k(4r+2)} + \sum_{r=0}^{N/4-1} x(4r+3)W_N^{k(4r+3)} \\ &= \sum_{r=0}^{N/4-1} x(4r)W_N^{k(4r)} + \sum_{r=0}^{N/4-1} x(4r+1)W_N^{k}W_{N/4}^{kr} \\ &+ \sum_{r=0}^{N/4-1} x(4r+2)W_N^{2k}W_{N/4}^{kr} + \sum_{r=0}^{N/4-1} x(4r+3)W_N^{3k}W_{N/4}^{kr} \\ &= X_0(k) + X_1(k)W_N^k + X_2(k)W_N^{2k} + X_3(k)W_N^{3k} \qquad (1)\end{aligned}$$

where $k = 0,1,\dots,N-1. W_N = e^{-j2\pi/N}$.

Due to the symmetrical property of twiddle factors, we get the Equations that:

$$\begin{cases} X(k) = X_0(k) + X_1(k)W_N^k + X_2(k)W_N^{2k} + X_3(k)W_N^{3k} \\ X(k+{}^{N}/_{4}) = X_0(k) - jX_1(k)W_N^k - X_2(k)W_N^{2k} + jX_3(k)W_N^{3k} \\ X(k+{}^{N}/_{2}) = X_0(k) - X_1(k)W_N^k + X_2(k)W_N^{2k} - X_3(k)W_N^{3k} \\ X(k+{}^{3N}/_{4}) = X_0(k) + jX_1(k)W_N^k - X_2(k)W_N^{2k} - jX_3(k)W_N^{3k} \end{cases} \quad (2)$$

where $k = 0 \sim N/4, W_N = e^{-j2\pi/N}$.

B. The Diagram Block

The design of the instrumentation system used in this study is the same, consisting of lead II electrode leads, which were then amplified by the ECG instrumentation and filtered using HPF and LPF as described in FIGURE 1. The difference on the design of the bi-polar supply and single supply instrumentation is the input voltage, where the single supply instrumentation amplifier used the AD623 IC that only requires positive and ground voltage inputs, while Bi-Polar instrumentation amplifier requires positive, negative, and ground input voltages. FIGURE 1 explains that the electrodes were mounted on the skin surface as

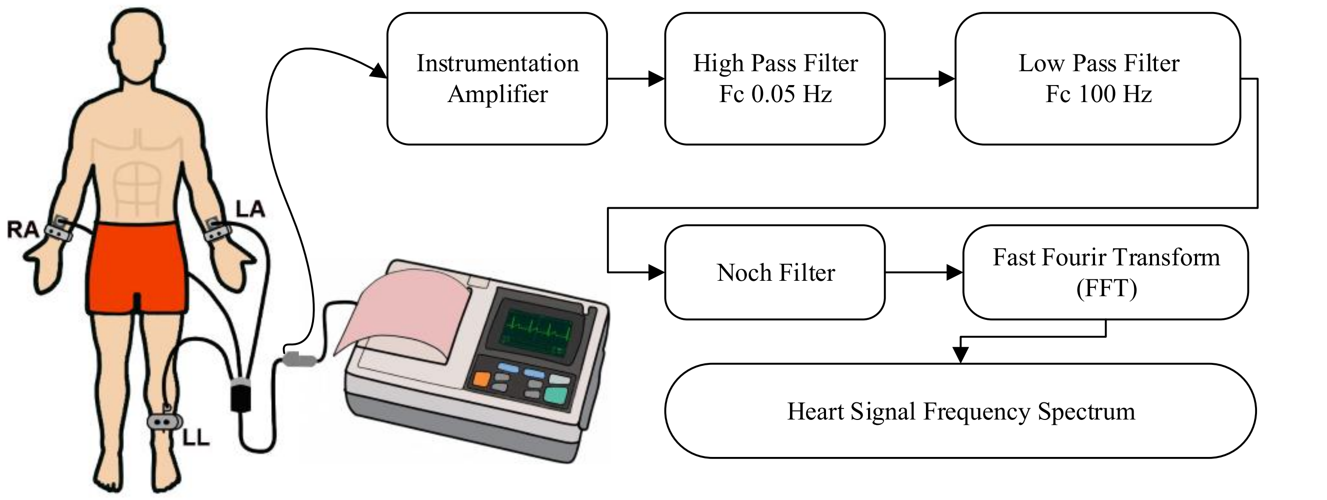

FIGURE 1. ECG instrument system design with single lead II lead. This design is used in the manufacture of single supply and Bi-polar supply ECG amplifier instruments with a cut off frequency of 0.05 Hz to 100 Hz.

indicated by Einthoven Equilateral Triangle to get lead II signal. The output electrode had a very low amplitude, so an instrumentation amplifier was needed with a minimum instrumentation amplifier gain of 100 times. The output of the instrumentation amplifier was still mixed with noise so an analog filter was needed to ward off the noise interference. In this case, the filter designed using HPF and LPF with a filtered frequency range was 0.05 Hz - 100 Hz. Furthermore, the Notch Filter circuit in this study was used to remove noise from the 50 Hz frequency grid on the supply voltage or generated by the oscilloscope. Furthermore, the data were stored and analyzed using FFT to determine the spectrum of the heart signal.

C. ECG Instrumentation Manufacturing

At the stage of making ECG instrumentation, researchers made two ECGs, namely ECG using IC AD620 and IC AD623 as a differentiator in making the Instrumentation amplifiers using Bi-polar supply and single supply. Meanwhile, the manufacture of HPF and LPF are the same, namely with a bandwidth frequency between 0.05 HZ to 100 Hz.

The design of the AD620 instrumentation amplifier circuit is shown in FIGURE 2 [28]. The gain of the instrumentation amplifier was 100 times, which was obtained from Eq. (3).

$$G = \frac{49.4\,K\Omega}{R_G} + 1 \quad (3)$$

where G is gain and R¬G is the amount of resistance to determine Gain.

Meanwhile, the design of the single supply instrumentation amplifier circuit used IC AD623 as shown in FIGURE 3. The gain AD623 is a resistor programmed by RG, or rather, with any impedance appearing between Pins 1 and 8. The AD623 was designed to offer accurate gain using 0.1%–1% tolerance resistors [29]. The gain was described in Eq. (4).

$$R_G = \frac{100k\Omega}{(G-1)} \quad (4)$$

where AD623 Gain is the resistor programmed by RG.

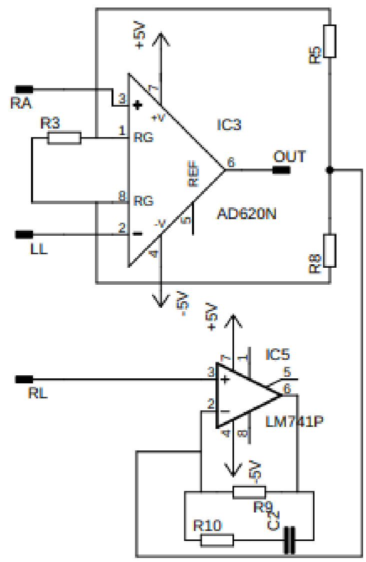

FIGURE 2. Bi-polar supply instrumentation amplifier circuit design using IC AD620

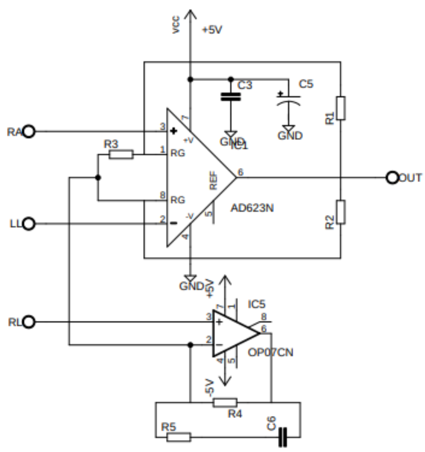

FIGURE 3. Single supply instrumentation amplifier circuit design using IC AD623.

As for the design of the HPF and LPF filter circuits, the same filter design was used for single supply instrumentation amplifier and Bi-polar supply instrumentation amplifier with cut off frequency ranges between 0.05 Hz to 100 Hz. The design of the HPF circuit is shown in FIGURE 4. In this case, the R and C values in the HPF filter design were calculated using Eq. 5.

$$f_c = \frac{1}{2\pi RC} \quad (5)$$

where f_c is cut off frequency, R is resistance value, and C is Capacitor value.

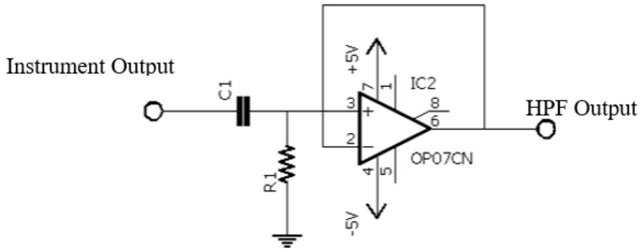

FIGURE 4. HPF filter circuit design with cut off frequency of 0.05 Hz

The low pass filter was designed with a cut-off frequency of 100Hz shown in FIGURE 5, while the 2nd order LPF circuit design used the Sullen-Key topology method. Value a1 = 1.8478; b1 = 1.0000; a2 = 0.7654 and b2 = 1.0000 are the Butterworth coefficients for order 2. The first order low pass filter can be calculated by Eq. (6) dan Eq. (7) with C1 valued of 47 nF.

$$\mathrm{R1, R2} = \frac{\left(\mathrm{a1} * \mathrm{C2} \pm \sqrt{(\mathrm{a1}^2 * \mathrm{C2}^2 - 4 * \mathrm{b1} * \mathrm{C1} * \mathrm{C2})}\right)}{(4 * \mathrm{Pi} * \mathrm{Fo} * \mathrm{C1} * \mathrm{C2})} \quad (6)$$

$$C_2 \geq C_1 = \frac{4b_2}{a_1^2} \quad (7)$$

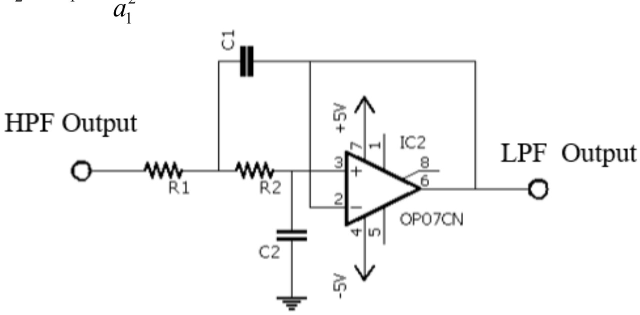

FIGURE 5. LPF filter circuit design with cut off frequency of 100 Hz

III. Result

Based on the results of data collection on the measurement of each instrumentation, five measurements were carried out to calculate the mean value and standard deviation. Furthermore, the acquisition of data obtained from data collection on the oscilloscope calculated the frequency domain to determine the frequency of the ECG signal. In this case, the ECG signal was taken using the ECG simulator.

A. Design Module Build

FIGURE 6 consists of a series of instrumentation amplifier, those are HPF with a cut off frequency of 0.05 Hz and a series of LPF with a cut off frequency of 100 Hz. Furthermore, in order to reduce the interference of the power lines, a notch filter circuit with a cut off frequency of 100Hz was used.

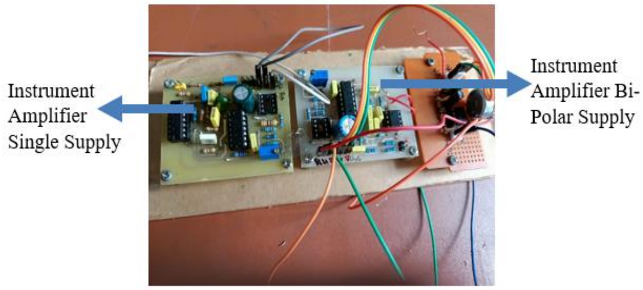

FIGURE 6. Bi-Polar Supply single supply and instrumentation amplifier module design for lead II ECG signal tapping

B. Test Results for Making ECG Instrumentation

FIGURE 7 shows the process of retrieving ECG signal data which later determined the frequency response in each ECG instrumentation.

FIGURE 7. Experimental ECG signal displayed on an oscilloscope using two phantoms to test two instrumentation amplifiers.

To compare the ECG signal output from each ECG instrumentation using a single supply and Bi-polar supply instrumentation amplifier, two ECG simulators were used as shown in FIGURE 7.

The results of testing the ECG signals from the two ECG instrumentations are described in FIGURE 8. Based on the output of each ECG instrumentation as shown in FIGURE 8, the yellow ECG signal was the output of the instrumentation amplifier using the AD623 IC, while the blue signal was the output of the instrumentation amplifier using the AD620 IC.

FIGURE 8. The results of the ECG signal obtained from the instrumentation amplifier of bipolar supply and Single supply.

TABLE 1 informs the results of the instrumentation test for single supply and bi-polar supply amplifiers by calculating the mean value of the test carried out 5 times with input voltage settings ranging from 1 Volt to 5 Volt.

TABLE 1
Measurement of the performance of the instrumentation amplifier AD620 and AD623 with a frequency setting of 10 Hz to 250 Hz

	Mean Amplitude (Volt)	
Input	Output AD620	Output AD623
1	6.08	6.08
1.1	6.8	6.8
1.2	7.2	7.2
1.3	7.52	7.52
1.4	8	8
1.5	8.2	8.2
1.6	8.2	8.2
1.7	8.2	8.2
1.8	8.2	8.2
1.9	8.2	8.2
2	8.2	8.2
2.1	8.2	8.2
2.2	8.2	8.2
2.3	8.2	8.2
2.4	8.2	8.2
2.5	8.2	8.2
2.6	8.2	8.2
2.7	8.2	8.2
2.8	8.2	8.2
2.9	8.2	8.2
3	8.2	8.2
3.5	8.2	8.2
4	8.2	8.2
4.5	8.2	8.2
5	8.2	8.2

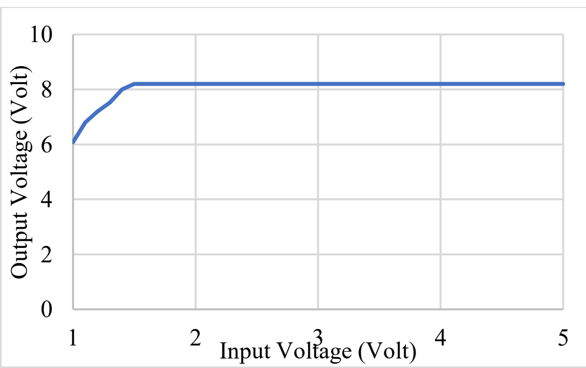

FIGURE 9. **The average calculation results on each instrumentation amplifier AD620**

Based on the explanation of TABLE 1, the gain produced by the single supply and bi-polar supply instrumentation amplifier obtained that the output voltage value is the same as the input voltage of 1 Volt to 5 Volt. In this case, the output value was stable when 1.5 Volt was applied to the output voltage of 8.2 Volt.

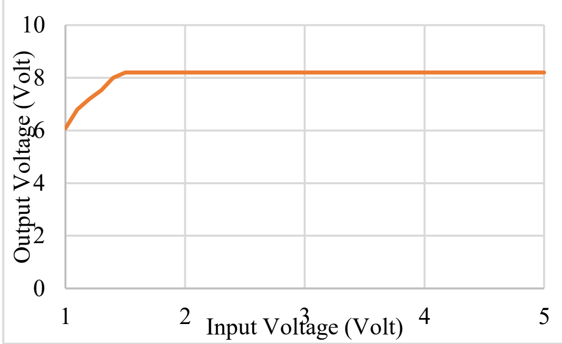

FIGURE 10. **The average calculation results on each instrumentation amplifier AD623**

More details are explained by the graph in FIGURE 9 and FIGURE 10. Based on the explanation FIGURE 9 and FIGURE 10, the gain value between the instrumentation amplifier AD620 and A623 had a gain that is almost the same as the minimum gain that was set, which is 100 times. In addition, the value of the output voltage on the instrument amplifier is the same as well. For the average results of HPF and LPF analog filter tests measured for 5 trials, it is shown in FIGURE 11 and FIGURE 12.

Based on the explanation FIGURE 11, The test is carried out by providing a frequency input to the generator function starting from a frequency of 0.1 Hz to 10 Hz.

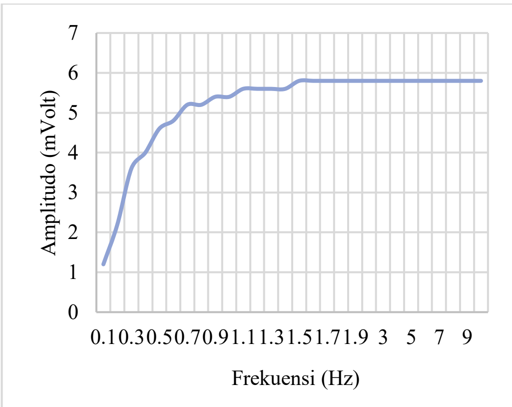

FIGURE 11. **HPF filter cut-off frequency response results**

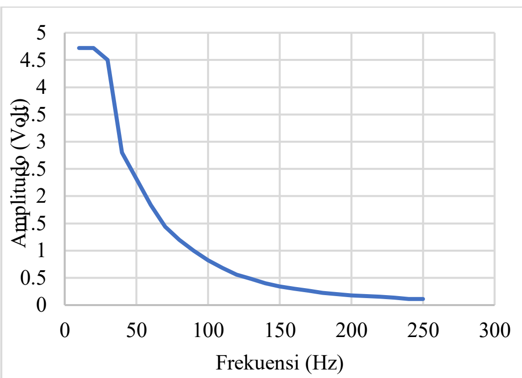

FIGURE 12. **LPF filter cut-off frequency response results**

The result at a frequency of 0.3 Hz, it began to be suppressed, while at frequency above 0.5 Hz, it began to be released. In this study, the circuit testing was carried out using an order 1 HPF circuit with a cut off frequency of 0.05 Hz. Based on the explanation in FIGURE 12, The test is carried out by providing a frequency input to the generator function starting from a frequency of 10 Hz to 250 Hz. The results at frequencies of more than 100 Hz, it was suppressed, while at frequencies of less than 100 Hz, it was released. The test was carried out using a series of Low pass filter order 3 with strengthening of 60 dB.

C. ECG Frequency Spectrum Results using FFT

ECG signals and frequency spectrum using the FFT are described in FIGURE 13, where the ECG signal data acquisition was carried out for one minute and data in txt format which was then processed by FFT signal.

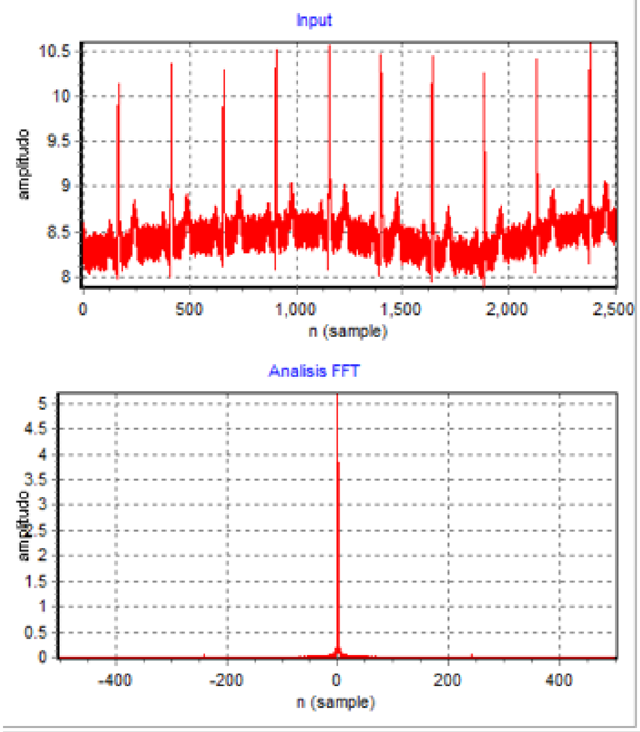

FIGURE 13. ECG signal searching for the frequency spectrum using FFT

FIGURE 13 further explains that while the results of the FFT was used to find the frequency spectrum, the FFT results on the ECG signal provided information that the ECG signal had a frequency area between 0.05 Hz to 100 Hz. After the frequency reached 100 Hz, the frequency was suppressed and the spectrum value of the ECG signal was reduced further.

IV. Discussion

Based on the test results of each single supply and bipolar supply instrumentation amplifier, the average gain value was almost the same as the minimum Gain set of 100 times. As for the results of the ECG signal output obtained, namely the instrumentation amplifier single supply, the results of the ECG signal are more capable in reducing the noise as evidenced in FIGURE 8. Meanwhile, concerning the output of the ECG signal from the instrumentation amplifier Bi-Polar supply noise, there was still noise in the signal. This shows that the use of a single supply instrumentation can reduce more noise compared to the Bi-Polar instrumentation amplifier. Meanwhile, the results of the FFT to find the frequency spectrum explains that the FFT results on the ECG signal provides information that the ECG signal had a frequency area between 0.05 Hz to 100 Hz. At frequency of more than 100 Hz, the frequency started to be suppressed, while at the frequency of less than 100 Hz, the frequency was passed.

Previous related research has been carried out by Enrique M. Spinelli et al, in applying a low-power scheme using one battery for the input of a biopotential amplifier with a gain of 60 dB and a DC input range of ± 200 mV. The system was implemented using a low-power operational amplifier for detecting the biopotential signals with a single supply [4]. However, because it only uses one battery, the performance of the ECG cannot be carried out for a long time. Meanwhile, another study that was carried out by Sugondo Hadiyoso et al, designed a wearable ECG using the Einthoven triangle method using a bi-polar supply, but the weakness in this study is the presence of noise interference [15].

This study compared two instrumentation amplifier using a single supply with bi-polar sulfur. Thus, the contribution of this research is that it can help other researchers to choose the right amplifier to reduce noise. Meanwhile, the weakness of this study is that the output of the ECG instrumentation is still displayed on the oscilloscope, making it difficult for researchers to directly see the signal output because it must be connected to the oscilloscope.

V. Conclusion

In this research, an ECG instrumentation has been made using a single supply instrumentation amplifier and a Bi-polar supply instrumentation amplifier. Based on the measurement results, the output of the ECG signal from the instrumentation amplifier Bi-Polar supply noise still contains noise in the signal. This shows that the use of a single supply instrumentation can reduce more noise compared to the Bi-Polar instrumentation amplifier. Meanwhile, the results of the FFT to find the frequency spectrum explain that the FFT results on the ECG signal provide information that the ECG signal has a frequency area between 0.05 Hz to 100 Hz. In this case, at frequency of more than 100 Hz, the frequency starts to be suppressed, while at the frequency of less than 100 Hz, the frequency is passed. Furthermore, it is recommended for further study by using digital filter to reduce the noise on the ECG signal.

References

[1] C. Suharinto, A. Budianto, and N. T. Sanyoto, “Design of Electrocardiograph Signal Simulator,” *Indones. J. Electron. Electromed. Eng. Med. informatics*, vol. 2, no. 1, pp. 43–47, 2020, doi: 10.35882/ijeeemi.v2i1.9.

[2] A. M. Maghfiroh, A. Arifin, and T. A. Sardjono, “Wavelet-Based

Respiratory Rate Estimation Using Electrocardiogram," *Proc. - 2019 Int. Semin. Intell. Technol. Its Appl. ISITIA 2019*, pp. 354–359, 2019, doi: 10.1109/ISITIA.2019.8937201.

[3] Z. Ai, L. Zheng, H. Qi, and W. Cui, "Low-Power Wireless Wearable ECG Monitoring System Based on BMD101," *Chinese Control Conf. CCC*, vol. 2018-July, pp. 7374–7379, 2018, doi: 10.23919/ChiCC.2018.8484125.

[4] E. M. Spinelli, N. H. Martinez, and M. A. Mayosky, "A single supply biopotential amplifier," *Med. Eng. Phys.*, vol. 23, no. 3, pp. 235–238, 2001, doi: 10.1016/S1350-4533(01)00040-6.

[5] H. C. Lee *et al.*, "An ECG front-end circuit with single power supply," *2015 IEEE Int. Conf. Consum. Electron. - Taiwan, ICCE-TW 2015*, pp. 270–271, 2015, doi: 10.1109/ICCE-TW.2015.7216893.

[6] B. S. Mohamad-Ali, "Single input adaptive 50 Hz noise canceller from ECG signal," *2013 Int. Conf. Electr. Commun. Comput. Power, Control Eng. ICECCPCE 2013*, pp. 64–69, 2014, doi: 10.1109/ICECCPCE.2013.6998736.

[7] A. S. AlMejrad, "A single supply standard 8051 microcontroller based medical K-grade isolation ECG module with graphics LCD," *Proc. - 2012 Int. Conf. Intell. Syst. Des. Eng. Appl. ISDEA 2012*, pp. 1184–1187, 2012, doi: 10.1109/ISdea.2012.584.

[8] J. S. Arteaga-Falconi, H. Al Osman, and A. El Saddik, "ECG and fingerprint bimodal authentication," *Sustain. Cities Soc.*, vol. 40, pp. 274–283, 2018, doi: 10.1016/j.scs.2017.12.023.

[9] U. Satija, B. Ramkumar, and M. Sabarimalai Manikandan, "A New Automated Signal Quality-Aware ECG Beat Classification Method for Unsupervised ECG Diagnosis Environments," *IEEE Sens. J.*, vol. 19, no. 1, pp. 277–286, 2019, doi: 10.1109/JSEN.2018.2877055.

[10] A. Appathurai *et al.*, "A study on ECG signal characterization and practical implementation of some ECG characterization techniques," *Meas. J. Int. Meas. Confed.*, vol. 147, p. 106384, 2019, doi: 10.1016/j.measurement.2019.02.040.

[11] S. Dilmac and M. Korurek, "ECG heart beat classification method based on modified ABC algorithm," *Appl. Soft Comput. J.*, vol. 36, pp. 641–655, 2015, doi: 10.1016/j.asoc.2015.07.010.

[12] H. Ozkan, O. Ozhan, Y. Karadana, M. Gulcu, S. Macit, and F. Husain, "A portable wearable tele-ECG monitoring system," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 1, pp. 173–182, 2020, doi: 10.1109/TIM.2019.2895484.

[13] L. Zeng, B. Liu, and C. H. Heng, "A Dual-Loop Eight-Channel ECG Recording System with Fast Settling Mode for 12-Lead Applications," *IEEE J. Solid-State Circuits*, vol. 54, no. 7, pp. 1895–1906, 2019, doi: 10.1109/JSSC.2019.2903471.

[14] A. J. A. Dhivya, "Quadcopter based technology for an emergency healthcare," *Int. Conf. Biosignals, images Instrum. (ICBSII), 16-18 March 2017, Chennai.*, no. March, pp. 16–18, 2017.

[15] S. Hadiyoso, K. Usman, A. Rizal, and R. Sigit, "Microcontroller-based Mini Wearable ECG Design Desain Mini wearable ECG Berbasis Mikrokontroler," *Inkom*, vol. 7, no. 2, pp. 1–8, 2013.

[16] N. Bayasi, T. Tekeste, H. Saleh, B. Mohammad, A. Khandoker, and M. Ismail, "Low-Power ECG-Based Processor for Predicting Ventricular Arrhythmia," *IEEE Trans. Very Large Scale Integr. Syst.*, vol. 24, no. 5, pp. 1962–1974, 2016, doi: 10.1109/TVLSI.2015.2475119.

[17] Z. Ai, Z. Wang, and W. Cui, "Low-power wireless wearable ECG monitoring chestbelt based on ferroelectric microprocessor," *Chinese Control Conf. CCC*, vol. 2019-July, no. Section 1, pp. 6434–6439, 2019, doi: 10.23919/ChiCC.2019.8865575.

[18] F. Morshedlou, N. Ravanshad, and H. Rezaee-dehsorkh, "A Low-Power Current-Mode Analog QRS-Detection Circuit for Wearable ECG Sensors," *2018 25th Natl. 3rd Int. Iran. Conf. Biomed. Eng.*, pp. 1–6, 2018, doi: 10.1109/ICBME.2018.8703577.

[19] G. Ehrmann, T. Blachowicz, S. V. Homburg, and A. Ehrmann, "Measuring Biosignals with Single Circuit Boards," *Bioengineering*, vol. 9, no. 2, pp. 1–21, 2022, doi: 10.3390/bioengineering9020084.

[20] N. Duda, A. Barthule, S. Ripperger, F. Mayer, R. Weigel, and A. Koelpin, "Non-Invasive Low Power ECG for Heart Beat Detection of Bats," *2019 IEEE Top. Conf. Wirel. Sensors Sens. Networks, WiSNet 2019*, pp. 1–4, 2019, doi: 10.1109/WISNET.2019.8711816.

[21] H. N. Abdullah and B. H. Abd, "Design and Implementation of Ecg Monitoring System," *Ijarse*, no. 4, 2015, [Online]. Available: http://www.ijarse.com.

[22] T. Alexander, G. Nickolay, and K. Igor, "Design of an Instrumentation Amplifier for a Mobile Electrocardiogram Recorder with Autonomous Power Supply," *2019 Int. Semin. Electron Devices Des. Prod. SED 2019 - Proc.*, pp. 1–4, 2019, doi: 10.1109/SED.2019.8798463.

[23] V. Rizzoli *et al.*, "r,,, . 7 8," vol. 39, no. 9, pp. 235–238, 1992.

[24] H. Kakigano, Y. Miura, and T. Ise, "Low-voltage bipolar-type dc microgrid for super high quality distribution," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 3066–3075, 2010, doi: 10.1109/TPEL.2010.2077682.

[25] J. Duvernoy, "Guidance on the Computation of Calibration Uncertainties," *World Meteorol. Organ.*, no. 119, 2015, [Online]. Available: http://www.wmo.int/pages/prog/www/IMOP/publications-IOM-series.html%0D.

[26] U. Oberst, "The fast Fourier transform," *SIAM J. Control Optim.*, vol. 46, no. 2, pp. 496–540, 2007, doi: 10.1137/060658242.

[27] M. Cuimei, C. He, and Ma Long, "AN EFFICIENT DESIGN OF HIGH-ACCURACY AND LOW-COST FFT," *IET Int. Radar Conf. 2013*, pp. 3–6, 2013.

[28] P. M. N and Q. Cerdip, "Low Cost, Low Power Instrumentation Amplifier," *Analog Device*, pp. 1–16, 1999.

[29] L. Power *et al.*, "Single Supply, Rail-to-Rail, Low Cost Instrumentation Amplifier," *Analog Device*. analog Device, USA, pp. 1–16, 1999.