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Low Noise Signal Conditioning Design for Electrostatic Sensors

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Abstract: The signal conditioning circuit of the electrostatic sensor is a small signal amplifier that collects and amplifies the detected electrostatic noise. Due to its high amplification properties, the output signal is highly susceptible to be defaced by intrinsic or extrinsic noise. This paper is proposed a low noise signal conditioning circuit for electrostatic sensor. A circuit model is proposed as the electrode of the sensor to be used in circuit design and circuit analysis. An electrostatic noise collector amplifier is designed using a high impedance FET operational amplifier. A dual power supply using a single battery is provided to isolate the circuit from 50 Hz extrinsic noise. The design is investigated for its gain, bandwidth and noise properties. The sensor test results verified the design objectives. The circuit can be used to design a low noise measurement system using an electrostatic sensor in powder and particle technologies. *Copyright © 2013 IFSA.*

Keywords: Electrostatic sensor, Metal electrode, Circuit model, Signal collector, Extrinsic noise, Frequency spectrum.

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1. Introduction

Electrostatic sensor is a robust and cost effective sensor that can detect the electric charge from moving dry charged materials. Particle movement in a pipeline or a conveyor can produce small amount electrical charge due to particle to particle and particle to pipe wall collision, and this led to extensive research to apply the electrostatic sensor as a device to measure flow parameters in powder and particle flow conveyors. Some major researches in this area are velocity measurement using the cross-correlation technique [1] or spatial filtering method [2], mass flow rate in direct method [3], concentration profile-map utilizing process tomography method [4], and particle mean-size measurement [5] are some studies to reveal the electrostatic sensor capabilities.

Electrostatic sensor consists of two main parts, sensor electrode and signal conditioning circuit. The electrode depends on application can get a different shapes include ring electrode, pin electrode and plate electrode. The ring electrode has been studied by Gajewski [6, 7] and Yan *et al*. [1] to model the electrode and measure the sensor bandwidth and amount of detected electrical charge in a pipeline. Pin electrode and plate electrode modelled by KrabiKa *et al*. [8] and Rahmat *et al*. [9] Respectively to find the characteristics of the electrodes.

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A typically signal conditioning circuit for electrostatic sensor consists of a signal collector and a signal amplifier. The signal conditioning circuit for electrostatic sensor is dealing with a random and a very small range of electric charge fluctuations. In a pipeline with a mass flow rate between 0.3-3 kg/s electric charge density is about $10^{-7} - 10^{-3} (C / kg)$ [1] where the current would be less the 3mA and for a single particle it would be about few Nano ampere [10]. In that condition, due to the high amplification requirement, the noise analysis is very important to be taken into account in circuit design. Furthermore, the electrostatic sensor output is extremely sensitive to extrinsic noise. An electromagnetic field from an AC power line near the sensor easily can be detected by sensor electrode and amplified by the signal conditioning circuit that can drown and damage the desired signal from the electrostatic charge source. The amplification gain of the signal conditioning circuit design depends on the amount of the electric charge in the pipeline or particle and the electrode dimension. A sensor that designed to detect small electric charges on a single particle can go into saturation in a particle flow conveyor due to higher levels of electrical charge in the pipeline.

In this study, a signal conditioning circuit is designed to collect and amplify the induced electrostatic noise from a single particle to the sensor electrode. The design is followed by detailed explanations for each step and possible noise measurement using Multisim simulator. To collect the electric charge fluctuation a current-to-voltage transducer is applied using an operational amplifier. A low-noise instrumentation amplifier is used as the second stage to amplify the collected signal from the electrode. To keep the sensor safe from the electromagnetic field noise produced by electric power line a double supply source from a 9-volt battery is provided by utilizing a voltage converter circuit. The circuit is tested using ring electrode to verify the expected results.

2. Electrostatic Noise Collector

The signal conditioning circuit design for electrostatic sensor starts with designing the electric charge collector. When a charged particle passes through a ring electrode or near a pin electrode, it induces some amount of electric charge into the electrode. This electric charge either can be collected as the original shape of electrostatic noise using a capacitor, or it can be collected as voltage or current using a resistor. Fig. 1 shows a particle passing near an electrode and the output signal shape. When the particle reaches to the electrode detecting area and passes through that area, it leaves a peak-shape output signal due to charging and discharging process of the capacitor. The output voltage is a function of the induced charge to the electrode, and it is equal to:

$$V = \frac{q'}{C}, \tag{1}$$

where q' is the induced charge on the electrode in *Coulomb* and C is the capacitance of the capacitor in *Farad*.

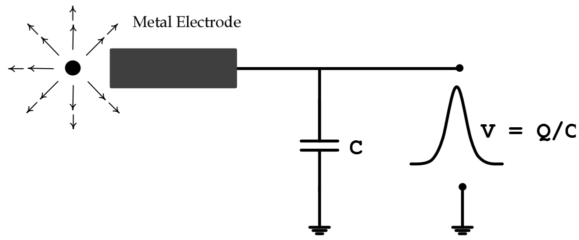

Fig. 1. Electrostatic noise collector using a capacitor.

In the second method, a resistor is used to convert the induced electric current to a voltage signal. The electric current is shaped as the rate of electric charge on the surface of the electrode that can be represented as Equation 2:

$$i = \frac{dq'}{dt}, \tag{2}$$

Passing the electrical current on resistor forms the *RI* voltage on resistor as it's depicted in Fig. 2. In the other word, the output signal in Fig. 2 can be formed by derivation of the output signal of the circuit in Fig. 1.

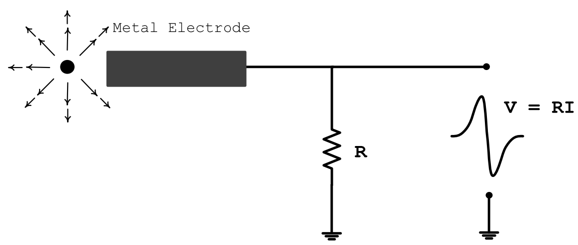

Fig. 2. Electrostatic charge noise collector circuit using a single resistor.

In a measurement system, the electric current could be converted into voltage in two methods. In the first method, a resistor is used to convert the electric current into the voltage as it showed in Fig. 2. The second method uses an operational amplifier where the electric current is injected into the summing node of the Op-Amp as it has shown in Fig. 3

Using the Current-to-voltage circuit in Fig. 3 is more desirable to collect and amplify the electrostatic noise. Since, using a resistor as it shown in Fig. 2, will insert a resistor in measuring system and causes the relative error. Furthermore, the resistor increases the offset voltage in the amplifier [11].

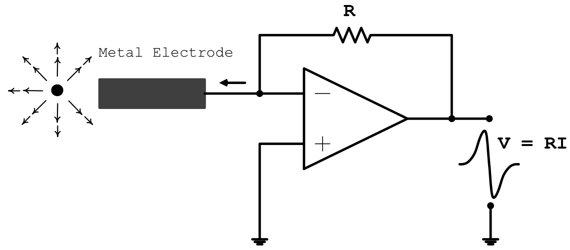

Fig. 3. Applying current-to-voltage converter to observe the electric charge fluctuation.

3. Circuit Design

3.1. The Electrode's Equivalent Circuit Model

To design the signal conditioning circuit, it is required to model the physical form of charged particle and electrode to its equivalent electrical circuit. The electrostatic sensor was modeled by Gajewski 1999 [10], as a three branch circuit, which is shown in Fig. 4. This model represents the relation between charged particle with the sensor electrode in reference to the ground. Branch 1-3 in this model represents the charged particle as a current generator $i_{13}(t)$ with the relative capacitive and resistive coupling of source to the ground. The capacitive and resistive coupling between particle surface and electrode wall represented as the circuit in branch 1-2. The circuit branch 2-3 represents the electrode's capacitive and resistive coupling in reference to the ground.

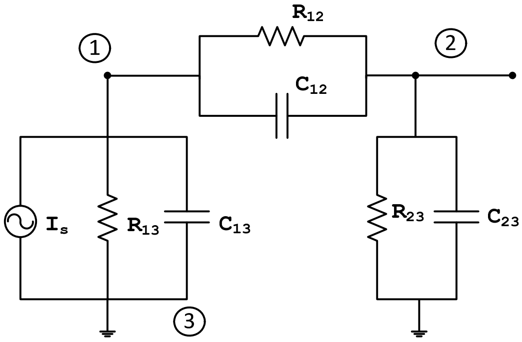

Fig. 4. Gajewski model of electrostatic sensor.

Gajewski used a metal earthed screen to protect the electrode from extrinsic environmental induction. Since the screen is not used in this paper the coupling resistance and Capacitance do not shape the 1-3 and 2-3 branches. The resistor in the branch 2-3 has a very high value of resistance where Gajewski [10] in his research suggested it a value of at least 1 TΩ. To have a simple model the resistor can be assumed to be open circuit. With that assumption, the new model of the charged particle and electrode can be descried as a current source and its equivalent coupling capacitor, which is shown in Fig. 5. The equivalent capacitance for C_s is equal to C_{12} which highly depends on the geometrical size of electrode area and distance between charged particle and electrode surface.

The current source model for the sensor describes the sensor as a high output impedance device.

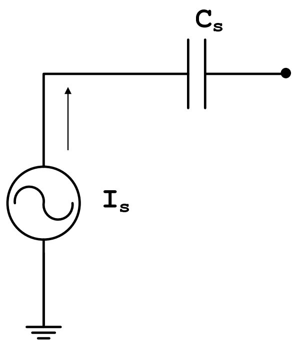

Fig. 5. The equivalent circuit model for the electrode.

3.2. The Signal Conditioning Circuit

To design the electric charge noise collector, a current-to-voltage converter is used in conjunction with the sensor's circuit model as it has shown in Fig. 6. In this circuit, the resistor R_f is used in parallel with the capacitor C_f in the feedback line to control the gain and frequency bandwidth. The value of the resistor R_f in the feedback loop determines the gain of the amplification which results the $R_f.I_s$ (Volt) signal at the output.

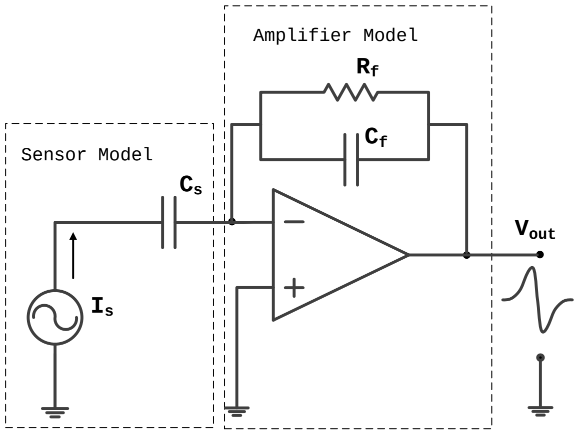

Fig. 6. Signal conditioning circuit for electrostatic sensor.

The cutoff frequency of the circuit can be given as:

$$f_c = \frac{1}{2\pi R_f C_f}, \tag{3}$$

The resistor R_f biases the amplifier's gain. The capacitor C_f is open in low frequencies and current passes through R_f. In the frequency higher than f_c the C_f is dominant and efficiently reduces the output gain. The value of the both feedback capacitor and feedback resistor can affect the amplifier frequency bandwidth. The resistor R_f is selected in a way that it produces the interested gain for the circuit; so, the bandwidth would be adjusted by selecting the suitable feedback capacitor.

The previous researches showed that, the electrostatic sensor electrode acts as a low-pass filter where a typical ring electrode which examined by C. Xu *et al.* [12, 13] didn't show to pass the frequency components more than 300 Hz. While the sensor electrode acts as a low-pass filter, it seems it is unnecessary to have a feedback capacitor in amplifier to filter the high frequencies. The point is, in actual applications of electrostatic sensor, for instance, when an electrode installed in a conveyor, the high-frequency noises may impose into the circuit from conveyor's or the pipe's vibration. It gets important, especially when the electrode is installed as an intrusive component; the direct impact of particle to the electrode imposes piezoelectricity noise into the circuit. The effect of piezoelectricity noise can be reduced by using the filtering circuit in the amplifier. Furthermore the noise magnitude produced by circuit component can be reduced effectively using a low pass filter.

One limitation of using the resistor in the feedback path is the biasing current. In the amplifier, the flow of the input-bias-current through the feedback resistor creates an output voltage offset. It can be reduced by selecting a very low input bias current amplifier. In addition, as it is shown in Fig. 7, the same value of the resistor and capacitor can be used in positive input of the Op-Amp to prevent any possible offset voltage from amplification.

The amount of electric charge on the surface of a moving particle in a pipeline is not predictable. Particles due to different material type, density, size and random impact or friction to pipe wall or to other particles can get different ranges of electric charge. One drawback of the aforementioned signal conditioning circuit for electrostatic sensor is that the sensor gain is fixed value. If it's supposed to use the sensor to detect the higher level of the electric charge, the output signal range goes to saturation. To solve this, it is suggested an adjustable-gain amplifier to be used as a second stage of amplification. The amplification gain of the first stage should be designed to amplify the highest available level of the electrostatic noise in the pipeline to an interested level. Then after, for lower ranges of the electrostatic noises, the second amplifier with adjustable gain capability will be applied to amplify the output of the first stage to a level of interest.

In the circuit shown in Fig. 7, an instrumentation amplifier is added to the signal conditioning circuit to able the circuit to be used for a wider range of electrostatic noise detection and amplification. Triple Op-Amp topology for instrumentation amplifier, in Fig. 7 is an integrated circuit with three Op-Amp and several resistors. Instrumentation amplifier amplifies the electric potential difference between its two inputs. It has a high common mode rejection, low output offset and high input impedance [14]. The first two integrated Op-Amps of the instrumentation amplifier provide voltage gain as a non-inverting amplifier and the last Op-Amp is a unity gain amplifier where in its integrated circuit R_1=R_2, and R_3=R_4=R_5=R_6. The most advantage of the instrumentation amplifier is its gain adjusting design. The gain can be adjusted only with a single external resistor R_G using the following equation.

$$Gain_{Ins} = 1 + \frac{2R_1}{R_G}, \tag{4}$$

The total gain of the signal conditioning circuit would be the multiplication of the gain in two stages, which is:

$$Gain = (1 + \frac{2R_1}{R_G}).R_f, \tag{5}$$

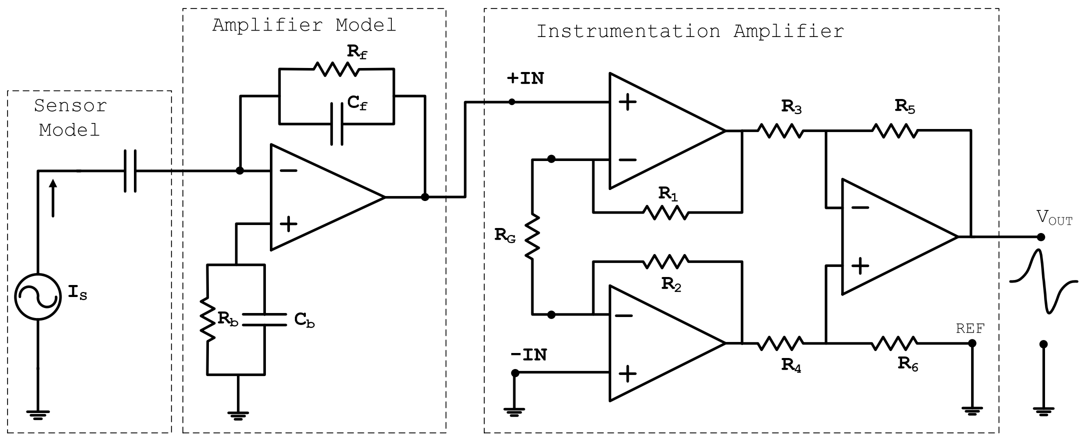

Fig. 7. Signal conditioning circuit for electrostatic sensor with two amplification stages.

4. Simulation Results

The signal conditioning circuit is simulated with the Multisim simulator to investigate the circuit for its frequency bandwidth and gain. Fig. 8 shows the signal conditioning circuit with the selected circuit component in Multisim.

A 5 nA current source with 200 Hz frequency is selected for the electrode's circuit model. The capacitance of the electrode model is assumed to be 100 pF. The selected values for electrode model are chosen to be close with proposed values in Gajewski's model [10]. A 20 MΩ resistor and a 10 pF capacitor are chosen for feedback resistor R_1 and feedback capacitor C_1. To compensate the effect of bias current the same value component in the feedback loop connected the non-inverting input of the Op-Amp to the ground. As it mentioned, the circuit model of the electrode is a high-output impedance source. To maximize the power transfer between the electrode and signal conditioning circuit a high input impedance FET amplifier, OPA2604 is chosen for signal collecting stage [15]. The OPA2604 amplifier is a low distortion, low noise, FET-input Op-Amp with input impedance of $10^{12}\|8$ (Ω‖pF).

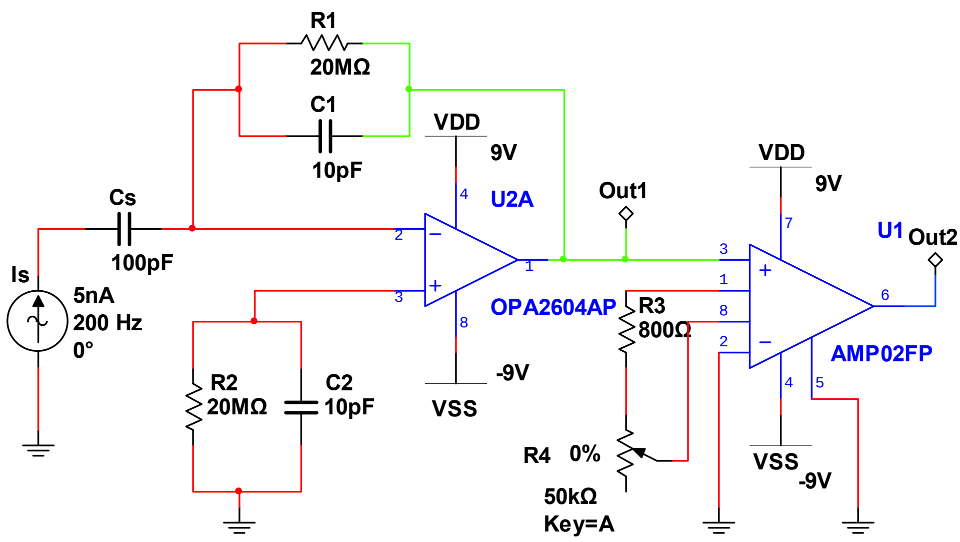

Fig. 8. The schematic of signal conditioning circuit in Multisim simulator.

In the next part, a high-accuracy instrumentation amplifier AMP02 is used as a second and adjustable amplifier. The AMP02 has a low offset voltage of maximum 100 μV, and it has a gain equation accuracy of 0.5 % [16]. The gain equation for this amplifier is given as:

$$Gain_{inst} = \frac{V_{out}}{(+IN)-(-IN)} = \left(\frac{50k\Omega}{R_G}\right)+1, \qquad (6)$$

To prevent the saturation in the output voltage range, an 800 Ω resistor R_3 is used in series with a 50 kΩ potentiometer R_4. The R_G in Equation 6 is equal to R_3+R_4 is provided to adjust the output voltage in the level of interest. The gain of the signal collector is equal to the value of the R_1 or 20×10^6. From Equation 6 and values of R_G, the gain of the instrumentation amplifier changes from 1.98 when the potentiometer is set in maximum range to 63.5 when the potentiometer is adjusted to Zero. The total gain range of the proposed signal conditioning circuit can be given by multiplication of these two stages that is an adjustable value from 39.6×10^6 to 1270×10^6.

From Equation 3, the frequency bandwidth of the circuit is determined by feedback resistor R_1 and feedback capacitor C_1. It is equal to 796 Hz, and it seems to be a suitable bandwidth for electrostatic sensor where the higher frequency electrostatic noise is not expected. The frequency response of the circuit is provided using an AC analysis in Multisim is shown in Fig. 9. It verifies the calculated gain and bandwidth of the system when the circuit is adjusted for the maximum gain.

The power supply for the circuit is selected to be ±9 Volt. From Multisim simulator results, this range of power supply is let the output signal to swing between a ranges of ±7 Volt in a 10 kΩ output load. The circuit in maximum amplification gain amplifies the 5 nA of the source signal peak to a voltage signal with a magnitude of 6.35 Volt. It shows that, the output signal magnitude at any gain exists between swing ranges of the output voltage. In high gains, some particles induce electrostatic noise that leads to saturation in the output signal level. Simply adjusting the gain to a lower level can bring back the signal into the desired range.

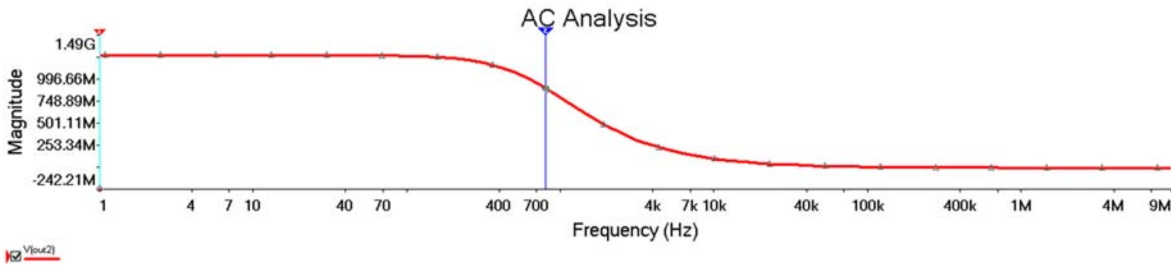

Fig. 9. The Gain versus frequency of the signal conditioning circuit.

5. Noise Observation

Noise is an electrical or electromagnetic energy that can damage the main signal. Thermal noise, Shot noise and Flicker noise are three main noises that can be contributed from resistors and semiconductor to the circuit. The noise investigation using the Multisim simulator will give a vision to the noise contribution from each component and as well as the filtering design efficiency. To investigate the noise, gain is adjusted to its maximum level where the noise is amplified with the signal to its highest level as well. The potentiometer is adjusted to Zero and R_1, R_2 and R_3 are investigated as the main intrinsic noise source for the circuit. Fig. 10 shows the noise spectrums of the total output noise of the circuit and the output noise from three mentioned resistors.

The noise spectrums in Fig. 10 show a great amplitude reduction on 800 Hz which is equal to the circuit's cutoff frequency. The circuit total noise magnitude reduces when the gain is adjusted in lower level using the potentiometer. Both Op-Amps in the circuit are considered as a low-noise amplifier. From the component data sheet [15, 16], the OPA2604 has the input noise of 11 $nV/\sqrt{Hz}$ at 1 kHz and AMP02 has 10 $nV/\sqrt{Hz}$ noise at the same frequency at gain 100.

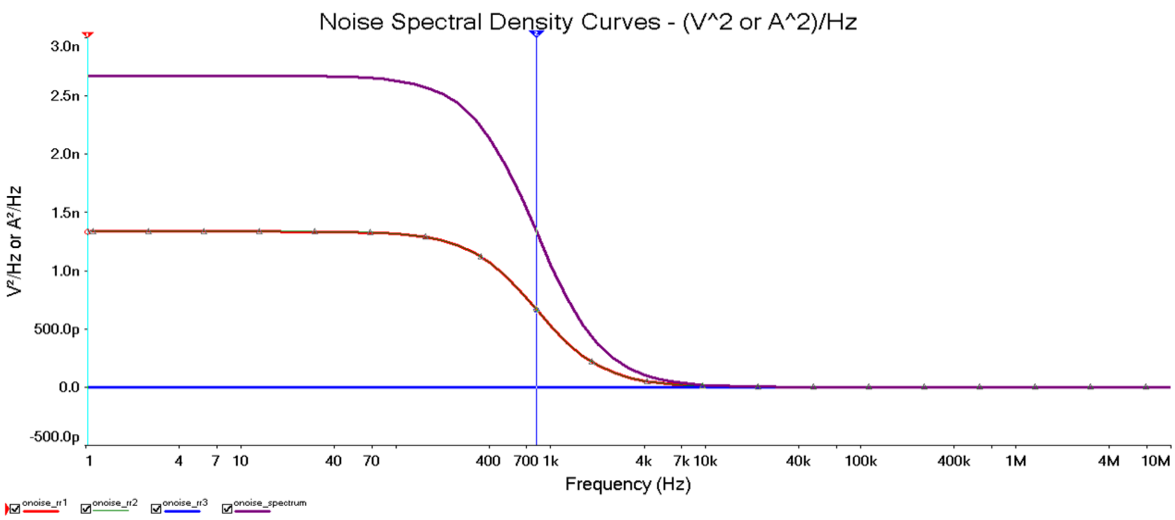

Fig. 10. The purple curve indicates the total output noise spectrum and red, green and blue curves are indication of noise spectrum from R1, R2 and R3 respectively.

6. Extrinsic Noise

The electrode of the electrostatic sensor acts as an antenna that can detect any electric fields in its detecting area, including unwanted fields from environmental sources. The sensor amplifies unwanted extrinsic noises along with the main signal which causes the interested output signal is damaged or totally drown by unwanted extrinsic noise. One of the most extrinsic noise problems can be imposed from a 50 Hz or 60 Hz power supply. This kind of noise can't be eliminated using a low-pass filter because its frequency coincides with the range of the desired signal's frequency which is from 0 to almost 250 Hz. This phenomenon would be the drawback of the using the electrostatic sensor as a measurement system when it is supposed to work near other electric devices. Fig. 11 is the output of the electrostatic sensor shown in Fig. 13 when it works near a 220 Volt 50 Hz power line. The 50 Hz peak shown in power spectrum density of the output voltage in Fig. 11 clearly indicates the source of this noise.

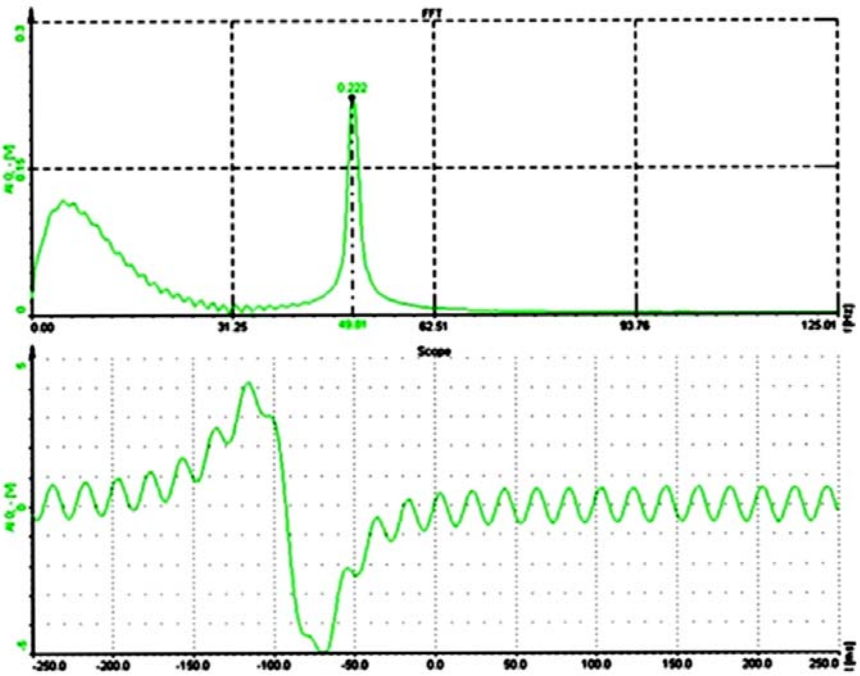

Fig. 11. Frequency spectrum in the top and output signal of the sensor in presence of 50Hz extrinsic noise induction.

In most researches related to the electrostatic sensor a metal earthed screen is proposed to protect the electrode from detection of environmental electric field's sources [3, 13]. However, adding a screen to cover the whole electrode and signal conditioning is a cumbersome structure and there is no guarantee that it can cover the whole induction from outside of the ring. In this paper, a voltage converter is used to provide a dual supply of ±9 Volt from a single 9-Volt battery for circuit amplifiers, as it depicted in Fig. 12.

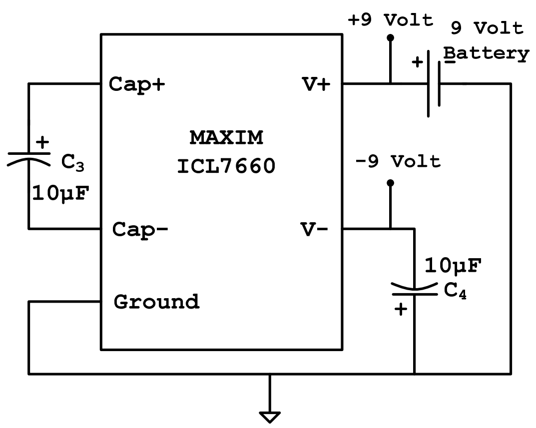

Fig. 12. 9 Volt dual power supply circuit using ICL7660 voltage converter.

The power supply using battery keeps safe the electrode from detection of the ac field from an AC-to-DC power supply. The proposed signal condition circuit in this paper is used for the electrostatic sensor design shown in Fig. 13. In the sensor, the output1 is provided for signal measuring after signal collector amplifier and output2 is the output of the sensor after the instrumentation amplifier. The sensor has a ring electrode with the diameter of 55.6 mm, 20 mm of axial length and 3 mm thickness.

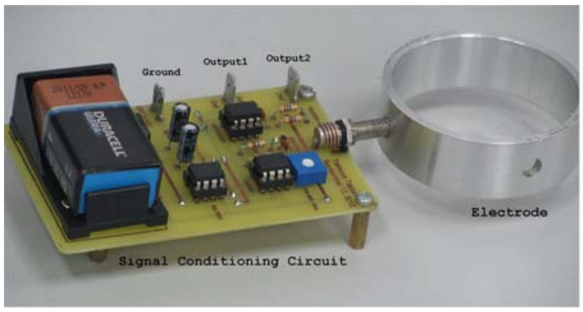

Fig. 13. The electrostatic sensor designed according proposed signal conditioning circuit.

The output investigation of the sensor in Fig. 13 shows the electrode can detect the power supply's electric field about 1.5 meters far from the electrode, for instance, while data collecting using a data-acquisition card with a laptop it is recommended the laptop is driven with its battery. The Fig. 14 shows a low noise signal from the sensor output when it's kept far from any AC power supply. As it depicted in Fig. 14 in comparison to Fig. 11 the frequency spectrum doesn't show any magnitude at 50 Hz and output voltage signal apparently is smooth and noiseless.

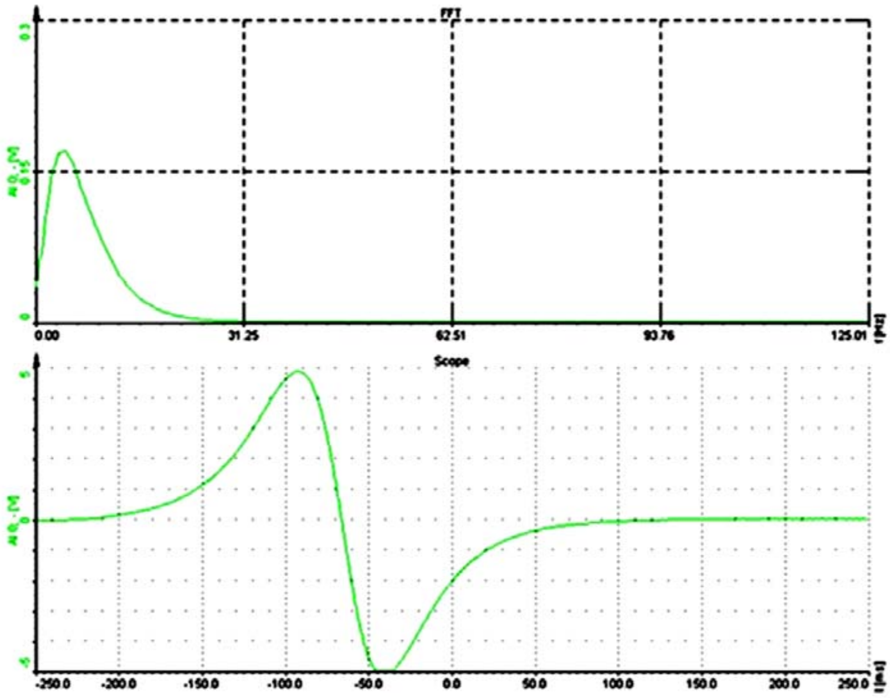

Fig. 14. Frequency spectrum in the top and output signal of the sensor in a noiseless environment.

7. Conclusion

A signal conditioning circuit is designed to collect and amplify the electrostatic noise from the electrostatic sensor electrode. The design was involved two stages of amplification where one of the stages has an adjustable gain. A circuit model for sensor electrode is proposed to be used for circuit simulation. The total gain of the circuit can amplify a 5nA source signal to a voltage signal from 0.2 to 6.35 Volt between a frequency bandwidth of about 800Hz. The bandwidth of the circuit is designed to filter the noise at high frequencies. The noise at high frequencies can be imposed from electronics component or through particles' impact to the electrode. However, the low frequency 50Hz extrinsic noise from an AC power supply electric field can be detected and amplified along with the main signal. A battery power supply is proposed to isolate the circuit from the AC electric field. The circuit is designed and tested with a ring electrode, and the results showed the output signal at the expected level with the least noise interference.

Acknowledgements

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