ECG Signal Processing and Heart Beat Rate Calculation Circuit

ECG Signal Structures

What is ECG?

An ECG is a representation of the rate of change of electrical signals due to the movement of heart muscles. The muscle contraction and relaxation of heart walls produces flow of dipoles causing electrical current generating differential potential spread throughout the body. The test that records this activity for a few seconds and presents it an amplified version known as Electrocardiography [1].

ECG Signal Cycle

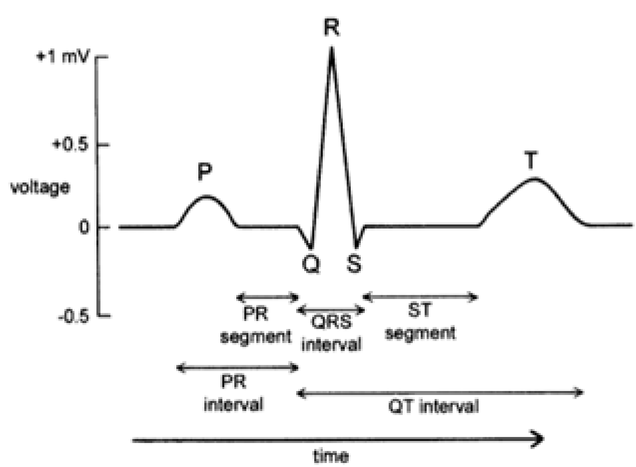

Fig.1. A typical ECG waveform for once cardiac cycle.

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The ECG signal is typically represented as voltage vs time signal. The voltages are usually in millivolts and time in seconds. The summation of electrical pulses of two atria is the first signal in ECG waveform is the P wave. The short delay represents atrioventricular node slowing down electrical depolarization as signal moves to ventricles. The signal moves to baseline as the signal is too small to be detected which is knowns as ‘PR’ segment. The baseline that is the straight horizontal line is called the isoelectric line. The end of P wave approximately 160ms after the waveform of ECG signal suggests complete depolarization of atria and contraction begins. This depolarization of ventricle results in the highest peak of the waveform called QRS complex. The Q wave is the first negative deflection. The R wave is the next positive or upwards deflection and the downwards deflection after R wave is called S wave. The S wave crosses the isoelectric line and goes to negative voltage before returning baseline. T wave is upright comprising of various deflection amplitudes and duration. The T wave and S-T segment show electrical signal reflecting repolarization of the myocardium. The T wave is the last potential recorded in the ECG waveform it is then followed by the P wave of the next cycle. [1][2]

Normal ECG Parameters:

Table 1: Amplitude Values for a normal ECG signal

Wave	**Amplitude**
P	0.25 mV
R	1.6 mV
Q	25 % of R wave
T	0.1 to 0.5 mV

Table 2: Timing information of normal ECG signal

Interval	**Duration**
PR wave	0.12 to 0.2 sec
QT wave	0.35 to 0.44 sec
ST wave	0.05 to 0.15 sec
P wave interval	0.11 sec

The common frequencies of the important components on the ECG:

Interval	Frequency
Heart rate	0.67 – 5 Hz (i.e. 40 – 300 bpm)
P-wave	0.67 – 5 Hz
T - wave	1 -7 Hz
High frequency potentials	100 – 500 Hz
QRS	10 – 50 Hz

Noise affecting ECG signals

1. Baseline Wander

As the name suggests in this effect the signal appears to 'wander' that is move upward from the baseline than being a straight line. This is caused due to various reasons such as improper electrodes causing electrode skin impedance, patient's movement and respiration. The baseline wander has frequency content in the range of 0.5Hz. These frequency content value can increase during body stress and exercises. During bradycardia, as the heart rate is not constant the frequency contents vary up to 0.67Hz. A finite impulse response high pass zero phase forward-backward filter with cutoff of 0.5 Hz can be used for filtering Baseline Wander effect from ECG signal. [6]

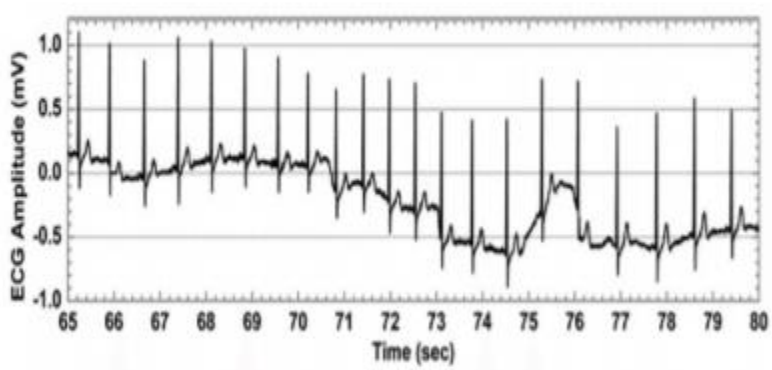


Fig 2. ECG signal with baseline wander. Rahul Kher (2019)[5]

2. Powerline Interferences

Any electromagnetic interference caused by either powerline or any other bioelectrical signal received from the body are considered as powerline interferences that makes ECG detection difficult due to its narrowband noise. They are 50 or 60 Hz sinusoidal interference with harmonics making the detected signal unreliable. Along with various precautions like appropriate shielding and grounding, selecting recording location with fewer electronic devices in surrounding, a proper signal processing like straightforward linear, stopband filter and other advanced techniques for handling variations becomes necessary. [5][6]

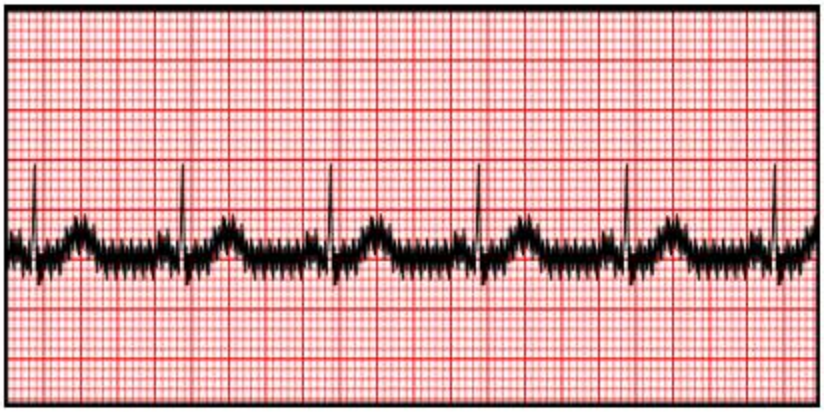


Fig 3. Powerline interference on ECG signal. Rahul Kher (2019) [5]

3. Electromyo- Graphic (EMG) Noise

It is the muscle noise present in the acquired ECG signal. It is a low amplitude signal and it is very difficult to filter this signal as it overlaps the QPRST complex. This noise can be removed by averaging restricting to one particular QRS morphology at a time requiring many beats to be available. It is typically in the range of 100Hz. [5]

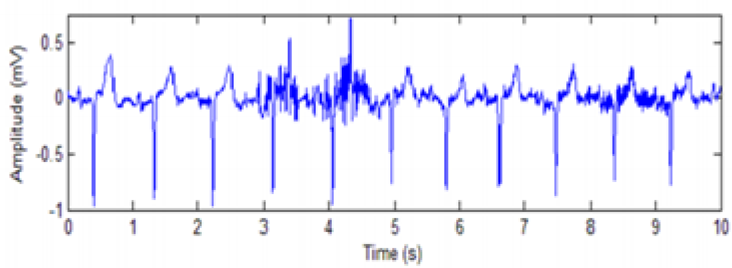


Fig. 4. EMG noise affect on ECG signal. Rahul Kher (2019)[5]

4. Electrode Motion Artifacts

Similar to baseline wander, the electrode motion artifact is caused due to skin stretching that shifts its impedance on to the electrodes. These render difficulty in interpretation of ECG signal as it overlaps the PQRST complex due to their large-amplitude waveforms with frequency range from 1 to 10 Hz. The electrode motion artifacts are problematic as they compose of major source of falsely detected heartbeats.[5]

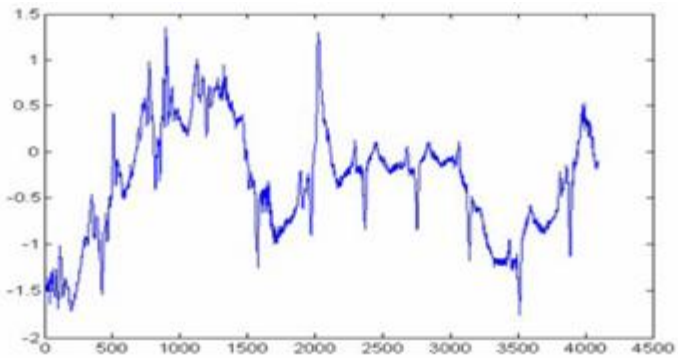


Fig.5. Typical 8-pin linear IC op-amp with power supply connections. Lamdageeks.com (2020).[8]

Study about operational amplifier and basic circuits:

Operational amplifier-

Ramakant Gaikwad in his book defines operational amplifier as a direct-coupled high-gain amplifier, usually consisting of one or more differential amplifiers and usually followed by a level translators and an output stages. The output stage is generally a push-pull or push-pull complementary-symmetry pairs. An operational amplifier is available in single integrated circuit package. The op-amp is a versatile device that can be used to amplify DC as well as input AC signals.

The modern op-amp can be used for a variety of applications such as AC and DC signal amplification, active filters, oscillators, comparators etc.

Functions of terminals of Op-amp:

1. +Vcc and -V_{EE} represent the positive and negative voltages, respectively. These are the biasing voltages required for operation of op-amp.

2. V- and V+ represent the negative and positive input voltages respectively.

3. Vout shows the output terminal of the op-amp.[7]

Types of amplifiers:

1. Differential amplifier

A differential amplifier is a type of amplifier that amplifies difference between the two inputs and removes the common factor.

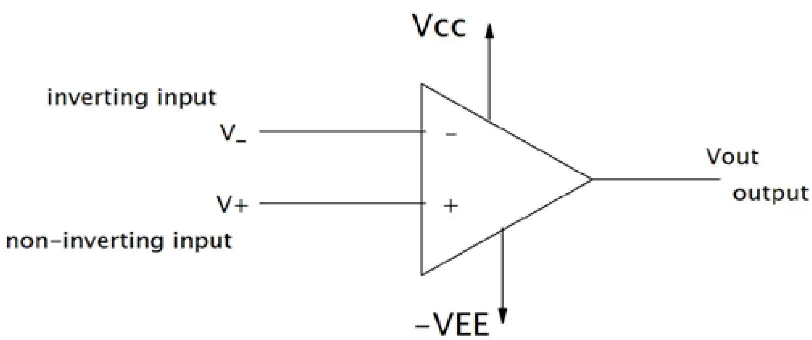


Fig.6. Differential amplifier. Wikipedia (2009) [9]

2. Inverting amplifier

An inverting amplifier is given input at the inverting terminal this gives a negative output i.e. an output which is out of phase with the given input.

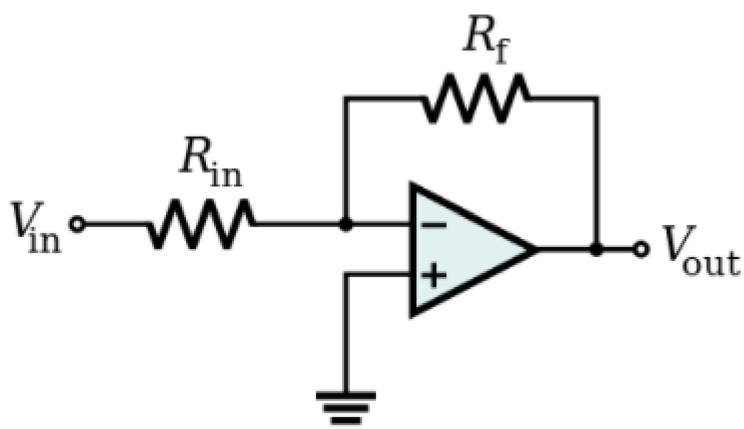


Fig.7. Inverting amplifier, Wikipedia (2009), [9]

3. Non inverting amplifier

In this the input is given to the non-inverting terminals so the gain is positive and output is in phase.

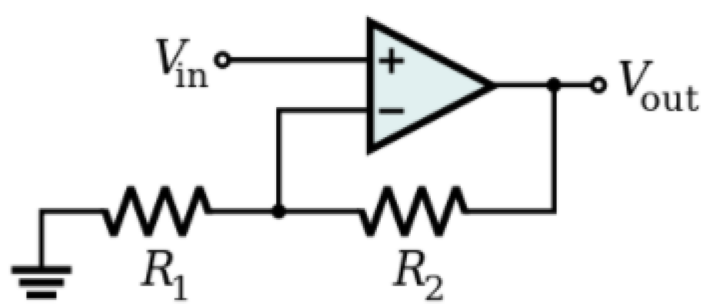


Fig.8. Non Inverting amplifier, Wikipedia (2009) [9]

4. Buffer Amplifier

A buffer amplifier reproduces electrical signal as it is. It is a unity gain amplifier.

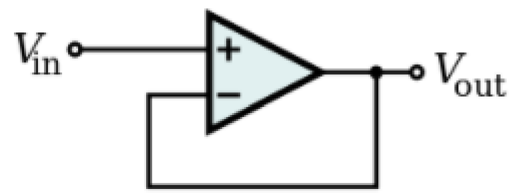


Fig.9. Buffer amplifier, Wikipedia (2009) [9]

5. Summing amplifier

In a summing amplifier, the sum of multiple inputs can be obtained as an output signal.

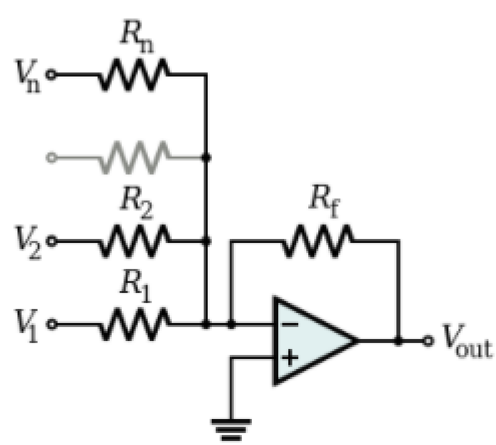


Fig.10. Summing amplifier, Wikipedia(2009) [9]

Averaging amplifier
An averaging amplifier can be made from the summing amplifier by replacing the resistors with same valued resistors.

6. Instrumentation amplifier

Instrumentation amplifier is a differential amplifier with additional input buffers. [7]

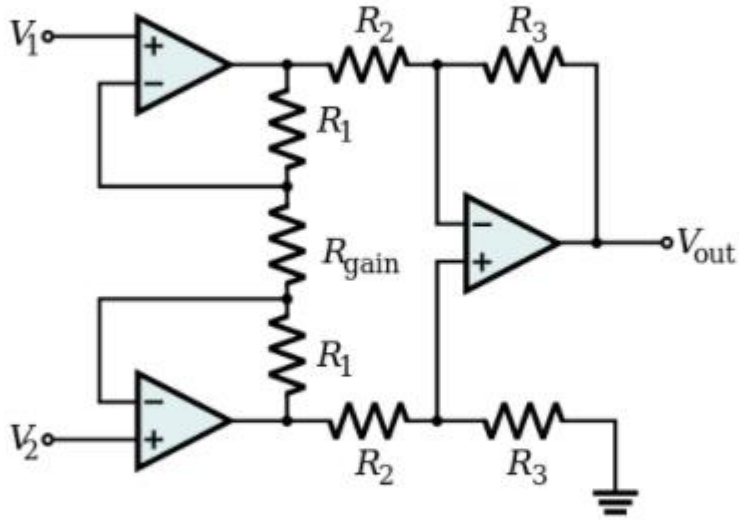


Fig.11. Instrumentation amplifier, Wikipedia(2009) [9]

Types of filters:

1. Low pass filter

It passes signals with a frequency lower than the cut off frequency.

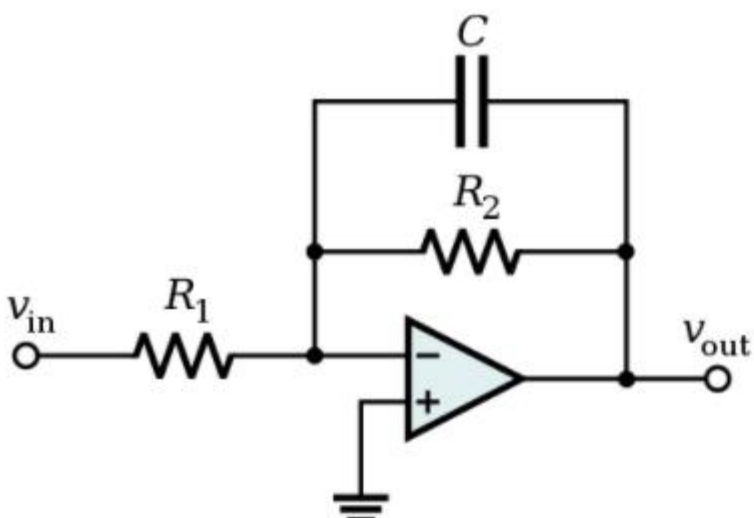


Fig.12. Low pass filter, Wiki (2008) [10]

2. High pass filter

It passes signals with a frequency higher than the cut off frequency.

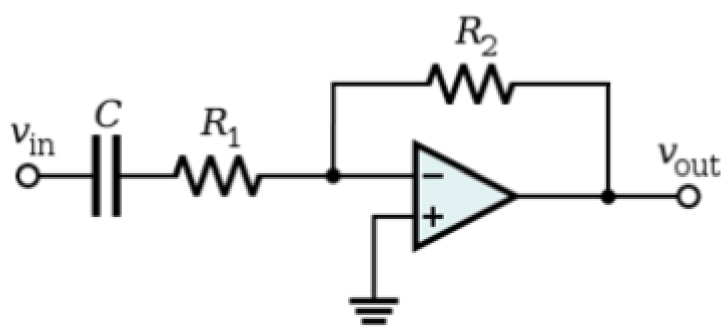


Fig.13. High pass filter, Wiki (2009) [11]

3. Band pass filter

A bandpass filter passes frequencies within a certain range and attenuates frequencies outside that range.

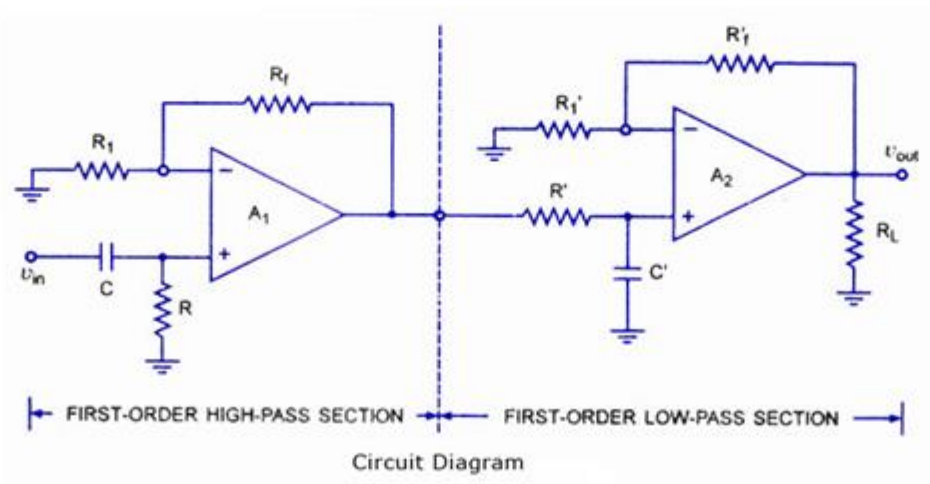


Fig.14. Wide band pass filter, CircuitsToday (2011),[12]

4. Band reject filter

A bandpass filter rejects frequencies within a certain range and allows frequencies outside that range.

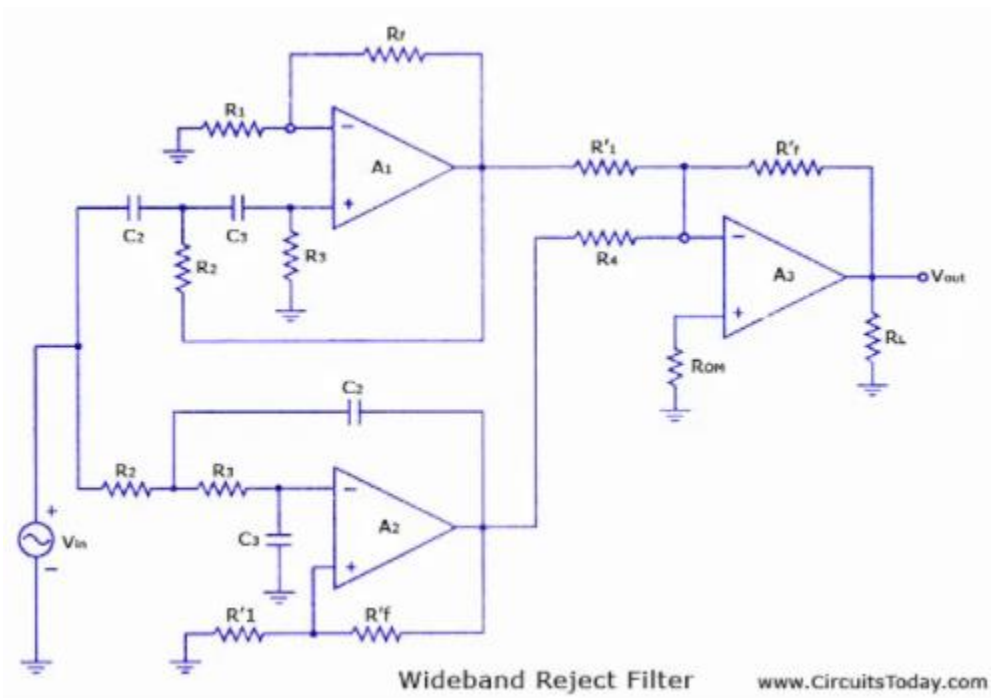


Fig.15. Wide band Reject filter, CircuitsToday(2011),[13]

5. Narrow band reject

A bandpass filter rejects frequencies within a certain limited range and allows frequencies outside that range.

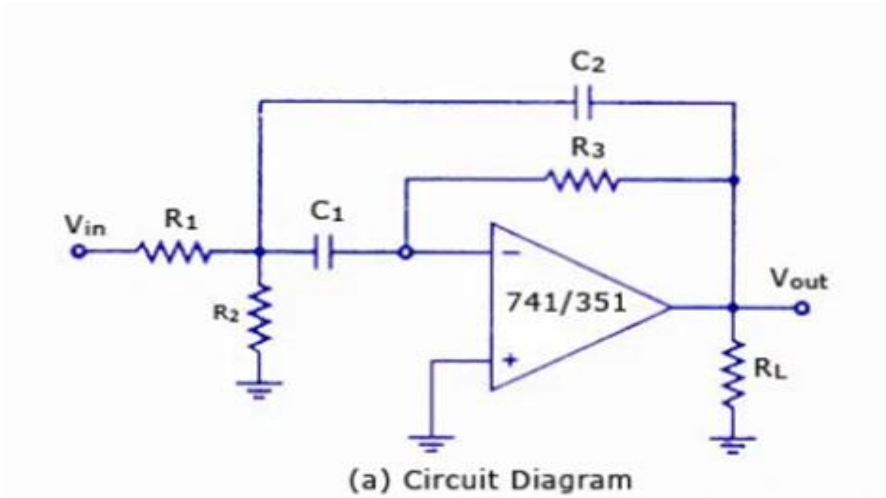


Fig.16. Narrow band reject filter, CircuitsToday(2011),[13]

6. Notch filter

It blocks frequencies within a specific frequency range and allows frequencies outside that range. [7]

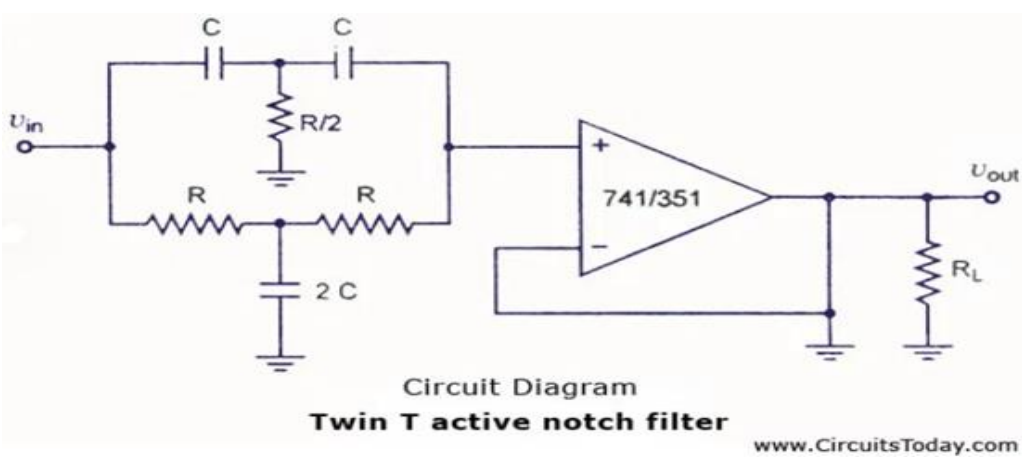


Fig.17. Notch Filter, CircuitsToday(2011),[13]

Output of the Filters:

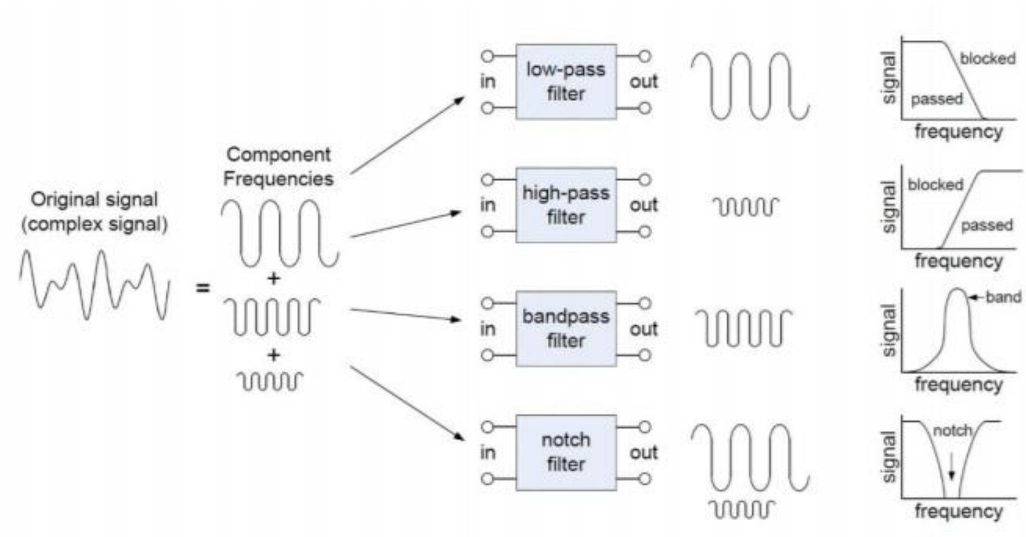


Fig.18. Filter outputs, AllAboutCircuits(2019),[14]

Individual Circuit Block Testing

Non-Inverting Amplifier:

A non inverting operational amplifier or non inverting op amp uses op amp as the main element. When we apply any signal to the non – inverting input of, it does not change its polarity when it gets amplified at the output terminal. So, in that case, the gain of the amplifier is always positive.

Formula:

Gain (A) = (1+Rf/R1)

Calculations:

Let the Gain be 2,

Therefore, 1+Rf/R1=2

Hence, Rf = R1

Let Rf = R1 = 1K

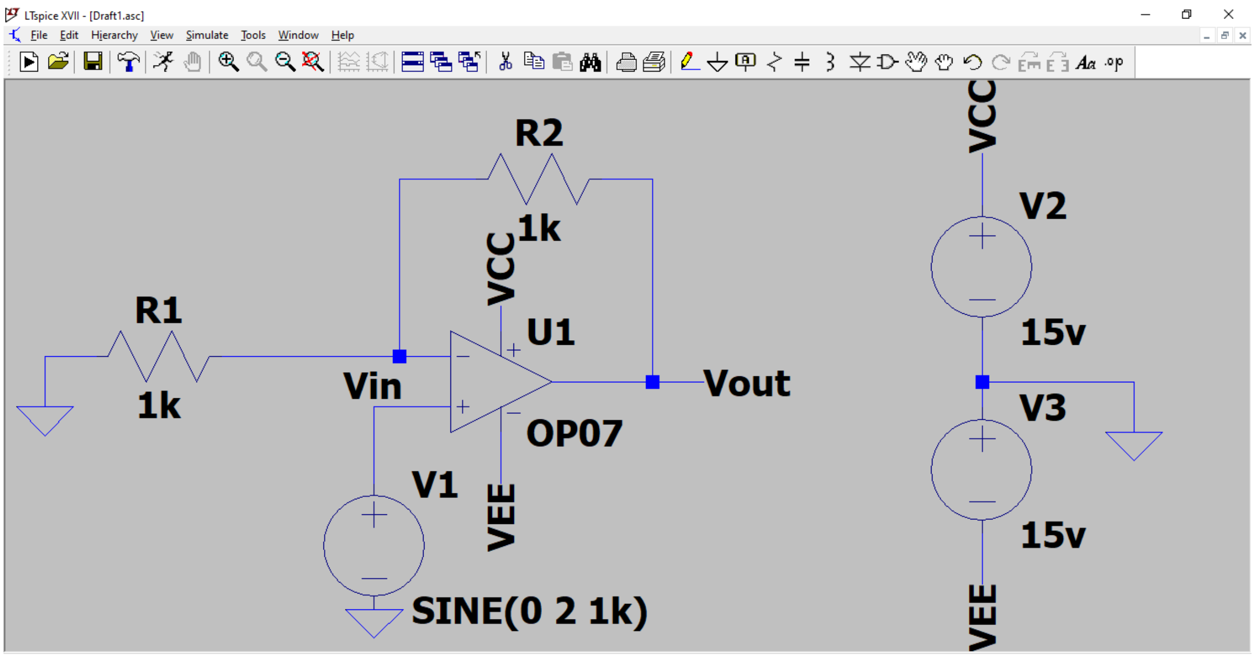


Fig 19. Circuit of Non Inverting Amplifier

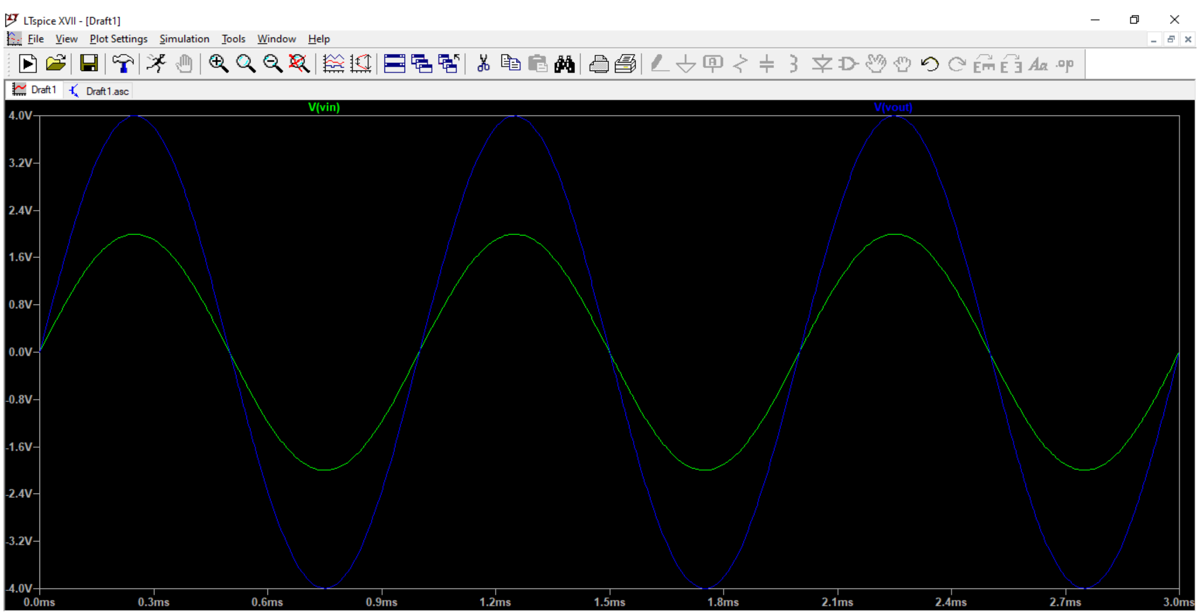


Fig 20. Output of Non Inverting Amplifier

Low Pass Filter

A low pass filter that passes a range of frequencies lower than a specific frequency that is the set cut off frequency and attenuates frequency higher than the specified range.

Calculations:

For Fc = 1kHz
Since it is a non inverting configuration
Gain (A) = (1 + Rf/R1)

Let the passband gain be 2,
∴ 1 + Rf/ R1 = 2
Hence, Rf = R1

Let Rf = R1 = 10kΩ
Assume C= 0.01μF
∴ R = 1/(2π)(10^3)(10^-8)
Hence, R = 15.9kΩ

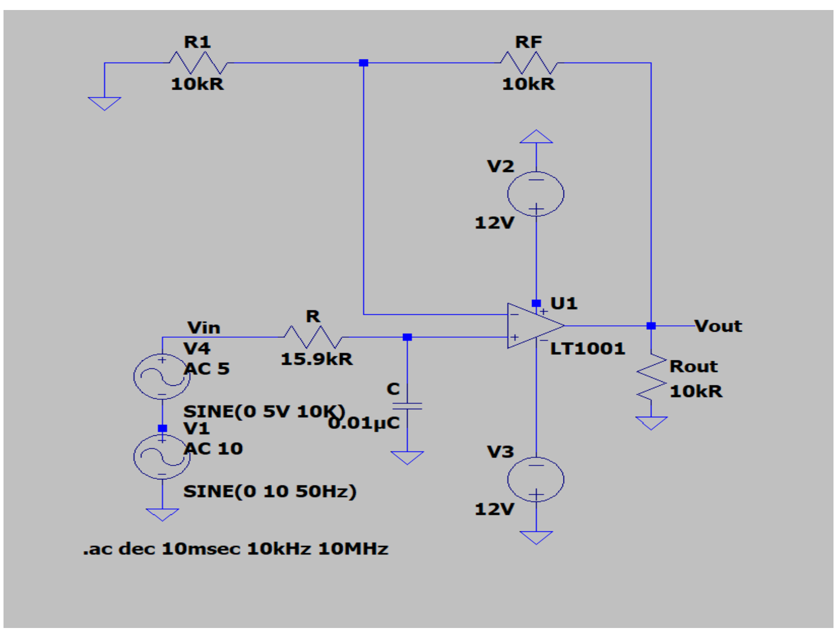


Fig. 21. Circuit Diagram of low pass filter

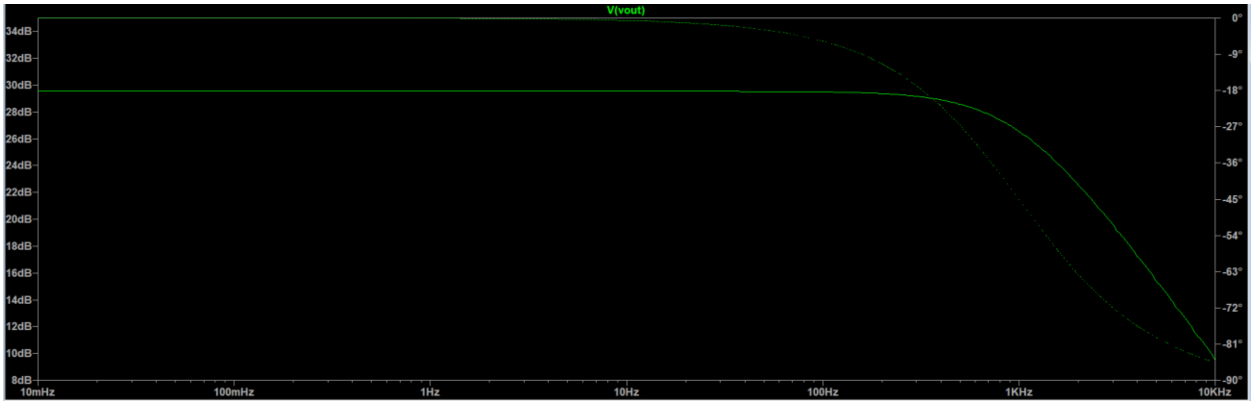


Fig.22. AC analysis output of low pass filter

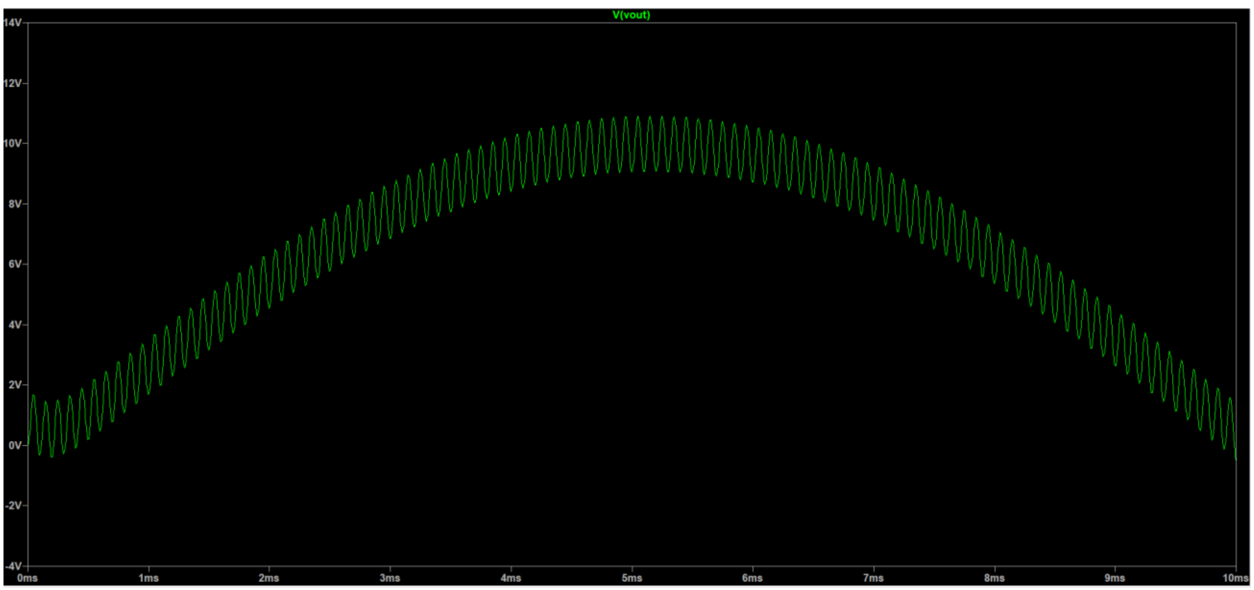


Fig.23. Transient Analysis of Input and Output Signals of low pass filter

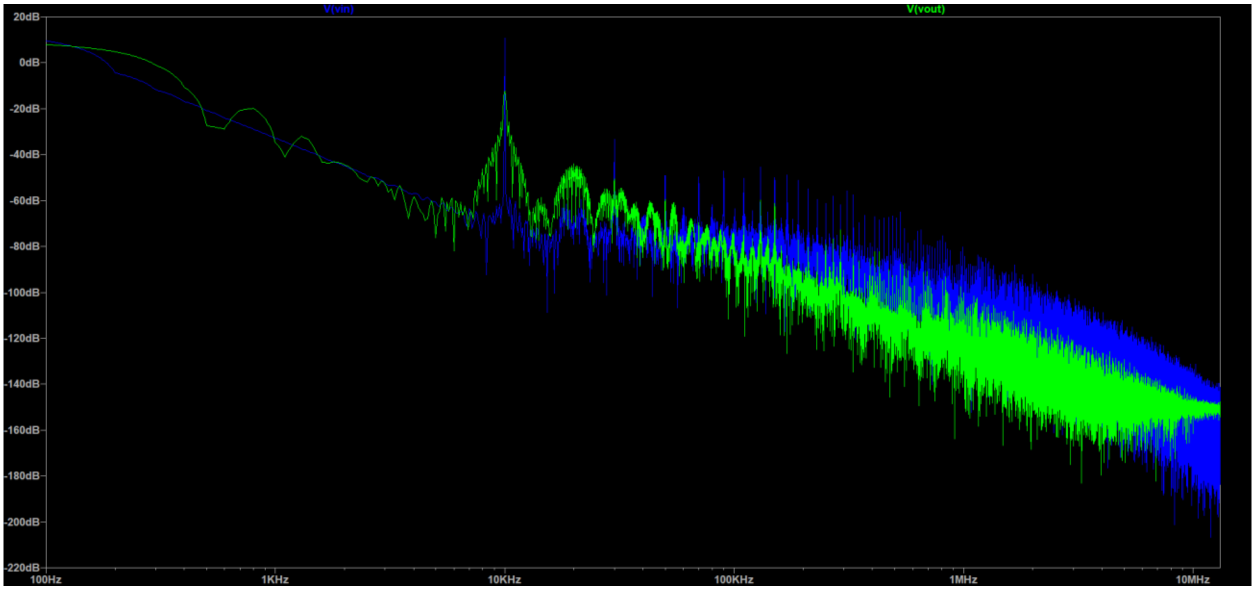


Fig. 24. Input and output FFT of Low pass filter

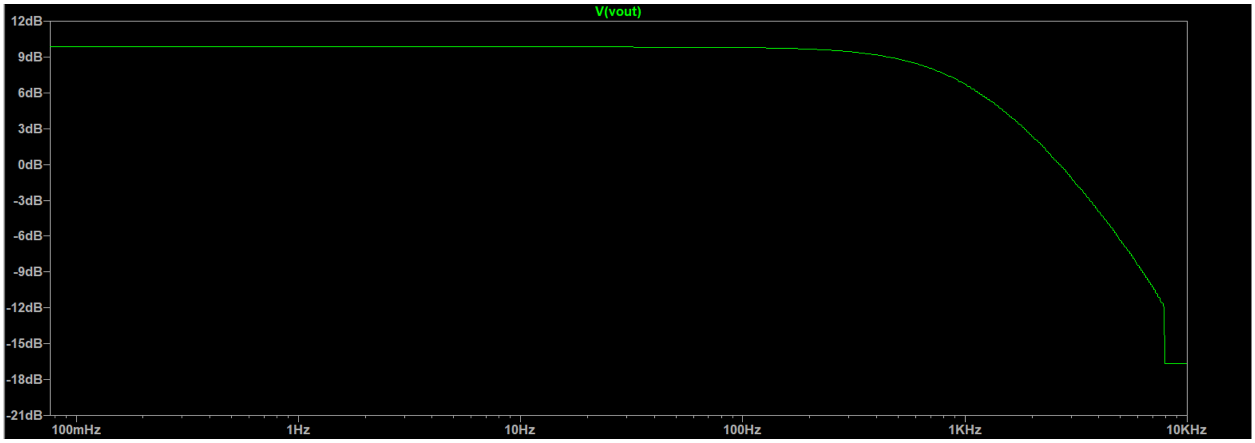


Fig.25. FFT output of Low pass filter output.

High Pass Filter

High Pass Filter is a circuit that allows frequencies higher than cut-off frequency to pass through and blocks frequencies lower than cut-off frequency.

In High Pass Filter, the Capacitor has high reactance at lower frequencies, so it acts as an open circuit for lower frequency signals until cut-off frequency is reached. The Capacitor has low reactance at higher frequencies, so it acts as a short circuit for the frequencies higher than cut-off frequency.

Calculations for High Pass Filter

Formula for Pass Band Gain is

$$A_F = (1+R3/R2)$$

Let the Pass Band Gain (A_F) = 11

$$\therefore 11 = (1+R3/R2)$$

$$\therefore 11-1 = R3/R2$$

$$\therefore 10 = R3/R2$$

$$\therefore R3 = 10 \times R2$$

$\therefore$ Let R2 be 10

$$\therefore R3 = 10 \times 10$$

$$\therefore R3 = 100$$

So, R2 = 10kΩ and R3 = 100kΩ

Formula for Cut-off Frequency is

$$f_c = 1/(2\pi R1C) \text{ Hz}$$

Let us design a High Pass Filter for f_c = 100Hz

So, $C = 1/(2\pi R1f_c)$

Let us take R1= 1kΩ

$\therefore C = 1/(2 \times 3.14 \times 1k\Omega \times 100Hz)$

$\therefore C = 1.6\mu F$

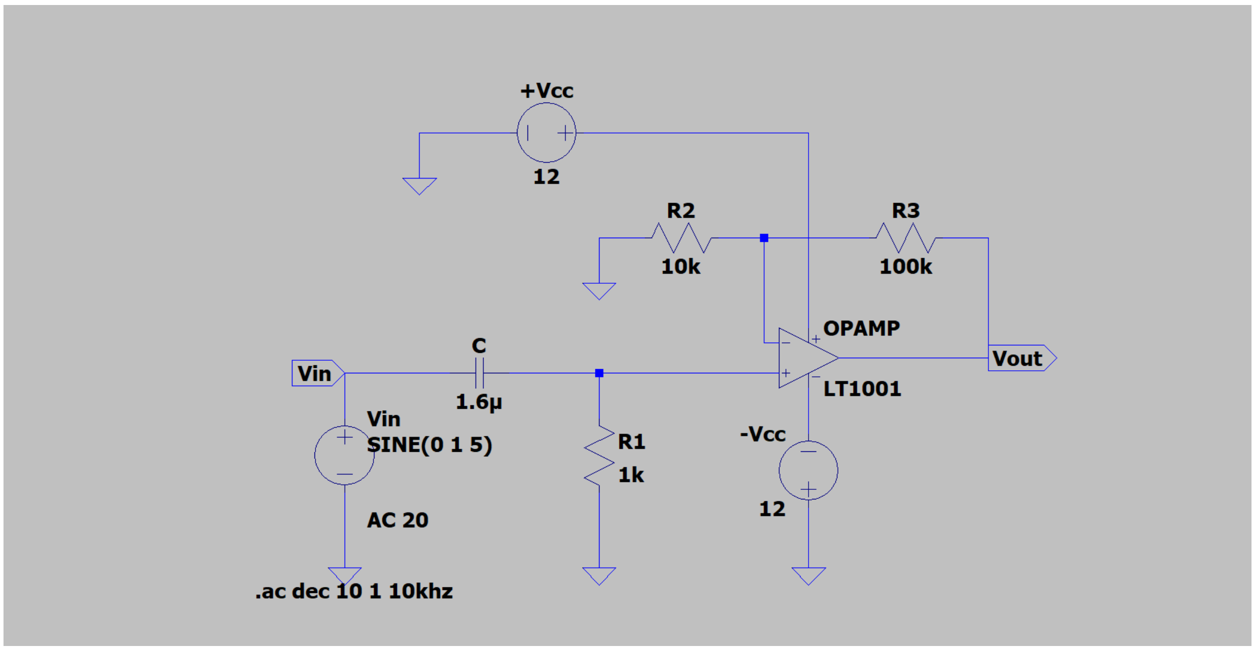


Fig 26: Circuit Diagram of High Pass Filter

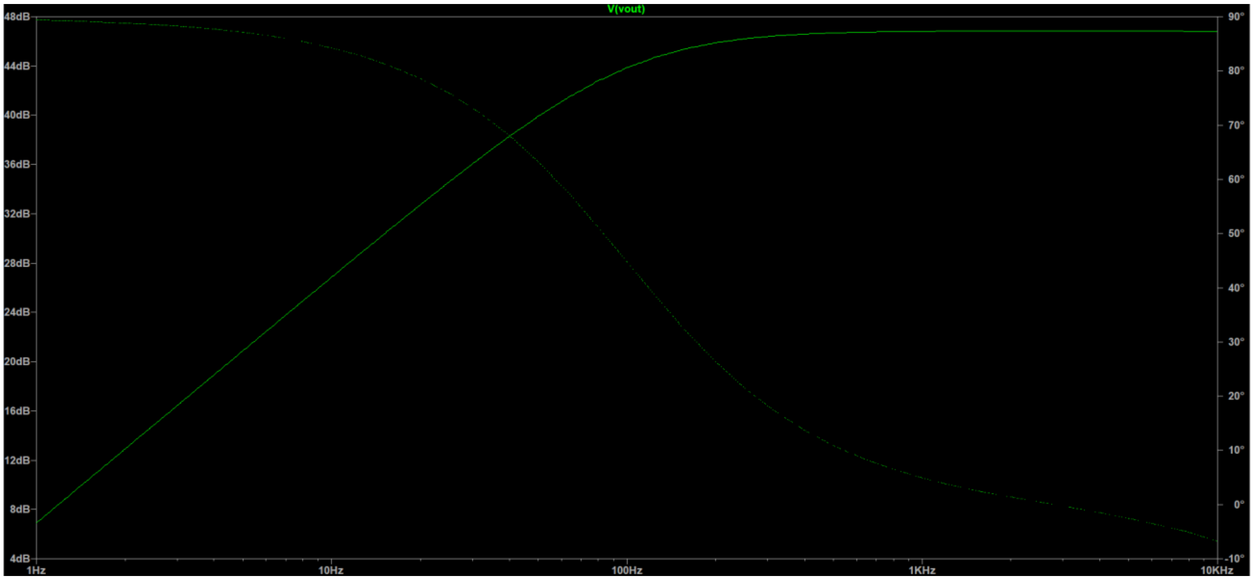


Fig 27: Frequency Response of High Pass Filter

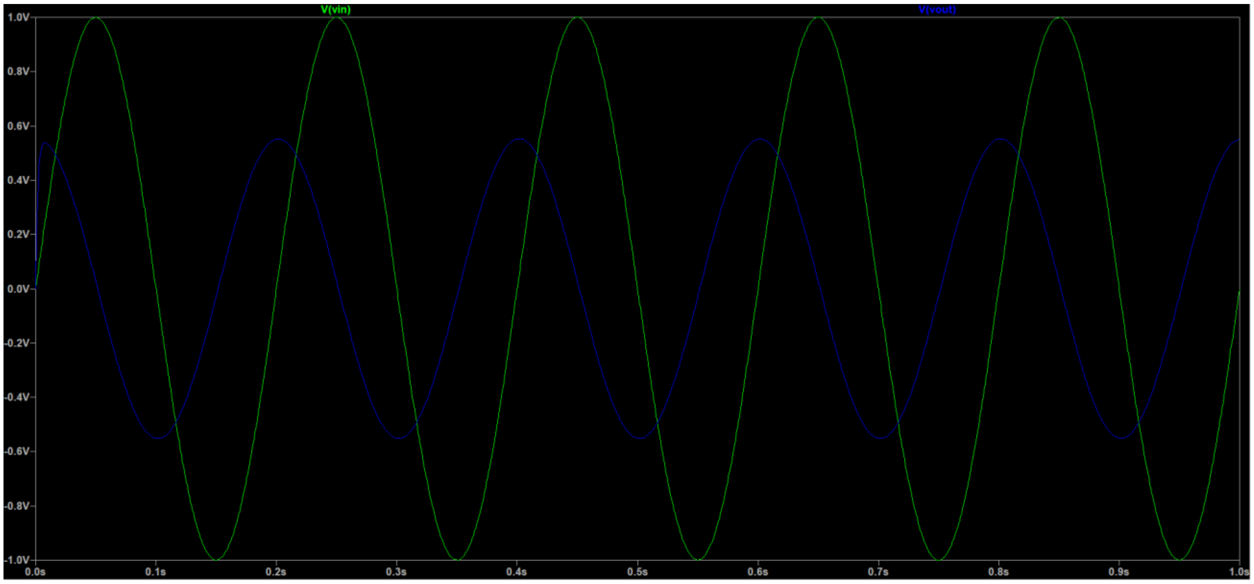


Fig 28: Input and Output waveform for High Pass Filter

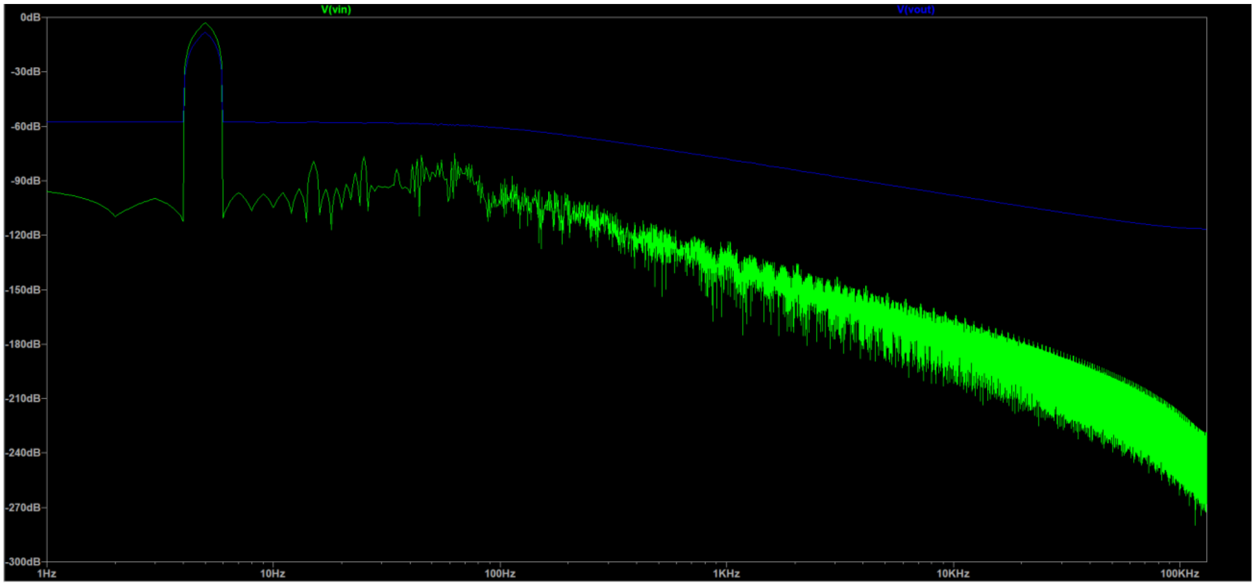


Fig 29: FFT for Input and Output waveform of High Pass Filter

Notch filter

A notch filter is a type of band stop filter, which attenuates frequencies within a specific range while passing all other frequencies unaltered. For a notch filter, this range of frequencies is very narrow. The range of frequencies that a band stop filter attenuates is known as stop-band.

The most common Notch filter design is the twin-T notch filter network. The twin-T filter is also called a parallel-T configuration. It consists of two RC branches in the form of two tee sections connected in parallel.

The basic twin-T Notch filter circuit is shown as:

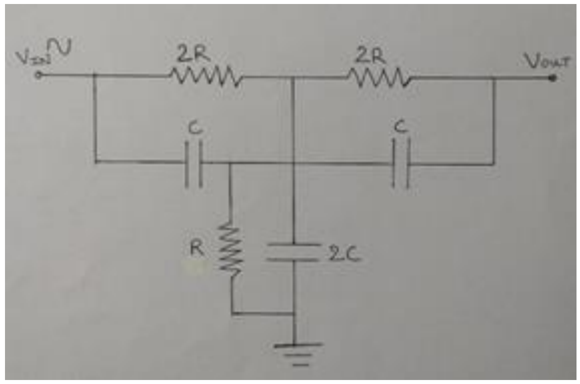


Fig 30. Twin T filter

The upper T-configuration of resistor 2R and capacitor 2C form the low pass filter section and the lower T-configuration of resistor R and capacitor C form the high pass filter section.

The frequency at which it offers maximum attenuation is called Notch frequency.

Notch frequency is given by, fn = 1/4πRC

Calculations:

Designing a 60 Hz notch filter:

Consider, C= 0.068uf

fn= 60 Hz

We know, $fn = \frac{1}{4\pi RC}$

∴ $60= \frac{1}{4\pi \times R \times 0.068\mu}$

∴ R= 19.5k Ω

∴ 2R= 39kΩ

Team 1

ECG Signal Processing and Heart Beat Rate Calculation Circuit

Circuit for simulation:

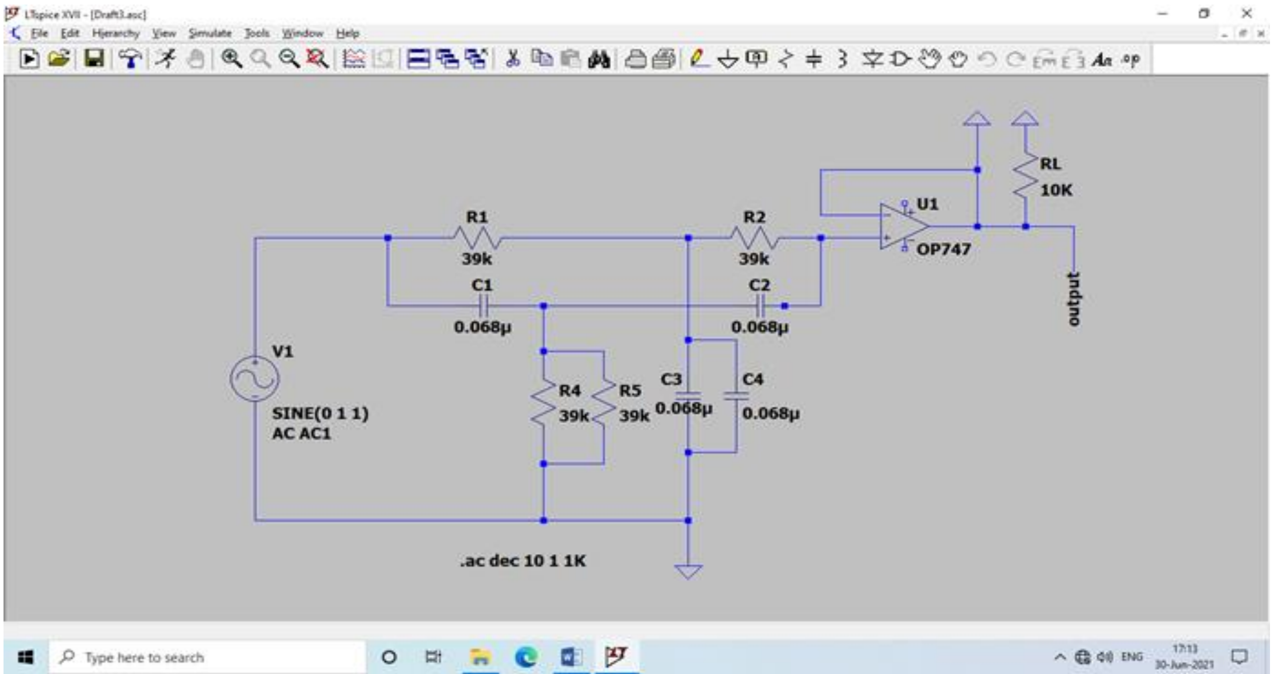


Fig 31. Notch filter circui

Output:

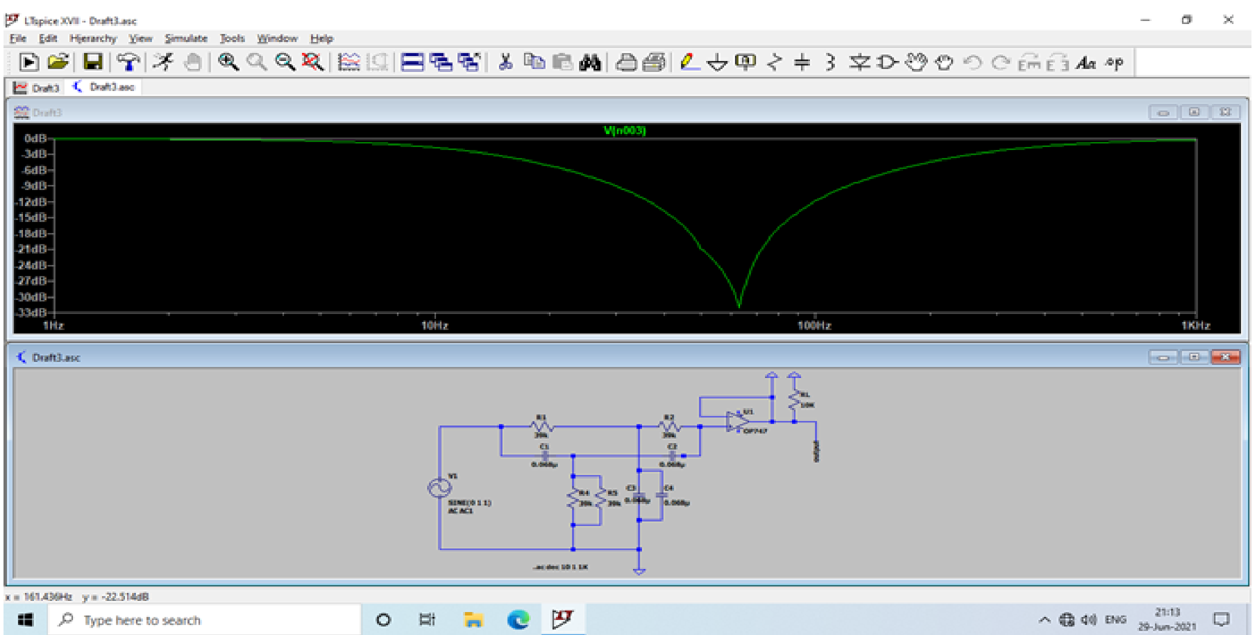


Fig 32. Circuit and output of Notch Filter

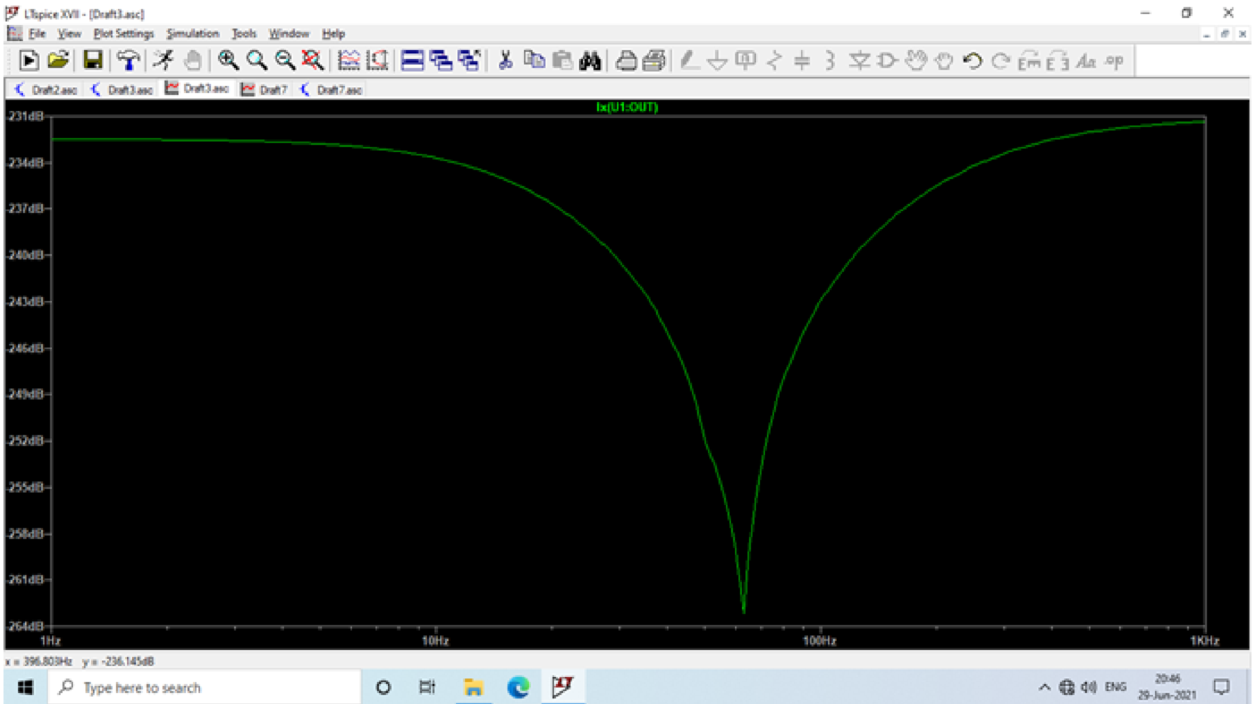


Fig 33. Output Waveform of Notch Filter

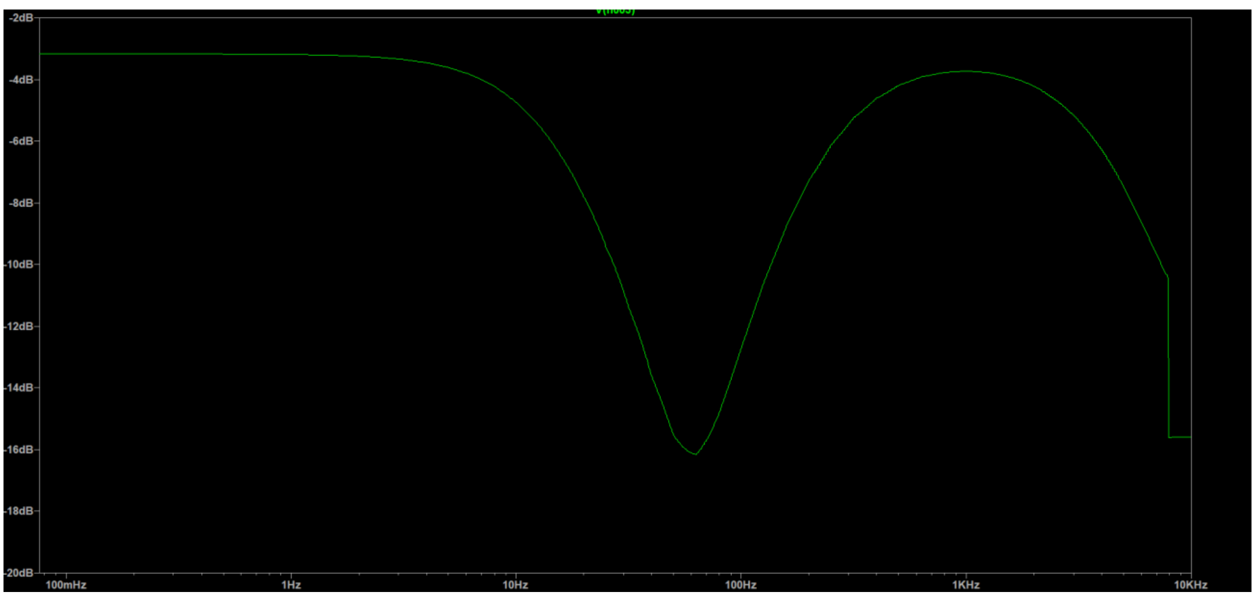


Fig 34. FFT waveform of Notch filter

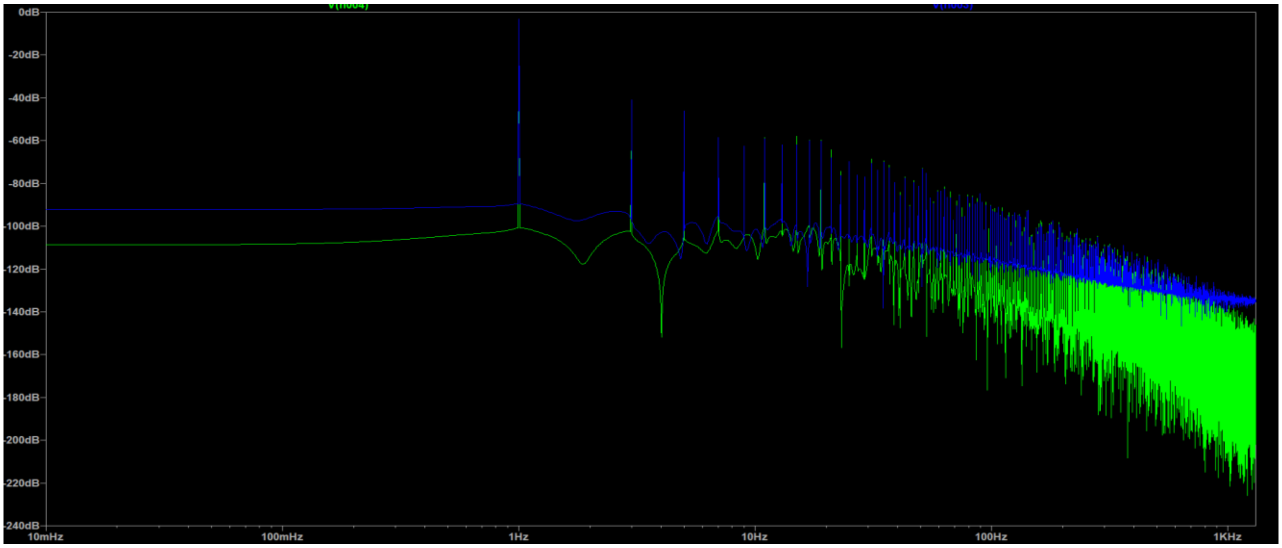


Fig 35.FFT waveform of Notch filter with input and output

Comparator:

Non - Inverting Comparator -

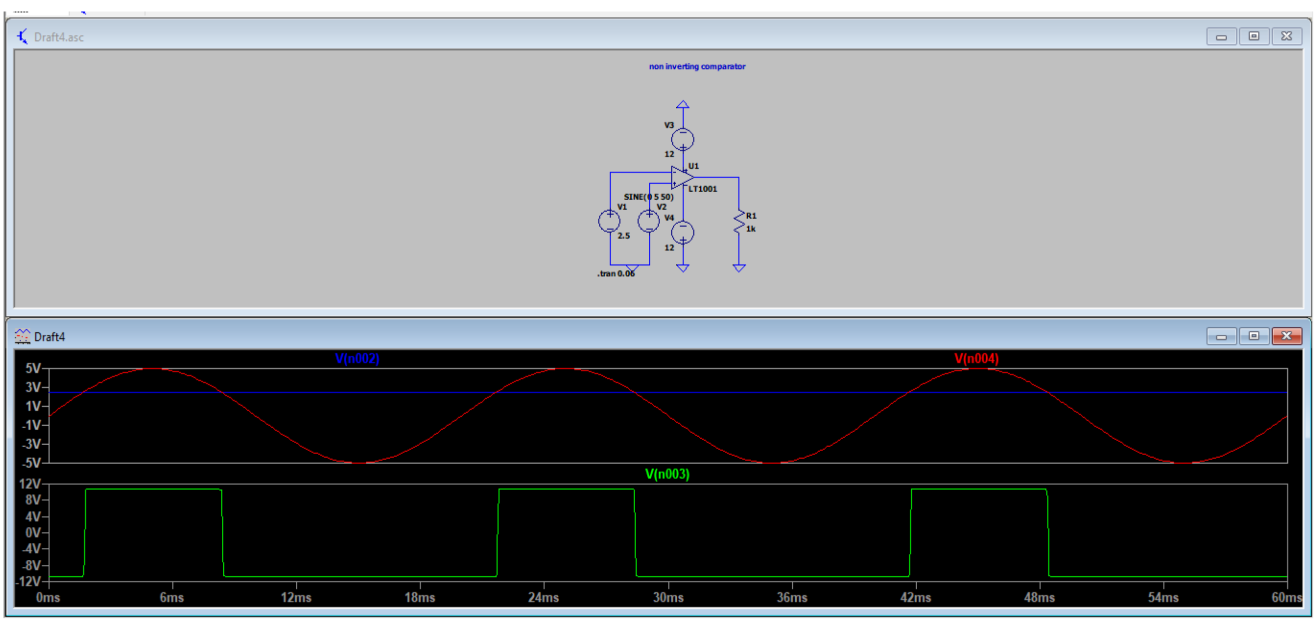


Fig 36. Circuit diagram and graphical representation of non- inverting comparator

In this non-inverting configuration, the reference voltage is connected to the inverting input of the operational amplifier with the input signal connected to the non-inverting input. To keep things simple, a fixed reference voltage , while the input voltage is variable from zero to the supply voltage. When VIN is greater than VREF, the op-amp comparators output will saturate towards the positive supply rail, Vcc. When VIN is less than VREF the op-amp comparators output will change state and saturate at the negative supply rail.

Inverting Comparator -

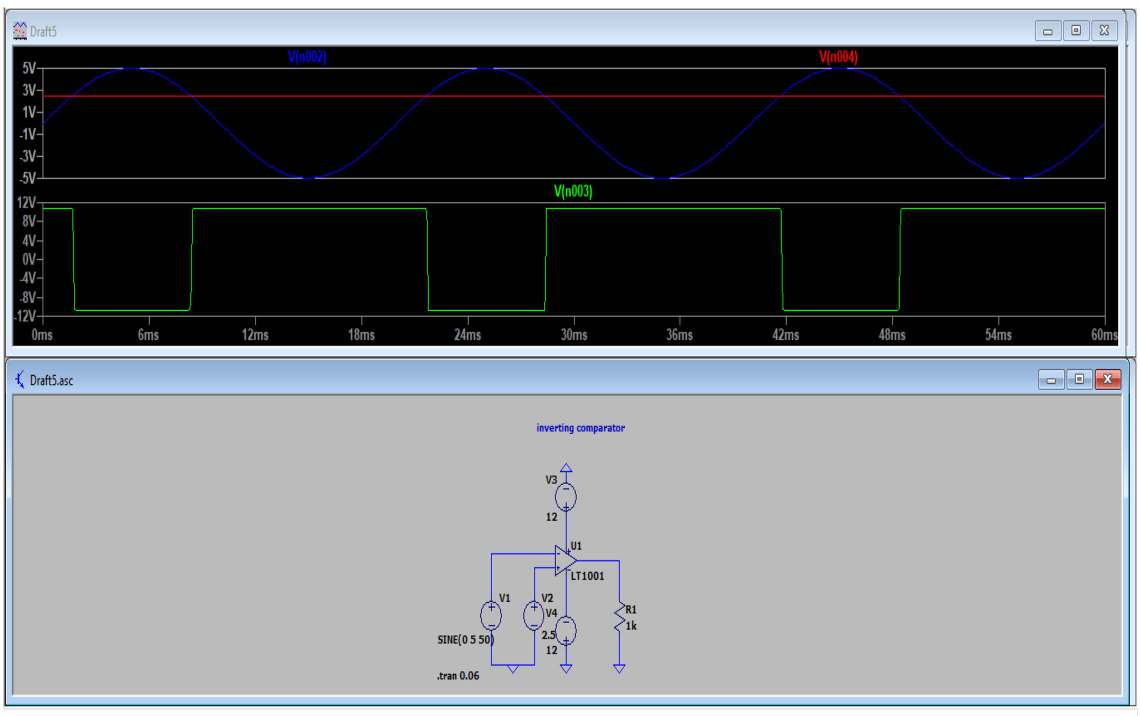


Fig 37. Circuit diagram and graphical representation of inverting comparator

In the inverting configuration, which is the opposite of the positive configuration above, the reference voltage is connected to the non-inverting input of the operational amplifier while the input signal is connected to the inverting input. Then when VIN is less than VREF the op-amp comparators output will saturate towards the positive supply rail, Vcc.

Likewise the reverse is true, when VIN is greater than VREF, the op-amp comparators output will change state and saturate towards the negative supply rail.

Observations:

1. The output of the non-inverting amplifier is inphase with the input applied and is twice the amplitude of the applied input.
2. The low pass filter response is cut off to 1kHz. The FFT output shows filtering of frequency and attenuation of the signal at cut off frequency.
3. By observing the frequency response of the High Pass Filter, we can say that the frequencies below cut-off frequency (in this case fc=100Hz) are blocked. Frequencies higher than cut-off frequency are allowed to pass through. By observing the FFT of the input and output signal, we can conclude that the input signal has higher harmonics which are reduced at the output.
4. A notch filter is a type of band-stop filter that attenuates frequencies within a specific range while passing all other frequencies unaltered. It is observed in the FFT that a 60Hz band frequency is notched while other frequencies are being passed through the filter.
5. In the non-inverting comparator, a reference voltage applied is 2.5V at the inverting terminal and the input voltage of 5V is applied to its non-inverting terminal. Whereas in inverting comparator, reference voltage applied is 2.5V at the non-inverting terminal and the input voltage of 5V is applied to its inverting terminal. Thus, a square waveform is obtained as a result of comparison operation when the input voltage is lower than the reference voltage.

Making Denoising Circuit and Determining Heart Rate

Input Waveform

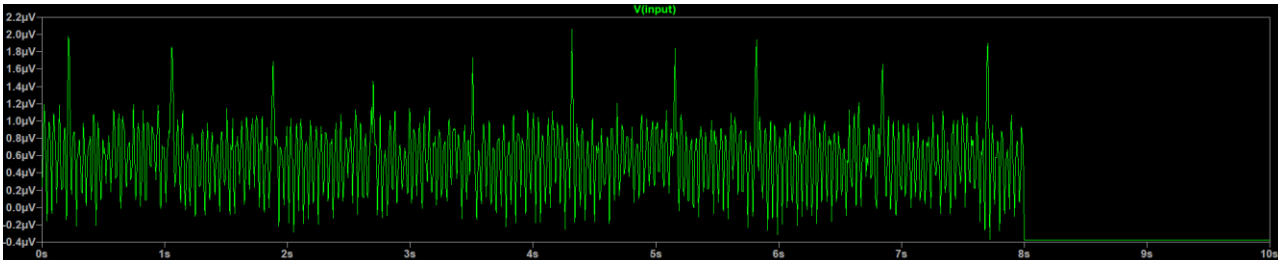


Fig.38. Input noisy signal

Circuit Diagram

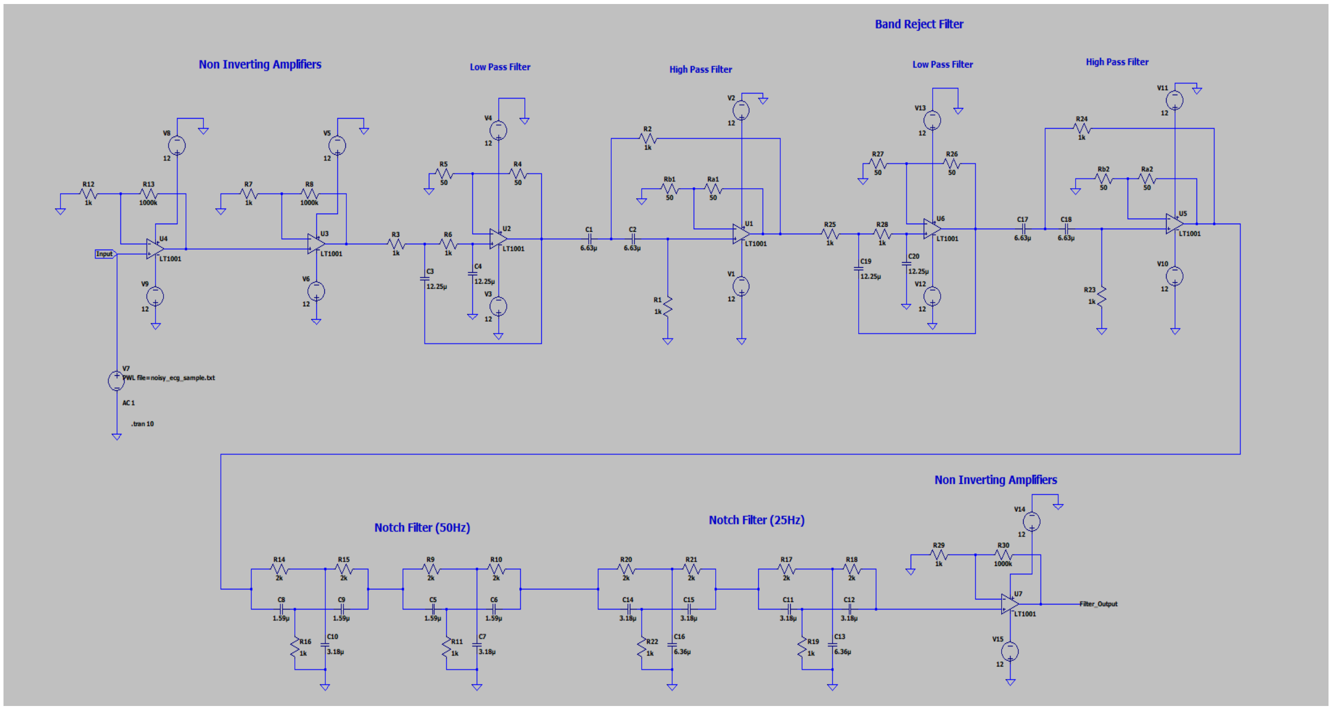


Fig:39. Circuit Diagram for Denoising a Noisy ECG Signal

Output Waveform

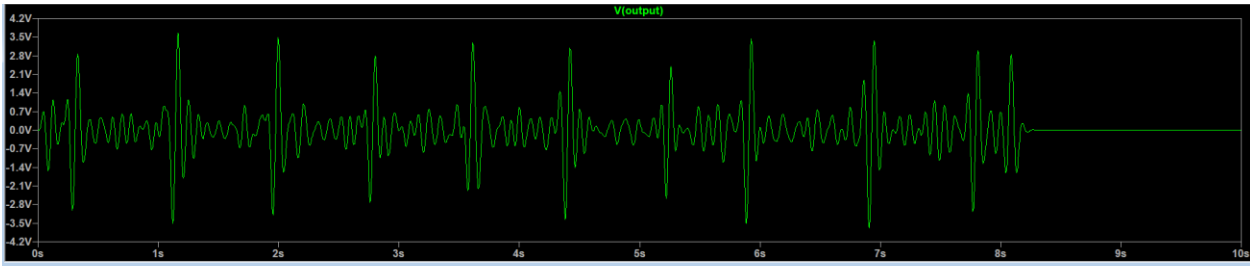


Fig.40. Denoised ECG signal

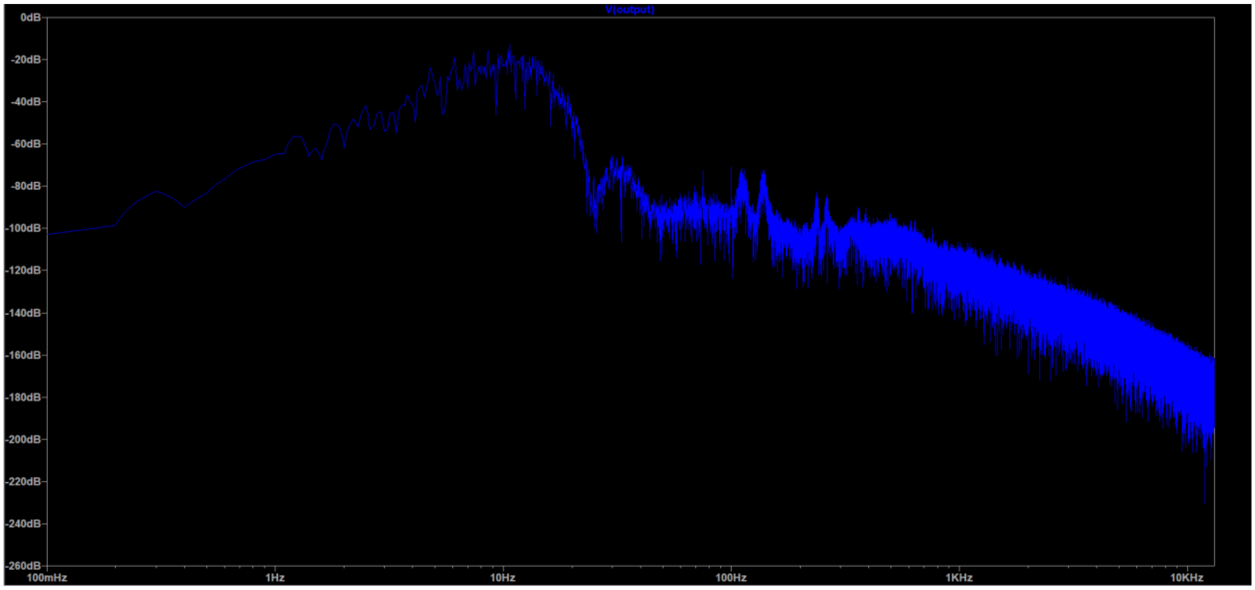


Fig.41. FFT of the output signal

Input signal - The provided noisy ECG input signal is in microvolts, it has to be amplified into volts so as to allow the filters to work properly. So two non-inverting amplifiers (Each having 1001 gain) are connected. Now with the total gain of 2002, the input signal which was in microvolts is amplified to volts.

Band Reject filter - The non inverting configurations are followed by two band reject filters with a frequency range 13Hz - 24Hz. This helps in blocking the frequency range of 13Hz to 24Hz .
Notch Filter - A notch filter attenuates a particular frequency. Here two notch filters of 50Hz cutoff frequency are used to block the 50Hz frequency component from the given noisy signal. Further, two notch filters of 25Hz cutoff frequency are used to block the 25Hz frequency from the noisy signal.
The signal is attenuated, so a non-inverting amplifier having gain of 1001 is used. We get the denoised ECG signal at the end.

Calculations

For Non-Inverting Amplifier

Let us design a non-inverting amplifier having gain 1001
Formula for Pass Band Gain is

$$A = (1+R13/R12)$$
$$1001 = (1+R13/R12)$$
$$1001 - 1 = R13/R12$$
$$1000 = R13/R12$$
Let R12 = 1k
$$1000 = R13/1$$
$$R13 = 1000k$$

So for a non-inverting amplifier to have gain of 1001, R12 must be 1kΩ and R13 must be 1000kΩ.

For Band Reject Filter

Let us design a Band Reject Filter for (13Hz-24Hz)

Low pass filter section,

Formula for Pass Band Gain is

$$A = (1 + R4/R5)$$

Let the gain be 2

$$2 = (1 +R4/R5)$$

$$1 = R4/R5$$

$$R4= R5$$

Let R4 = R5 = 50Ω

Formula for Cut-off frequency is

$$Fc = 1/(2\pi RC) \text{ Hz}$$

Let us design a LPF for Fc = 24Hz

Let us take R = 1kΩ

$$24 = 1 / (2 \text{ x } 3.14 \text{ x } 1 \text{ x } C)$$

$$C = 1 / (2 \text{ x } 3.14 \text{ x } 1 \text{ x } 24)$$

$$C = 6.63 \ \mu F$$

High pass filter section,

Formula for Pass Band Gain is

$$A = (1 + Ra1/Rb1)$$

Let the gain be 2

$$2 = (1 +Ra1/Rb1)$$

$$1 = Ra1/Rb1$$

$$Ra1= Rb1$$

Let Ra1 = Rb1 = 50Ω

Formula for Cut-off frequency is

$$Fc = 1/(2\pi RC) \text{ Hz}$$

Let us design a HPF for Fc = 13Hz

Let us take R = 1kΩ

$$13 = 1 / (2 \times 3.14 \times 1 \times C)$$

$$C = 1 / (2 \times 3.14 \times 1 \times 13)$$

$$C = 12.25\ \mu F$$

So for a Band Reject Filter (13Hz-24Hz),

For LPF section: R4 = R5 =50Ω, R = 1kΩ, C = 6.63μF.

For HPF section: Ra1 = Rb1 = 50Ω, R = 1kΩ, C = 12.25 μF

For Notch Filter

Let us design a Notch filter for Fc = 50Hz

Let R = 1kΩ

Formula for Cut-off frequency is

$$Fc = 1/(4\pi RC) \text{ Hz}$$

$$50 = 1 / (4 \times 3.14 \times 1 \times C)$$

$$C = 1 / (4 \times 3.14 \times 1 \times 50)$$

$$C = 1.59\mu F$$

Let us design a Notch filter for Fc = 25Hz

Formula for Cut-off frequency is

$$Fc = 1/(4\pi RC) \text{ Hz}$$

$$25 = 1 / (4 \times 3.14 \times 1 \times C)$$

$C = 1 / (4 \times 3.14 \times 1 \times 25)$

$C = 3.18\mu F$

So for a Notch Filter of 50Hz: R = 1kΩ, C = 1.59µF

So for a Notch Filter of 25Hz: R = 1kΩ, C = 3.18µF

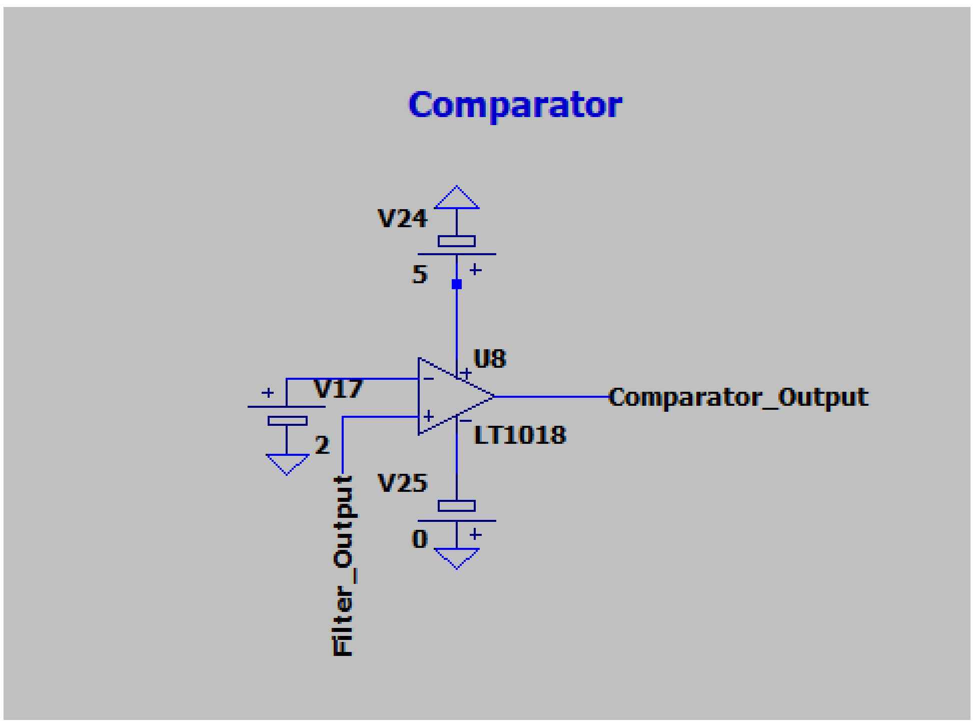
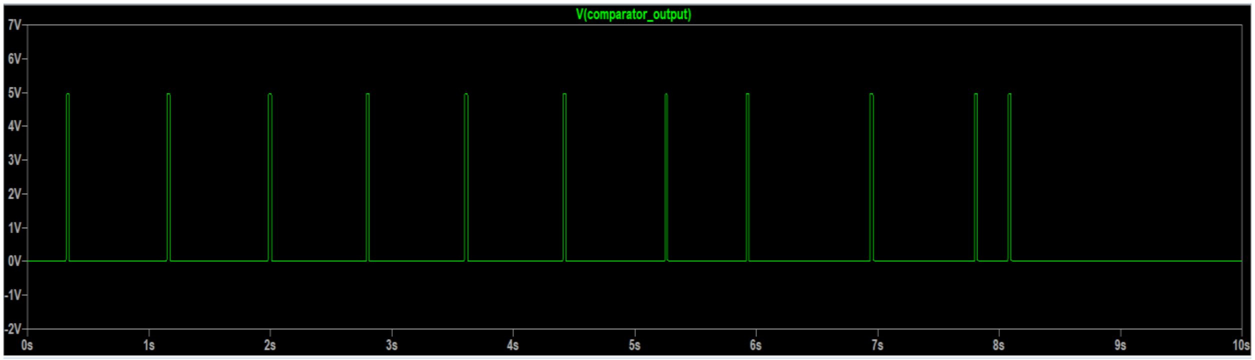


Fig.42. Circuit Diagram of the comparator

In order to measure the heart rate, the R peaks are required to be counted. For obtaining this, we have to acquire only the R-peaks from the denoised signal. A comparator is used for this purpose. It is given a threshold value of at is the signal above 2V will only appear. It further provides 5 V peaks for the R peaks and 0V for rest of the signal voltages. This helps in counting the heart beats from the filtered ECG signal. We have obtained 11 peaks at the end of the comparator. The heart rate depends on the distance between the two peaks that is ON time of comparator (T_{ON}).



` Fig.43. Output waveform of the comparator

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