LECTURE 180 – POWER SUPPLY REJECTION RATIO
(READING: GHLM – 434-439, AH – 286-293)

Objective
The objective of this presentation is:
1.) Illustrate the calculation of PSRR
2.) Examine the PSRR of the two-stage, Miller compensated op amp

Outline
• Definition of PSRR
• Calculation of PSRR for the two-stage op amp
• Conceptual reason for PSRR
• Summary

What is PSRR?

PSRR = \( \frac{A_v(V_{dd}=0)}{A_{dd}(V_{in}=0)} \)

How do you calculate PSRR?
You could calculate \( A_v \) and \( A_{dd} \) and divide, however

\[
V_{out} = A_{dd}V_{dd} + A_v(V_1-V_2) = A_{dd}V_{dd} - A_vV_{out} \quad \rightarrow \quad V_{out}(1+A_v) = A_{dd}V_{dd}
\]

\[
\therefore \quad \frac{V_{out}}{V_{dd}} = \frac{A_{dd}}{1+A_v} = \frac{A_v}{PSRR^+} \quad \text{(Good for frequencies up to } GB)\]
The nodal equations are:

\[(g_{ds1} + g_{ds4})V_{dd} = (g_{ds2} + g_{ds4} + sC_c + sC_l)V_1 - (g_{m1} + sC_c)V_{out}\]

\[(g_{m6} + g_{ds6})V_{dd} = (g_{m6} - sC_c)V_1 + (g_{ds6} + g_{ds7} + sC_c + sC_{II})V_{out}\]

Using the generic notation the nodal equations are:

\[G_I V_{dd} = (G_I + sC_c + sC_l)V_1 - (g_{ml} + sC_c)V_{out}\]

\[(g_{mII} + g_{ds6})V_{dd} = (g_{mII} - sC_c)V_1 + (G_{II} + sC_c + sC_{II})V_{out}\]

where \(G_I = g_{ds1} + g_{ds4} = g_{ds2} + g_{ds4}, G_{II} = g_{ds6} + g_{ds7}, g_{ml} = g_{m1} = g_{m2}\) and \(g_{mII} = g_{m6}\)

We may solve for the approximate roots of numerator as

\[PSRR^+ = \frac{V_{dd}}{V_{out}} = \left(\frac{g_{ml}g_{mII}}{G_{II}g_{ds6}}\right) \left[\frac{sC_c}{g_{ml} + 1} \left(\frac{s(C_cC_I+C_{II}+C_{II}C_c)}{g_{mII}C_c} + 1\right)\right]

where \(g_{mII} > g_{ml}\) and that all transconductances are larger than the channel conductances.

\[\therefore PSRR^+ = \frac{V_{dd}}{V_{out}} = \left(\frac{g_{ml}g_{mII}}{G_{II}g_{ds6}}\right) \left[\frac{sC_c}{g_{ml} + 1} \left(\frac{sC_{II}}{g_{mII} + 1}\right) + 1\right] = \left(\frac{G_{II}A_{vo}}{g_{ds6}}\right) \left[\frac{s}{GB + 1} + \frac{s}{|p|^2 + 1}\right] \left(\frac{sG_{II}A_{vo}}{g_{ds6}GB + 1}\right)\]
Positive PSRR of the Two-Stage Op Amp - Continued

At approximately the dominant pole, the PSRR falls off with a -20dB/decade slope and degrades the higher frequency PSRR+ of the two-stage op amp. Using the values of Example 6.3-1 we get:

\[ PSRR^+(0) = 68.8\text{dB}, \quad z_1 = -5\text{MHz}, \quad z_2 = -15\text{MHz} \quad \text{and} \quad p_1 = -906\text{Hz} \]

Concept of the PSRR+ for the Two-Stage Op Amp

1.) The M7 current sink causes \( V_{SG6} \) to act like a battery.
2.) Therefore, \( V_{dd} \) couples from the source to gate of M6.
3.) The path to the output is through any capacitance from gate to drain of M6.

Conclusion:
The Miller capacitor \( C_c \) couples the positive power supply ripple directly to the output. Must reduce or eliminate \( C_c \).
Negative PSRR of the Two-Stage Op Amp with $V_{Bias}$ Grounded

Nodal equations for $V_{Bias}$ grounded:

$$0 = (G_I + sC_C + sC_I) V_1 - (g_{mI} + sC_c) V_o$$

$$g_{mI} V_{ss} = (g_{MII} - sC_c) V_1 + (G_{II} + sC_c + sC_{II}) V_o$$

Solving for $V_{out}/V_{ss}$ and inverting gives

$$\frac{V_{ss}}{V_{out}} = s \frac{[sC_C C_I + C_I C_{II} + C_{II} C_c] + s[G_I (C_c + C_{II}) + G_{II} (C_c + C_I) + C_c (g_{mII} - g_{mI})] + G_{II} + g_{mII} g_{mI}}{[s(C_c + C_I) + G_I] g_{mI}}$$

Assuming the values of Ex. 6.3-1 gives a gain of 23.7 dB and a pole -147 kHz. The dc value of PSRR$^-$ is very poor for this case, however, this case can be avoided by correctly implementing $V_{Bias}$ which we consider next.
Negative PSRR of the Two-Stage Op Amp with $V_{Bias}$ Connected to $V_{SS}$

If the value of $V_{Bias}$ is independent of $V_{SS}$, then the model shown results. The nodal equations for this model are

$$0 = (G_I + sC_c + sC_I)V_1 - (g_{ml} + sC_c)V_{out}$$

and

$$(g_{ds7} + sC_{gd7})V_{SS} = (g_{ml} - sC_c)V_1 + (G_{II} + sC_c + sC_{II} + sC_{gd7})V_{out}$$

Again, solving for $V_{out}/V_{SS}$ and inverting gives

$$\frac{V_{SS}}{V_{out}} = \frac{s^2[C_{I}C_I + C_{II}C_{II} + C_{I}C_{II} + C_{I}C_{gd7} + C_{II}C_{gd7}]}{(sC_{gd7} + g_{ds7})(s(C_{I}C_I) + G_I)}$$

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Comments:
- DC gain has been increased by the ratio of $G_{II}$ to $g_{ds7}$
- Two poles instead of one, however the pole at $-g_{ds7}/C_{gd7}$ is large and can be ignored.

Using the values of Ex. 6.3-1 and assume that $C_{ds7} = 10fF$, gives,

$$PSRR(-0) = 76.7dB$$

and

Poles at -71.2kHz and -149MHz
Frequency Response of the Negative PSRR of the Two-Stage Op Amp with $V_{Bias}$ Connected to $V_{SS}$

Approximate Model for Negative PSRR with $V_{Bias}$ Connected to Ground

Path through the input stage is not important as long as the CMRR is high.
Path through the output stage:

$v_{out} = i_{ss}Z_{out} = g_mZ_{out}V_{ss}$

$\therefore \quad \frac{V_{out}}{V_{ss}} = g_mZ_{out} = g_mR_{out}\left(\frac{1}{sR_{out}C_{out}+1}\right)$
**Approximate Model for Negative PSRR with \( V_{Bias} \) Connected to \( V_{SS} \)**

What is \( Z_{out} \)?

\[
Z_{out} = \frac{V_{t}}{I_{t}} \Rightarrow
\]

\[
I_{t} = g_{mII}V_{1} = g_{mII}\left(\frac{g_{mI}V_{t}}{G_{I}+sC_{I}+sC_{c}}\right)
\]

Thus, \( Z_{out} = \frac{G_{I}+s(C_{I}+C_{c})}{g_{mI}g_{mII}} \)

\[
\therefore \quad \frac{V_{SS}}{V_{out}} = \frac{1+\frac{r_{ds7}}{Z_{out}}}{1} = \frac{s(C_{c}+C_{f})+G_{I}+g_{mI}g_{mII}r_{ds7}}{s(C_{c}+C_{f})+G_{I}} \Rightarrow \text{Pole at } \frac{-G_{I}}{C_{c}+C_{I}}
\]

The two-stage op amp will never have good PSRR because of the Miller compensation.

**SUMMARY**

- PSRR is a measure of the influence of power supply ripple on the op amp output voltage
- PSRR can be calculated by putting the op amp in the unity-gain configuration with the input shorted.
- The Miller compensation capacitor allows the power supply ripple at the output to be large
- The two-stage op amp will never have good PSRR unless some modifications are made.