PWM-CM model in LTspice

Simulation Description

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REVISION HISTORY

Issue	Date	Change	Prepared
0.01	03/09/2017	First Issue	MD
0.02	05/09/2017	Minor Formatting Changes	MD

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FIGURES

TABLES

No table of figures entries found.

1 INTRODUCTION

Many engineers face the challenge of designing power supplies quickly and without the advantage of expensive simulators. LTspice is a fully featured SPICE program and provides engineers, working for budget conscience companies, a means of simulating their designs. Quite often designs are taken from application notes and the design needs to be tweaked to meet the product requirements. For example a change in output voltage, output current or output capacitance may require a change in the loop compensation components. An accurate averaged model provides a means to iteratively test new loop compensation values in a timely manner.

The PWM-CM model from [1] Switch-Mode Power Supplies by Christophe Basso allows the designer to analyse their power supply designs and with some small modifications can be made to work consistently in LTspice.

2 CHANGES TO THE PWM-CM MODEL

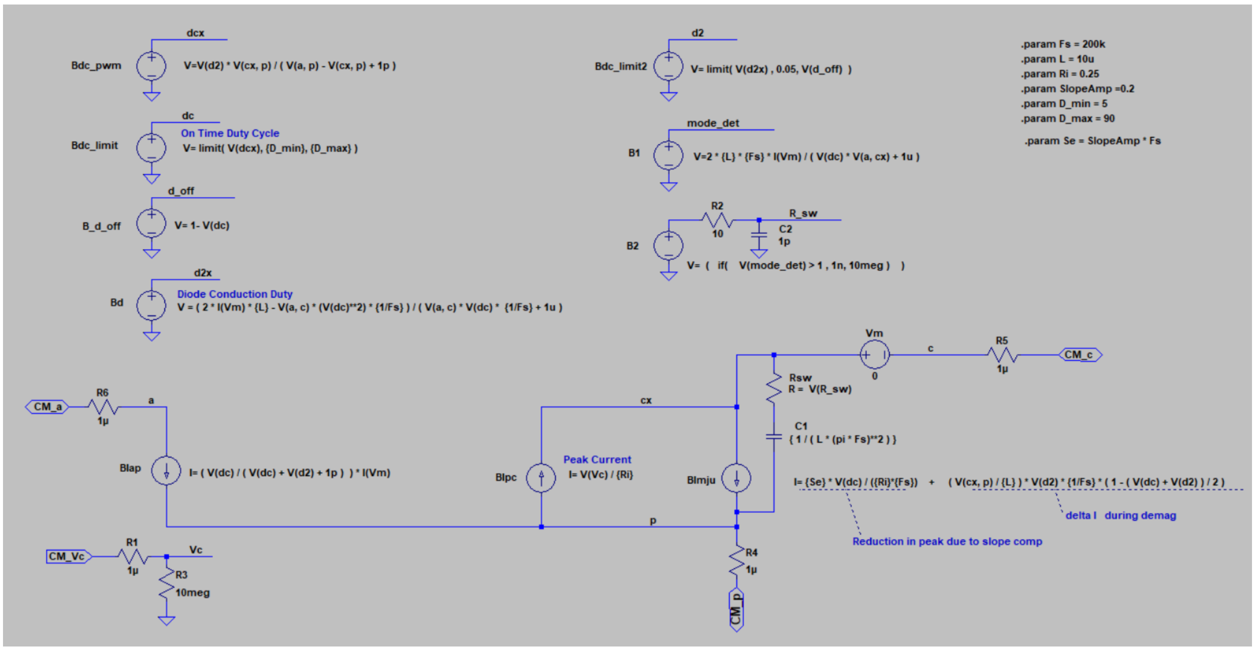


Figure 1 PWM-CM

In LTspice the original PWM-CM model occasionally has difficulty finding a DC bias point and will often stop during a Transient simulation with a “Time step too small error”. This occurrence of this error can be reduced by adding single pole, low pass filters to some signals.

Firstly though, some simplification of the equations will also help the Transient simulation. In the denominator of B_{dc_pwm}, “*V(a, p) – V(cx, p)*” can be changed to *V(a_c)* so the transistor’s duty cycle *dcx = V(d2) * V(c_p) / V(a_c)* . Where the *a_c* signal is the filtered *V(a, cx)* signal from B_{17}, *c_p* signal is the filtered *V(cx, p)* signal from B_{19} and *V(d2)* is the diode conduction duty.

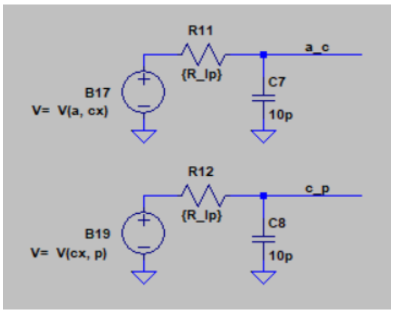


Figure 2 LP Filtered signals

The denominator of B_{dc_pwm} is *V(a_c)* and this requires limiting to avoid a "div by 0" error. Also, for a Boost Converter the *V(a_c)* signal will be negative so limiting the signal to a minimum value will not work for a Boost converter. To keep a common model for Buck and Boost converters an *a_c_lim* signal with a dead zone of +/- 1 mV was introduced.

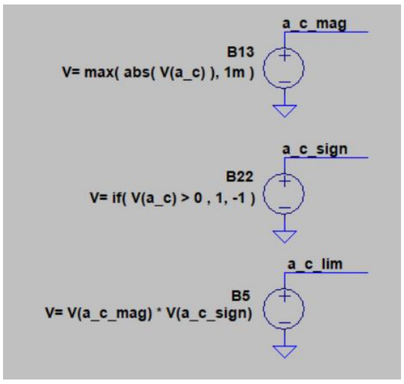


Figure 3 *V(a_c_lim)* with Dead zone

The output of the duty cycle calculation *dc* is also filtered to help with the Transient simulation.

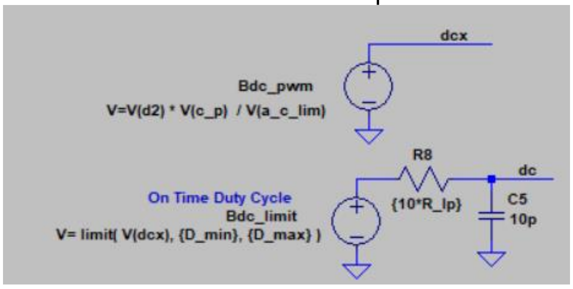


Figure 4 LP Filtered Duty Cycle *dc* and *d2x*

The pole of the filters is scaled by the switching frequency *Fs*. The filters where R = *R_lp* have a cut off frequency of 1592 F_s and the filters where R = 10**R_lp* have a cut off frequency of 159 F_s. These filters are scaled by the switching frequency to be more effective at low frequencies and less intrusive at high frequencies.

The original model had a switched resonating cap C_s and switching this cap often caused “Time step too small” errors. Also, when operating in DCM with C_s switched out the current sources B_{Ipc} and B_{Imju} were driving into the converters inductor also causing “Time step too small” errors. To solve both of these issues the inductor was moved inside the model. This allows the current flowing from *p* to *c* to be calculated for CCM and DCM at the same time with the *mode_det* signal simply choosing the appropriate current.

A new intermediate current *I_pk* is calculated from the original B_{Ipc} “*V(Vc) / {Ri}*” and the first half of B_{Imju} *“-{Se} * V(dc) / ({Ri}*{Fs})*”. The magnitude of the peak current (*I_pk_mag*) is calculated *“(V(Vc) - {SlopeAmp} * V(dc)) / {Ri}*” and the magnitude of the minimum peak current due to the minimum On-Time (*I_pk_min_mag*) is calculated “*V(a_c_mag) * {D_min / (Fs * L) }*”. The final value of *I_pk* is the larger of these 2 values. By determining the direction of the current with the polarity of *V(a, c)* the resistance of R_i is positive for Boost as well as Buck converters. (In the original model R_i was negative for Boost converters).

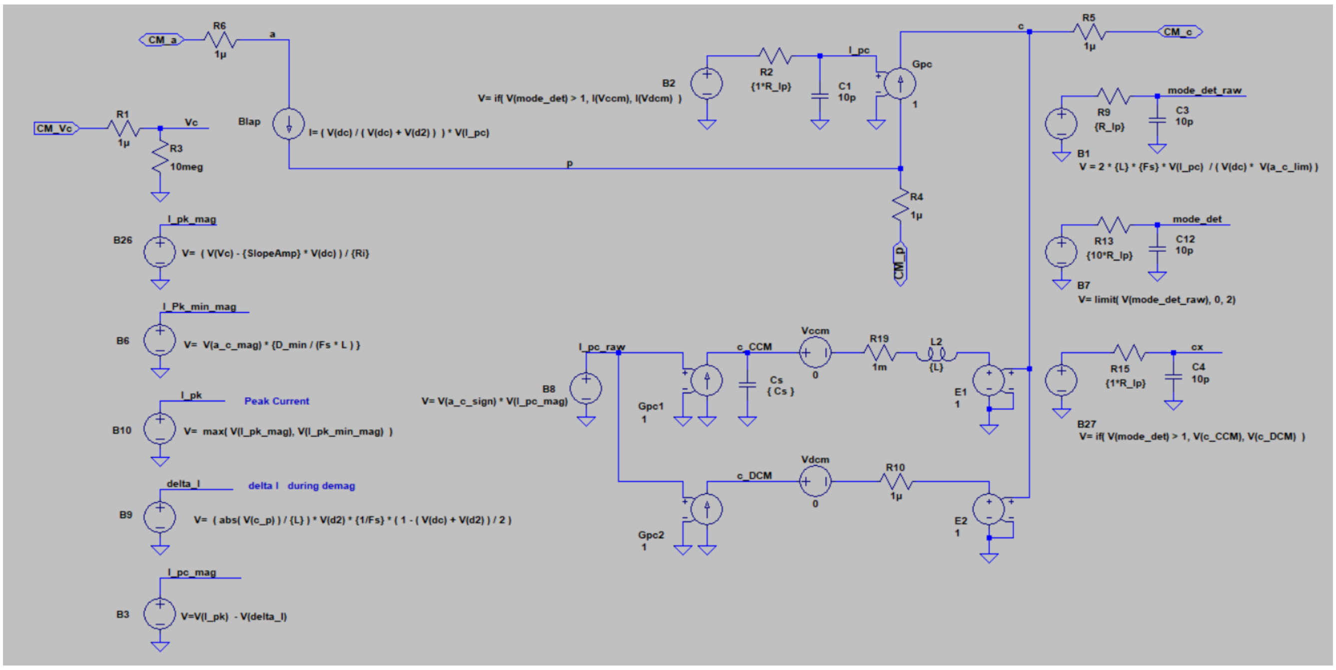


Figure 5 New DCM-CCM Toggle Mechanism

Now that the inductor's peak current (I_pk) is available the calculation for the diode conduction duty d2x can be simplified. A small offset of 1 µV is added to the denominator to avoid a "div by zero" error.

To make the model work for synchronous converters as well, a new parameter *sync* was introduced. The signal *d2_fw* represents the freewheeling diode's conduction duty time. This allows current to flow out of the output capacitors back into the source when the load is removed for synchronous converters.

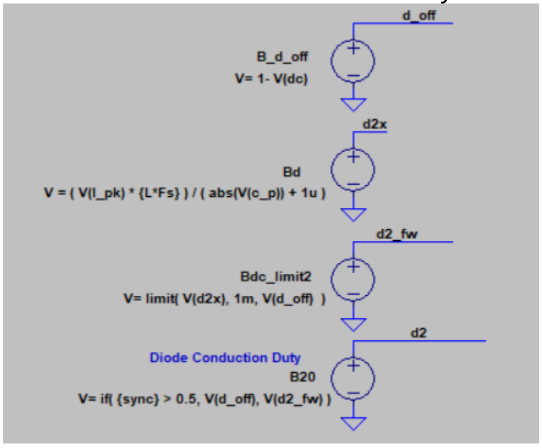
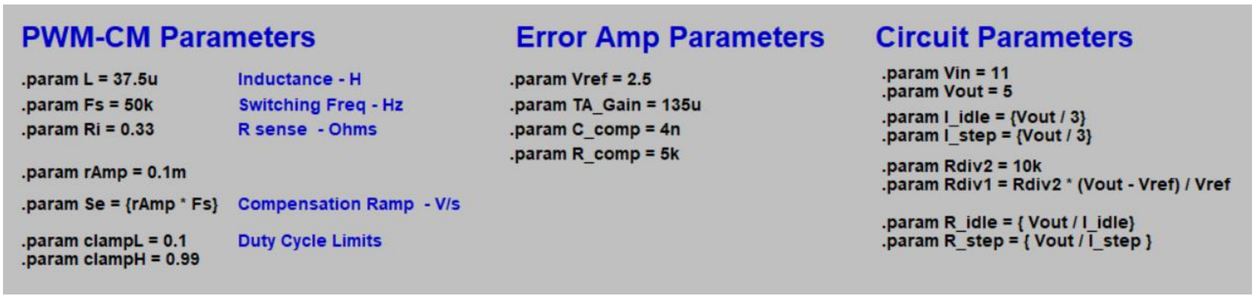


Figure 6 Diode conduction Duty d2

3 PWM-CM BUCK VERFICATION

The circuit values that resulted in the Averaged AC converter response of Figure 2-81 of [1] were entered into LTspice. The response of the PWM-CM model and the PWM-CM2 model look almost identical to Figure 2-81 in the text.



PWM-CM Parameters

.param L = 37.5u Inductance - H
.param Fs = 50k Switching Freq - Hz
.param Ri = 0.33 R sense - Ohms

.param rAmp = 0.1m

.param Se = {rAmp * Fs} Compensation Ramp - V/s

.param clampL = 0.1
.param clampH = 0.99 Duty Cycle Limits

Error Amp Parameters

.param Vref = 2.5
.param TA_Gain = 135u
.param C_comp = 4n
.param R_comp = 5k

Circuit Parameters

.param Vin = 11
.param Vout = 5

.param I_idle = {Vout / 3}
.param I_step = {Vout / 3}

.param Rdiv2 = 10k
.param Rdiv1 = Rdiv2 * (Vout - Vref) / Vref

.param R_idle = { Vout / I_idle}
.param R_step = { Vout / I_step }

Figure 7 Parameters

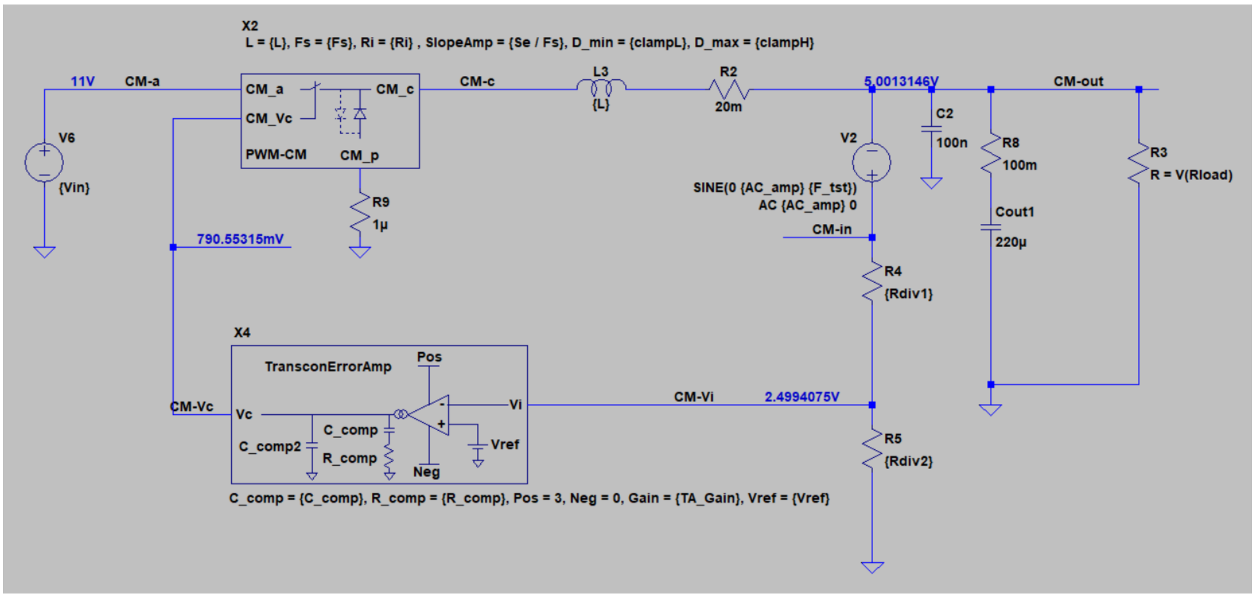


Figure 8 PWM-CM

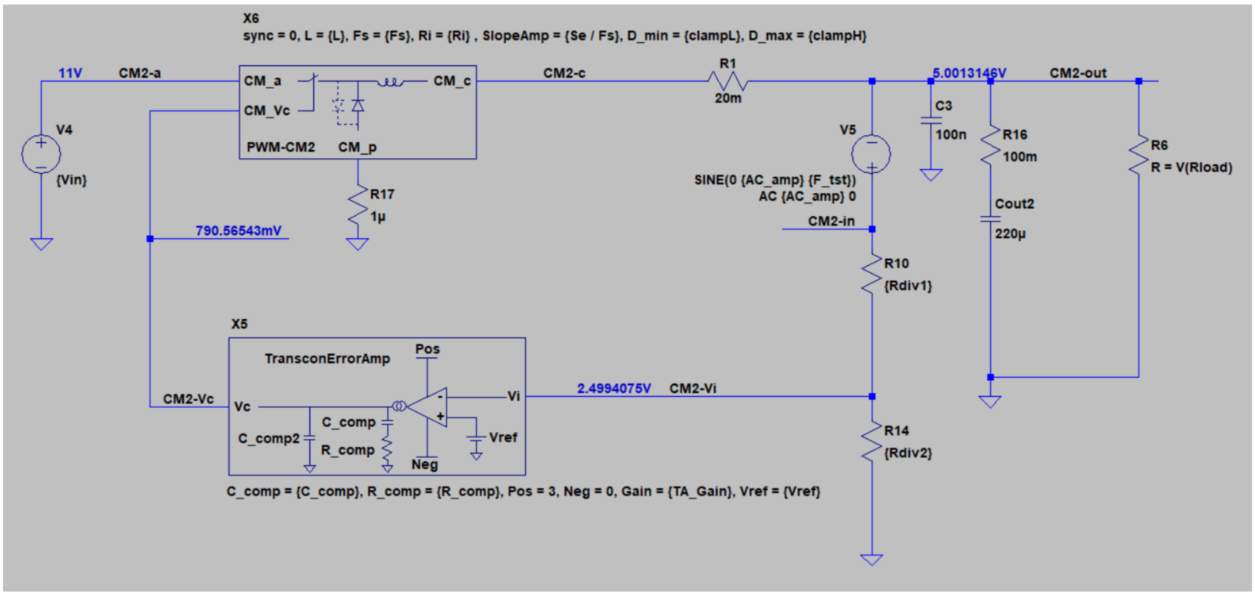


Figure 9 PWM-CM2

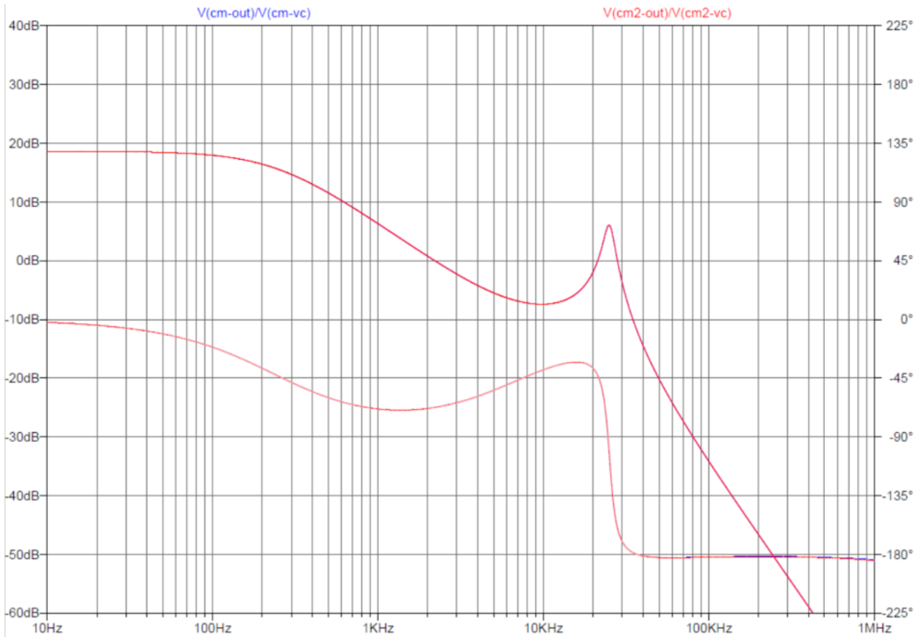


Figure 10 Comparative Converter Response to Fig 2-81 from [1]

3.1 SUB-HARMONIC OSCILLATIONS

For a Buck converter sub-harmonic oscillations can be predicted using the averaged model by analysing the Open Loop Response of the circuit. When the phase increases close to $F_s/2$, sub-harmonic oscillations will be present in the output. In this case sub-harmonic oscillations are present when V_{out} = 6 V but not at V_{out} = 5 V.

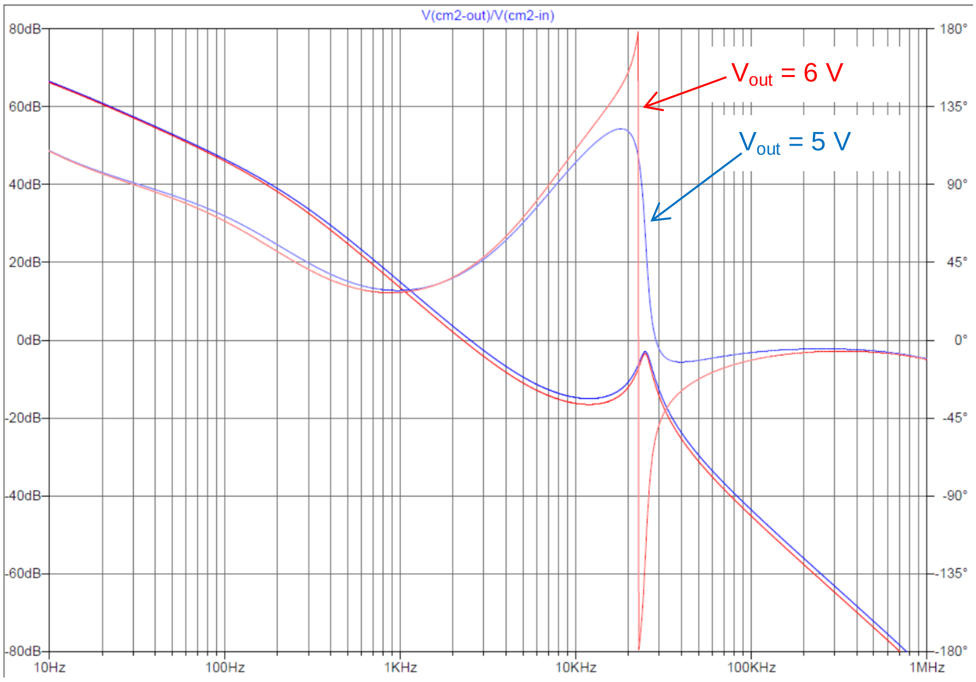
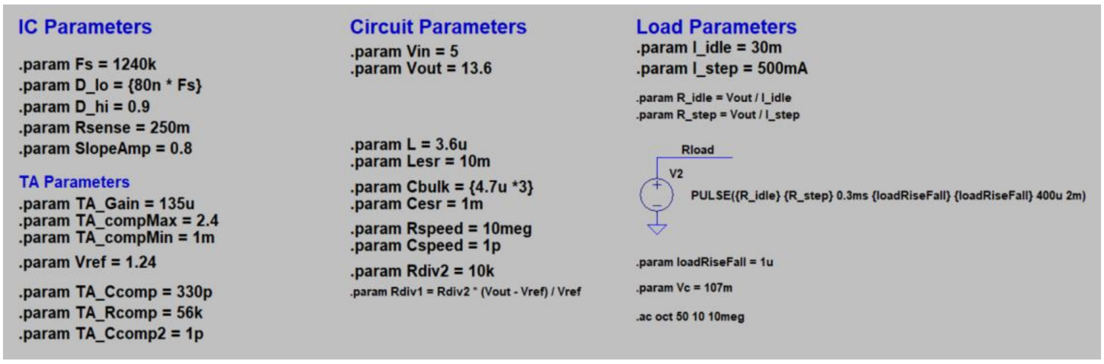


Figure 11 Sub-harmonic Oscillations in a Buck Converter

4 PWM-CM BOOST

Like the original PWM-CM, the PWM-CM2 can be configured to operate as a Boost converter but the PWM_CM2 works with a positive resistance value for the sense resistor R_i.



IC Parameters

```
.param Fs = 1240k
.param D_lo = {80n * Fs}
.param D_hi = 0.9
.param Rsense = 250m
.param SlopeAmp = 0.8
```

TA Parameters

```
.param TA_Gain = 135u
.param TA_compMax = 2.4
.param TA_compMin = 1m
.param Vref = 1.24
.param TA_Ccomp = 330p
.param TA_Rcomp = 56k
.param TA_Ccomp2 = 1p
```

Circuit Parameters

```
.param Vin = 5
.param Vout = 13.6
.param L = 3.6u
.param Lesr = 10m
.param Cbulk = {4.7u *3}
.param Cesr = 1m
.param Rspeed = 10meg
.param Cspeed = 1p
.param Rdiv2 = 10k
.param Rdiv1 = Rdiv2 * (Vout - Vref) / Vref
```

Load Parameters

```
.param I_idle = 30m
.param I_step = 500mA
.param R_idle = Vout / I_idle
.param R_step = Vout / I_step
```

```
PULSE({R_idle} {R_step} 0.3ms {loadRiseFall} {loadRiseFall} 400u 2m)
.param loadRiseFall = 1u
.param Vc = 107m
.ac oct 50 10 10meg
```

Figure 12 Boost Parameters

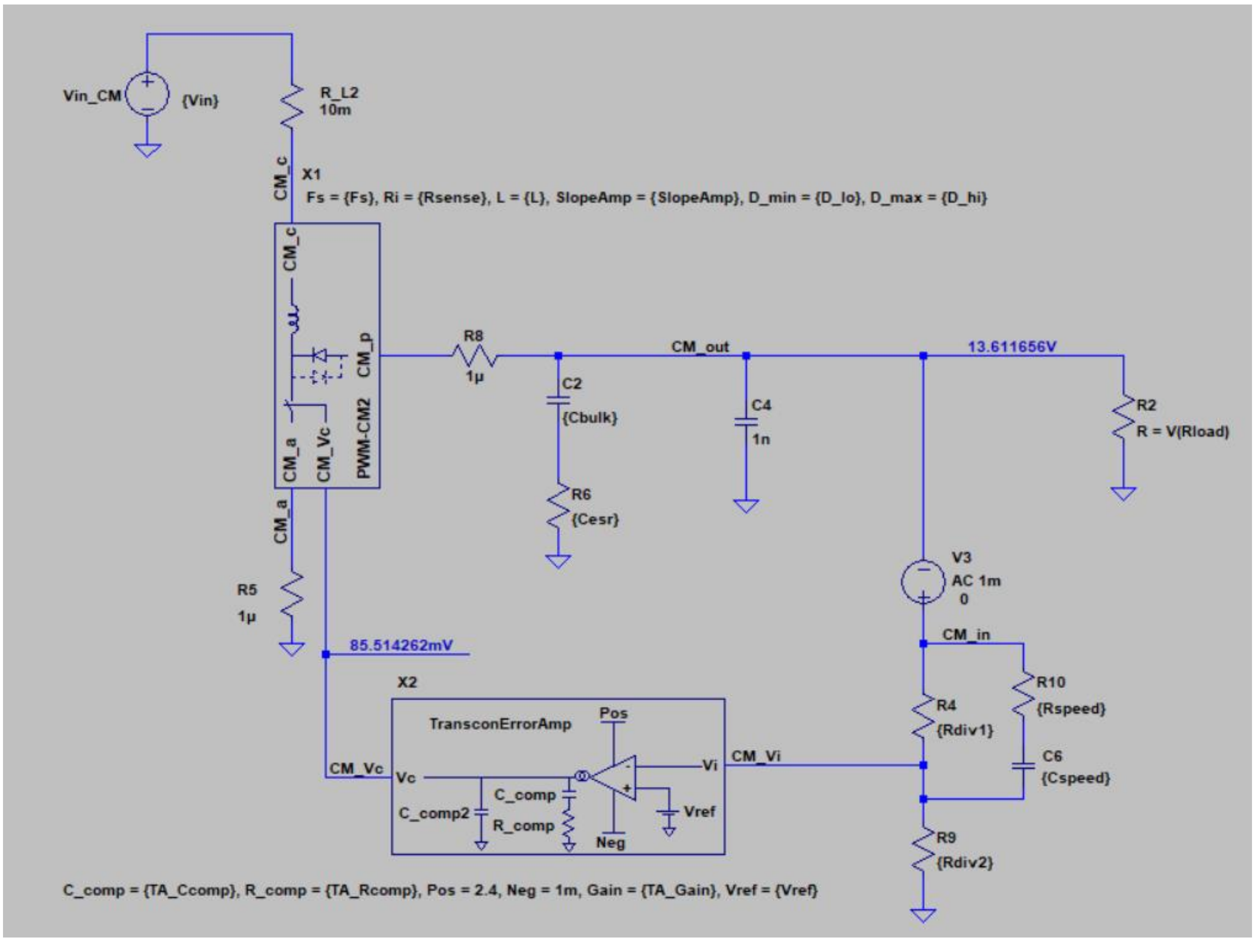


Figure 13 Boost RT9297 Example

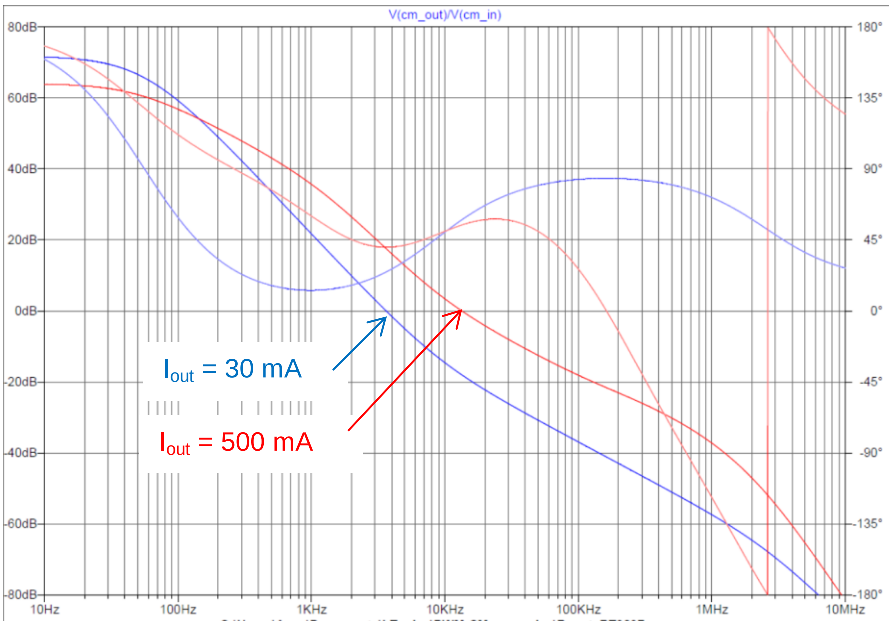


Figure 14 Boost RT9297 Example, Bode Plot

The lower frequency at the 0dB point of the DCM response (30 mA) in the Bode plot predicts the slower DCM Transient Response.

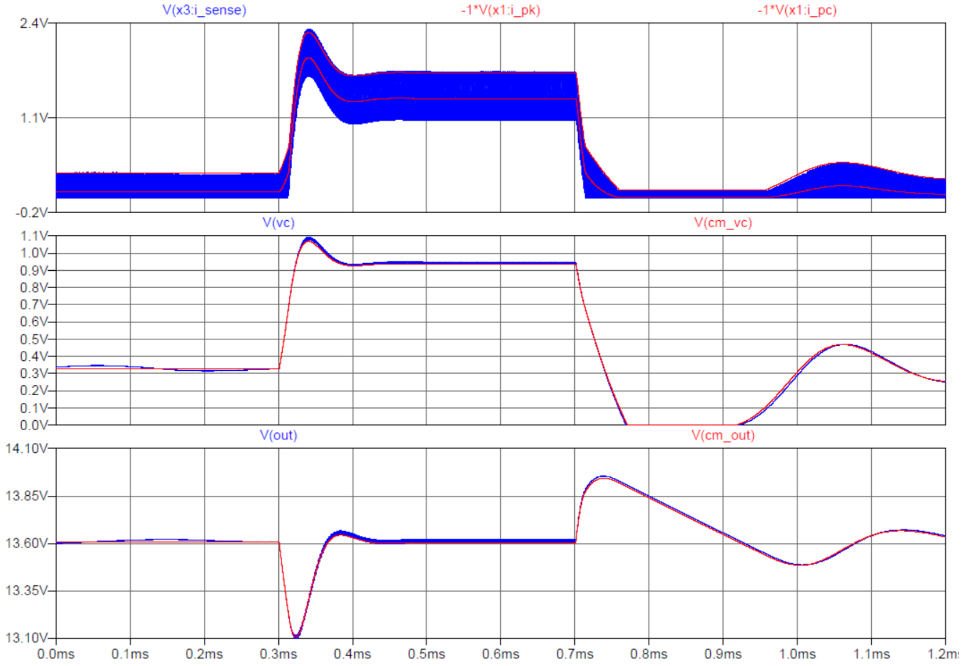


Figure 15 Boost RT9297 Example, Transient Response

4.1 SUB-HARMONIC OSCILLATIONS

Setting the slope compensation ramp to 0 V and comparing the 500-mA CCM responses for V_{out} = 8 V and 12 V provides a good example of a response without sub-harmonic oscillations (V_{out} = 8 V) and a response with sub-harmonic oscillations (V_{out} = 12 V). When the phase increases close to $F_s/2$, sub-harmonic oscillations will be present in the output. Unlike the Buck example, for the Boost converter the phase wrap occurs at -180 deg when sub-harmonic oscillations are not present.

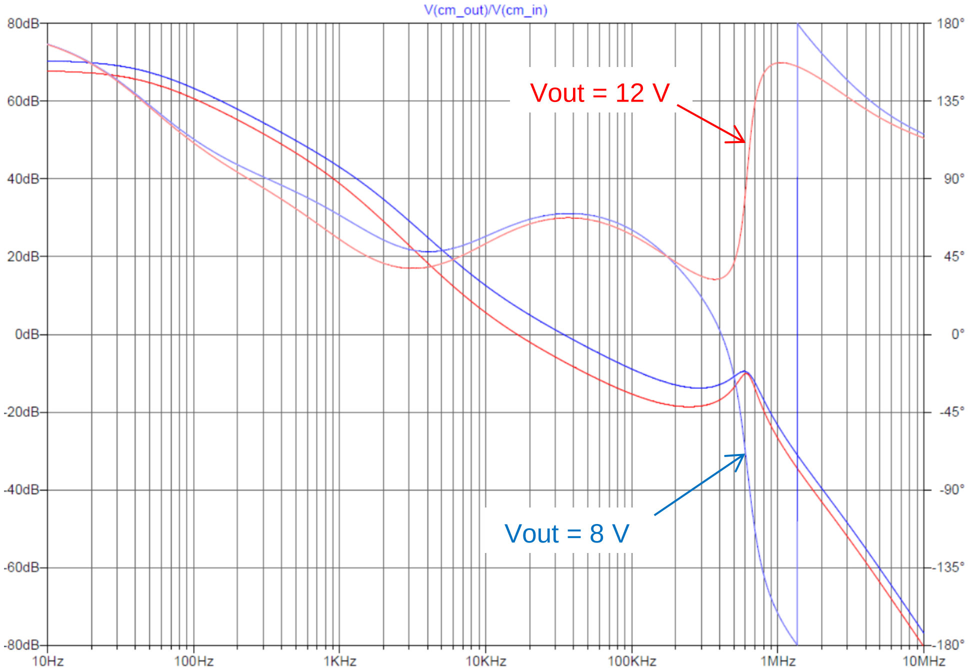


Figure 16 Boost Sub-harmonic oscillations

4.2 RT9297 SLOPE COMPENSATION VALUE

The component values used in the Boost example are started in the “Loop Compensation” section of the data sheet. The data sheet, however, does not give a value for the compensation ramp. Figure 17 shows the open loop response does not change much for different compensation ramp values. A value of 0.8 was used for the previous Boost simulations.

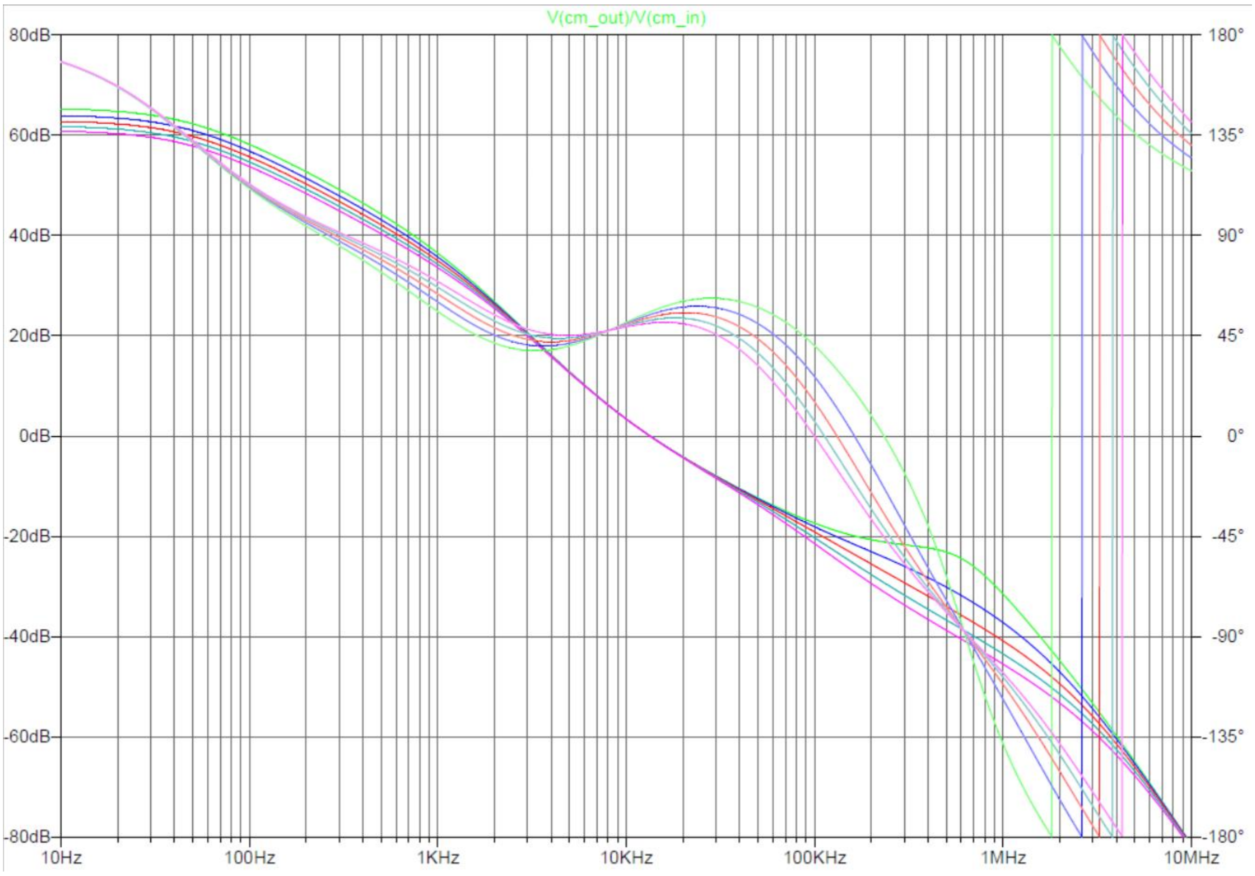
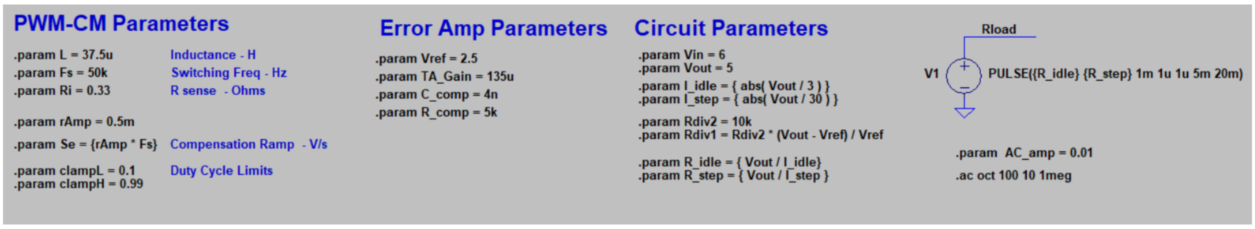


Figure 17 Open Loop Gain for Different Compensation Ramp Values: *SlopeAmp* = 0.4 to 2.0

5 BUCK-BOOST NEGATIVE OUTPUT

The Buck-Boost with negative output configuration for the PWM-CM2 is shown in Figure 19. The PWM-CM2 control voltage *CM_Vc* is still referenced to GND but for most Buck controllers the error amp is referenced to the negative rail *CM_p*. In this example the feedback voltage is “level shifted” to GND potential via E_1.



PWM-CM Parameters

```
.param L = 37.5u          Inductance - H
.param Fs = 50k           Switching Freq - Hz
.param Ri = 0.33          R sense  - Ohms

.param rAmp = 0.5m

.param Se = {rAmp * Fs}   Compensation Ramp  - V/s

.param clampL = 0.1       Duty Cycle Limits
.param clampH = 0.99
```

Error Amp Parameters

```
.param Vref = 2.5
.param TA_Gain = 135u
.param C_comp = 4n
.param R_comp = 5k
```

Circuit Parameters

```
.param Vin = 6
.param Vout = 5
.param I_idle = { abs( Vout / 3 ) }
.param I_step = { abs( Vout / 30 ) }
.param Rdiv2 = 10k
.param Rdiv1 = Rdiv2 * (Vout - Vref) / Vref
.param R_idle = { Vout / I_idle}
.param R_step = { Vout / I_step }
```

```
.param  AC_amp = 0.01
.ac oct 100 10 1meg
```

Figure 18 Buck-Boost Negative Output Parameters

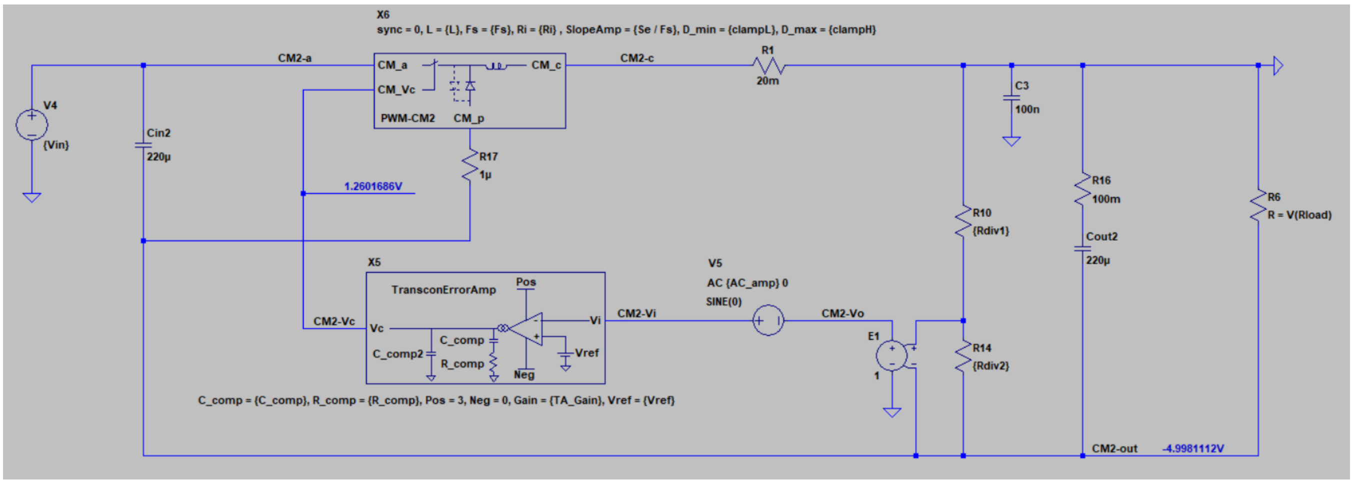


Figure 19 Buck-Boost Negative Output

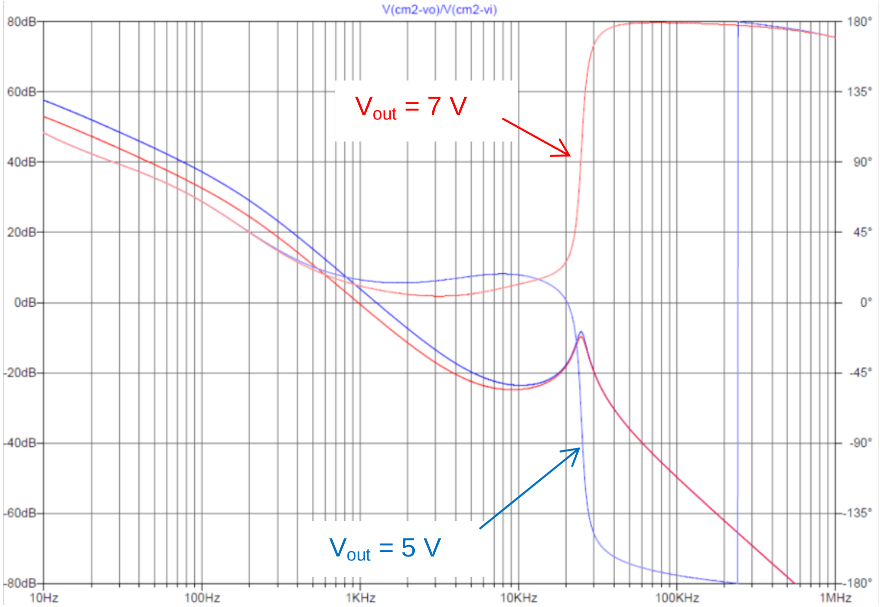
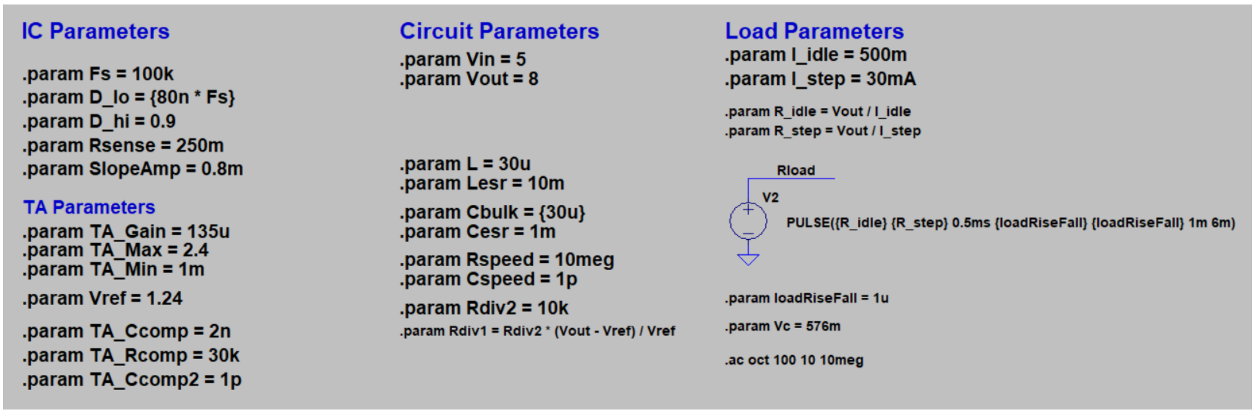


Figure 20 Buck-Boost, Neg O/P, Bode Plot

When the phase increases close to $F_s/2$, sub-harmonic oscillations will be present in the output.

6 BUCK-BOOST NEGATIVE INPUT

The Buck-Boost with negative input configuration for the PWM-CM2 is shown in Figure 22. The PWM-CM2 control voltage *CM_Vc* is still referenced to GND but for most Boost controllers the error amp is referenced to the negative rail *CM_a*. In this example the feedback voltage is still referenced to GND but a practical implementation may require a separate shunt regulator like the LM385 to provide a reference and a convenient way to level shift the feedback to the negative input power source.



IC Parameters

```
.param Fs = 100k
.param D_lo = {80n * Fs}
.param D_hi = 0.9
.param Rsense = 250m
.param SlopeAmp = 0.8m
```

TA Parameters

```
.param TA_Gain = 135u
.param TA_Max = 2.4
.param TA_Min = 1m

.param Vref = 1.24

.param TA_Ccomp = 2n
.param TA_Rcomp = 30k
.param TA_Ccomp2 = 1p
```

Circuit Parameters

```
.param Vin = 5
.param Vout = 8

.param L = 30u
.param Lesr = 10m

.param Cbulk = {30u}
.param Cesr = 1m

.param Rspeed = 10meg
.param Cspeed = 1p

.param Rdiv2 = 10k
.param Rdiv1 = Rdiv2 * (Vout - Vref) / Vref
```

Load Parameters

```
.param I_idle = 500m
.param I_step = 30mA

.param R_idle = Vout / I_idle
.param R_step = Vout / I_step

Rload
V2
PULSE({R_idle} {R_step} 0.5ms {loadRiseFall} {loadRiseFall} 1m 6m)

.param loadRiseFall = 1u

.param Vc = 576m

.ac oct 100 10 10meg
```

Figure 21 Buck-Boost Negative Input Parameters

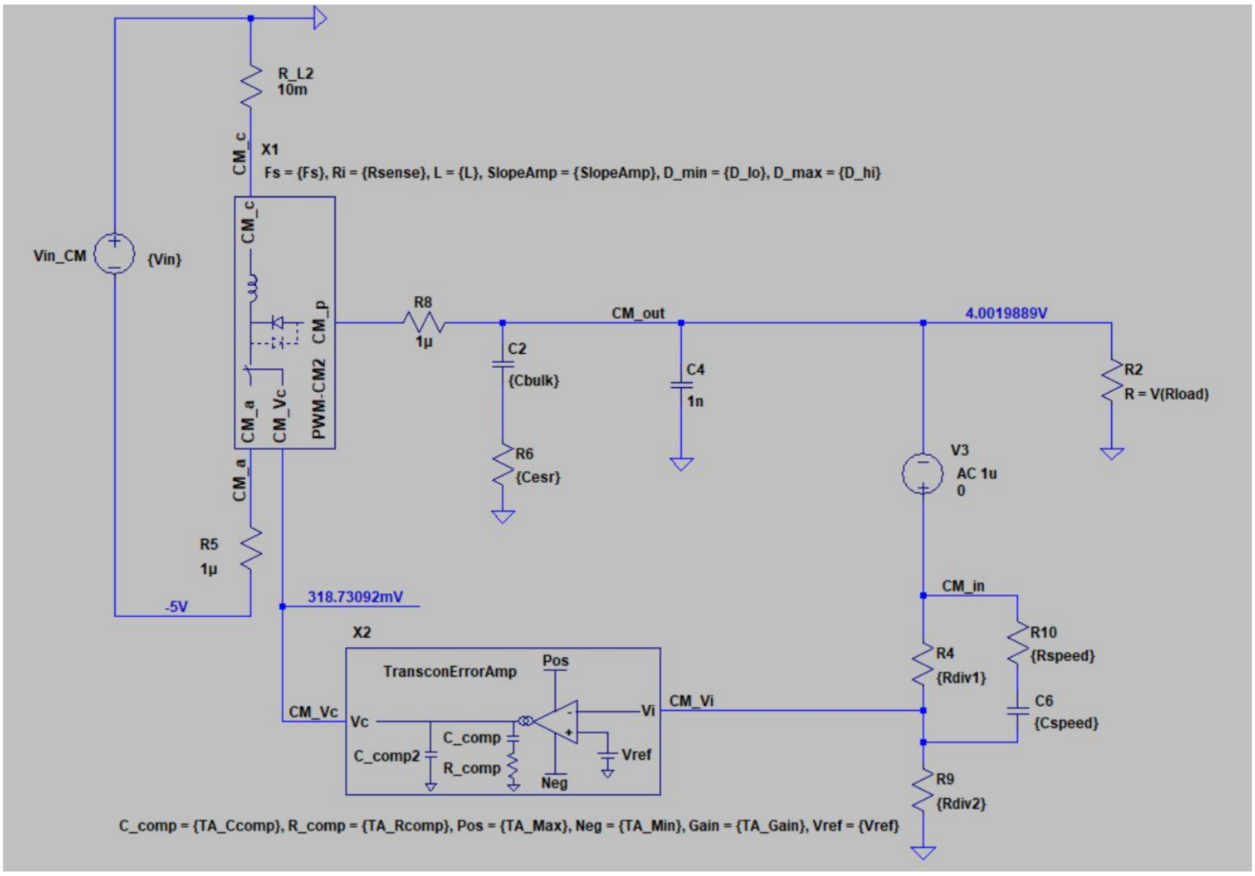


Figure 22 Buck-Boost Negative Input

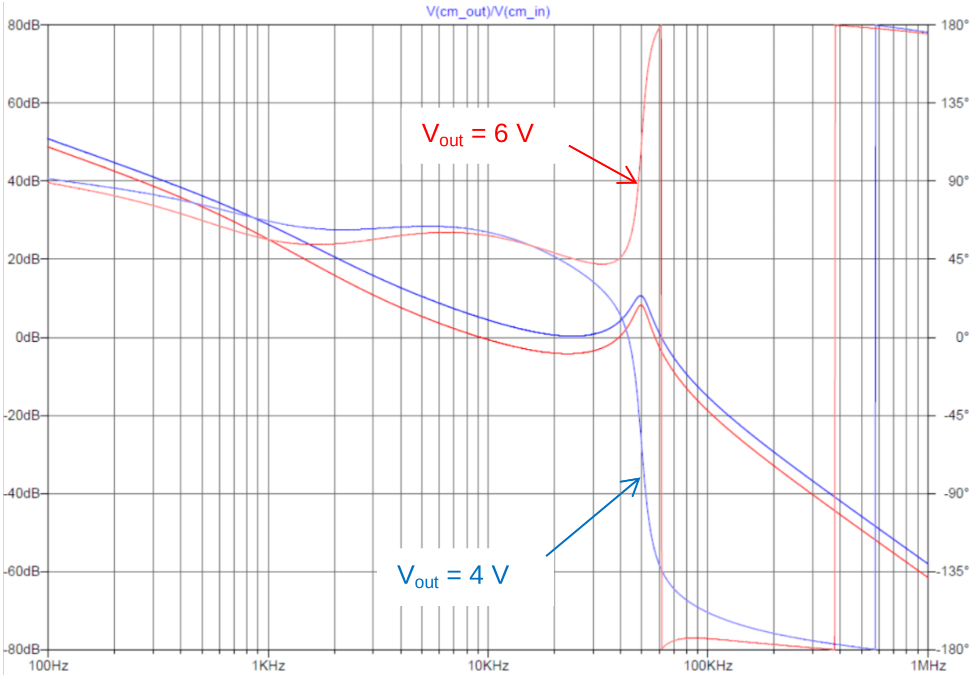


Figure 23 Buck-Boost, Neg I/P, Input Bode Plot

Once again, when the phase increases close to Fs/2, sub-harmonic oscillations will be present in the output.