# Analysis for the Implementation of Capacitive Couple Readout Circuit for Contact-less ECG and EEG

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**Abstract—In modern medicine, the two most common and actively used techniques for measuring electrophysiological signal for human are Electrocardiography (ECG) and Electroencephalography (EEG) systems. These physiological signals are very weak in amplitude in terms of few millivolts down to 10's of millivolts. The major amount of power is located at very low frequencies from below 1Hz up to 40 Hz. The measurement of the above parameters is very tough job in electrical circuit designs. Generally, the measurement of these parameters is done by electrodes with direct skin contact by applying of some gels. For this, time consuming clinical set up is required. This paper introduces a method for the measuring the above type of signals using a capacitive coupled sensor. This sensor is completely non-contact type, but this method has to face some difficulties, such as: high input impedance and interfaces and some circuit nose problems. A capacitive coupled sensor is realized by the printed circuit board (PCB) bottom layer as a one capacitor plate and the signal source is considered as another plate. In this, PCB layer mask acting as an insulator. The high input impedance amplifier gives the gain for the sensed signals is 60 dB and filtering also taken place. Two measurements were made off using the same circuit for two different input impedances. The results of these measurements show that high input impedance is a crucial parameter for the functionality of the sensor circuit and the high input impedance circuit provides always good signal to noise ratio (SNR).**

**Index Terms—Sensors, ECG, EEG, Readout, PCB, Electrophysiological signals, Amplifier, Instrumentation amplifier, Low Noise, Low Frequency and SNR.**

## I. INTRODUCTION

In health monitoring and diagnostics, the measurement of Electrophysiological signals play a vital role. The real information of health state is given by the electrical activity of nerve and muscles. The mostly used measuring techniques for the above electrical signals are EEG and ECG. The EEG is used to measure the electrical signals originating from the brain and ECG is used to measure the electrical signals generated by heart muscle. The EEG can be used to develop prosthesis, which can be control the patient's thoughts. Another application is detection of drowsiness of vehicle drivers to avid the accidents [1, 2]. Generally, EEG and ECG generate very weak signals with an amplitude of millivolts and have the major amount of the power is mainly located at very low frequencies [3].The SNR and linearity of the interfacing circuitry, are affected by the above two characteristics and it is difficult to measurement. The most important challenge regarding EEG and ECG signal is the interfacing sensor circuit with high accuracy in the noise environment.

These days EEG and ECG signal are measured by direct contact with skin using conductive coupling. For this direct skin contact measurement the glue gels are used with the help of fixating electrodes. The electrodes are silver chloride or gold type electrodes. This combination setup working as an electrical transducer to convert skin surface-ionic current to electron current. This current is amplified by electrical read-out circuit with high precision and low noise.

### *A. Idea about Circui Designs*

The authors Sullivan et.al[4] and Harland et.al [5] introduced electrical read-out circuit for bio-medical signals. This design considered PCB itself as a sensor and this sensor treated as a low noise read out sensor circuit. The PCB metal layer acts as one plate of the capacitor and it is charged by another plate is nothing but skin of the patient. This circuit is couple with the amplifying circuitry. The entire readout circuit is large in size, so it was split into two PCBs. These two PCBs are placed on top of each other to reduce the total size of the sensor. The area reduction means that within the same place more sensors can be occupied. One important aspect regarding to EEG measurement where it is beneficial to have a large number of sensors [6].The readout circuit is implemented using a bottom layer of the sensor board, which is filled with a metal. This acts as an antenna to receive the electromagnetic signals in the vicinity. This board is put in the form of flat, like a capacitor with its metal layer and the skin as two plates of the capacitor. The soldering mask or air is used as dielectric isolation between the plates. The overall interference in the circuit is reduced by a metal shield layer, which is placed between the sensor layer and the remaining circuitry This capacitor picks the signal, which is amplified by low noise, low input bias current and high input impedance instrumentation amplifier up to gain 50. Next, filtered by band pass filter and again amplified 20 times by another low noise operational amplifier. The total gain obtained as 1000 by amplifiers. From the input side of the instrumentation amplifier the capacitor cuts off the DC connection to ground effectively. Then the input bias current integrates onto the capacitor to increasing the offset voltage. This offset voltage slowly increasing and it would cross the common mode input voltage range. Finally, at particular stage the amplifier the operation becomes undefined and output gets distorted. To overcome this problem, a resistor is used to provide a return path for the input bias current. This resistor and sensor capacitor combination forms a high pass filter. Here,

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the capacitor should be small and resistance will be high enough to pass the EEG and ECG signals. If this simple circuit is suitable for these applications then the complex design presented in the paper [6] can be ignored. By observing the possibilities and limitations this simple circuit can be used for the read out circuits.

## II. SYSTEM OVERVIEW

The complete Readout circuit system consists of four parts. The actual sensor, first amplification stage, notch filters and second amplification stage. The actual sensor is the capacitor plate. A high input impedance instrumentation amplifier used as first amplification stage and second amplification stage is for additional gain is combination of op-amp and band pass filter. For filtering the interfering signals two notch filters are used. The complete readout circuit shown in Figure.1.

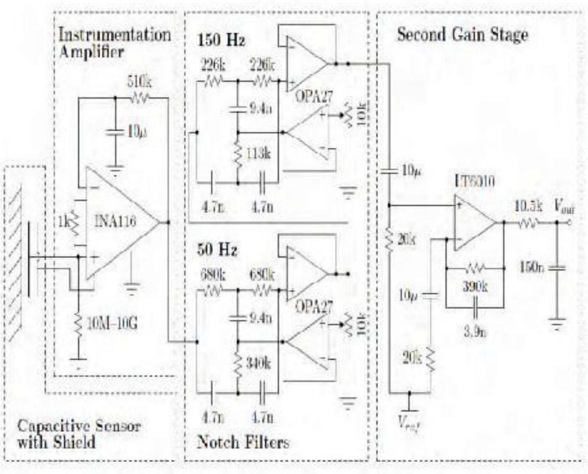

Figure 1. Circuit diagram of the complete system.

The sensor consists of two plates, such as PCB metal layer and skin of the subject to measure. The soldering mask or any material can be used as dielectric material. This sensor or capacitor is separated from the remaining circuit using a shielded layer and it is connected to the non-inverting terminal of the instrumentation amplifier. This instrumentation amplifier amplifies the signal by the gain of 50 and provides the feedback loop. In the feedback loop, the low pass filter makes the inverting terminal slowly follows the non-inverting terminal. The final circuit in the readout system is another amplifier, which gives the further gain of 20 and also provides the appropriate filtering by the band pass filter. Then the total gain in the system over the pass band is equal to the 1000 or 60 decibels theoretically.

### *A. The Capacitive Sensor*

The capacitor sensor is implemented as a parallel plate capacitor. It means two metal plates are separated by a dielectric material. One plate is PCB metal layer and the second is skin of the patient. The figure 2. Shows the sensor setup. Here, the capacitor plates area is greater than the distance between the plates. Then the parallel plate capacitance is given by,

$$C = or\frac{A}{d}$$

Where, $\varepsilon o$and $\varepsilon r$ are the dielectric constant and relative dielectric constant, d is the distance between the plates and A is area of the platesrespectively.

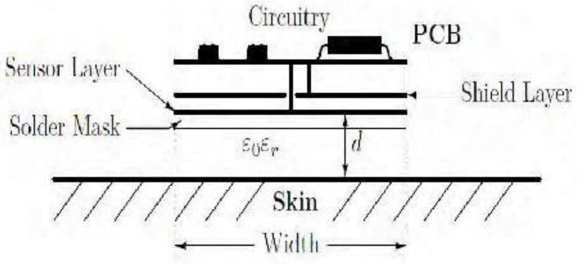

Figure 2. The cross sectional view of the PCB sensor.

The above figure represents the Capacitance equation variables and how those are physically determined. In this, the dielectric constant and distance‘d’ are varying with the position of the sensor. Due to this variation the determination of exact capacitance value is little bit difficult. The isolation dielectric constant value between the plates is defined by the air and solders mask material. The input resistance of the first stage amplifier and the sensor capacitance forms a high pass filter. For this low capacitance value is required. To lowering the capacitance, the sensor is moved away from the skin or source of the signal. It will change the cut-off frequency of the filter. Hence high input resistance is required to enable the low frequencies of the EEG and ECG. This high input resistance makes the less impact of the capacitance change to alter the cut-off frequency of the filter.

### *B. Instrumentation Amplifer*

In this readout circuit, the INA116 used as instrumentation amplifier, which is provided by Texas instruments. It gives very low input bias currents and very high input impedance. It has low noise with respect to current and it is used for low noise applications. The buffer guard pins on output side to provide low output impedance [7]. These parameters are ideal to use for the reduction of the leakage currents in the sensor circuit

### *C. Notch Filters*

The narrow band reject filter is used as a notch filter, which selects the specific frequency component from the input signal. Generally, these filters are used to reject the unwanted interfered signals and suppress the hum due to main power. From the input side of the instrumentation amplifier, at 150 Hz and50 Hz frequencies the sufficient large amplitudes are identified to saturate the last stage of the readout circuit. Two notch filters are used to suppress these interferences, which are inserted between two stages. Two operational amplifiers are require to implement the notch filters. In this design totally four OPA27 amplifiers are used from Texas Instruments. It is low noise and high precision amplifier.

### *D. Second Gain Stage and Band Pass Filtering*

This stage is realized by one operational amplifier and the band pass filter. This stage provides the additional gain

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and interested frequency selection. The LT6010 Op-Amp IC selected for this stage. It is operated for 3 volts supply voltage with high precision [9]. It is designed as a band pass filter with pass band gain of 20.5. This circuit is followed by another filter i.e. Low pass filter, is used for the limiting the upper band frequencies and aliasing problem is eliminated by this low pass filter. If any DC voltage is provided by instrumentation amplifier, is overcome by first stage high pass filter.

## III. CIRCUIT ANALYSIS

In this section, the complete analysis of the system is presented. The Laplace transforms are used to obtain the frequency response of all the circuits.

The actual sensor circuit part is shown in the figure. 3. It is meant to create a capacitor between the circuit board and the human skin to pick up the weak signals that are generated by the human body. This capacitor and biasing resistance provides the very high input impedance to Dc voltages of instrumentation amplifier. It constitutes a filter with a high-pass characteristic. The overall capacitance of this sensor is determined using many parameters, such as area of the sensor, dielectric constant, and distance between the sensor and the skin etc.

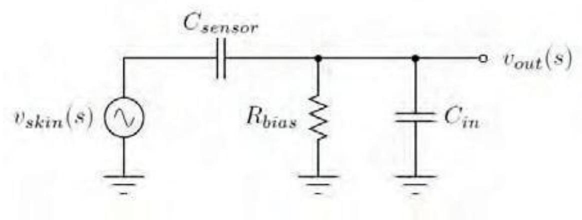

Figure 3. Small signal model of the capacitive sensor

The $C_{in}$ is the input capacitance of the instrumentation amplifier. From this we can understand it is a simple high pass filter in nature. Here, the instrumentation amplifier input resistance is greater than the bias resistance, then the output is

$$V_{out}(s) = \frac{R\,bias \,||\, \frac{1}{sCin}}{\frac{1}{sCsensor} + (R\,bias \,||\, \frac{1}{sCin})} \quad V_{skin}(s)$$

After some algebra the transfer function H(s) is found as

$$H(s) = \frac{V\,out\,(s)}{V\,skin\,(s)} = \frac{C\,sensor}{C\,sensor + cin} \frac{s}{s + Wo}$$

$$W_o = \frac{1}{R\,bias\,(C\,sensor + C\,in)}$$

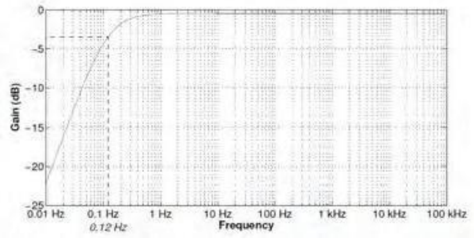

Figure 4. Transfer function of the filter at the input.

The cutoff frequency and high pass characteristics are given by the above equations. Another noticeable thing in the first equation is the constant loss of $\frac{C\,sensor}{C\,sensor + cin}$ in the pass band. The magnitude of the loss is depends on the capacitance value. If the capacitance drops to within one order of magnitude of the input capacitance, the loss will be more than 10 % of the amplitude.

The Figure 4 shows the frequency response of the filter with $R_{bias}$ =10GΩ, $C_{in}$ =7pF as per the amplifier datasheet [10] and $C_{sensor}$ = 125 pF. In the above figure the -3 dB cutoff frequency is indicated with the dashed line and is 0.12 Hz.

### A. *Input Amplification Stage*

The instrumentation amplifier (INA116) consists of three operational amplifiers as shown in Figure.5. The first two amplifiers provide gain to both the inputs. The gain is adjusted to suitable value by varying an external resistor $R_G$ which is connected between the first two stages. The third operational amplifier acts as a difference amplifier, which amplifies the difference between these two amplified signals. A buffer is added for each input line of the instrumentation amplifier [7]. Those are considered for analysis, because they ideally will not alter the signals. The external feedback network is connected to the inverting terminal of the amplifier and input is applied for the non-inverting terminal of the amplifier. For the analysis of the instrumentation amplifier, the ideal op-amp characteristics are considered. Such as infinite gain, infinite input resistance and zero output resistance.

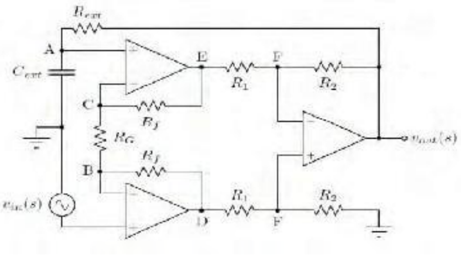

Figure 5. Small signal AC equivalent model of the instrumentation amplifier

The internal nodes A, B, C, D, E, FAND R1, R2, RF are marked out in the above equivalent circuit. The $R_G$ and $R_{ext}$ , $C_{ext}$ are gain resistance and external feedback filter elements respectively as shown in the Figure. 5. The nodal equations with respect to above small signal model are:

At A node: $$- V_a(s)\,.sC_{ext} + \frac{V\,out\,(s) - V\,a\,(s)}{R\,ext} = 0,$$

At B node: $$\frac{V\,a\,(s) - V\,in\,(s)}{R\,G} + \frac{V\,d(s) - V\,in\,(s)}{R\,f} = 0,$$

At C node: $$\frac{V\,in\,(s) - Va\,(s)}{R\,G} + \frac{V\,e(s) - V\,a\,(s)}{R\,f} = 0,$$

At F node: $$\frac{V\,d(s) - V\,f\,(s)}{R\,1} - \frac{V\,f(s) - V\,in\,(s)}{R\,2} = 0,$$

$$\frac{Ve\,(s) - V\,f\,(s)}{R\,1} + \frac{V\,out(s) - V\,f\,(s)}{R2} = 0,$$

The above equations can be rewritten as

$$V_a(s) = V_{out}(s)\,.\,\frac{1}{1 + s\,Rext\,Cext}$$

$$V_d(s) = \frac{Rf}{RG}(V_{in}(s) - V_a(s)) + V_{in}(s)$$

$$V_e(s) = -\frac{Rf}{RG}(V_{in}(s) - V_a(s)) + V_a(s)$$

$$V_{out}(s) = \frac{R2}{R1}(V_d(s) - V_e(s))$$

Figure. 6 represents the filter frequency response for the component values $R = 20$ k and $C = 10\ \mu$F, the cutoff frequency is at 0.8 Hz.

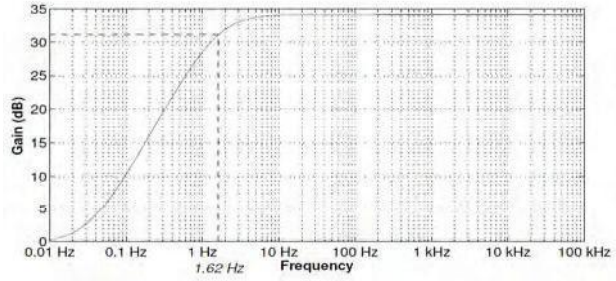

Figure 6. The frequency response of the input amplification stage.

### B. Inter-stage Filter and Level Shifter

The inter stage filter is a simple passive HPF (high pass filter) but it working as a level shifter. The circuit shown in the figure 7 is used as level shifter circuit. This circuit brings the DC bias voltage to the middle of the Voltage rails VDD and GND of the second amplifier. That uses a single ended supply voltage.

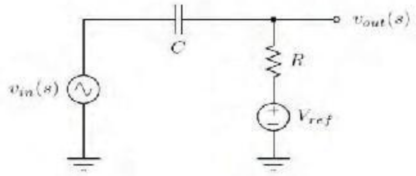

Figure 7. The AC equivalent mode of the inter stage high pass filter and level shifter.

In the DC analysis, the capacitors are open and nod $V_{out}$ is floating. Then the output is equal to input DC voltage because no current in resistor. i.e. there isa level shift.

$$V_{out} = V_{ref}$$

For the AC equivalent model analysis, one of the condition with respect to DC voltage sources is short circuit. After shorting the Dc source the current in the circuit is given by

$$i_{out}(s) = \frac{Vin\ (s)}{R+\frac{1}{sc}}.$$

The o/p voltage then voltage drop in resistor due to $i_{out}$ and is given by:

$$V_{out}(s) = \frac{sRC}{R+\frac{1}{sc}} . V_{in}(s)$$

The transfer function of the circuit is given as

$$H(s) = \frac{V\ out\ (s)}{V\ in\ (s)} = \frac{s}{s+Wo} \qquad \text{where} \quad w_o = \frac{1}{RC}$$

The above transfer function represents that the HPF with $w_o = \frac{1}{RC}$ as cut off frequency. The frequency response of this HPF is shown in the figure. 8. For this response the practical values are C=10μf and r=20KΩ and cut off frequency assumed as 0.8 Hz.

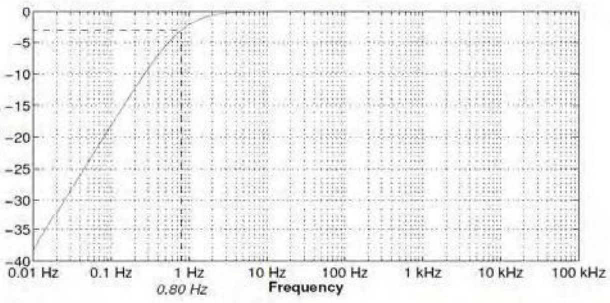

Figure 8. The frequency response of the inter stage HPF

### C. Second Amplification Stage

The next stage is combination of amplification stage and band pass filter. This provides more gain and the selection of interesting frequency band using band pass filter. The filter is implemented using one active band pass filter and followed by passive low pass filter. The figure 9 represents filter circuit in the second stage of the read out circuit. The operational amplifier is considered as ideal amplifier with DC voltage as short circuit for the small signal AC analysis. Looking at Figure 9 we get the following nodal equations:

$$\text{Node A : } \frac{-V\ in(s)}{R+\frac{1}{sC1}} - \frac{V\ b(s) - V\ in\ (s)}{R\ 2||\frac{1}{sC2}} = 0,$$

$$\text{Node C : } \frac{V\ b(s) - V\ out\ (s)}{R\ 3} - v_{out}(s) .s\ C_3 = 0,$$

Solving the above equations for $v_b(s)$ and equating them gives the output voltage as

$$V\ out\ (s) = v\ in\ (s)\ \left(1 + \frac{R2||1/sC2}{R1+1/sC1}\right) . \frac{1}{1+sR3C3}$$

This results in the transfer function

$$H(s) = \left(1 + \frac{R2}{R1} . \frac{s}{s+w\ HP} . \frac{W\ LP1}{s+w\ LP1}\right) . \frac{W\ LP2}{s+w\ LP2}$$

Where

$$W_{HP} = \frac{1}{R1C1},\ W_{LP1} = \frac{1}{R2C2},\ W_{LP2} = \frac{1}{R2C2}$$

If $W_{LP1} \approx W_{LP2} >> W_{HP}$, this stage acts as a band-pass filter with a DC gain of 1 and a pass band gain of $1+\frac{R2}{R1}$.

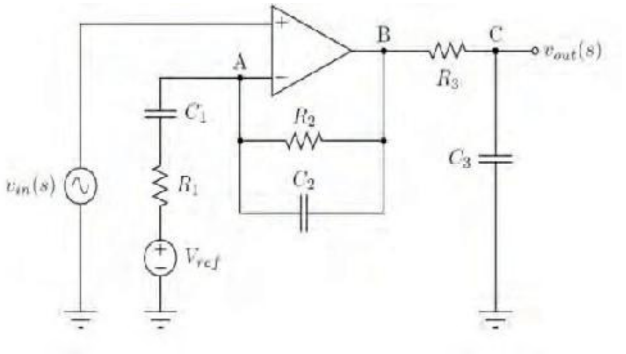

Figure 9. Small signal model of the second amplification stage

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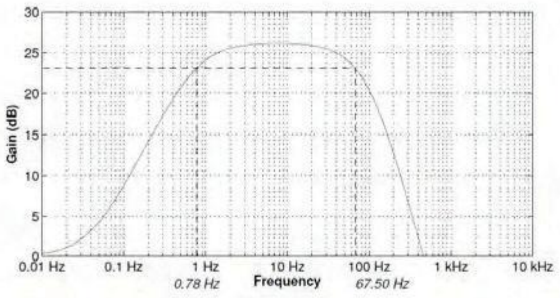

Figure 10. The second amplification stage frequency response.

The figure. 10 represents the frequency response of the second amplification stage with the following component values: $R1 = 20$ k $C1 = 10\ \mu$F,$R2 = 390$ k $C2 = 3.9$ nF and $R3 = 10.5$ k $C3 = 150$ nF. The pass band of the filter in the figure is between 0.78 Hz and 67.5 Hz. The -3 dB cutoff frequencies are marked by the dashed lines and are 0.78 Hz and 67.50 Hz.

### *D. Notch Filter*

The filter response and effectiveness depends on the quality factor Q value of the filter. The notch filter has to remove the selected sing frequency component. For this notch filter high Q value is required. The high quality factor filter working as is very narrow band notch filter.

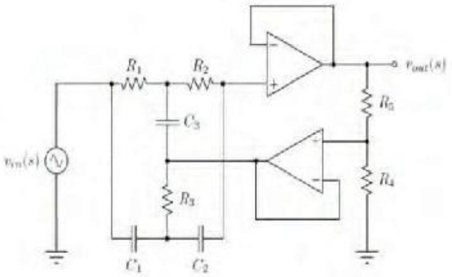

Figure 11. Circuit diagram of an active twin-T notch filter circuit.

The figure11 represents the notch filter circuit. It consists of an active filter with common passive twin-T notch filter. The Q value 14 is considered for original filter, the further Q value is much improved by active feedback. This type of circuit can be easily implemented by few elements and this circuit also makes Q quite sensitive for matching the components. The matching problem is eliminated by this notch filter.

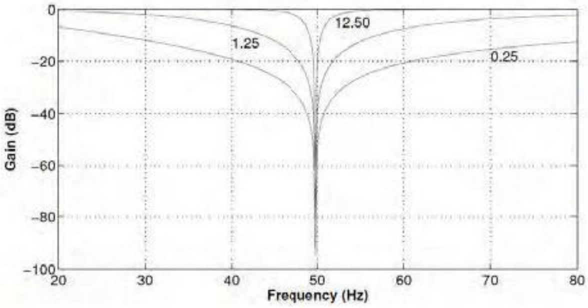

Figure 12. The notch filter Transfer function for different Q values.

## IV. RESULTS

The Figure 13 shows the complete frequency response of the system. This is achieved by combining or multiplying all the individual frequency responses of the sub blocks in the entire readout system. The another response also taken of all sub blocks are included to the total response except frequency response of the notch filter is presented in the Figure 14.

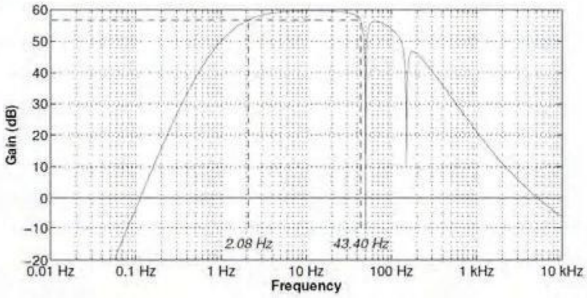

Figure 13.The complete Frequency response of the readout circuit including notch filters

The comparison between the figure 14 and figure 15 reveals that the without notch filters the frequency response is normal. The notch filter response limits the notch at 50 Hz and in the upper bound on the bandwidth. i.e 69.2 Hz to 43.4 Hz. This not considered as the big issue in the ECG and EEG measurements, because the most of the power is concentrated below the 40 Hz frequencies.

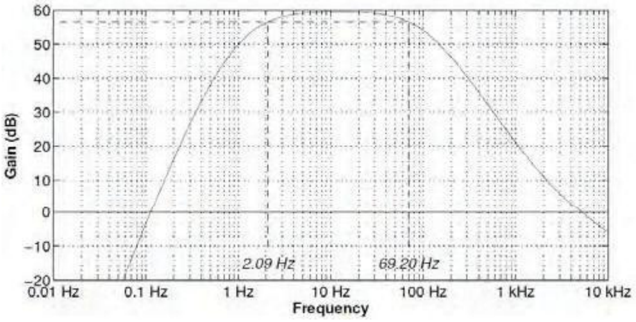

Figure 14. The Frequency response of the complete readout system without notch filters.

## V. CONCLUSIONS

The low level, low frequency EEG and ECG signals are measured using a non-contact type readout circuit with simple PCB sensor. In this system implementation two major issues are, i) The high value of input resistor is required for the sensing low frequency signals; ii) the sensor amplifies the more noise generated from the main power lines.

The capacitive sensor is implemented using a PCB metal layer as one plate and the skin of the patient is considered as another plate for the capacitor. The air and solder masks are treated as isolation dielectric insulating material, which is placed between the capacitor plates. Due to the size complexity, the two PCBs are implemented and placed on one top to another. Then the overall size of the readout circuit is approximately 25 X25mm.

In the read-out circuit, the first stage is instrumentation amplifier which provided the gain of 50. The sensor input capacitance and the input bias resistance of instrumentation amplifier are very high to pass the low frequency signals sought to be measured. The second stage is a combination of amplifier with gain 20 and band-pass filter. To reduce the

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unwanted interfering signal or noise one additional filter is required at some frequencies. This filter is inserted in the place between the two PCB circuits.

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