

Improving OTA Compensator Performance By Using Series Termination Feedback

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Almost all semiconductor manufacturers currently recommend using shunt-termination compensation for their OTA-based compensators. However, this makes the compensator much more sensitive to the transconductance g_m compared to using series-termination compensation as initially described in references [1] and [2].

The use of shunt termination does not provide local feedback around the OTA. Local feedback can be added by switching to series termination which places the compensation components between the COMP pin and the feedback pin of the error amplifier. This practice is not unlike using negative feedback around operational amplifiers which reduces the impact of the large and often widely varying open loop gain A_v .

Most available guidance provides steps for determining compensation component values for shunt termination.^[3,4] A notable exception is reference [5], which offers a procedure for series termination. However, it does not point out the benefit of reduced sensitivity to the transconductance g_m .

This article determines a general impedance transformation formula to convert shunt-termination compensation to an equivalent series-termination compensation. Results from Monte Carlo analysis for types I and II style compensators confirm that the OTA compensator stage gain using series termination varies less than the shunt termination configuration. This reduced variation can improve the design of the overall dc-dc control loop.

Model Description

This article considers the OTA compensator stage that is typically found in dc-dc converters (Fig. 1).

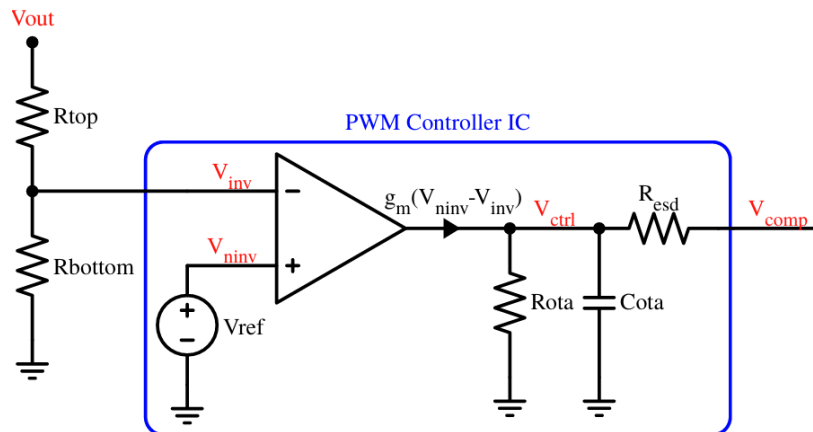


Fig. 1. PWM controller OTA model.

There is a resistor divider that samples the output voltage V_{out} consisting of R_{top} and R_{bottom} with the middle node connected to the error amplifier OTA inverting input.

The OTA parameters are its transconductance g_m , and output resistance R_{ota} and capacitance C_{ota} which are in parallel as $Z_{ota} = R_{ota} \parallel 1/sC_{ota}$. Some datasheets may not define the OTA output resistance explicitly, but it can be derived by dividing the OTA dc voltage gain by its transconductance g_m .

The OTA output capacitance may also not be defined explicitly, but it can be computed as $C_{ota} = 1/2\pi R_{ota} BW_{ota}$ where BW_{ota} is the OTA bandwidth. On the PWM controller, there is a COMP pin accessible to the user to adjust the compensator stage as necessary for proper loop stability.

The compensation components' equivalent impedance connected between the COMP pin and ground for shunt termination is designated as Z_{shunt} .

The series termination has the compensation components connected between the COMP pin and the OTA inverting input pin. The equivalent impedance is designated as Z_{series} . (The connections for the shunt and the series terminations are shown below in Figs. 2 and 3.)

Note that reference [6] has discussed the existence of a nonnegligible amount of parasitic resistance that may exist between the OTA output V_{ctrl} and the COMP pin. This parasitic resistance R_{esd} would be considered as part of Z_{shunt} or Z_{series} as a series term with the compensation components the user connects to the COMP pin. V_{ctrl} is the output voltage that goes onto the power stage of the dc-dc converter.

Equations of the compensator stage gain with shunt and series termination are determined and then set equal to each other. Z_{series} is then solved for and is an impedance transformation function of Z_{shunt} to Z_{series} .

Shunt Termination Gain

In Fig. 2, the gain from the top of the resistor divider V_{out} to the output voltage of the OTA V_{ctrl} is

$$A_{V_{shunt}} = \frac{V_{out}}{V_{ctrl}} = \frac{-R_{bottom}}{R_{bottom} + R_{top}} g_m (Z_{shunt} \parallel Z_{ota}) \quad (1)$$

V_{ninv} does not appear in the equation above as it is an ac ground.

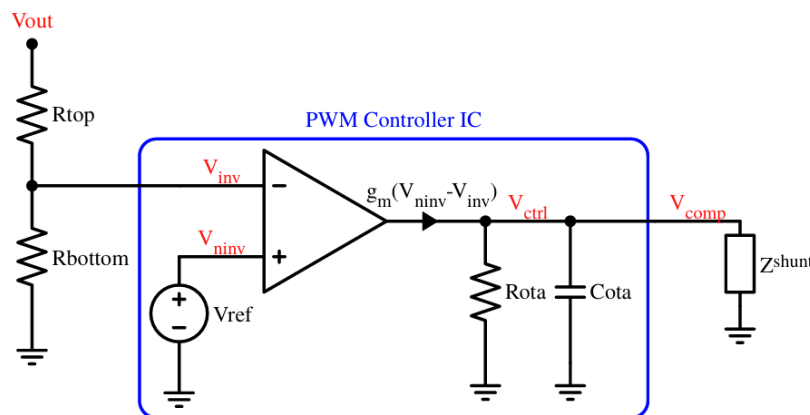


Fig. 2. OTA compensator using shunt termination.

Series Termination Gain

First an expression for the inverting input V_{inv} is determined, then the output voltage of the OTA V_{ctrl} , and finally the gain (Fig. 3).

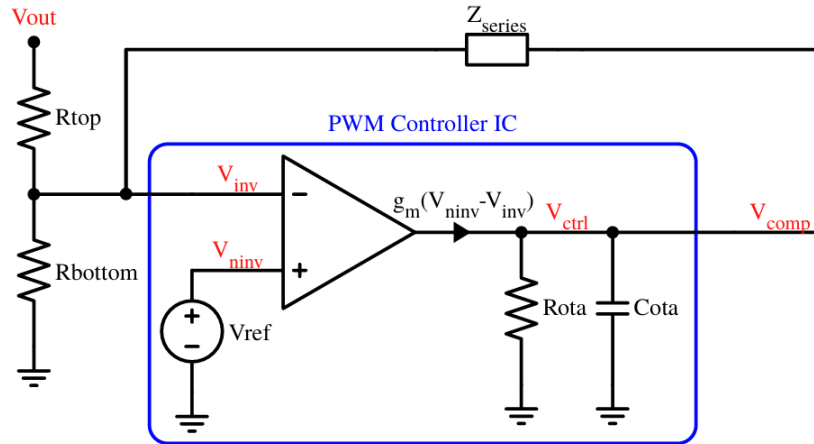


Fig. 3. OTA compensator using series termination.

The inverting input V_{inv} is computed by superposition from V_{out} and I_{ota} sources. The contribution from V_{out} is

$$V_{inv} \Big|_{V_{out}} = V_{out} \frac{R_{bottom} \parallel (Z_{series} + Z_{ota})}{R_{bottom} \parallel (Z_{series} + Z_{ota}) + R_{top}} \quad (2)$$

The contribution from I_{ota} is

$$V_{inv} \Big|_{I_{ota}} = I_{ota} \frac{Z_{ota}}{R_{par} + Z_{series} + Z_{ota}} R_{par} \quad (3)$$

where

$$R_{par} = R_{top} \parallel R_{bottom} \quad (4)$$

and

$$I_{ota} = -g_m V_{inv} \quad (5)$$

Equation (5) is substituted into (3). Then (2) and (3) are summed to get the overall expression for V_{inv} and is solved for

$$V_{inv} = V_{out} \frac{\frac{R_{bottom} \parallel (Z_{series} + Z_{ota})}{R_{bottom} \parallel (Z_{series} + Z_{ota}) + R_{top}}}{1 + g_m \frac{Z_{ota}}{R_{par} + Z_{series} + Z_{ota}} R_{par}} \quad (6)$$

The OTA output voltage V_{ctrl} is computed by superposition from V_{out} and I_{ota} sources. The contribution from V_{out} is

$$V_{ctrl} \Big|_{V_{out}} = V_{out} \frac{R_{bottom} \parallel (Z_{series} + Z_{ota})}{R_{bottom} \parallel (Z_{series} + Z_{ota}) + R_{top}} \frac{Z_{ota}}{Z_{ota} + Z_{series}} \quad (7)$$

The contribution from I_{ota} is

$$V_{ctrl} \Big|_{I_{ota}} = I_{ota} [Z_{ota} \parallel (R_{par} + Z_{series})] \quad (8)$$

Equations (5) and (6) are substituted into (8) which is summed with (7) to get the overall expression for V_{ctrl} as a function of V_{out} . The gain $A_{Vseries}$ is solved for

$$A_{Vseries} = \frac{R_{bottom}}{R_{bottom} + R_{top}} \frac{Z_{ota}(1 - g_m Z_{series})}{Z_{ota}(1 + g_m R_{par}) + 1 + Z_{series}} \quad (9)$$

If $|Z_{series}| \ll |Z_{ota}|$, then the expression can be simplified to

$$A_{Vseries} = \frac{R_{bottom}}{R_{bottom} + R_{top}} \frac{(1 - g_m Z_{series})}{(1 + g_m R_{par})} \quad (10)$$

A form of the above expression also appears in the previous works [1] and [2].

Shunt-To-Series Impedance Transformation

Equations (1) and (9) are set equal to each other and Z_{series} is solved for

$$Z_{series} = Z_{shunt} \left(1 + g_m R_{par} \right) + \frac{Z_{shunt}}{Z_{ota}} \left(1 + \frac{1}{g_m} \right) + \frac{1}{g_m} \quad (11)$$

If $|Z_{shunt}| \ll |Z_{ota}|$, then the expression can be simplified to

$$Z_{series} = Z_{shunt} \left(1 + g_m R_{par} \right) + \frac{1}{g_m} \quad (12)$$

Type I Compensation

Type I shunt compensation consists of a capacitor C_1 connected from COMP pin to ground (Fig. 4). Its impedance is

$$Z_{shunt I} = \frac{1}{sC_1} \quad (13)$$

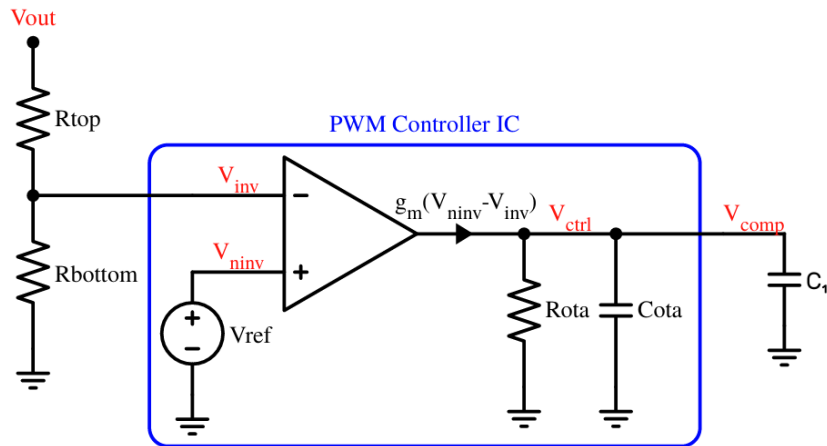


Fig. 4. OTA compensator stage using type I shunt termination. Note that R_{esd} is not present and is considered as a short.

Assuming $|Z_{shunt}| \ll |Z_{ota}|$, the equivalent series termination impedance using (12) is

$$Z_{\text{series I}} = \frac{1}{s \frac{C_1}{1+g_m R_{\text{par}}}} + \frac{1}{g_m} \quad (14)$$

This is equivalent to a series combination of a resistor R and capacitor C (see Fig. 5) with the following values:

$$R = \frac{1}{g_m} \quad (15)$$

$$C = \frac{C_1}{1+g_m R_{\text{par}}}$$

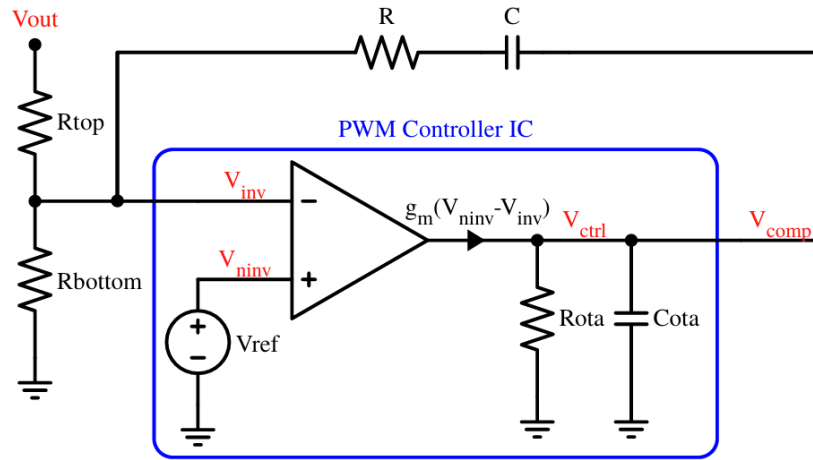


Fig. 5. OTA compensator stage using a transformed type I series termination.

Type II Compensation

Type II shunt compensation consists of a series combination $C_1 + R_2$ that is in parallel with a capacitor C_3 which is set open for this first calculation (Fig. 6). The impedance is

$$Z_{\text{shunt II, } C_3 \text{ open}} = \frac{1}{sC_1} + R_2 \quad (16)$$

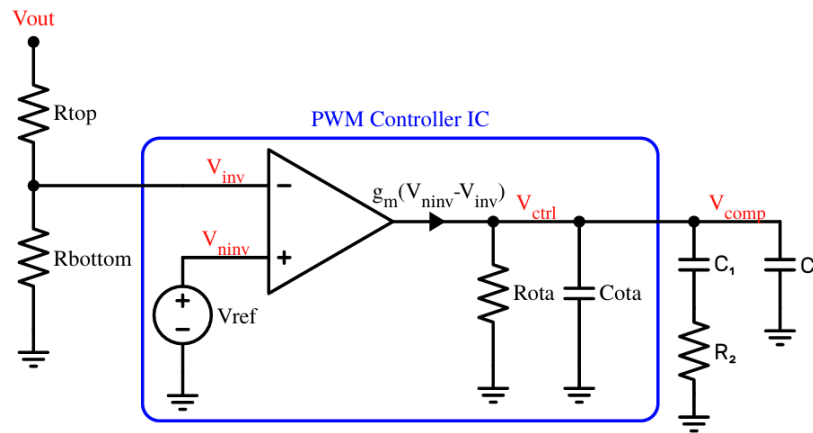


Fig. 6. OTA compensator stage using type II shunt termination.

Assuming $|Z_{shunt}| \ll |Z_{ota}|$ the equivalent series termination impedance using (12) is

$$Z_{\text{series II, } C_3 \text{ open}} = \frac{1}{s \frac{C_1}{1+g_m R_{\text{par}}}} + R_2(1 + g_m R_{\text{par}}) + \frac{1}{g_m} \quad (17)$$

This is equivalent to a series combination of a resistor R and capacitor C with the following values:

$$R = R_2(1 + g_m R_{\text{par}}) + \frac{1}{g_m}$$

$$C = \frac{C_1}{1+g_m R_{\text{par}}} \quad (18)$$

If C_3 is present, the impedance is

$$Z_{\text{shunt II, } C_3 \text{ present}} = \left(\frac{1}{s C_1} + R_2 \right) \parallel \frac{1}{s C_3} \quad (19)$$

Assuming $|Z_{shunt}| \ll |Z_{ota}|$ and that $1/g_m$ is negligible, the equivalent series termination impedance using (12) is

$$Z_{\text{series II, } C_3 \text{ present}} = \left(\frac{1}{s \frac{C_1}{1+g_m R_{\text{par}}}} + R_2(1 + g_m R_{\text{par}}) \right) \parallel \frac{1}{s \frac{C_3}{1+g_m R_{\text{par}}}} \quad (20)$$

This is equivalent to the shunt termination network with the resistor value multiplied by $1 + g_m R_{\text{par}}$ and the capacitors' values each divided by $1 + g_m R_{\text{par}}$ (Fig. 7). Note that reference [5] also provides guidance on computing the series termination OTA compensator component values for type II.

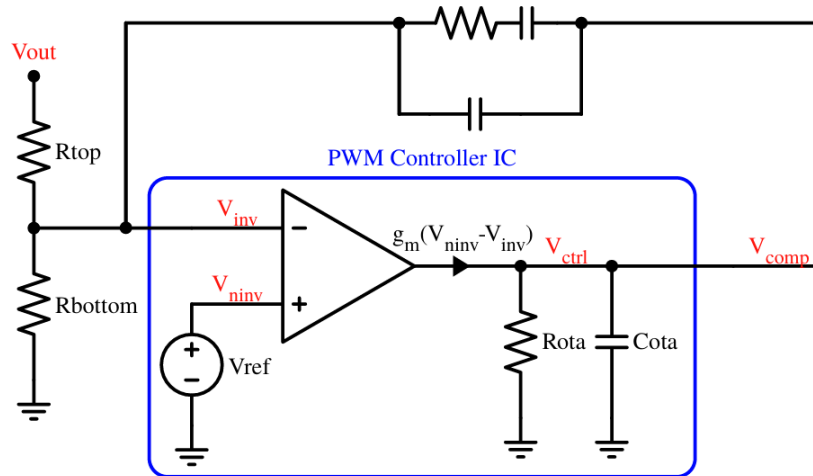


Fig. 7. OTA compensator stage using type II series termination.

Comparisons

Circuit simulations are performed to verify the preceding equations and the improvement due using series termination instead of shunt termination.

Type I Compensation

TPS7H5001-SP compensator stages using type I shunt termination compensation along with its equivalent series termination are captured in PSpice in Fig. 8. The ac voltage injection is placed in the same location as would be used when determining the overall loop gain. The compensator gain would then simply be $V(V_{comp})/V(V_{inj})$.

An MC parameter is set to 0 for the nominal simulation and to 1 for the Monte Carlo simulation which is used for the OTA transconductance property.

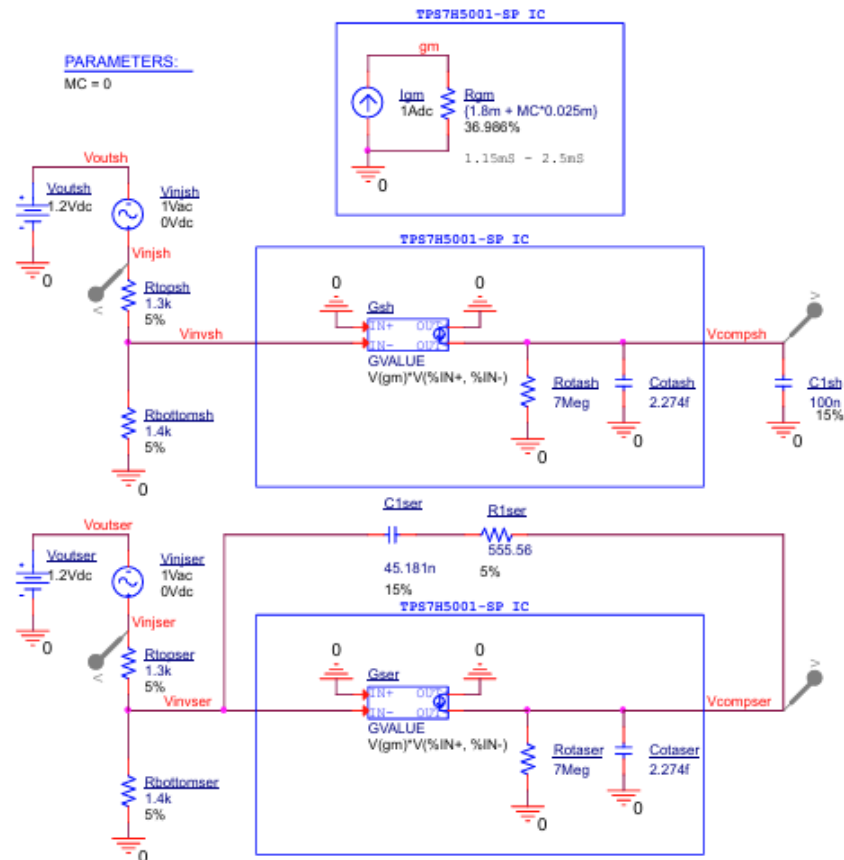


Fig. 8. PSpice schematic of the OTA type I compensators.

The value of the OTA output capacitance is computed as discussed in the section above on model description. The transconductance is 1.8 mS typical with a range of 1.15 mS to 2.5 mS from the TPS7H5001-SP datasheet.^[7]

The external resistor tolerances are 5% and the external capacitor tolerances are 15%. The series termination impedance is computed using (14). Uniform distribution is used for the tolerances. 1440 random cases are run which corresponds with 99%/90% population coverage/certainty.^[8,9]

The resulting nominal simulation shows that the dB gain and phase over frequency for both compensators in Fig. 9 are nearly identical. dB gain and phase plots from the Monte Carlo analysis are shown in Figs. 10, 11, and 12.

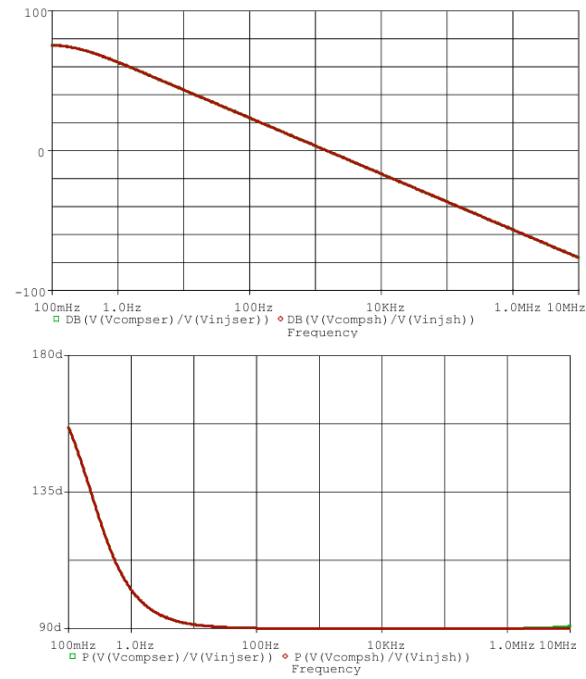


Fig. 9. Nominal dB gain (top) and phase (bottom) of the OTA type I shunt and its series termination transformation.

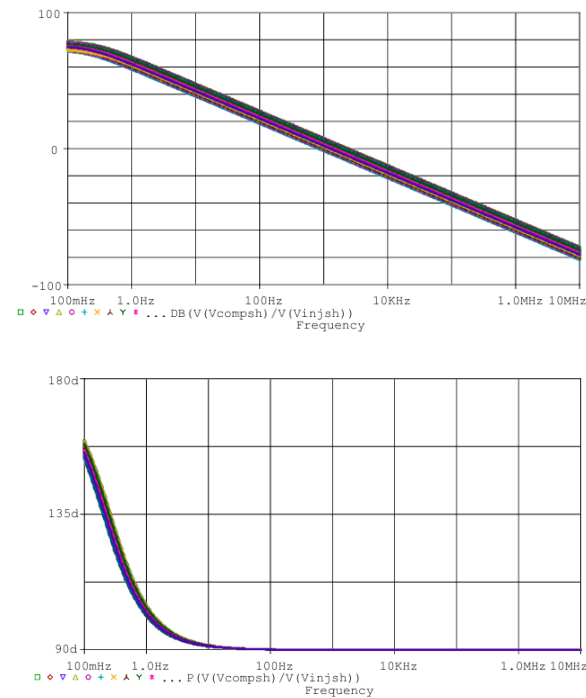


Fig. 10. Monte Carlo dB gain (top) and phase (bottom) of the OTA type I shunt termination.

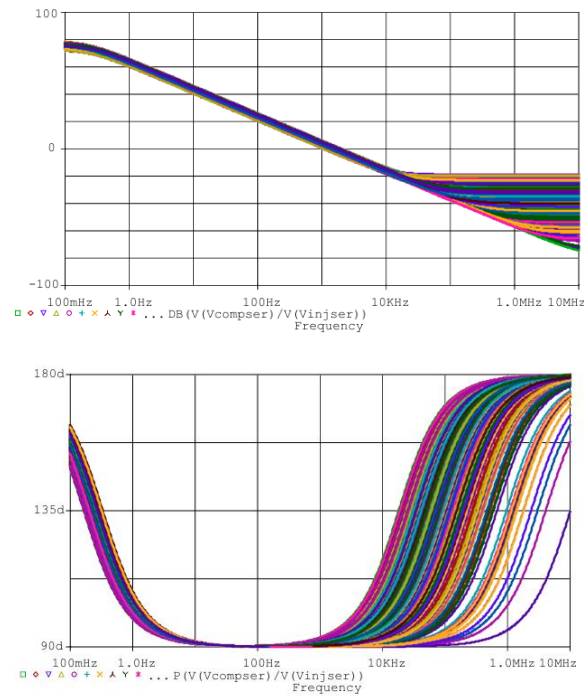


Fig. 11. Monte Carlo dB gain (top) and phase (bottom) of the OTA type I series termination transformation.

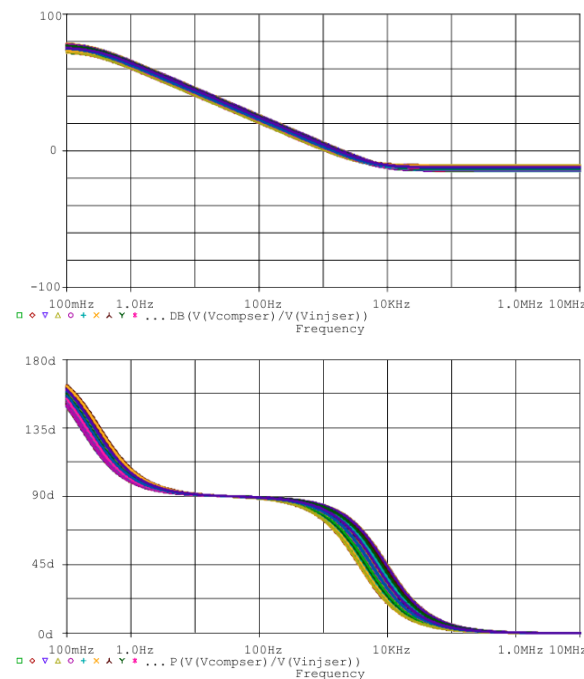


Fig. 12. Monte Carlo dB gain (top) and phase (bottom) of the OTA type I series termination transformation with R1ser replaced with a short.

There is more dB gain and phase variation in Fig. 11 compared to Fig. 10 above 10 kHz so R1ser is replaced with a short and its simulation results are shown in Fig. 12. The dB gain above 10 kHz does not continue with a –20-dB slope so some care must be taken to determine whether this is acceptable for the overall loop gain.

Histograms of the dB gain values at 1 kHz from Figs. 10 and 12 are obtained in Figs. 13 and 14.

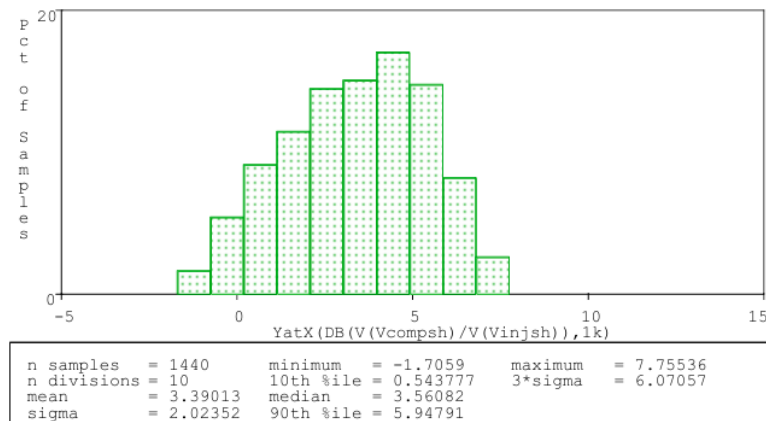


Fig. 13. Histogram of the dB gain at 1 kHz of the OTA type I shunt termination.

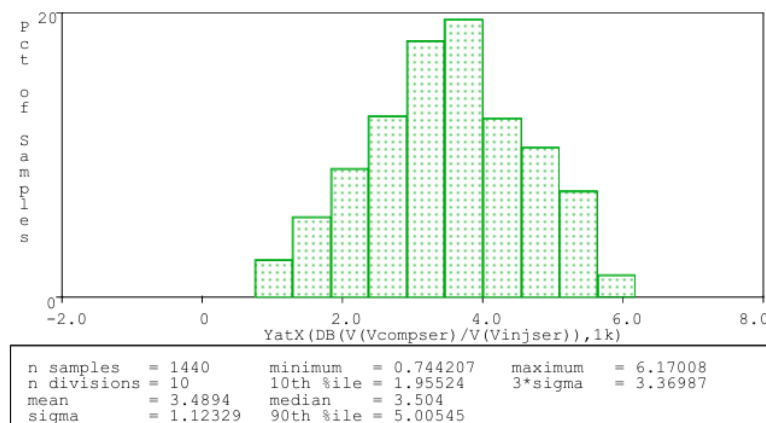


Fig. 14. Histogram of the dB gain at 1 kHz of the OTA type I series termination.

The dB gain ranges for type I shunt and series terminations are –1.706 dB to 7.755 dB and 0.744 dB to 6.170 dB, respectively. The series termination results in a range that is narrower than the shunt termination by approximately 4 dB.

Type II Compensation

NCV8871 compensator stages using type II shunt termination compensation along with its equivalent series termination are captured in PSpice in Fig. 15. The shunt termination compensation components, Rota, Cota, Rtop, and Rbottom values come from reference [5].

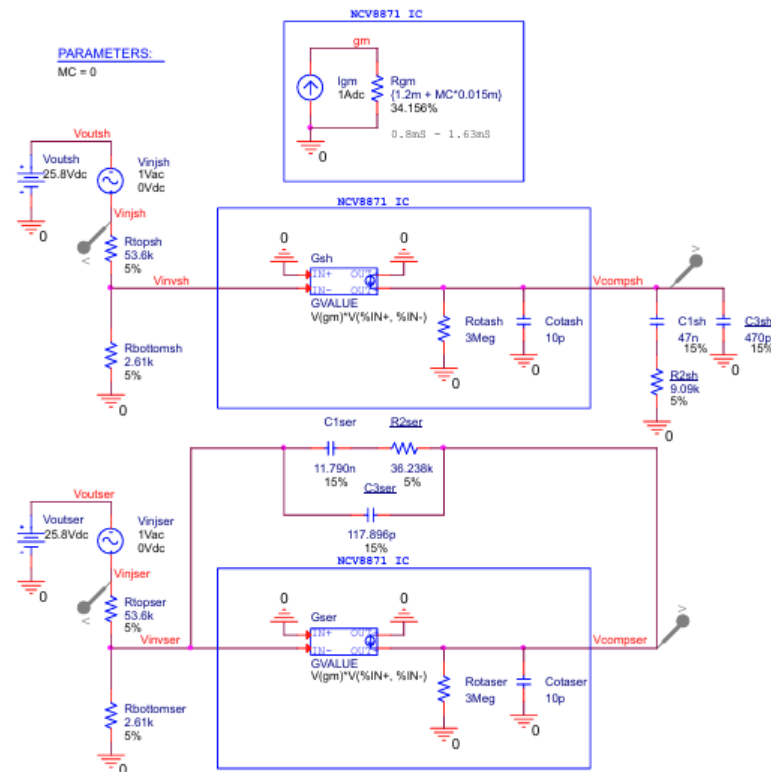


Fig. 15. PSpice schematic of the OTA type II compensators.

The transconductance is 1.2 mS typical with a range of 0.8 mS to 1.63 mS from the NCV8871 datasheet.^[10] The external resistor tolerances are 5% and the external capacitor tolerances are 15%. The series termination component values are computed using (20). Uniform distribution is used for the tolerances. In this experiment, 1440 random cases are run which corresponds with 99%/90% population coverage/certainty.^[8,9]

The resulting nominal simulation shows that the frequency response for both compensators in Fig. 16 are similar up to approximately 1 MHz. However, this is at a frequency that is typically greater than the crossover and switching frequencies of a dc-dc converter so the mismatch is not important.

The dB gain and phase plots from the Monte Carlo analysis are shown in Figs. 17 and 18. Histograms of the dB gain values at 1 kHz from Figs. 17 and 18 are shown in Figs. 19 and 20.

The dB gain ranges for type II shunt and series terminations are -9.727 dB to -1.952 dB and -7.463 dB to -4.187 dB, respectively. The series termination results in a range that is narrower than the shunt termination by approximately 4.5 dB.

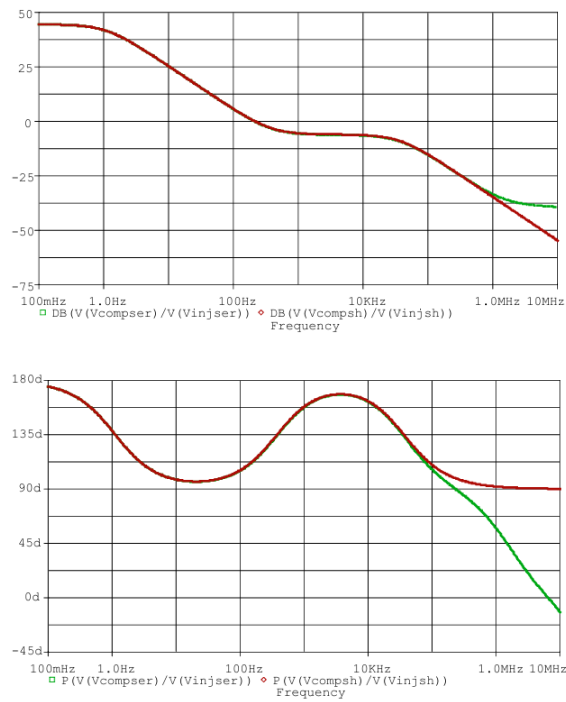


Fig. 16. Nominal dB gain (top) and phase (bottom) of the OTA type II shunt and its series termination transformation.

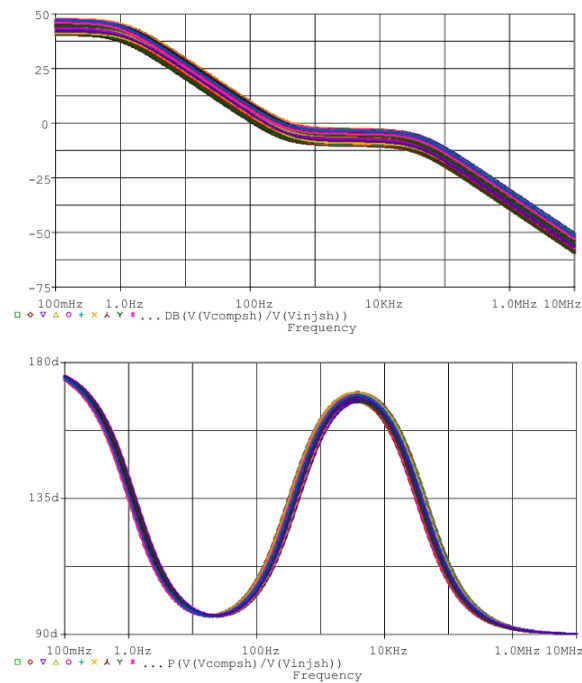


Fig. 17. Monte Carlo dB gain (top) and phase (bottom) of the OTA type II shunt termination.

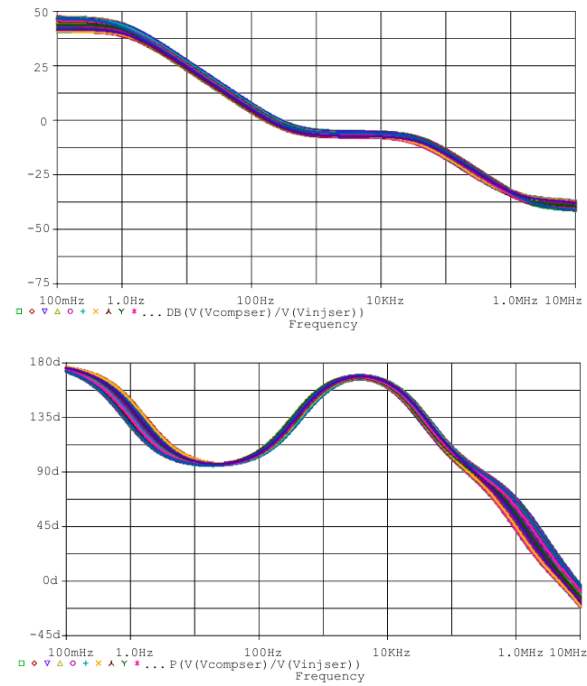


Fig. 18. Monte Carlo dB gain (top) and phase (bottom) of the OTA type II series termination transformation.

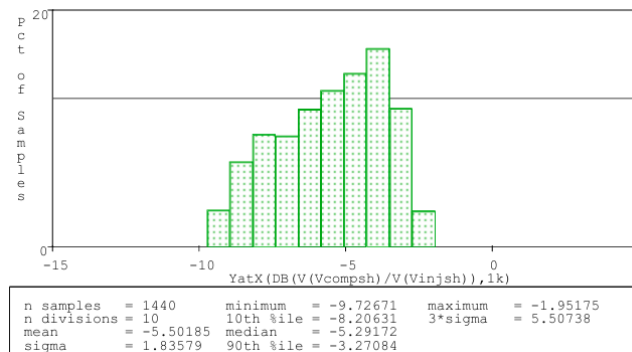


Fig. 19. Histogram of the dB gain at 1 kHz of the OTA type II shunt termination.

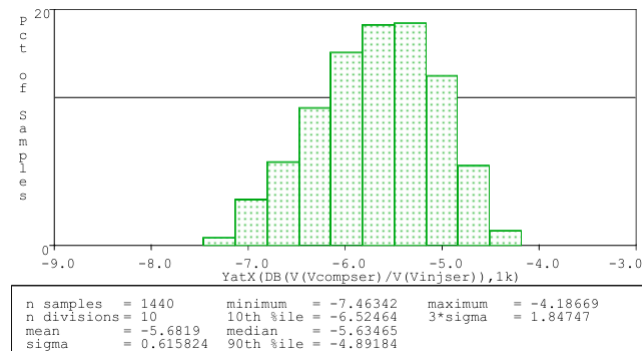


Fig. 20. Histogram of the dB gain at 1 kHz of the OTA type II series termination.

Conclusions

In this article, an impedance transformation formula to convert OTA shunt termination to series termination was derived and series termination was shown to be an improvement over the usual shunt termination used for OTA compensation stages. This improvement is due to the introduction of local negative feedback around the OTA.

The variation in the dB gain versus frequency is narrower with series termination which can ease the design of the control loop by a relatively simple change. The article demonstrated examples for type I and II which resulted in a dB gain variation reduction of 4 dB and 4.5 dB, respectively.

The improved OTA compensator stage can be included in the overall dc-dc converter model to observe the effects on the loop gain stability metrics such as phase margin and gain margin. If the loop gain dB gain were -20 dB/decade around its crossover frequency, then a dB gain variation reduction of 4 dB would result in a crossover frequency variation reduction of 0.2 decade ($= 4 \text{ dB}/20 \text{ dB/decade}$).

A designer deciding whether to use series termination compensation should perform similar analysis to determine the amount of improvement to expect compared to shunt termination compensation. The improvement is increased when the transconductance g_m variation is wider.

It's important to note is that series compensation may result in much larger resistor values compared with shunt compensation. Values larger than $100 \text{ k}\Omega$ are not desirable in automotive applications due to increased noise pickup. In addition, prohibitively small capacitance values may also result. These undesirable values can be mitigated by reducing R_{par} (4).

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About The Author



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