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A review and Exploration of various Elements Inducing noise in Scheming Instrumentation amplifier

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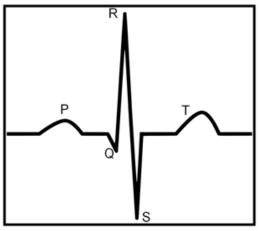
Abstract—**The objective of the paper is to propose the Noise model of a three op-amp instrumentation amplifier focusing the noise awareness features to be considered when designing the instrumentation amplifier to sense and amplify low voltages which finds delicate application like biomedical instrumentation. Change of gain and CMRR (Common mode rejection ratio) due to unexpected reaction from the environment and tolerance value of the externally connected components are considered and discussed in detail. Impact factors like temperature and gain in Amplification of noise are also taken as factors while calculating Total Noise and tried to simulate with Cadence tool for Analog and Mixed signal analysis. This paper is intended as a step to analyze the noise there by incorporate suitable safety measurements to optimize the accuracy of Output while using the instrumentation amplifier as signal conditioning circuits in sensitive signal measurements in future.**

Index Terms— **Tolerance, gain, CMRR, Temperature, Noise Model, accuracy.**

I. INTRODUCTION

When considering the instrumentation amplifier as a part of data acquisition system in biomedical instrumentation the main factor to be considered is accuracy, because the Electrodes or sensor in the outer skin of human body detect the small voltages according to the function of organs in the order of 1 micro volt to hundreds of microvolt. But the signal is too small and contains a lot of added noise [1], [2]. For an example Fig.1 showsThe small electrical signal from the heart generates a common-mode voltage and noise in the system. The signals from the heart are too small and it is necessary to amplify the signal and reduce the common-mode voltage on the system. Other aspects that generate noise are muscle Contractions, respiration,



Electromagnetic interference and Electromagnetic emissions from electronic components. The signal has amplitude of approximately 1 mV peak to peak and contains common-mode voltage noises. While processing a low amplitude signal and accuracy is a key factor to be fulfilled the various causes that deviates the optimum value of accuracy in the data acquisition system are essential to find out results scheming of low noise instrumentation amplifier. A low noise instrumentation amplifier is an extremely sensitive device that can measure even the smallest signals in noisy environments or in the presence of large unwanted voltages. In order to process the low voltage signals the instrumentation amplifier must have high common mode rejection ratio. The instrumentation amplifier with high CMRR cancels the noise appearing commonly at their input terminals and increases the likelihood to amplify the low voltage input signals more accurately. A low noise instrumentation amplifier combines a very low wideband Noise with a low 1/f corner [3] which makes it useful in the most demanding precision applications that too while measuring bio-signals the amplifier, has to satisfy few requirements such as (i) The low noise instrumentation amplifier must provide best isolation between signal and noise.(ii) It has to provide the electrical isolation between patient and device. (iii) It should not affect the process to be monitored and should not alter the function in any way. (iv)It has to provide at most accurate result. (v)It has to tolerate the fluctuations in the input and protect the instrument in case of high input voltage occurred suddenly.

Basic configuration

The basic instrumentation amplifiers are differential amplifiers added with input buffers in order to give high input

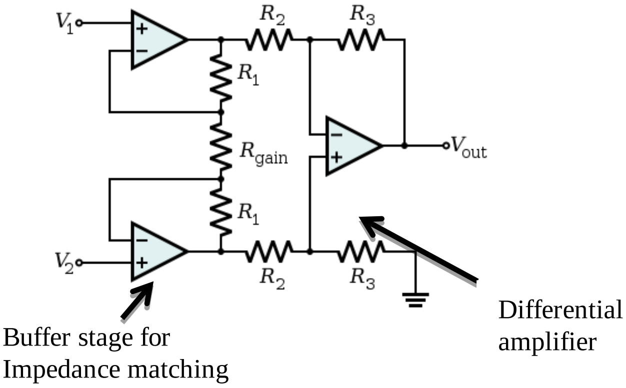


Fig.2 3-op-amp Basic instrumentation amplifier

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impedance. The gain of the circuit is

$$\frac{V_{out}}{V_2 - V_1} = (1 + \frac{2R_1}{R_{gain}})\frac{R_3}{R_2}$$

The differential amplifier has the ability to reject the common signals appearing at its both inverting and non-inverting terminals and senses the small difference in signal across its input terminals and amplifies based on the gain. By taking proper corrective measurements and considering design parameters it is possible to provide high signal to noise ratio and eliminate the interferences raised magnetically or electrostatically

II. CALCULATION OF DESIRABLE VALUE OF CMRR IN LOW AMPLITUDE APPLICATIONS

In order to identify even a very smaller difference of signal across the input terminals, the ideal instrumentation amplifier must have infinite CMRR value.

The dB value of CMRR is given as $20\log\left(\frac{A_d}{A_{cm}}\right)$ -----> (1)

A_d =differential mode gain

A_{cm} =common mode gain. For common noise signal appearing at the both of input terminals the gain should be zero for optimum accuracy. It requires a very high degree of resistance value matching, but due to tolerance value of resistors generally the CMRR will not be infinite.

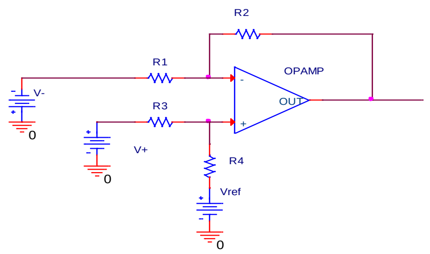

Fig.3 Differential amplifier

Interms of resistors the CMRR of a differential amplifier is represented by referring fig.3 as

CMRR = $20\log_{10}(m)$

Where $m = \frac{R_4}{R_3+R_4} X \frac{R_1+R_2}{R_1} - \frac{R_2}{R_1}$----> (2)

The influency of tolerance value of resistors over the CMRR at various gain values specified in an application note of Intersil Corporation is given in Table 1.

RESISTOR	CMRR		
TOLERANCE	GAIN 1	GAIN 10	GAIN 100
±5%	-20.4dB	-15.6dB	-14.8dB
±1%	-34.1dB	-28.9dB	-28.1dB
±0.1%	-54.0dB	-48.8dB	-40.0dB
±0.01%	-74.0dB	-68.8dB	-68.0dB

TABLE 1 Resistors over CMRR at various gain values

From Table 1. Designing the Instrumentation amplifier with the resistors of lower tolerance value increases the CMRR. But the other side the requirement of High gain of the amplifier lowers the CMRR. So it is evident that the calculation of minimum CMRR to reject interferences in order to handle low voltage signals required. From the reference of Bio medical applications it has been identified that the minimum CMRR is100dB to handle low voltage signals.[2]

Referring equation (1) $20\log\left(\frac{A_d}{A_{cm}}\right)$ =100dB

$$20\log A_d - 20\log A_{cm} = 100$$

Consider differential mode gain (Ad) =1; above expression turns as

$$-20\log A_{cm} = 100$$

$$A_{cm} = 10^{\frac{100}{-20}}$$

Maximum common mode gain should be Acm = 0.00001 to satisfy the minimum requirement of 100dB or in other terms the noise amplification factor must be lesser than   to meet the application demands while measuring low amplitude signals.

III. A SIMPLE NOISE MODEL OF AN INSTRUMENTATION AMPLIFIER

The three main noise sources of instrumentation amplifier are (i) Voltage noise (ii) Current Noise (iii) Thermal Noise on source resistance. These noise sources are totally un correlated. The term source resistance takes the account of externally connected resistors and internal resistance of the sensor connected at the input terminals of Op-amp. The externally connected resistors match the input impedance of the circuit. Voltage noise can be classified as Input voltage noise (e_i) output voltage noise (e_o).

The rms (root mean square) value of source resistance is

$E_{rms}(R_s) = \sqrt{4kTR_sB}$ Volts.

Where k = Boltzmann's constant, T=absolute temperature, R_s= total source resistance and B=Bandwidth in Hz.

The total input noise

$$E_{rms}^2\,(Total\ input\ noise) = \int_{f1}^{f2} e_n^2 + R_S^2\int_{f1}^{f2} i_n^2 + \sqrt{4kTR_sB}$$

$$E_{rms}^2 = voltage\ noise + current\ noise + source\ resistance\ noise$$

Throughout the bandwidth $(f2 - f1)$ the total input noise is also designated as referred to input or RTI noise signified in the unit of $nV\sqrt{Hz}$ given as

$$RTI\ noise\left(nV\sqrt{Hz}\right) = \sqrt{e_s^2 + e_i^2 + \left(\frac{e_o}{G}\right)^2 + (i_{ni} \times R_s)^2}$$

$$RTI\ noise\left(nV\sqrt{Hz}\right) = \sqrt{source\ voltage\ noise + input\ voltge\ noise + output\ voltage\ noise + current\ noise}$$

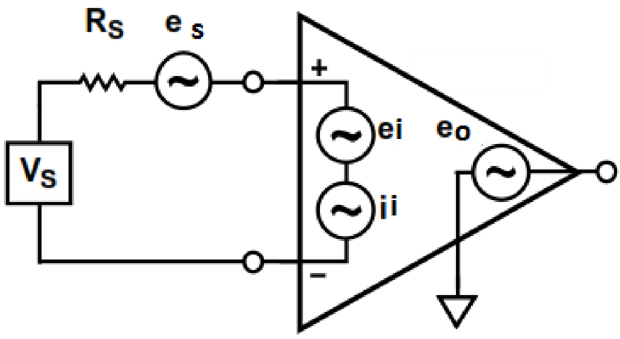

Fig.4 Simple noise model of instrumentation amplifier

The source resistance includes the following noises. (i) Thermal noise (ii) Contact Noise (iii) Johnson noise (iv) Parasitic noise. Among above noises the Johnson noise increases with square root of the resistance. A 1kΩ resistor has4 $nV\sqrt{Hz}$ approximately at room temperature, but for highest performance amplifiers should have 1 $nV\sqrt{Hz}$ as total voltage noise [4]. These resistive noise sources can be decreased by selecting an amplifier which has negligible noise affect than source resistance noise, connecting external resistors of minimum value and low noise contribution. They can also be reduced by compromising the range of operating frequency of an amplifier.

IV. Categories Of Internal Amplifier Noise

The noise sources of Op-amp have Random behavior can be formulated by Gaussian distribution. The noises are generally unrelated so it is useful that inclusive of correlated coefficient factor. The correlated noise is discarded if it lies between the ranges of 10-15%. The internal noise of O-amp can be classified as follows(i) input referred voltage noise ,discussed in chapter III.(ii) input referred current noise.(iii) flicker noise and (iv) popcorn noise.

Input referred current noise:

Shot noise or schottky noise is referred as current noise due to random flow of charge carriers during current flow. This can be computed through the formula $I_n = \sqrt{2I_B qB}$ Where I_B-Bias current in ampere(A), q-electron charge in coulomb and B-Bandwidth in Hz.

Flicker noise:

The noise of op-amp is Gaussian with constant spectral density or white noise over wide range of frequencies. But when the frequency decreases spectral density starts to rise because of the fabrication process. This low frequency noise characteristic is known as Flicker noise. Bipolar and JFET amplifiers have low corner frequency than CMOS amplifiers.

Popcorn noise:

A sudden shift of offset voltage or current from several µV to hundreds of µV for few milliseconds due to contamination or silicon surface defects is called popcorn noise. The desirable situation for popcorn noise is low temperature and high source resistance.

However the interference of noise can be minimized by proper layout techniques to avoid parasitics, proper grounding and by proper shielding.

V. In-Amps Versus Op-Amps

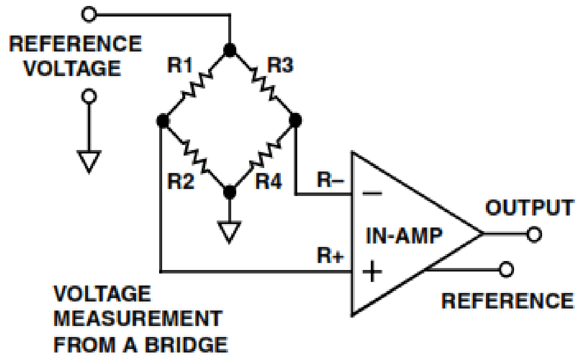

Fig.5 In-Amp circuit

In Op-amps (Operational amplifiers) the closed loop gain is determined by the externally connected resistor across the non-inverting input terminal and Output pins. But the specially designed In-Amps or instrumentation amplifier the gain resistor is integrated internally or can be connected externally; in both the cases the gain resistor is isolated from input signal.

In-amp circuit has integrated buffer and gain stage makes less requirement to externally connected resistors there by reduces total source resistance that produces noise.

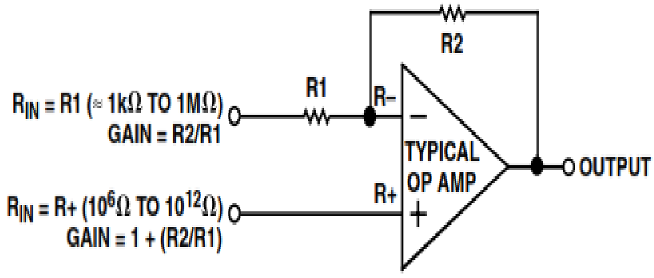

Fig.6 Op-amp circuit

Because of less or no external resistors the RTI (Referred to Input noise) equation of In-Amps are given as

$$RTI\ noise\left(nV\sqrt{Hz}\right) = \sqrt{e_i^2 + \left(\frac{e_o}{G}\right)^2}$$

With input Bias current compensation the total voltage noise can be reduced to 8 .

Noise model of In-Amp

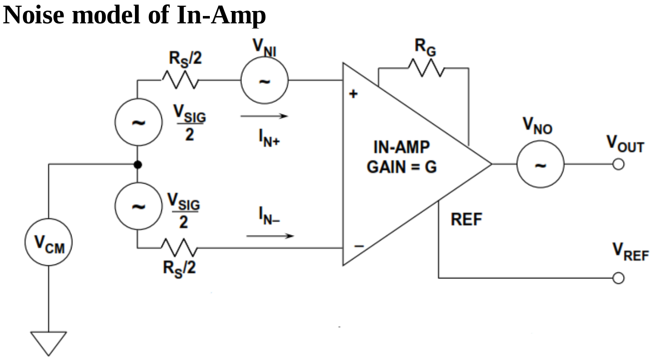

Fig.7 Noise model of In-amp

Where Rs is the source resistance, V_{NI} is the Input noise voltage which is appeared at the input terminals and

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amplified by gain G results output noise V_{NO}. I_{N+} and I_{N-} are input noise current usually they are equal but uncorrelated. The noise created by input noise current is $I_N R_s/2$ in one terminal. The total output noise is calculated by

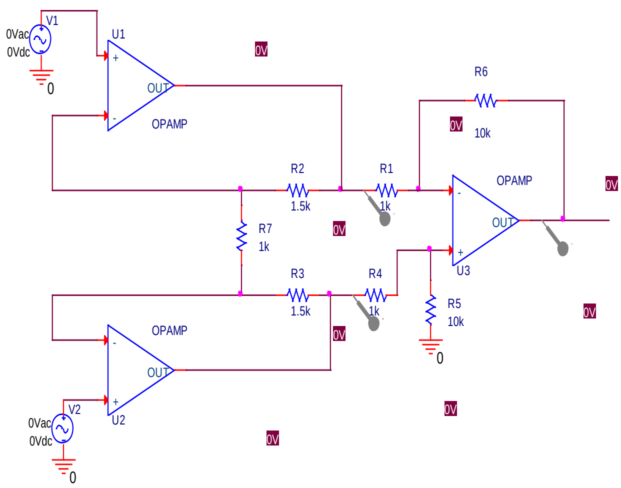
$$RTO\left(Referred\ to\ \frac{o}{p} noise\right) = \sqrt{BW}\sqrt{V_{NO}^2 + G^2\left(V_{NI}^2 + \frac{I_{N(+)}^2 R_S^2}{4} + \frac{I_{N(-)}^2 R_S^2}{4}\right.}$$

The total input noise is calculated by

$$RTI(Referred\ to\ \frac{i}{p} noise = \sqrt{BW}\sqrt{\frac{V_{NO}^2}{G^2} + \left(V_{NI}^2 + \frac{I_N^2 R_S^2}{2}\right)}$$

VI. Calculation of Output Noise Using OrCAD 16.6

The below figure.8 shows a 3 –op amp instrumentation amplifier with externally connected resistors for input impedance matching and gain. In order to calculate the interference of noise in the input terminal and its value after amplification at the output input voltages are connected to ground. Total noise voltage is calculated for various gain and in various temperature using OrCAD 16.6. It is a tool set for windows application, can be used to simulate analog and mixed signal circuits.



(1)

Fig.8 Simulated 3 op-amp instrumentation amplifier

(2) pSPICE CODING OF ABOVE INSTRUMENTATION AMPLIFIER for ac sweep &NOISE ANALYSIS

```
.lib "nomd.lib"
*Analysis directives:
.AC DEC 10khz 100khz 10Ghz
.NOISE v(E_U3) V_V1 1
.OPTIONS ADVCONV
.PROBE64 V(alias(*)) I(alias(*)) W(alias(*)) D(alias(*)) NOISE(alias(*))
.INC "..\SCHEMATIC1.net"
**** INCLUDING SCHEMATIC1.net ****
* source IA7
E_U1         N00212 0 VALUE {LIMIT(V(N00437,N00203)*1E6,-15V,+15V)}
E_U2         N00256 0 VALUE {LIMIT(V(N00611,N00260)*1E6,-15V,+15V)}
E_U3         N00239 0 VALUE {LIMIT(V(N00269,N00216)*1E6,-15V,+15V)}
R_R1         N00212 N00216  1k TC=0,0
R_R2         N00203 N00212  1.5k TC=0,0
R_R3         N00260 N00256  1.5k TC=0,0
R_R4         N00256 N00269  1k TC=0,0
R_R5         0 N00269  10k TC=0,0
R_R6         N00239 N00216  10k TC=0,0
R_R7         N00203 N00260  1k TC=0,0
V_V1         N00437 0 DC 0Vdc AC 0Vac
V_V2         N00611 0 DC 0Vdc AC 0Vac

**** RESUMING IA7.cir ****
.END
```

RESULT: at 27°C and Gain =10

TOTAL OUTPUT NOISE VOLTAGE = 2.354E-14 (SQ V/HZ)

EQUIVALENT INPUT NOISE ATV_V1 = 3.835E-09 (V/RT HZ)

CODINGS FOR TRANSIENT ANALYSIS

```
.lib "nomd.lib"
*Analysis directives:
.TRAN  0 1000us 0 10us
.OPTIONS ADVCONV
.PROBE64 V(alias(*)) I(alias(*)) W(alias(*)) D(alias(*)) NOISE(alias(*))
.INC "..\SCHEMATIC1.net"
**** INCLUDING SCHEMATIC1.net ****
* source SAMPLE7
E_U1         N00212 0 VALUE {LIMIT(V(N00437,N00203)*1E6,-15V,+15V)}
E_U2         N00256 0 VALUE {LIMIT(V(N00611,N00260)*1E6,-15V,+15V)}
E_U3         N00239 0 VALUE {LIMIT(V(N00269,N00216)*1E6,-15V,+15V)}
R_R1         N00212 N00216  1k TC=0,0
R_R2         N00203 N00212  1.5k TC=0,0
R_R3         N00260 N00256  1.5k TC=0,0
R_R4         N00256 N00269  1k TC=0,0
R_R5         0 N00269  10k TC=0,0
R_R6         N00239 N00216  10k TC=0,0
R_R7         N00203 N00260  1k TC=0,0
V_V1         N00437 0 0Vdc
V_V2         N00611 0 200mVdc
**** RESUMING IA7.cir ****
.END
```

RESULT: at 27°C and Gain =10

Node number followed by voltage at node are given as

(N00203) 300.0E-09 (N00212) -.3000 (N00216) .4545 (N00239) 7.9999 (N00256) .5000 (N00260) .2000 (N00269) .4545 (N00437) 0.0000 (N00611) .2000

The above circuit is simulated for various gain values at various temperatures in order to calculate the influence of gain and temperature in noise amplification and values are tabulated.

TOTAL VOLTAGE NOISE					
GAIN =10			GAIN =100		
temp°C	o/p noise (V/RT Hz)	i/p noise (V/RT Hz)	temp°C	o/p noise (SQ V/HZ)	i/p noise (V/RT Hz)
20	1.516E-07	3.791E-09	20	1.506E-06	3.766E-09
27	1.534E-07	3.835E-09	27	1.524E-06	3.811E-09
30	1.542E-07	3.855E-09	30	1.532E-06	3.830E-09
35	1.554E-07	3.886E-09	35	1.544E-06	3.862E-09

TABLE 2.

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VII. CONCLUSION

This paper consists of a 3 op-amp instrumentation model and calculation of noise using a verification tool from Cadence OrCad 16.6. Low noise instrumentation amplifiers require precision amplification to meet the today's challenges in measuring low amplitude signals. The best amplifier is not always the one with minimum $nV\sqrt{Hz}$ voltage noise. The gain, source resistance and frequency range must be considered to find best amplifier. For low value of source resistance voltage noise dominates and for high value of source resistance current noise dominates. Consider $R_V = \frac{[TOTAL\ VOLTAGE\ NOISE(\frac{nV}{\sqrt{Hz}})]^2}{16}$ and $R_I = \frac{16}{[TOTAL\ VOLTAGE\ NOISE\,(\frac{pA}{\sqrt{Hz}})]^2}$.

If Source resistance Rs $<R_V$ Voltage noise dominates and source resistance $R_s>R_I$ current noise dominates. For the source value of 5kΩ to 10Ω the noise performance of all the instrumentation amplifiers are almost close to same. Under such situation Bandwidth, power, distortion and cost are to be considered as optimizing parameters.

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