AC-coupling of the 3 opamp INA

In the field of biopotential measurements (such as LFP recordings, which is my area of interest), AC-coupling is necessary while CMRR and power consumption are very important. Thus, the aim is to optimize both for power consumption and CMRR while achieving the necessary DC rejection. This is a rudimentary analysis of different AC-coupling methods for the 3-opamp INA. It only accounts for the saturation non-ideality and assume (amongst others) infinite opamp bandwidth and input impedance, zeros output impedance and perfect matching of internal resistors. These are all valid assumptions when dealing with reasonable source impedances, reasonably slow signals and you pick you filtering resistors carefully.

The motivation for this analysis came from reading a very interesting paper by Petkos et. al. on artefact suppression during DBS (link: https://iopscience.iop.org/article/10.1088/1741-2552/ab2610).

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i. Standard Analysis

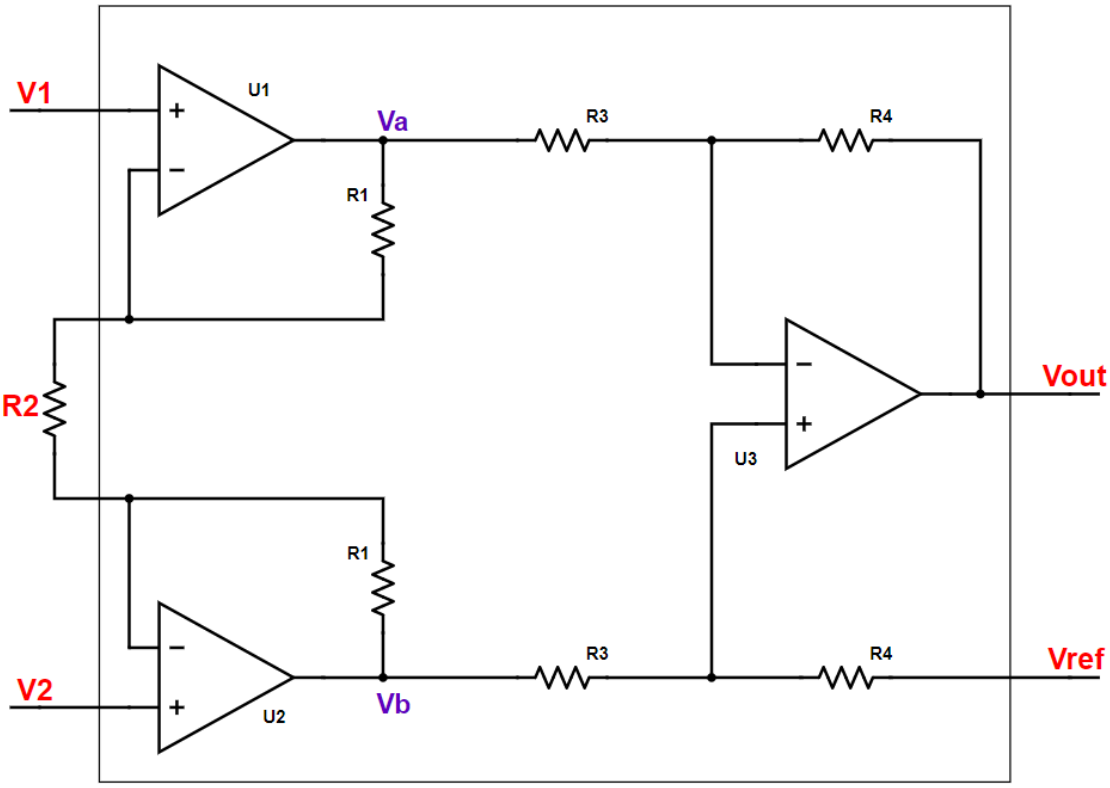

Figure 1 - 3-opamp INA

$V_a = V_1 + \frac{V_1 - V_2}{R_2} \cdot R1$	$V_b = V_2 - \frac{V_1 - V_2}{R_2} \cdot R1$	$V_{OUT} = \frac{R_4}{R_3} \cdot (V_b - V_a) + V_{ref} = \frac{R_4}{R_3} \cdot \left(1 + \frac{2R_1}{R_2}\right) \cdot (V_2 - V_1) + V_{ref}$

Generally, it is preferable that when R_2 is open-circuit, the differential gain is 1. Hence, R_4 is set equal to R_3.

We can further define: $V_{COM} = \frac{1}{2} \cdot (V_2 + V_1)$	$\Delta V = V_2 - V1$	$G = 1 + \frac{2R_1}{R_2}$

Then, the nodal voltages can be rewritten as:

$V_a = V_1 - \frac{G-1}{2} \cdot \Delta V = V_{COM} - \frac{G}{2} \cdot \Delta V$	$V_b = V_2 + \frac{G-1}{2} \cdot \Delta V = V_{COM} + \frac{G}{2} \cdot \Delta V$	$\mathbf{V_{OUT} = G \cdot \Delta V + V_{ref}}$

Assuming a rail-to-rail INA with dual supply ($\pm V_S$), saturation occurs if any of $|V_a|$, $|V_b|$ or $|V_{out}|$ is larger than V_S.

If we observe that $\max\{|V_a|, |V_b|\} = |V_{COM}| + \frac{G}{2} \cdot |\Delta V|$, the saturation conditions can be summarized as:

$$|V_{COM}| + \frac{G}{2} \cdot |\Delta V| > V_S \qquad \text{or} \qquad |G \cdot \Delta V + V_{ref}| > V_S$$

ii. HP – Filtering before the INA

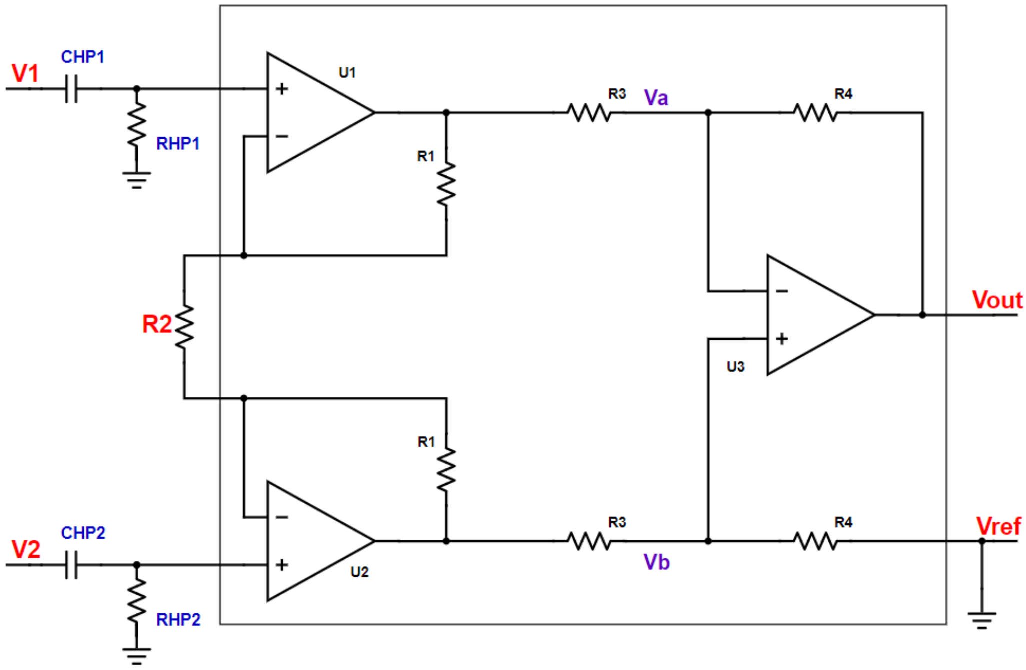

Figure 2 - Matching HP filters before INA

HP filters are placed before the INA inputs and the reference is set to ground. In ideal conditions, these filters would perfectly match ($\tau_{HP1} = \tau_{HP2} = \tau$) and the output would be given by: $V_{OUT} = G \cdot \frac{\tau s}{1+\tau s} \cdot \Delta V$

In practice, there is component mismatch outside the INA IC. Thus, the real output is given by:

$$V_{OUT} = G \cdot \left(\frac{\tau_{HP2}\, s}{1+\tau_{HP2}\, s} V_2 - \frac{\tau_{HP1}\, s}{1+\tau_{HP1}\, s} V_1\right) = G \cdot \left(\left(\frac{\tau_{HP2} s}{1+\tau_{HP2} s} - \frac{\tau_{HP1} s}{1+\tau_{HP1} s}\right) V_{COM} + \frac{1}{2} \cdot \left(\frac{\tau_{HP2} s}{1+\tau_{HP2} s} + \frac{\tau_{HP1} s}{1+\tau_{HP1} s}\right) \Delta V\right)$$

We can then rewrite $\tau_{HP1} = (1+\alpha_1) \cdot \tau$ and $\tau_{HP2} = (1+\alpha_2) \cdot \tau$, with α_1, α_2 small positive or negative deviations due to component mismatch. Doing some algebra along with some logical simplifications for small α_1, α_2 yields the following expressions for common-mode and differential gains as well as CMRR:

$$\frac{A_{CM}}{G} = \frac{\tau_{HP2} s}{1+\tau_{HP2} s} - \frac{\tau_{HP1} s}{1+\tau_{HP1} s} = \ldots algebra \ldots \approx \frac{(\alpha_2 - \alpha_1)}{2} \frac{2\tau\, s}{(\tau\, s)^2 + 2\tau\, s + 1}$$

$$\frac{A_d}{G} = \frac{1}{2} \cdot \left(\frac{\tau_{HP2} s}{1+\tau_{HP2} s} + \frac{\tau_{HP1} s}{1+\tau_{HP1} s}\right) = \ldots \text{algebra} \ldots \approx \frac{\tau s}{1+\tau s} + \frac{\alpha_1 + \alpha_2}{4} \frac{2\tau s}{(\tau\, s)^2 + 2\,\tau\, s + 1}$$

$$CMRR = \left|\frac{A_d}{A_{CM}}\right| = \ldots \text{algebra} \ldots \approx \left|\frac{1}{\alpha_2 - \alpha_1}\right| \cdot (1 + \tau s)$$

[Note that, in practice, CMRR does not increase infinitely with frequency. Once the INA IC CMRR specification is reached, the CMRR will not increase further and in fact it will degrade at high frequencies due to parasitics etc (see any INA datasheet)].

Hence, while the differential gain deviates only slightly from the desired HP response, CMRR degrades significantly for frequencies close to the HP-cut-off.

Within the bandwidth set by the HP-filters (ω from $1/\tau$ to ∞), CMRR is minimum at $\omega = 1/\tau$ $\left(CMRR = \left|\frac{\sqrt{2}}{\alpha_2 - \alpha_1}\right|\right)$.

Thus, even for capacitor tolerance of 1%, the CMRR can degrade to below 40db ($20 \log\left(\left|\frac{\sqrt{2}}{0.02}\right|\right) \approx 37dB$).

This method eliminates the risk of saturation due to DC offset (both differential and common mode) but significantly reduces CMRR.

iii. HP – Filtering after the INA

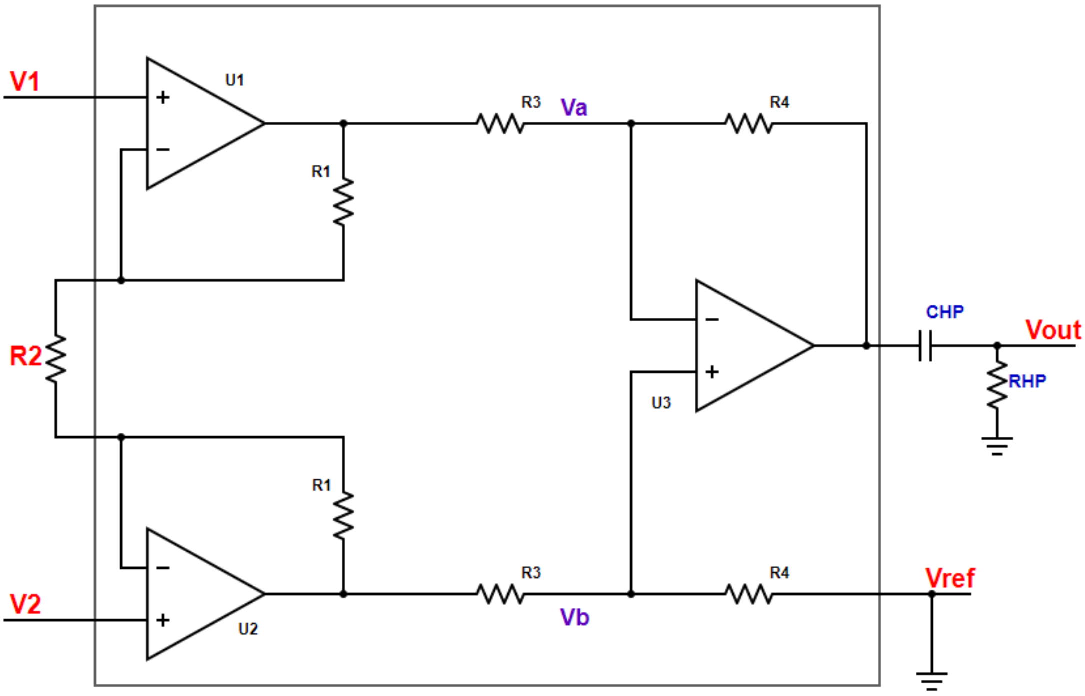

Figure 3 - HP filter after INA

In this implementation, the INA reference is set to ground, and a high pass filter is placed after the INA output.

The output would be given by:

$$V_{OUT} = G \cdot \frac{\tau\, s}{1 + \tau\, s} \cdot \Delta V$$

However, this method works only as long as the DC components of V_{COM} and ΔV do saturate the INA. The saturation conditions in this case can be simplified to:

$$|V_{COM}| + \frac{G}{2} \cdot |\Delta V_{AC} + \Delta V_{DC}| > V_S \qquad \text{or} \qquad G \cdot |\Delta V_{AC} + \Delta V_{DC}| > V_s$$

In this case, if the sum of the AC and DC components of the differential signal is too larger, the system will saturate. However, CMRR is not reduced.

The common mode voltage becomes relevant only if it is larger than $G \cdot |\Delta V_{AC} + \Delta V_{DC}|/2$.

iv. Integrator within the INA feedback loop

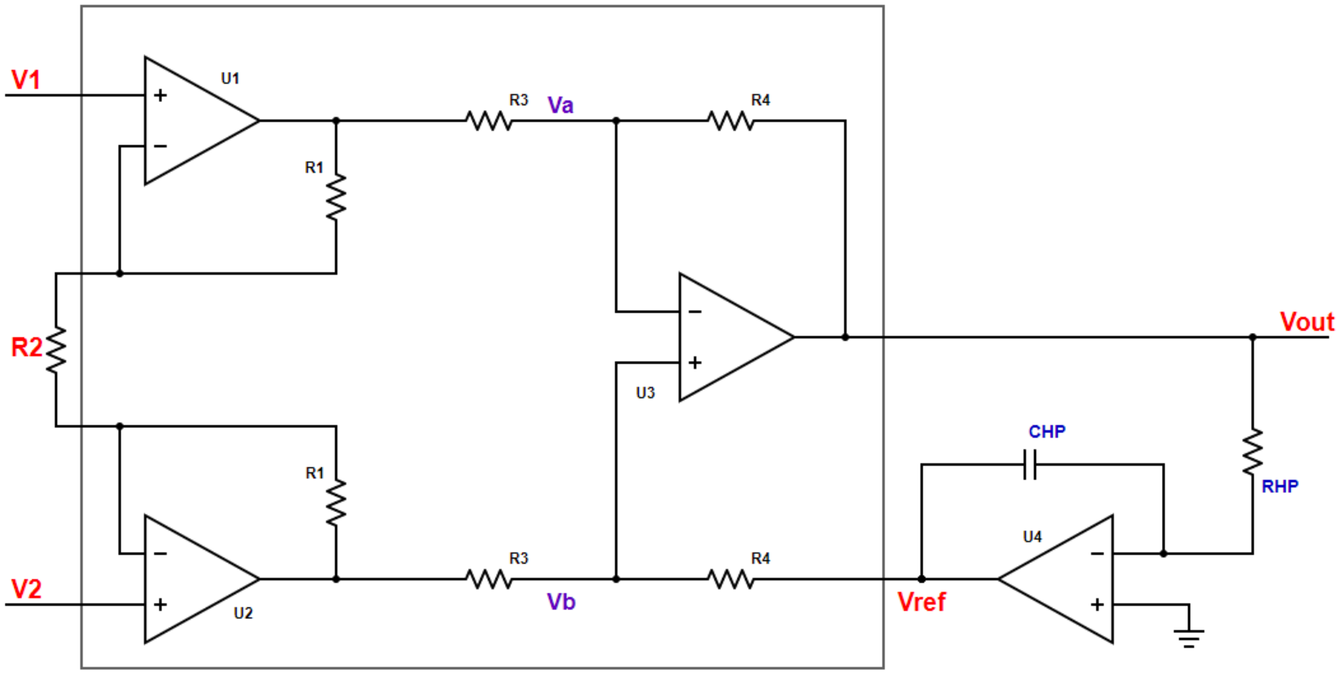

Figure 4 - Integrator within the INA feedback loop

In this implementation, the integrator output is connected to the reference voltage: $V_{ref} = -\frac{V_{OUT}}{\tau s}$.

Resulting in:	$V_{OUT} = G \cdot \Delta V + V_{ref} \Rightarrow V_{OUT} = G \cdot \frac{\tau s}{1+\tau s} \cdot \Delta V$	$V_{ref} = G \cdot \frac{1}{1+\tau s} \cdot \Delta V$
Which at steady state is:	$V_{OUT} = G \cdot \Delta V_{AC}$	$V_{ref} = -G \cdot \Delta V_{DC}$

Assuming that the opamp forming the integrator is also rail to rail and $\pm V_S$, the saturation conditions must be expanded to include the case where V_{ref} is outside the rails and at steady state they can be summarized by:

$$|V_{COM}| + \frac{G}{2} \cdot |\Delta V_{AC} + \Delta V_{DC}| > V_S \quad \text{or} \quad G \cdot |\Delta V_{AC}| > V_s \quad \text{or} \quad G \cdot |\Delta V_{DC}| > V_s$$

In this case, the condition involving the common mode voltage does not change but the condition involving only the differential signal has been decoupled into two conditions each involving only the DC or AC component of the differential signal. This is significant as it gives the designer the opportunity to squeeze out some more performance out of the circuit (as long as the common mode signal is low enough).

Take for example a differential signal of 20mV peak-to-peak sinusoid with a 45mV dc offset and 0 common mode signal. Then, for ±5V supply rails and gain of 100 (G=100), the output will saturate when the HP-filter is placed after the INA (see section iii) but will not be distorted when the integrator is included.

v. Simulations of HP after INA vs Integrator in Feedback

The two methods were simulated and compared using TINA-TI. The INA chosen was the AD8422 (because it is rail-to-rail, low power, low noise and I like it) and the opamp chosen was the OPA192 (since it is rail-to-rail). The power supplies were set to ±5V. The HP filter cut-off was set to 1.6Hz. The set-up is shown in the figure below and simulation files can be found in public-link-to-simulation-on-google-drive.

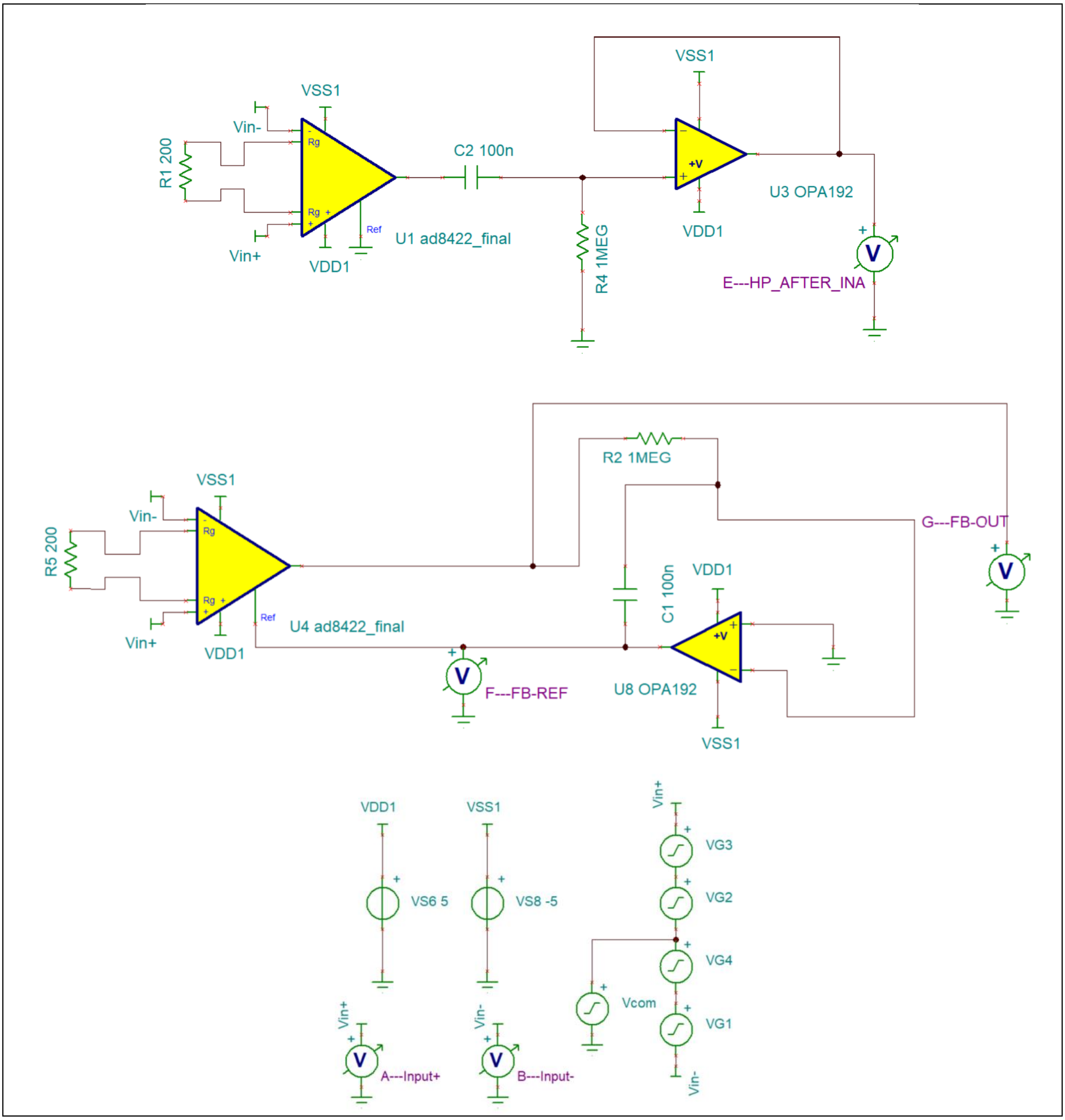

Figure 5 - Simulation Setup for Comparison

a. {Dif-Input}= {(20mV peak-to-peak, 100Hz sinusoid)+45mV DC}, {Com-Input}=0

$$\max\left\{|\mathrm{V_{COM}}| + \frac{\mathrm{G}}{2}\cdot|\Delta\mathrm{V_{AC}} + \Delta\mathrm{V_{DC}}|\right\} = 0 + 50\cdot(10mV + 45mV) = 2.75V < 5V$$

$$\max\{\mathrm{G}\cdot|\Delta\mathrm{V_{AC}} + \Delta V_{DC}|\} = 100\cdot(10mV + 45mV) = 5.5V > \mathbf{5V}$$

$$\max\{\mathrm{G}\cdot|\Delta\mathrm{V_{AC}}|\} = 100\cdot(10mV) = 1V < 5V$$

$$\max\{\mathrm{G}\cdot|\Delta V_{DC}|\} = 100\cdot(45mV) = 4.5V < 5V$$

The "HP-after-INA" should saturate, while the "integrator feedback" should not.

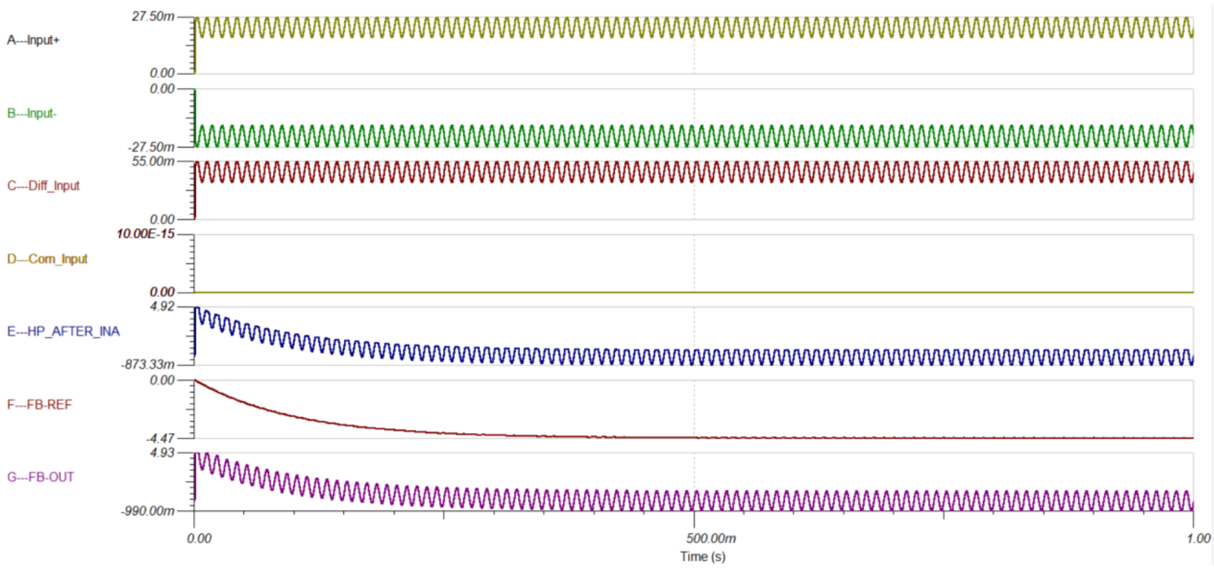

Figure 6 - Transient response. Settles within less than 1s.

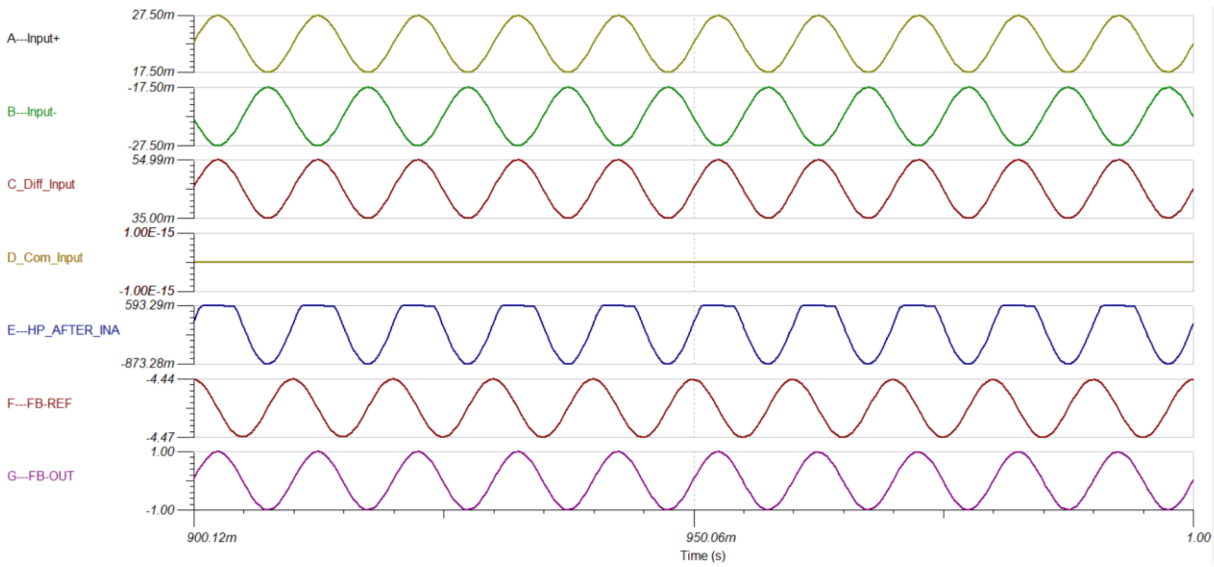

*Figure 7 - Response zoomed to 0.9s to 1s. The "HP-after-INA" response shows clear clipping (as expected). The reference voltage in the feedback case is a low-pass filtering of the inverted amplified differential voltage (sitting at around -4.5V superimposed by an approximately 30mV peak-to-peak sinusoid, which is expected since 20mV*100/sqrt(1+(100/1.6)^2)=32mV). The output in the feedback case does not show any clipping and is approximately 2V peak-to-peak (as expected).*

In this case, the total differential voltage would saturate the system, but the ac and dc components separately do not. Additionally, the common voltage is 0 and hence does not contribute to saturation.

Lets now see an example where the common mode voltage is such that saturation occurs both for the feedback case and the "HP-after-INA" case.

a. {Dif-Input}= {(20mV peak-to-peak, 100Hz sinusoid)+45mV DC}, {Com-Input}=3V

$$\max\left\{|V_{COM}| + \frac{G}{2}\cdot|\Delta V_{AC} + \Delta V_{DC}|\right\} = 3 + 50\cdot(10mV + 45mV) = \mathbf{5.75V > 5V}$$

$$\max\{G\cdot|\Delta V_{AC} + \Delta V_{DC}|\} = 100\cdot(10mV + 45mV) = 5.5V > \mathbf{5V}$$

$$\max\{G\cdot|\Delta V_{AC}|\} = 100\cdot(10mV) = 1V < 5V$$

$$\max\{G\cdot|\Delta V_{DC}|\} = 100\cdot(45mV) = 4.5V < 5V$$

Both the “HP-after-INA” and the “integrator feedback” should saturate.

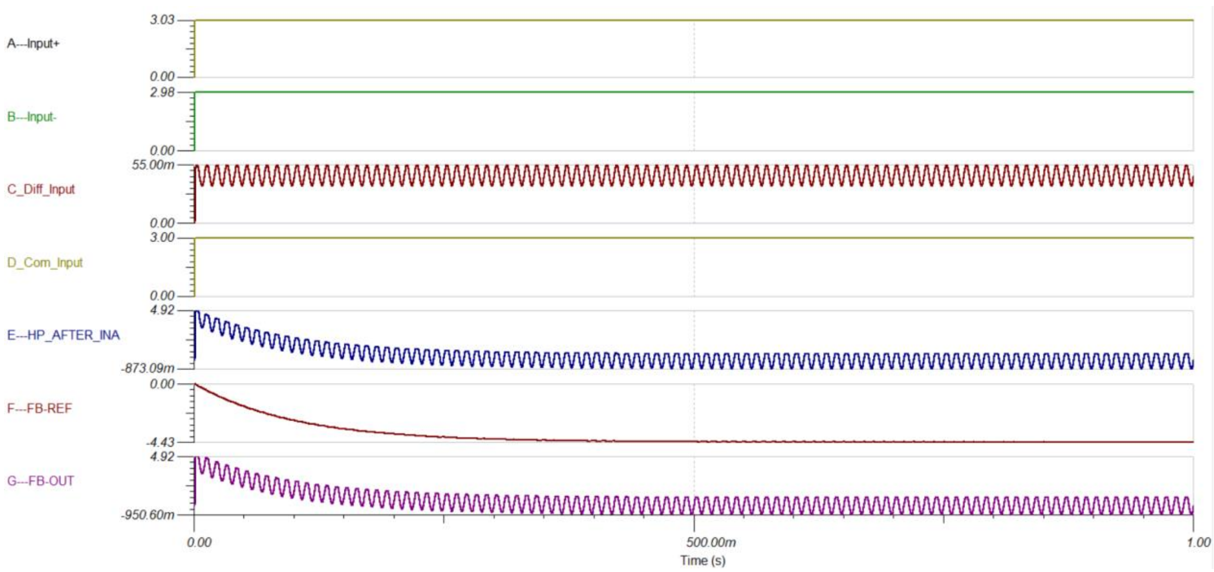

Figure 8 - Transient Response. Settles within less than 1s.

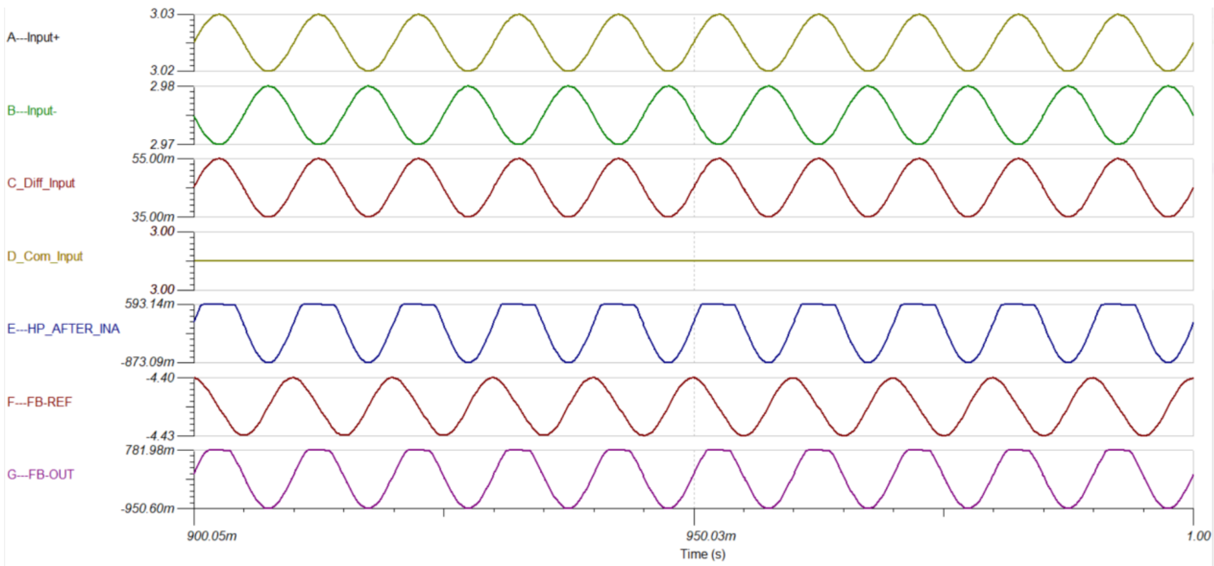

Figure 9 - Response zoomed to 0.9s to 1s. Both cases show clipping as expected.

In this case the common mode voltage is high enough that both methods fail. The solution here is to decrease the gain, or to place HP- filters before the INA and take the penalty of degraded CMRR.

Generally, the only reasons to not use the feedback method is space and power consumption or incredibly high DC common voltages. The “HP-after-INA” method should be used only when the space/power consumption of a single op-amp is more important than the system dynamic range (unlikely scenario), while the “HP-before-INA” method should only be used if the common mode voltages are close to the INA rail voltages.