Department of Electronic and Telecommunication Engineering
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BM4111 - Medical Electronics and Instrumentation

Building an Instrumentation Amplifier - Part 1

Group Members

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Circuit Design

As per the provided guidelines, three circuit designs for a part of the ECG monitor comprising an instrumentation amplifier (INA), driven right leg (DRL), and a reference voltage (AGND), are given below.

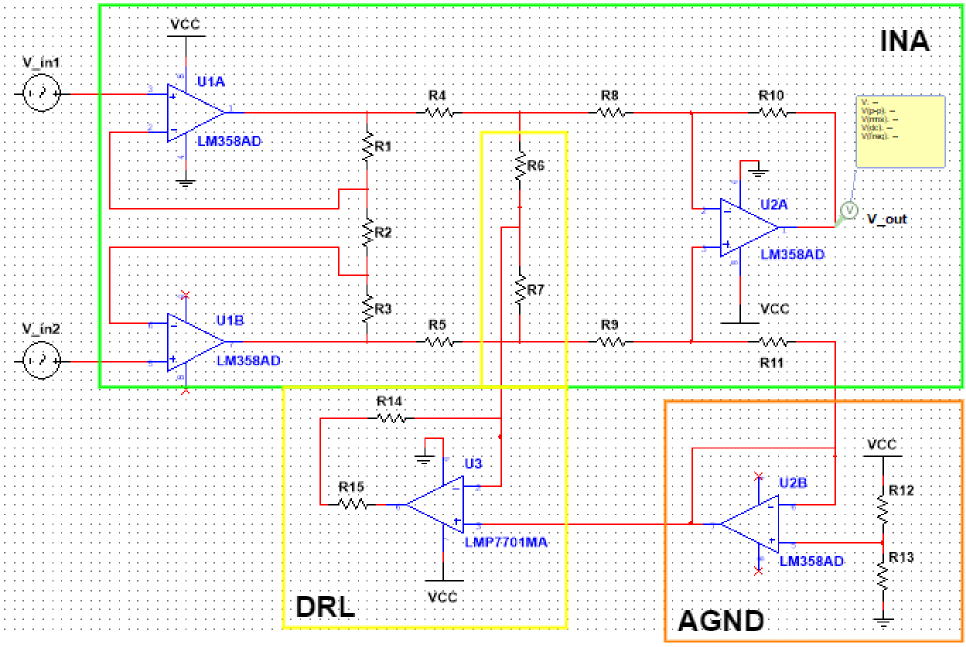

Figure 1.1: Proposed Design - 1

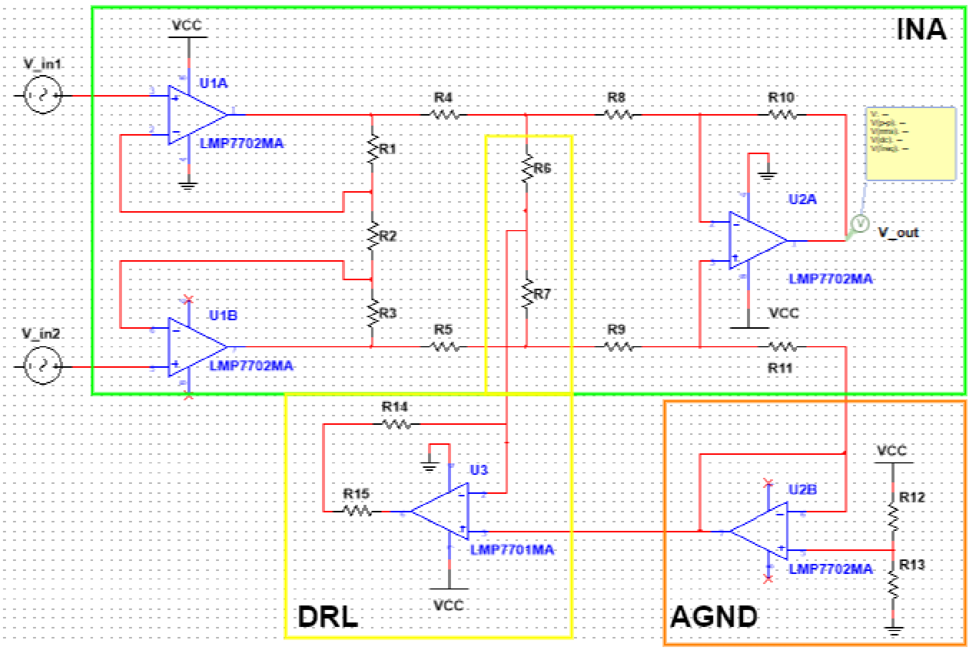

Figure 1.2: Proposed Design - 2

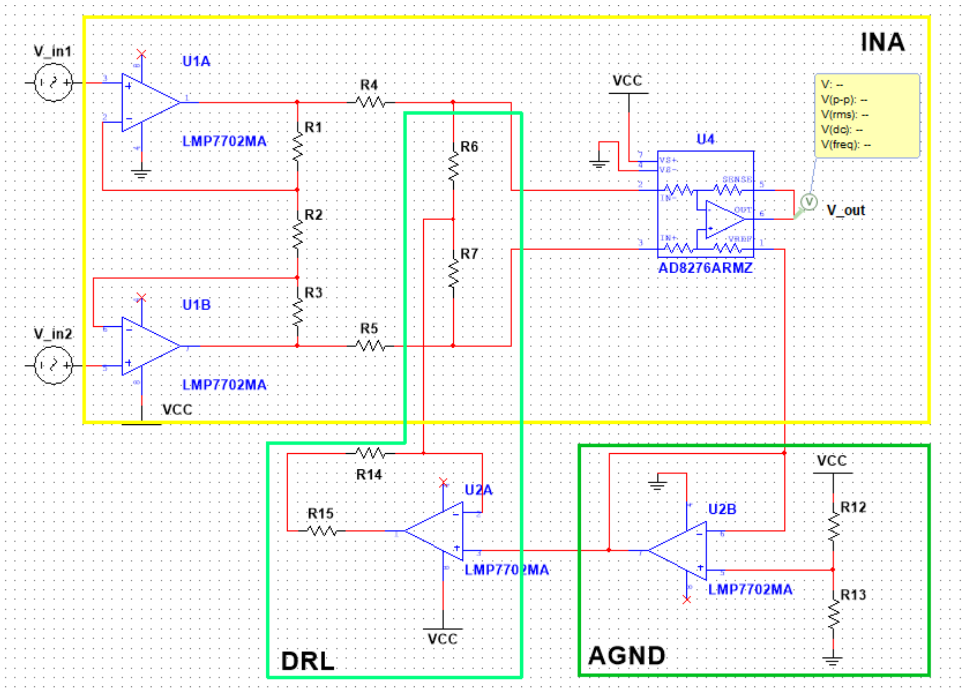

Figure 1.3: Proposed Design - 3

Different ICs used in the three sub-circuits (INA, DRL, AGND) of each design are summarized in the following table.

-	INA	DRL	AGND
Design 1	LM358	LMP7701	LM358
Design 2	LMP7702	LMP7701	LMP7702
Design 3	LMP7702, AD8276	LMP7702	LMP7702

Table 1.1: Different ICs used in the Sub-circuits

1.1 Design Overview and Considerations

For designs 1 and 2, the INA is designed using three ICS, whereas each of the DRL and AGND circuits are designed using a single IC. In the differential amplifier portion of the INA, we realized that it is convenient to use $R8 = R9$ and $R10 = R11$. The reference voltage in the AGND circuit is made $\frac{V_{cc}}{2}$ by taking two identical resistors for R12 and R13. Moreover, to remove the common mode voltage, identical resistors are used for R6 and R7. Design 3 is similar to design 1 and 2, except the resistors R8, R9, R10, R11 are not mentioned explicitly as they are embedded in the AD8276 IC (could be observed in the schematic).

Circuit Evaluation

2.1 Calculating the Limiting CMRR

The following assumptions were made during the calculations.

- 1% tolerance of resistor values
- Electrode-skin impedance mismatch of 10k
- Input resistance of LMP7702 and LMP7701: 10T
- Input resistance of LM358: 10M

2.1.1 Electrode Mismatch ($CMRR_E$)

An approximated equation for the $CMRR_E$ is given below. Note that the $z_2 - z_1$ represents the electrode-skin impedance mismatch provided under the assumptions and z_{in} represents the input impedance of the ICs.

$$
\begin{aligned}
CMRR_E &= 20\log\left(\frac{z_{in}}{z_2 - z_1}\right) \\
CMRR_{E(\text{Design 1})} &= 20\log\left(\frac{10^7}{10^4}\right) = 20\log(10^3) = 60 \text{ dB} \\
CMRR_{E(\text{Design 2})} &= 20\log\left(\frac{10^{13}}{10^4}\right) = 20\log(10^9) = 180 \text{ dB} \\
CMRR_{E(\text{Design 3})} &= 20\log\left(\frac{10^{13}}{10^4}\right) = 20\log(10^9) = 180 \text{ dB}
\end{aligned}
$$

2.1.2 Resistor Mismatch ($CMRR_R$)

For the first two designs, when the tolerance is given by T, the $CMRR_R$ could be calculated as follows.

$$
\begin{aligned}
CMRR_R &= 20\log\left(\frac{1+\frac{R9}{R8}}{4T}\right) \\
CMRR_R &= 20\log\left(\frac{1+\frac{R9}{R9}}{4T}\right) && [\because \quad R9 = R8] \\
CMRR_R &= 20\log\left(\frac{2}{4\times 0.01}\right) = 34 \text{ dB}
\end{aligned}
$$

2.1.3 Amplifier Characteristics ($CMRR_O$)

Following $CMRR_O$ values are obtained via the datasheet.

$$
\begin{aligned}
CMRR_{O(\text{LM358})} &= 65 \text{ dB} && \text{(5V supply)} \\
CMRR_{O(\text{LMP7701/LMP7702})} &= 84 \text{ dB} && \text{(3V supply)} \\
CMRR_{O(\text{AD8276})} &= 86 \text{ dB} && \text{(5V supply)}
\end{aligned}
$$

2.1.4 Overall $CMRR$

When the gain of the differential amplifier is 1, (i.e. R8 = R9 = R10 = R11), the overall CMRR is given by,

$$
CMRR = \left(\frac{1}{CMRR_E} + \frac{1}{CMRR_R} + \frac{1}{CMRR_O}\right)^{-1}
$$

Let's first compare designs 1 and 2. $CMRR_R$ of the two cases are equal. However, the $CMRR_E$ and $CMRR_O$ are different. From the derived values, we can see that there is a significant disparity between the $CMRR_E$ of the two designs. Thus, with respect to the first two designs, $CMRR_E$ is the limiting factor. If we compare design 2 with design 3, we could observe that the $CMRR_E$ and $CMRR_O$ are nearly similar. Further, $CMRR_R$ of design 3 is improved compared to the other designs.

2.2 Why is Design 2 better than Design 1?

According to the question 1 explanation, overall CMRR is limited by the CMRR values that occur due to impedance mismatching and the characteristic of the amplifier (Resistor mismatch is common for both design 1 and design 2). Design 2 claims a higher total CMRR value compared to design 1 (In design 1 both $CMRR_E$ and $CMRR_O$ values are higher than the value in design 2. As a result, the total CMRR of design 2 is higher). Therefore, noise equivalent voltage and input bias current are reduced which means design 2 has a lower output noise level compared to design 1. The following table 2.2 shows the noise-related parameter values of LM358 IC and LMP7702 IC.

-	LM358	LMP7702
Equivalent Noise Voltage	40 nV/Hz	9 nV/Hz
CMRR	65-80 dB	84-130 dB
Input Resistance	10MΩ	10TΩ

Table 2.2: Noise-related parameter values of LM358 IC and LMP7702 IC

2.3 Why is Design 3 better than Design 2?

We observed that CMRR between designs 2 and 3 differs due to the disparity between $CMRR_R$. In design 2, we use resistors R8, R9, R10 and R11 and the mismatches in these resistors would degrade the performance which is the case in most scenarios. However, design 3 uses AD8276 which comprises built-in resistors with really small tolerances (higher precision). Thus, the performance of design 3 is expected to be better.

2.4 Gain of the Stages in the Circuits

In the provided circuits, the overall gain is dependent on the input stage gain, output stage gain and the gain from the PGA of the microcontroller. It is given in the guidelines that the supply voltage is 3.3V and if we assume that the maximum amplitude of the ECG signal is roughly 3.3mV, then the gain would be 1000. Moreover, it is said that the maximum gain of the PGA is 16. Accordingly, the INA has to account for a gain of 62.5.
The overall gain of the INA could be expressed as (when R1=R3),

$$G_{INA} = \frac{2R_1 + R_2}{R_2} \times \frac{R_{10}}{R_8}$$

Further, if we make the gain of the differential amplifier 1 (i.e. R10 = R8), then $\frac{2R_1+R_2}{R_2} = 62.5$. Then, by solving the equation, we get $R_1 = 30.75R_2$. Therefore, let's pick $R_2 = 1k\Omega$ and $R_1 = 30k\Omega$.

2.5 Usage of the LMP7701 in the First Design

LMP7701 was used for the DRL circuit designing part. The selected op-amp should have the following characteristics to prevent the patient from being under-grounded by saturation of the op-amp.

- High input resistance
- Low input bias current
- Low input offset voltage
- Minimum noise (High CMRR)

The following table 2.3 compares the above characteristics with LMP358 and LMP7701. According to the

-	LMP7701	LM358
Input Resistance	10TΩ	10MΩ
CMRR	84-130 dB	65-80 dB
Input Bias Current	±0.2 - ±1pA	±20 - ±250nA
Input offset voltage	37-200 μV	3-7mV

Table 2.3: Characteristic parameter values of LM358 IC and LMP7701 IC

above table, most suitable op-amp for the DRL circuit designing is LMP7701 (For the first design). Although LMP7701 can be used for the DRL part, it cannot be used for the differential part of the amplifier as the CMRR is limited by the electrode mismatch.

2.6 Explain why Increased Electrode-skin Impedance Increases the Noise Level

When the electrode-skin impedance is high, the tendency of the signal being corrupted is high and there is a higher chance of motion artefacts ruining the desired signal. Moreover, the impact of thermal noise increases as the electrode-skin impedance increases. Owing to these reasons, noise level increases when the electrode-skin impedance increases.