The POWER Behind Your Designs

Practical Loop Compensation for Switching Power Converters

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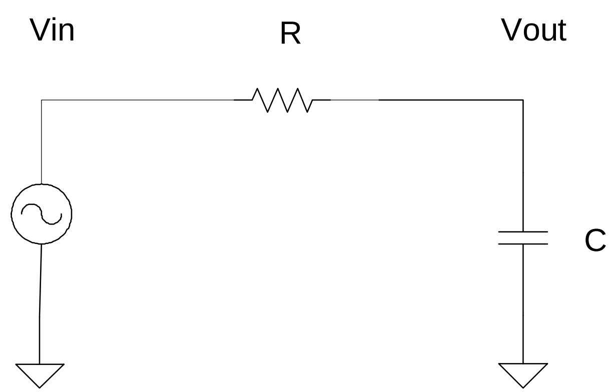
- Agenda
  - Review a Simple RC Filter Network Transfer Function
  - Review a Second Order LC Network Transfer Function
  - Simplified Control Block Diagram for Power Converters
  - Continuous Conduction Mode (CCM)
  - Discontinuous Conduction Mode (DCM)
  - Compensation Examples
    - Voltage Mode Buck Converter
    - Voltage Mode Buck Converter with Voltage Feed Forward (VFF).
    - Peak Current Mode Forward Converter

RC Filter Network



- Simple RC Network is Used to Filter Out High Frequency Noise
  - First Order Filter with Single Pole Roll off at -20dB/decade after fp

$$Gf(s) = \frac{\Delta Vout}{\Delta Vin} = \frac{1}{(SRC+1)} \qquad fp = \frac{1}{2\pi RC}$$

Bode Plot Review

- Bode Plots are one of the simplest tools that can be used to evaluate transfer functions
  - Zeros add a 20dB per decade change in gain and add 45 degrees of phase per decade
    - At the zero frequency there is 45 degrees of added phase and a added positive 3dB of gain
    - Each zero will add a maximum of 90 degrees of phase
  - Poles add a -20dB per decade change in gain and add -45 degrees of phase per decade
    - At the pole frequency there is -45 degrees of added phase and a added -3dB gain
    - Each pole will add a maximum of -90 degrees of phase

$$GdB(f) = 20\log\left(\left|\frac{(2*j*\pi*f*tz+1)}{(2*j*\pi*f*tp+1)}\right|\right)$$

$$fp = \frac{1}{2*\pi*tz} \qquad fz = \frac{1}{2*\pi*tz}$$

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Review Complex Numbers

Adding complex numbers

$$(a+jb)+(c+jd)=j(b+d)+(a+b)$$

When multiplying or dividing complex numbers it is best to convert them to vectors first

$$\text{Magnatude}=\sqrt{(\text{Real})^2+(\text{Imaginary})^2}$$

$$\text{Phase}=\tan^{-1}\left(\frac{\text{Imaginary}}{\text{Real}}\right)$$

$$\text{Magnatude}\angle\text{Angle}$$

Review Vector Manipulation

Multiplying Vector

$$M1\angle\Theta1 * M2\angle\Theta2 = (M1 * M2)\angle(\Theta1 + \theta2)$$

Dividing Complex Numbers

$$\frac{M1\angle\Theta1}{M2\angle\Theta2} = \left(\frac{M1}{M2}\right)\angle(\theta1 - \theta2)$$

RC Filter Small Signal Characteristics

Transfer Function

$$\frac{\Delta Vout}{\Delta Vin} = \frac{1}{(SRC+1)}$$

Magnitude

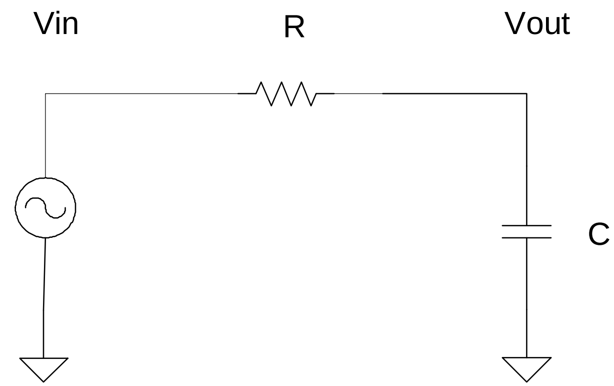
$$|Gf(f)| = \frac{1}{\sqrt{(1)^2 + (2\pi fRC)^2}}$$

Phase

$$Phase = -\tan^{-1}\left(\frac{2\pi fRC}{1}\right)$$

dB Gain

$$GdB(f) = 20 * \log(|G(f)|)$$

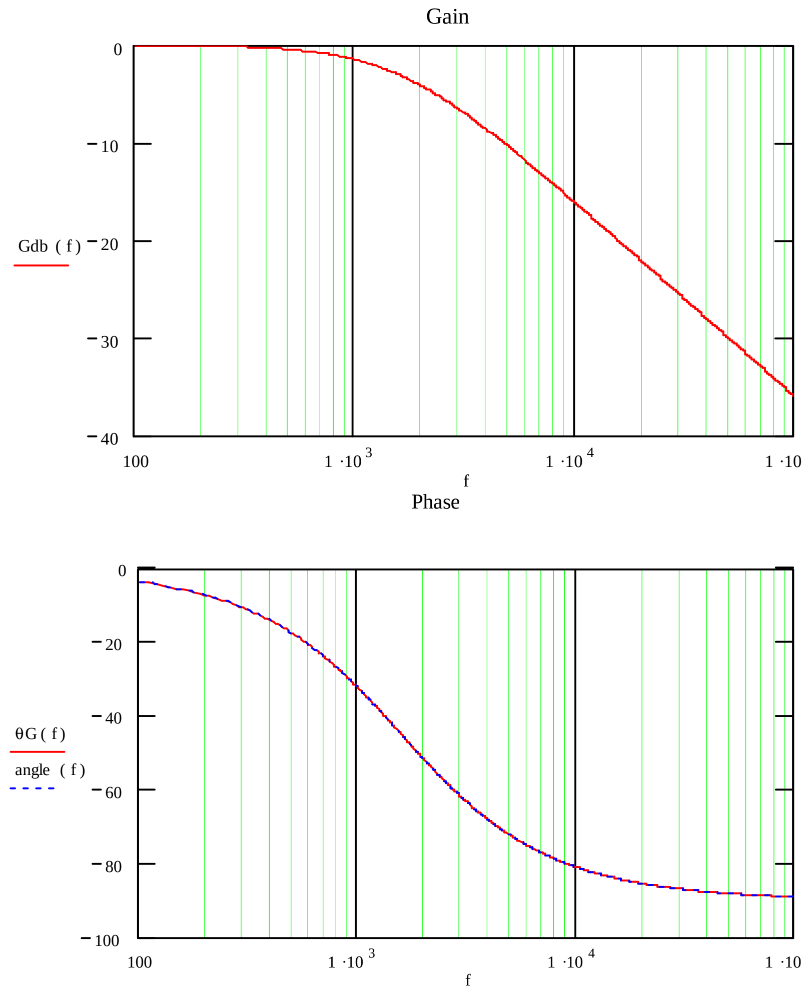


Bode Plot of RC Filter Network

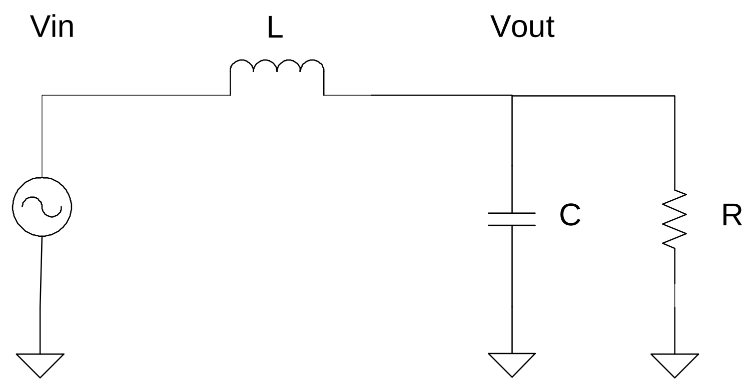
- Bode Plot of RC filter with an R of 100 ohm and a C of 1 uF.
  - This puts a pole roughly 1.6 kHz
    - Gdb(fp)= -3db
    - Phase= -45 degrees
  - A decade later at 16.5k Hz the phase lag is -90 degrees

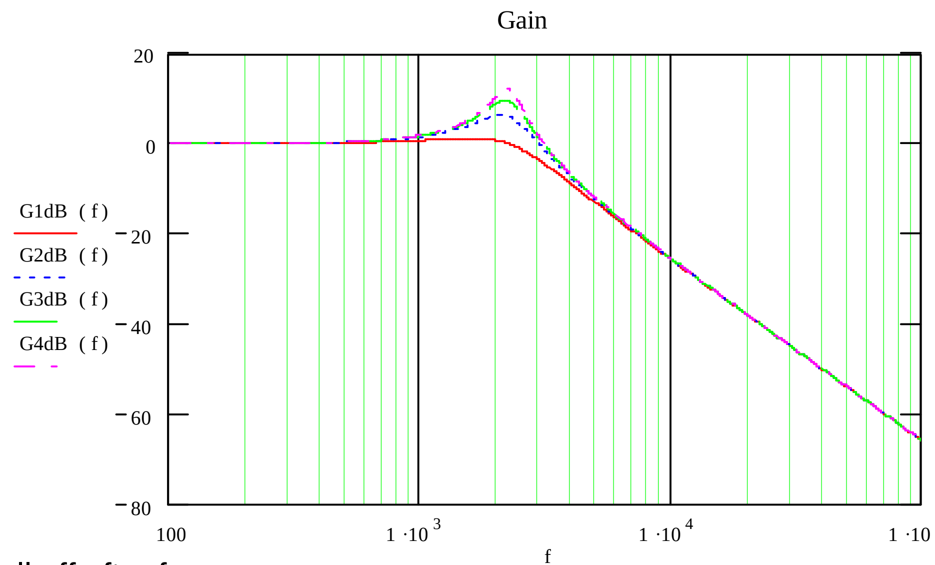
$$Gf(s) = \frac{\Delta Vout}{\Delta Vin} = \frac{1}{(SRC+1)} \qquad fp = \frac{1}{2\pi RC}$$

$$GdB(f) = 20 * \log(|G(f)|)$$



LRC Filter Network





- LRC Filter Network Transfer Function
  - Second order filter -40dB per decade gain roll off after fp.

$$Gf(s) = \frac{\Delta Vout}{\Delta Vin} = \frac{1}{1 + \frac{s}{wp * Q} + \left(\frac{s}{wp}\right)^2}$$

$$\mathrm{wp} = \frac{1}{\sqrt{\mathrm{LC}}} \qquad \mathrm{fp} = \frac{1}{2\pi\sqrt{\mathrm{LC}}} \qquad \mathrm{Q} = \frac{\mathrm{R}}{\mathrm{wp} * \mathrm{L}}$$

LRC Filter Small Signal Characteristics

Transfer Function

$$Gf(f) = \frac{1}{1 + \frac{s}{wp * Q} + \left(\frac{s}{wp}\right)^2} \qquad wp = \frac{1}{\sqrt{LC}} \qquad Q = \frac{R}{wp * L}$$

Magnitude

$$\left|Gf(f)\right| = \frac{1}{\sqrt{\left(1 - \left(\frac{2\pi f}{wp}\right)^2\right)^2 + \left(\frac{2\pi f}{wp * Q}\right)^2}}$$

Phase

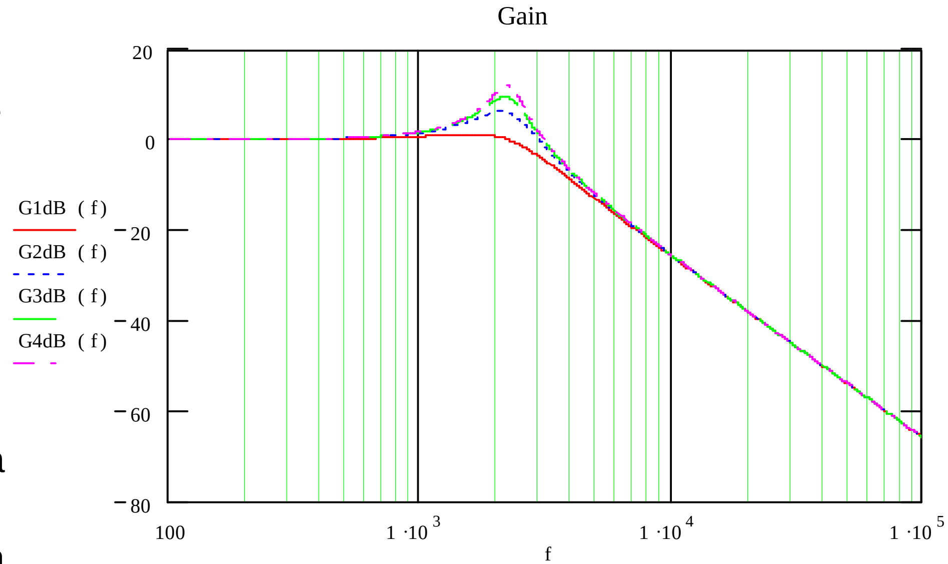
$$Phase = -\tan^{-1}\left(\frac{\frac{2\pi f}{wpQ}}{1 - \left(\frac{2\pi f}{wp}\right)^2}\right)$$

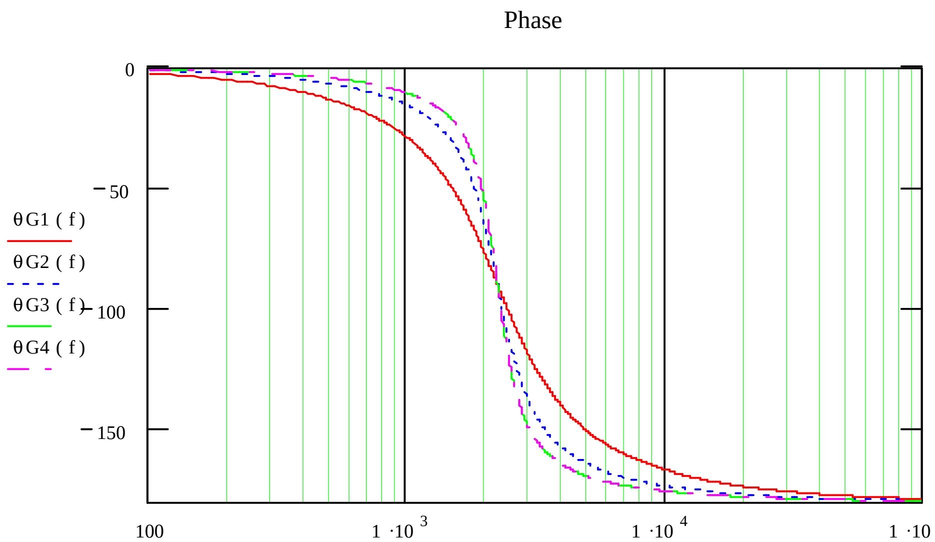
dB Gain

$$GdB(f) = 20 * \log(|G(f)|)$$

Review LCR Filter Response with Different Q Factors

- As Q increases so does the peak magnitude
  - G1dB(f) is the LCR filter response with a Q of 1
  - G4dB(f) is the LCR filter response with a Q of 4
- As Q increases so does the steepness of the phase roll off.
  - ΘG1(f) is the LCR filter response with a Q of 1
  - ΘG4(f) is the LCR filter response with a Q of 4





$$Gf(f) = \frac{1}{1 + \frac{s}{wp * Q} + \left(\frac{s}{wp}\right)^2} \qquad Q = \frac{R}{wp * L}$$

Note the only thing changing in the circuit is the load impedance RL

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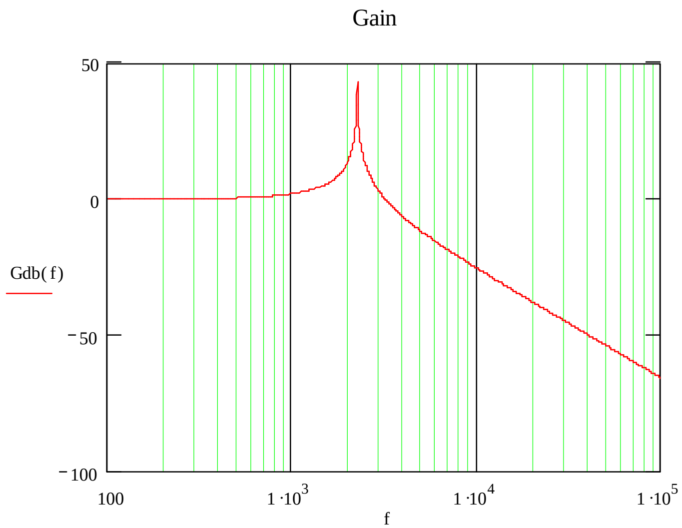
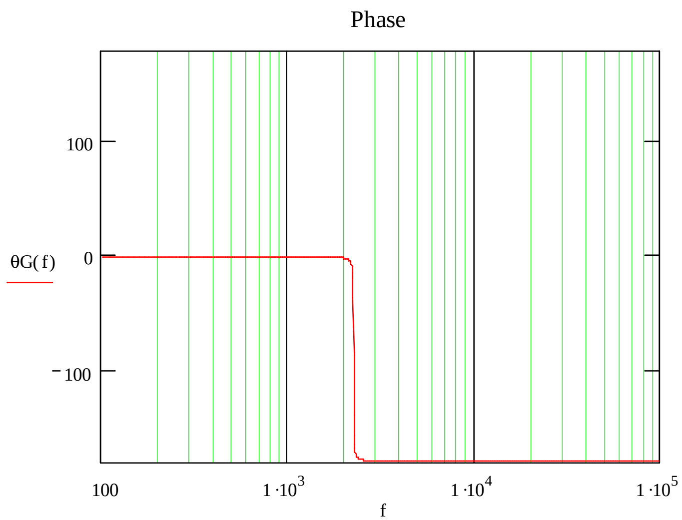
Bode Plot of LRC Filter Network

- Bode Plot of LRC filter with an L of 50 uH, R of 100 ohm and a C of 100 uF.
  - This puts a double pole roughly 2.25 kHz
    - Q = 142
  - Phase roll off the double pole is very steep

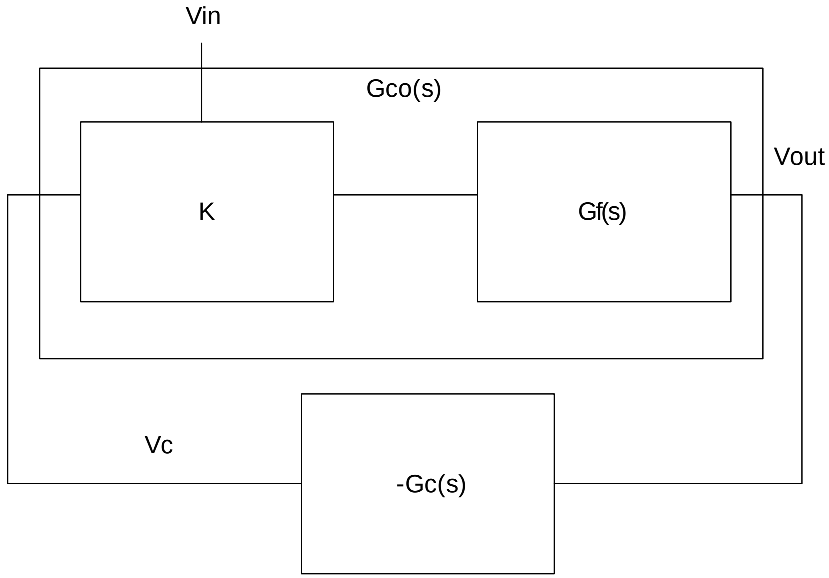
$$Gf(f) = \frac{1}{1 + \frac{s}{wp*Q} + \left(\frac{s}{wp}\right)^2} \qquad fp = \frac{1}{2\pi\sqrt{LC}}$$

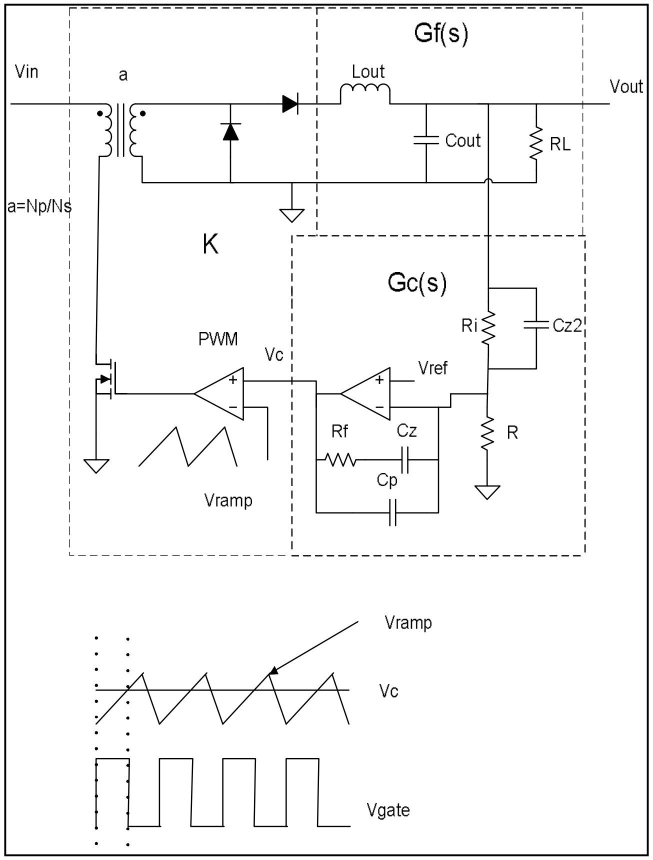
$$GdB(f) = 20 * \log(|G(f)|)$$





Simplified Loop Gain Control Block Diagram for a Power Converter





$$T(s) = K * Gf(s) * (-Gc(s)) = -Gco(s) * Gc(s)$$

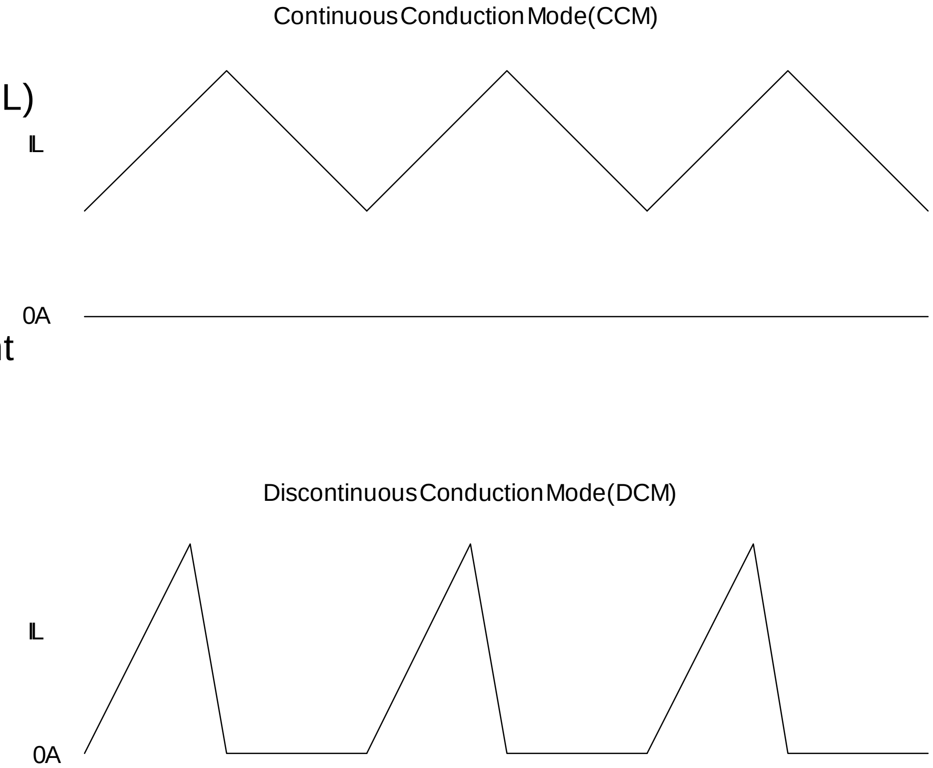
Simplified Loop Gain Control Block Diagram

- The simplified control block diagram can be used to control several different types of power converters
  - Voltage Mode Control
  - Voltage Mode Control with Voltage Feed Forward (VFF)
  - Peak Current Mode Control
- It is just a matter of correctly setting up the transfer function control blocks
  - K is the modulator transfer function and represents the average voltage that is applied to the power stages output filter (Gf(s)).
  - Gc(s) is the compensation transfer function
  - The control to output gain Gco(s) is the combination of K and Gf(s)
- This control block diagram is used to compensate the feedback loop gain
  - The models that are used in this presentation are based on ideal components
  - Bode plots can be used to compensate the feedback loop
- The voltage feed back loop T(s)=K*Gf(s)*(-Gc(s))

CCM and DCM Power Converter Operation

- Continuous Conduction Mode (CCM)
  - The Inductor has continuous current (IL)
  - Used in forward/buck converters to meet output ripple voltage requirements
- Discontinuous Conduction Mode (DCM)
  - The inductor has discontinuous current (IL)
  - This is mostly used in flyback converters to make voltage loop compensation easier.
- The current mode of operation will have an affect on the control to output gain of the power converter Gco(s).

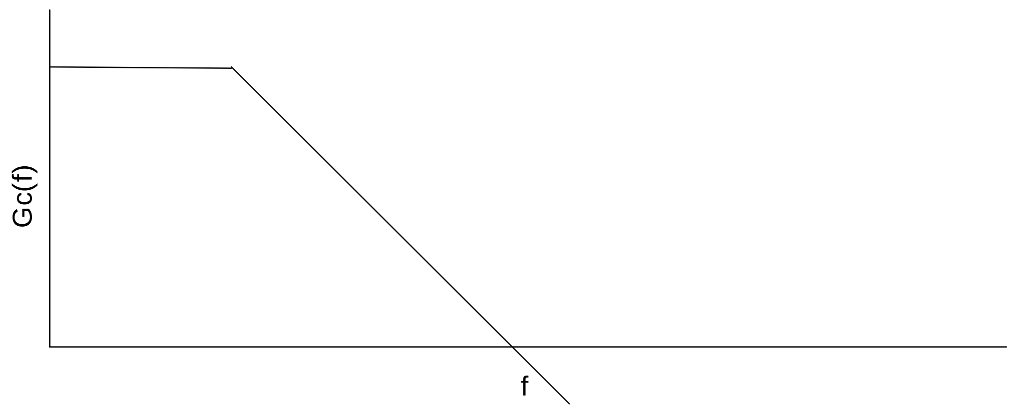
$$Gco(s) = \frac{\Delta Vout}{\Delta Vc} = K * Gf(s)$$

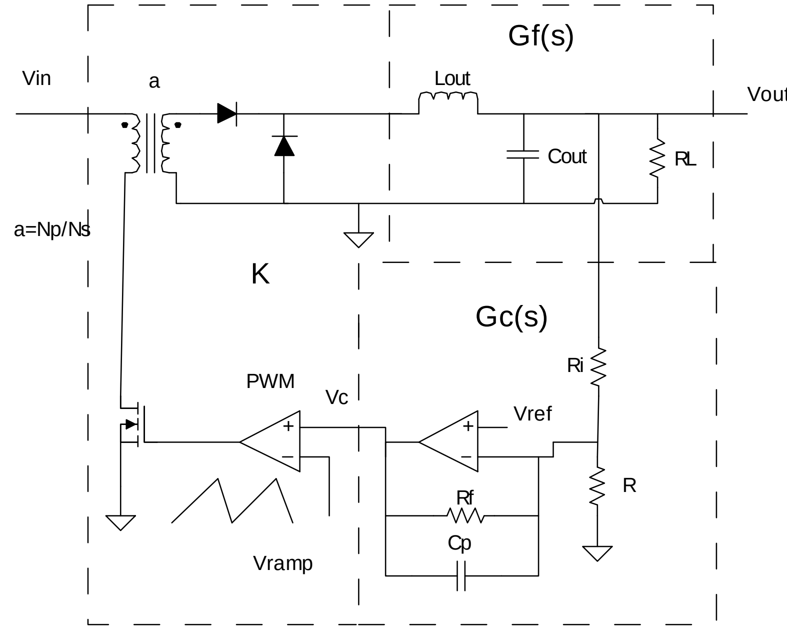


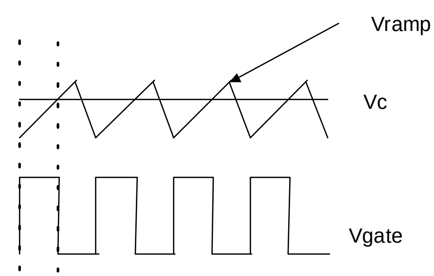
Compensation Networks Gc(s)

- Type 1 Compensation Gf(s)

$$Gc(f)=\frac{\Delta V1}{\Delta Vout}=\frac{Rf}{Ri*((s*Rf*Cp+1)}$$



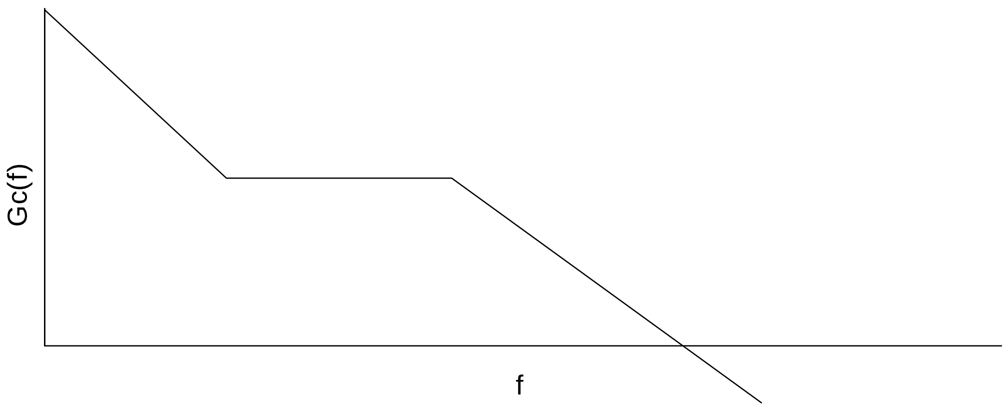


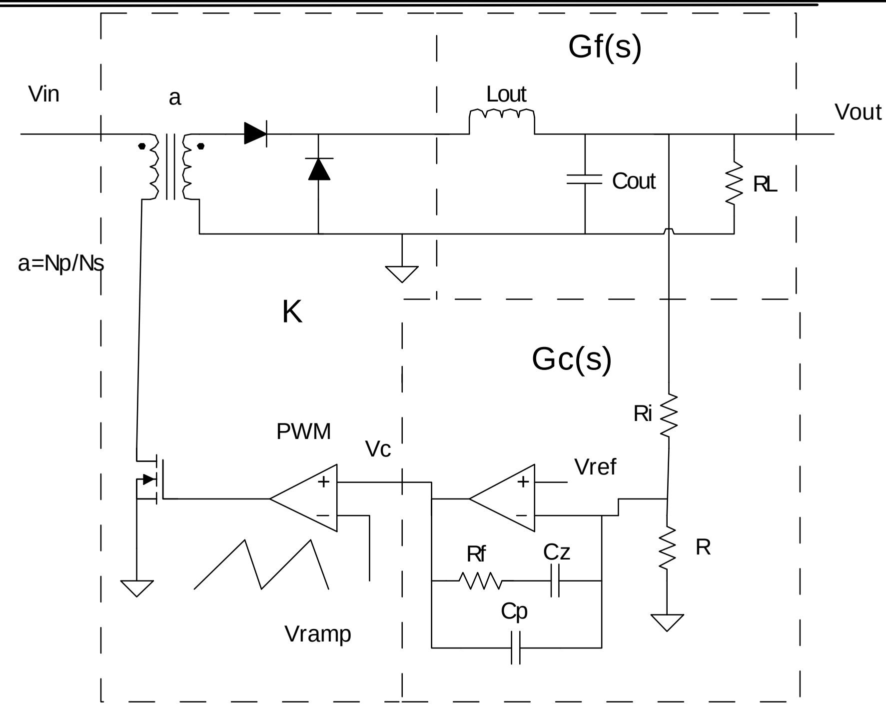


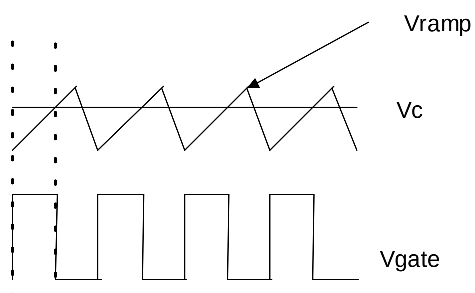
Compensation Networks Gc(s)

- Type 2 Compensation Gf(s)

$$Gc(f) = \frac{\Delta V1}{\Delta Vout} = \frac{(s*Rf*Cz+1)}{s*Ri*(Cp+Cz)((s*Rf*Cp+1)}$$







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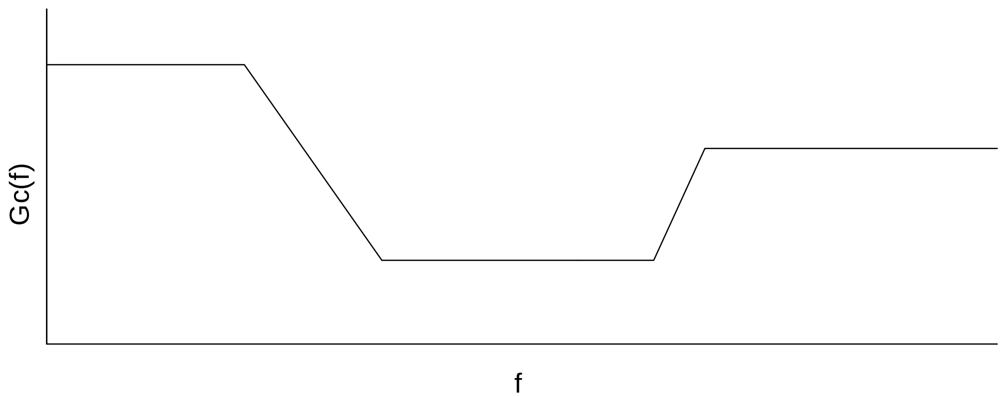
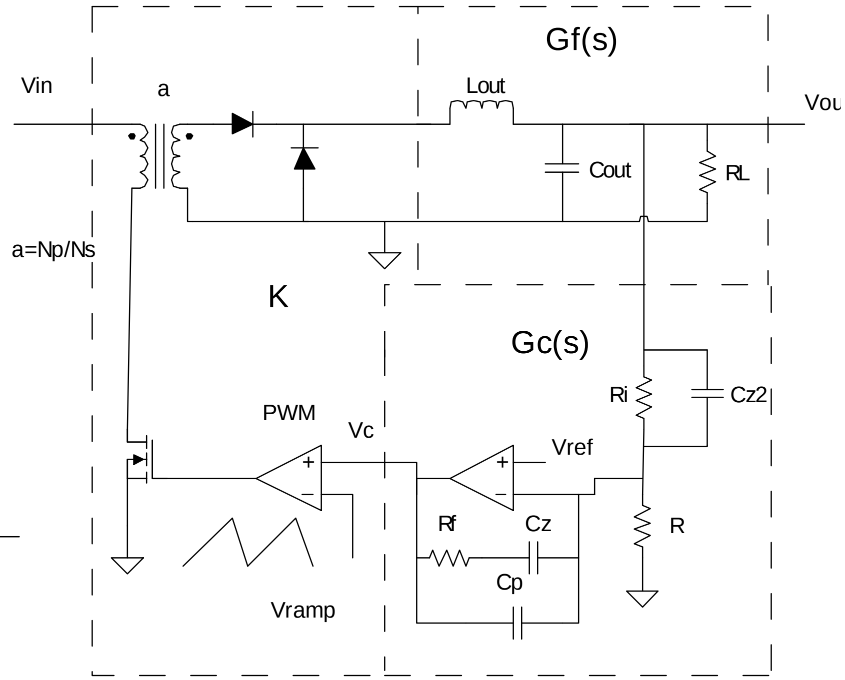
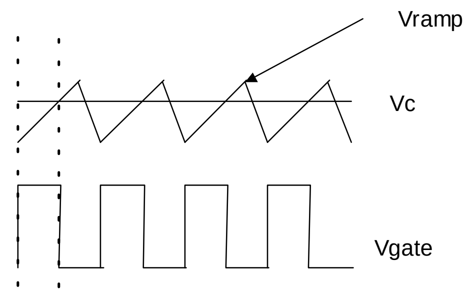
Compensation Networks Gc(s)

- Type 3 Compensation Gf(s)

$$Gc(f) = \frac{\Delta Vc}{\Delta Vout} = \frac{(s*Rf*Cz+1)*(s*Ri*Cz2+1)}{s*Ri*(Cp+Cz)((s*Rf*Cp+1)}$$







PM and GM

- Phase Margin (PM) is the difference in phase from the voltage loop T(s) and 180 degrees at the loop crossover frequency.
  - Gain at fc is 20log(T(s))=0dB
  - At DC the phase of (T(s)) is 180 degrees out of phase. 180 degrees out of phase would be 0 degrees or 360 degrees
  - PM = Phase – 0 degrees or 360 degrees – Phase

    >Use the smaller of the two
  - The control loop needs to be designed for 45 degrees of phase margin at crossover.
  - The loop is generally designed to crossover below one sixth of the switching frequency. For this design example we chose to crossover at 1/10 of the switching frequency
- Gain Margin
  - Is the gain when the voltage loop (T(s)) is 180 degrees out of phase
  - The control loop needs to be designed for a -6dB gain margin to ensure loop stability

Voltage Mode (VM) Control Buck Converter CCM Design Example

- Power Converter Specifications
  - Vin = 12 to 24 V
  - Vout = 5 V
  - Vref = 2.5 V internal reference used by the compensation Gc(f)
  - Switching Frequency fs = 100 kHz
  - Lout = 5 uH
  - Cout = 1000 uF with an ESR of 5 mohm
  - Pout = 100W / Load Impedance (RL) =0.25 ohm
  - PWM Ramp (Vramp) = 5V

Voltage Mode Forward/Buck Converter CCM

- Define the control block transfer functions
  - Filter is required to filter chopped input voltage

$$Gf(s) = \frac{(s*Cout*ESR+1)}{1+\frac{s}{wp*Q}+\left(\frac{s}{wp}\right)^2}$$

  - Modulator Transfer Function

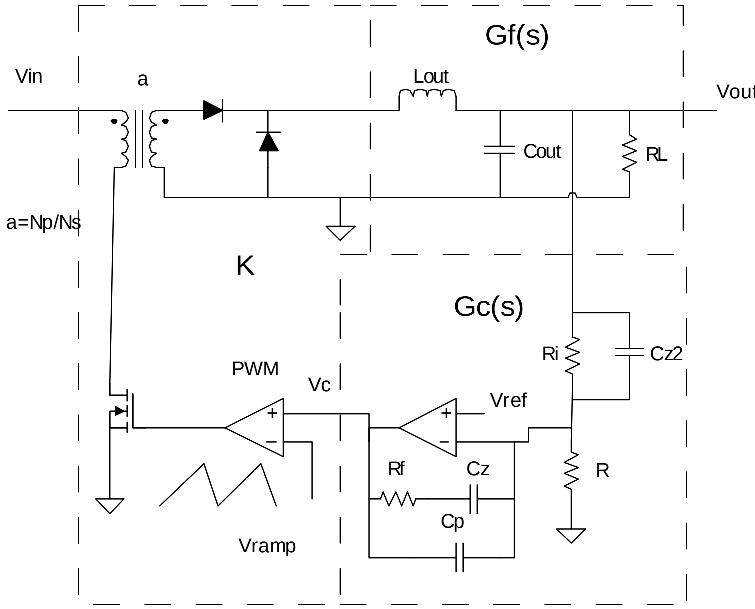
$$K = \frac{1}{a}\frac{Vin}{Vramp}$$

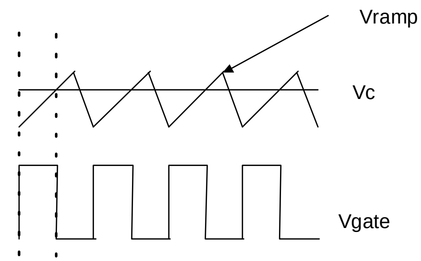
  - Control to Output Transfer Function

$$Gco(s) = K*Gf(s)$$

  - Type 3 Compensation Feedback

$$Gc(f) = \frac{\Delta Vc}{\Delta Vout} = \frac{(s*Rf*Cz+1)*(s*Ri*Cz2+1)}{s*Ri*(Cp+Cz)((s*Rf*Cp+1)}$$





Evaluate the Gco(f)=K*Gf(f) Transfer Function

With a bode plot it is possible to easily evaluate the control to output gain

$$Gcodb(s) = 20\log\left(\left|K*G(f)\right|\right) = 20\log\left(\left|\frac{Vin}{Vramp}*\frac{(s*Cout*ESR+1)}{1+\frac{s}{wp*Q}+\left(\frac{s}{wp}\right)^2}\right|\right)$$

The control to output gain (GcodB(s)) at 12V is 8dB and when the input is 24V the DC gain is 12dB

$$GcodB(0Hz) = 20\log\left(\left|\frac{Vin}{Vramp}\right|\right) \approx 8dB\_to\_12dB$$

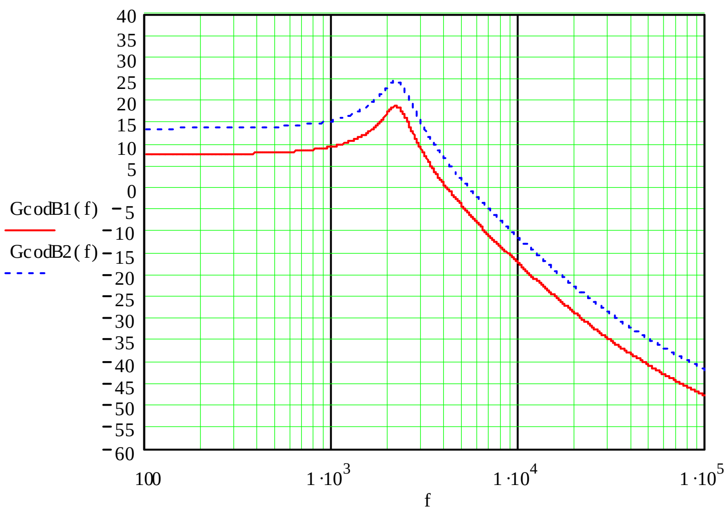
The double pole occurs at roughly 2.25kHz

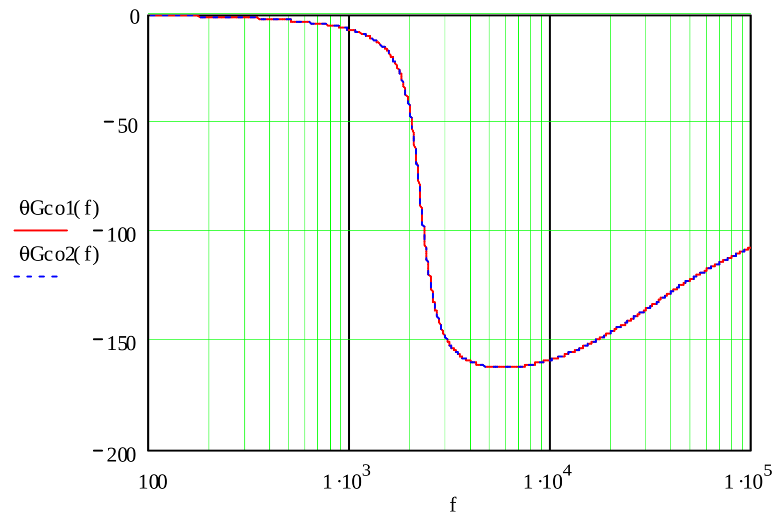
$$fp1 = fp2 = \frac{1}{2\pi\sqrt{5uH*1000uF}} = 2.25kHz$$

The ESR zero occurs at roughly 32 kHz

$$fz = \frac{1}{2\pi(ESR)*Cout} \approx 32kHz$$

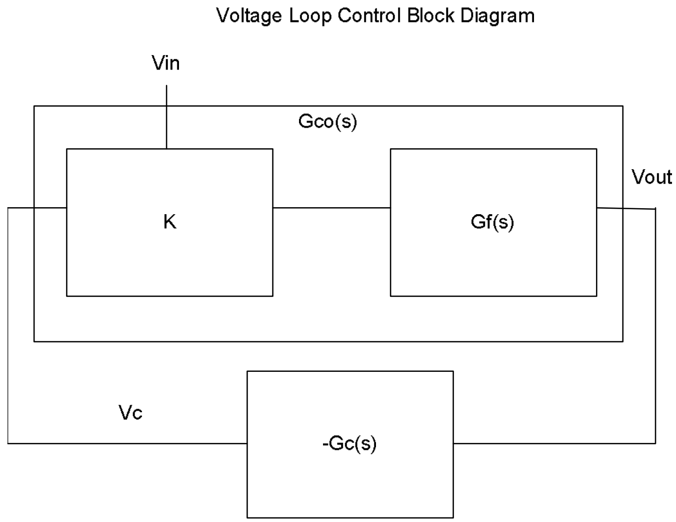
The Gco(f) Transfer Function Evaluation





- The Gco(f) of a voltage loop is an LCR network that is unstable by nature
  - The double pole needs to be dampened out by the compensation network Gf(f) for stability.
  - Gco(f) magnitude varies with line which is another challenge for compensating the loop.
  - The voltage loop (T(f)) for this example will be designed for crossover frequency of 10 kHz.
  - The compensation is based on low line input conditions of 12V
    - If you design the loop to crossover at high line, the loop will have less than 45 degrees of phase margin at low line.
  - The first step in compensating the loop is calculating the gain at the desired crossover frequency of 10kHz. The gain at the crossover frequency of 10 kHz is roughly -17dB. The compensation network Gc(f) is going to have to adjust the gain at crossover.

Closing the Feedback Loop (T(s))



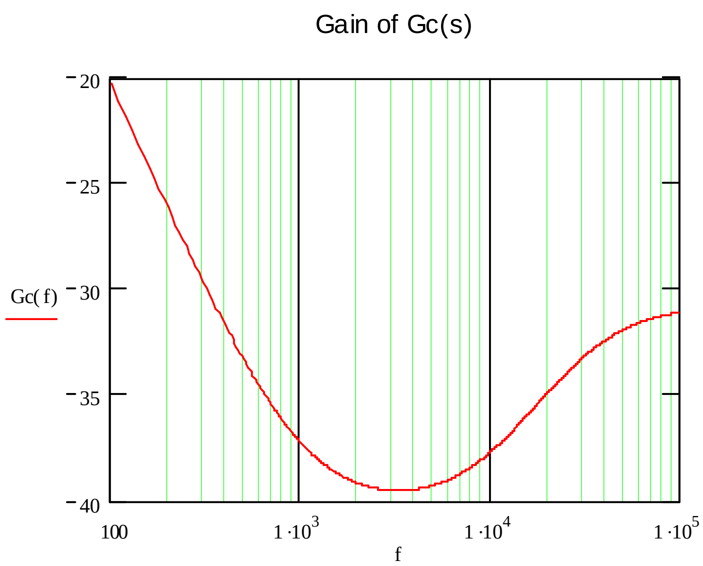
$$T(s) = K * Gf(s) * (-Gc(s))$$

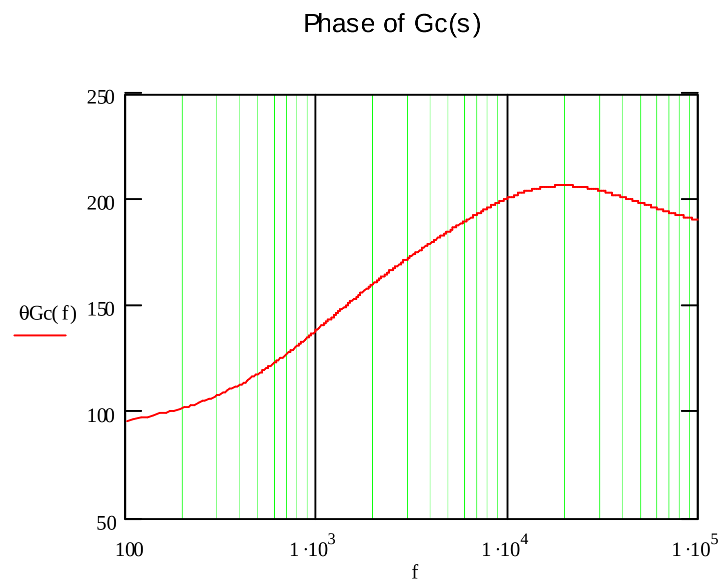
$$Gco(s) = K * Gf(s)$$

$$GcodB(s) = 20\log(|K * Gf(s)|)$$

- The first step of compensating the voltage loop was to estimate the GcodB(s) at the desired crossover frequency (fc).
- The next step is to set up the compensation network Gc(s)

Type 3 Compensation Scheme





- Gc(s) used for this design is type 3 compensator

$$Gc(f) = \frac{\Delta Vc}{\Delta Vout} = \frac{(s*Rf*Cz+1)*(s*Ri*Cz2+1)}{s*Ri*(Cp+Cz)((s*Rf*Cp+1)}$$

Setting up Type 3 Gc(s) for VM Buck Converter

- The voltage divider Ri/(Ri+R) sets up the DC output voltage

$$Ri = \frac{R*(Vout - Vref)}{Vref} = \frac{10k(5V - 2.5V)}{2.5V} = 10K$$

- Rf is sized to offset the Gco(f) gain at the desired crossover frequency

$$Rf = 10^{\frac{-GcodB(fc)}{20}} \approx 37k$$

$$Rf = 36k$$

Choose a standard resistor for Rf of 36k ohm

Setting up Type 3 Gc(s) for VM Buck Converter

•The first zero of the compensation scheme will be set to give the feedback loop a phase boost at 1/10 of the double pole frequency of the output filter (Gf(s))

$$Ri = 10k \qquad Rf = 36k$$

$$fz1 = \frac{1}{2\pi\sqrt{Lout * Cout}} = 2.25kHz \qquad Cz = \frac{1}{2\pi * fz1 * Rf} \approx 22nF$$

•The second zero of the compensation scheme will be set to add 45 degrees of PM at crossover

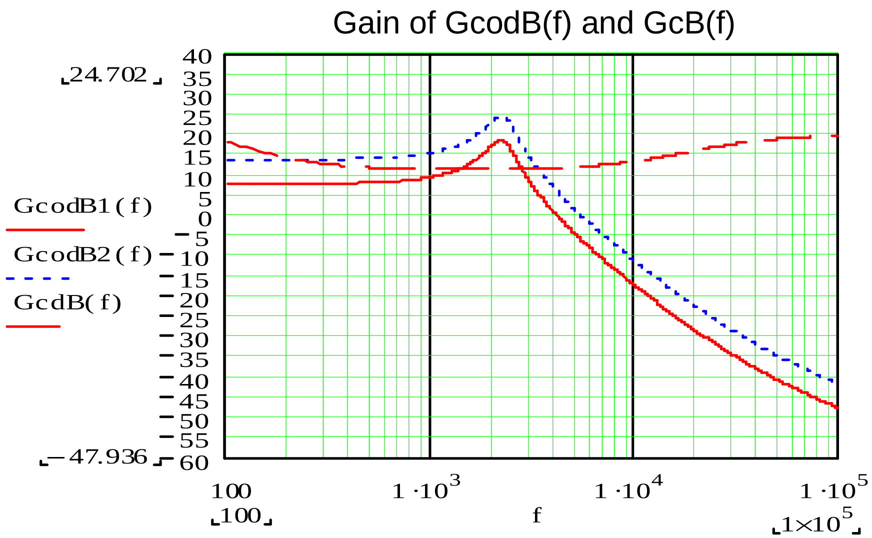
$$fz2 = \frac{fs}{10} = 10kHz \qquad Cz2 = \frac{1}{2\pi * Ri * fz2} \approx 1.5nF$$

•A pole will be added to cancel out the effects of the ESR zero

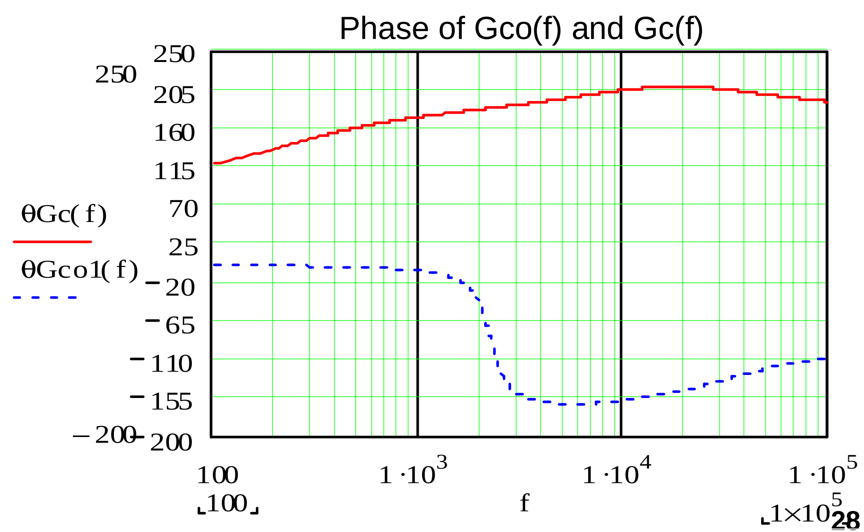
$$fp = \frac{1}{2\pi * Cout * ESR} \approx 32kHz \qquad Cp = \frac{1}{2\pi * Rf * fp} \approx 150pF$$

Bode Plots of The VM Buck Converter Design Example

•The sum of GcodB(f) and GcB(f) is the loop gain Tdb(s)



•The sum of ΘGco(f) and ΘGc(f) is the loop phase ΘT(s)



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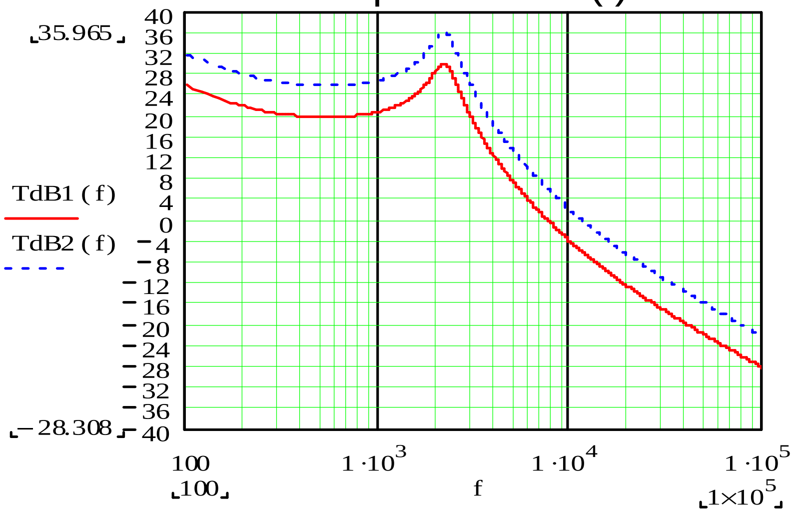
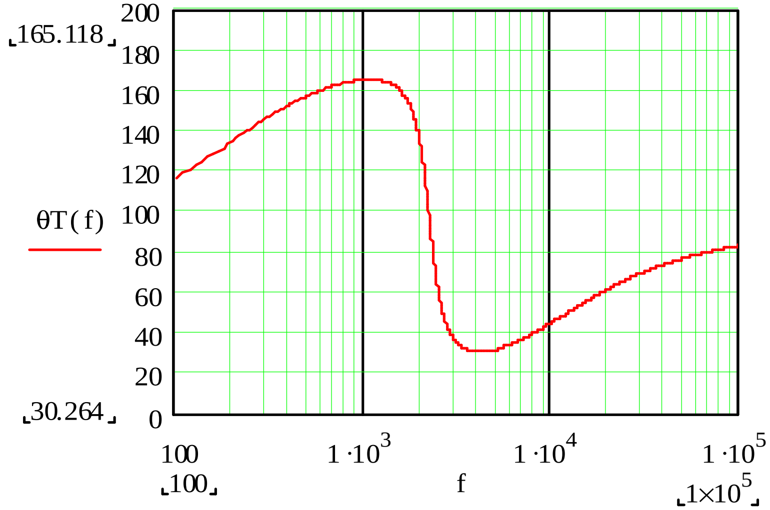
Evaluate The Voltage Feedback Loop T(f)





From the bode plots of loop gain it can be observed that voltage loop T(s) was stable

- -The loop crossover was between 8 and 15 kHz
- -The PM was between 40 and 45 degrees
  - *The design goal was to have better than 45 degrees of phase margin but the system can work with as little as 35 degrees of phase margin
  - *The real point of instability occurs when the loop is 180 degrees out of phase.
    - >This is because the loop will have positive feedback
    - >When the loop is 180 degrees out of phase the gain needs to be less than -6dB to ensure stability

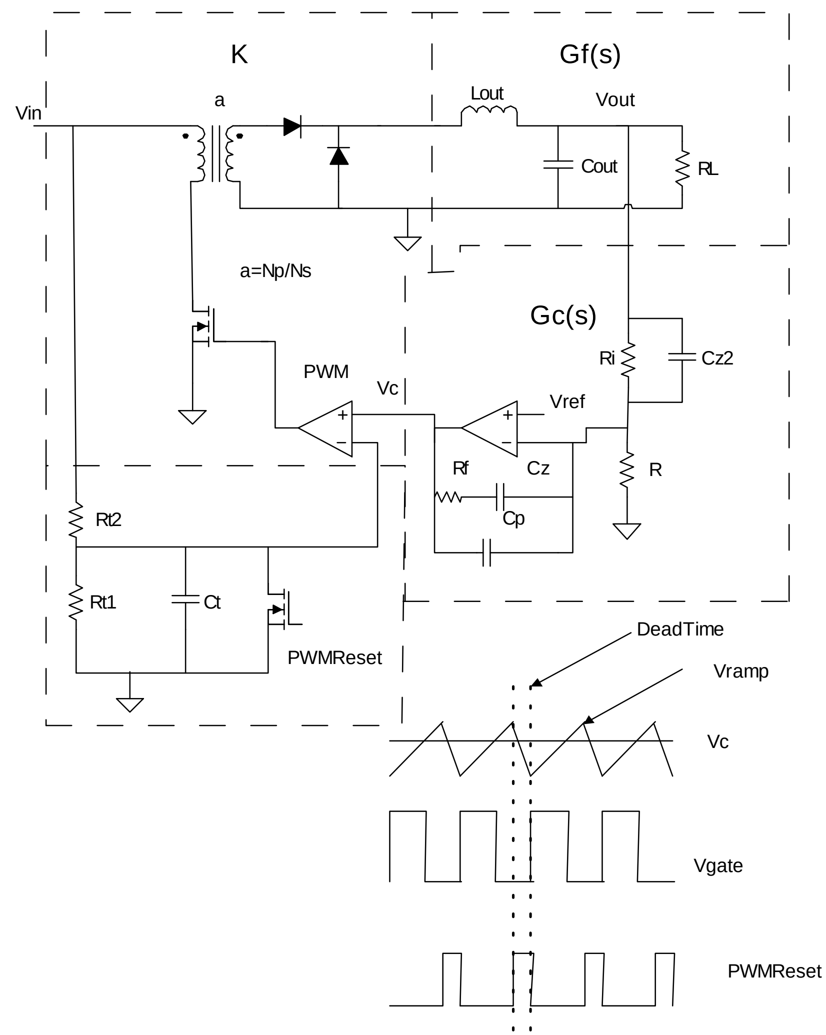
Voltage Feed Forward Makes Compensation for VM Control Easier

- •Voltage Feed Forward (VFF)
  - -Keeps the Gco(s) gain constant with varying input voltage.
  - -This is generally accomplished by making the PWM ramp voltage proportional to the input voltage
  - -Compensating a buck derived converter with VFF is much easier.

$$\mathrm{Vramp} = \mathrm{VFF} = \frac{\mathrm{Vin} * \mathrm{Rt1}}{\mathrm{Rt1} + \mathrm{Rt2}}$$

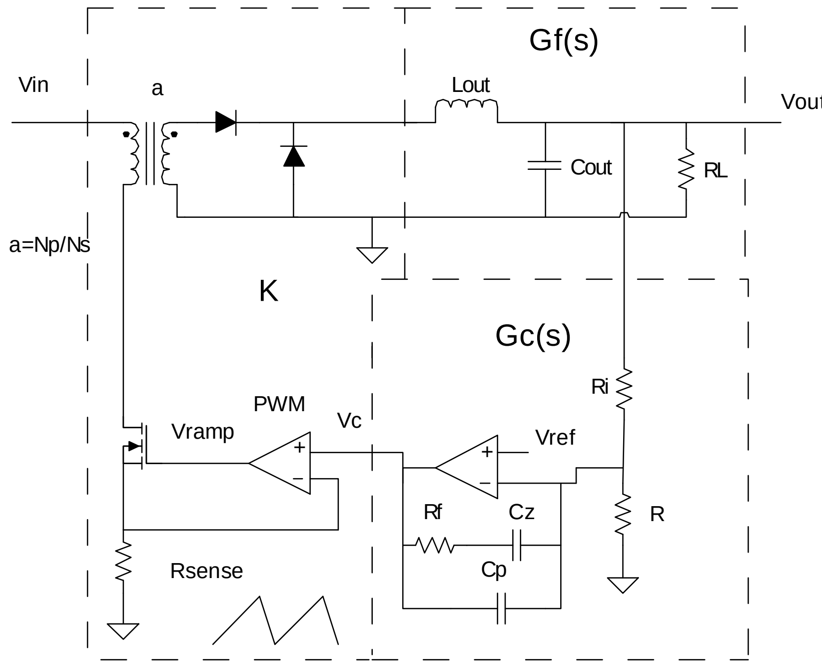
$$K = \frac{1}{a}\frac{\mathrm{Vin}}{\mathrm{Vramp}} = \frac{1}{a}\frac{\mathrm{Vin}}{\frac{\mathrm{Vin} * \mathrm{R1}}{\mathrm{R1} + \mathrm{R2}}} = \frac{1}{a}\frac{\mathrm{Rt1} + \mathrm{Rt2}}{\mathrm{Rt1}}$$

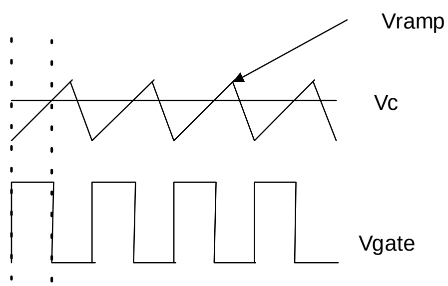
$$\mathrm{Gco(s)} = 20\log\left(\left|\frac{1}{a}\frac{\mathrm{Rt1} + \mathrm{Rt2}}{\mathrm{Rt1}} * \frac{(s * \mathrm{Cout} * \mathrm{ESR} + 1)}{1 + \frac{s}{wp * Q} + \left(\frac{s}{wp}\right)^2}\right|\right)$$



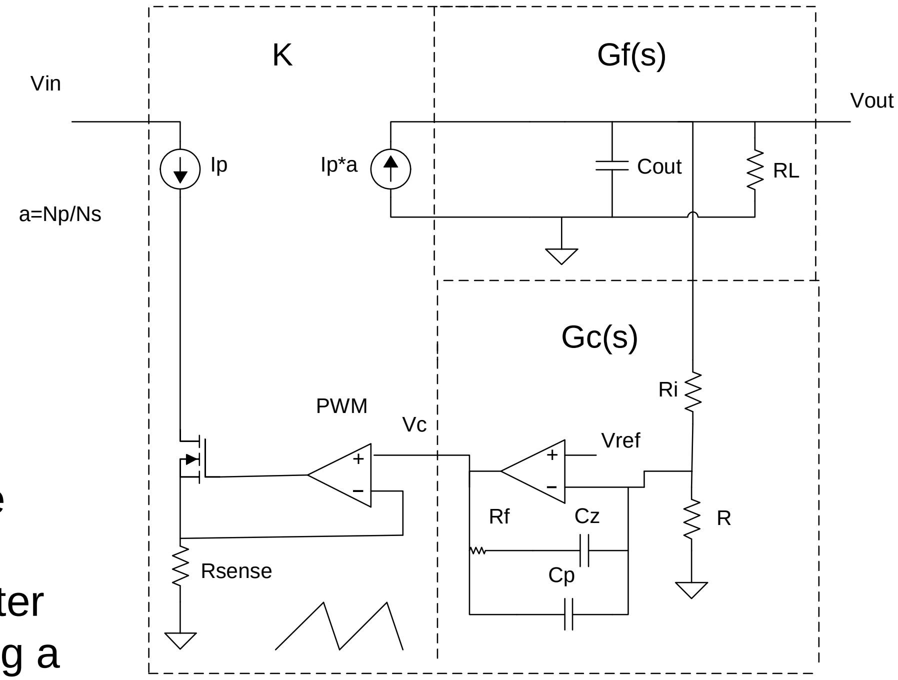
Peak Current Mode (PCM) Control

- A Peak Current Mode Control forward converter
  - -PWM Ramp is built of a current sense signal



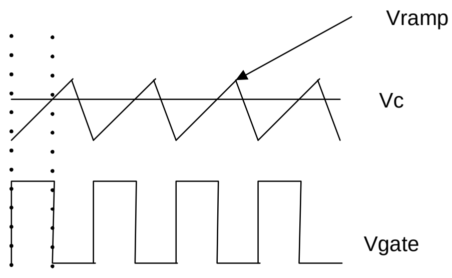


Peak Current Mode (PCM) Control

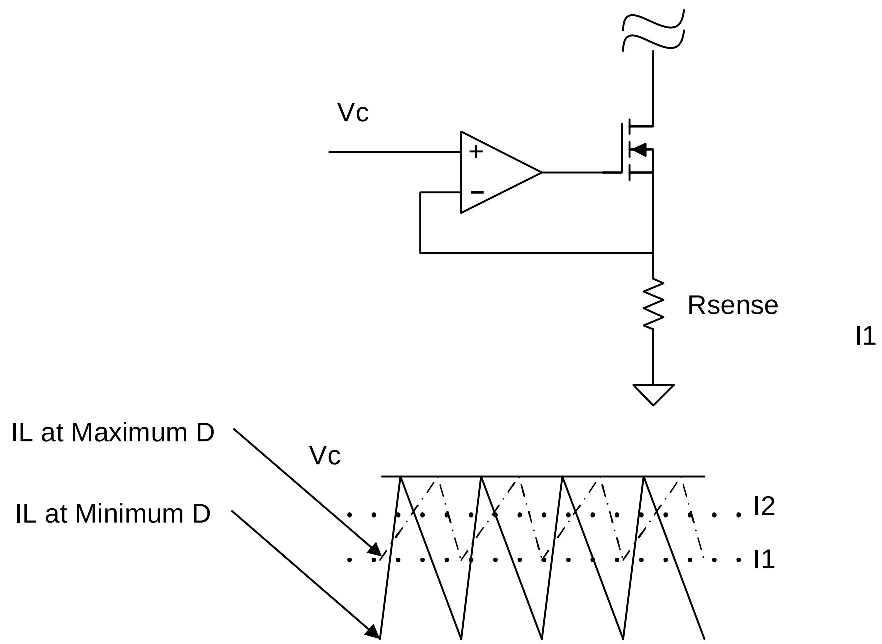


The output inductor in the output filter (Gf(s)) look like a current source

- -This removes the double pole from the voltage loop T(s) and makes the loop much easier to compensate
- -To compensate PCM control converter the designer can get away with using a type 2 compensation scheme Gc(s)

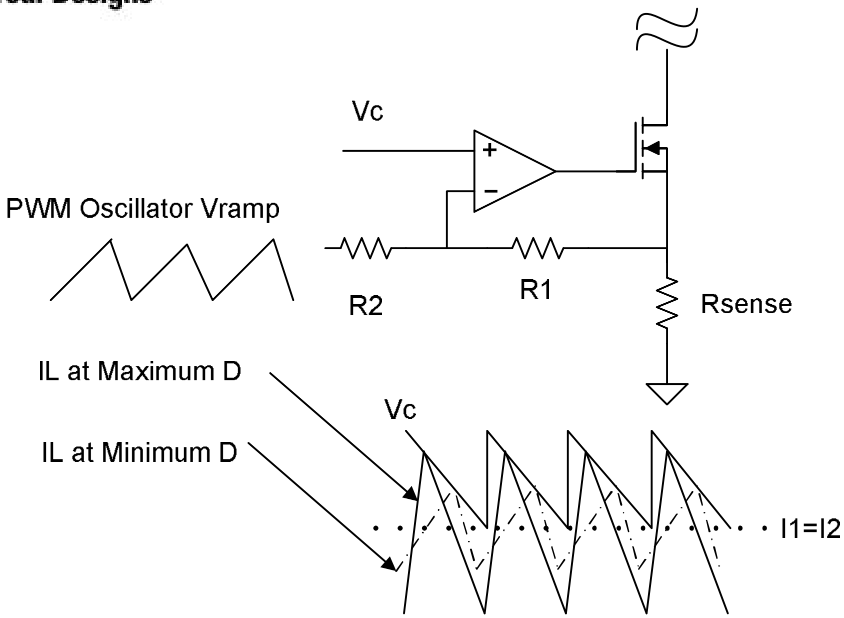


Known Instability in Peak Current Mode Control Power Converters



- The objective in peak current mode control is to control the inductors average current
  - -At max. input voltage the converter is at minimum D and the inductors ripple current is at its maximum
  - -At min. input voltage the converter is at maximum D and the inductors ripple current is at its minimum
  - -Any change in duty cycle can cause a change in average inductor current creating an instability.
  - -This problem can be corrected with slope compensation

Slope Compensation



$$Vslope \geq \frac{Vout * (1 - D\min) * Rsense}{2 * Lout * fs}$$

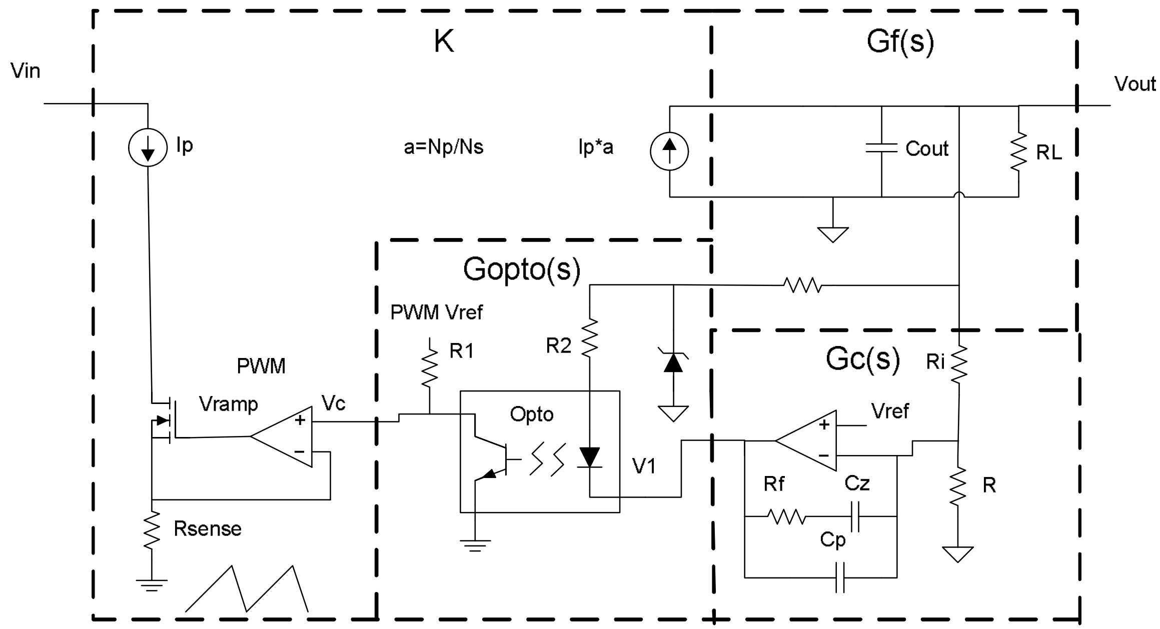
$$R2 = \frac{R1 * Vosc}{Vslope}$$

•By adding a ramp to the current sense signal the converter will be forced to have the same average inductor current independent of duty cycle

-The slope can be added by summing in a portion of the PWM's oscillator ramp into the current sense signal.

-To ensure stability the added slope needs to be at least equal to ½ the inductor currents down slope

Example of a Peak Current Mode Forward Converter

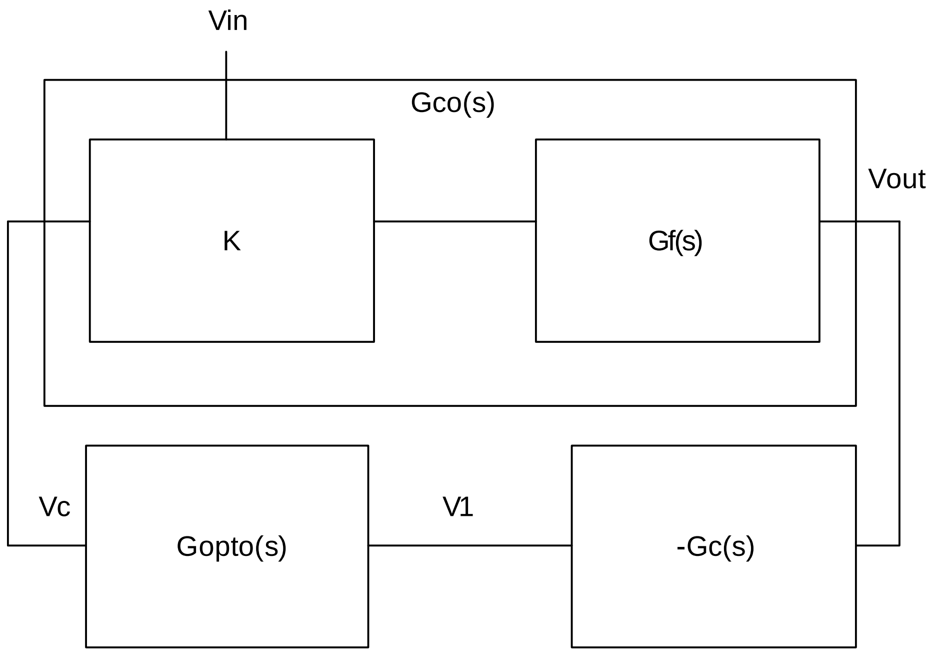


•Type 2 compensation is generally used for feedback Gc(s) in peak current mode converters

•A transformer and opto isolator are generally used to isolate the input from the output

-The opto isolator will add a gain block Gopto(s) that will have an affect on the loop compensation

Control Block Diagram For PCM Forward Converter Design Example



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Review Control to Output Gco(f) Transfer Block for This Design Example

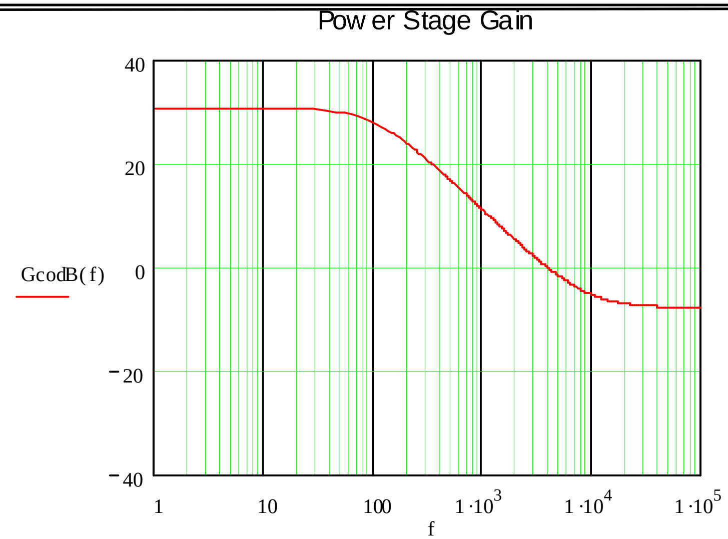
$$a = \frac{Np}{Ns} = \frac{Vp}{Vs} = \frac{Is}{Ip}$$

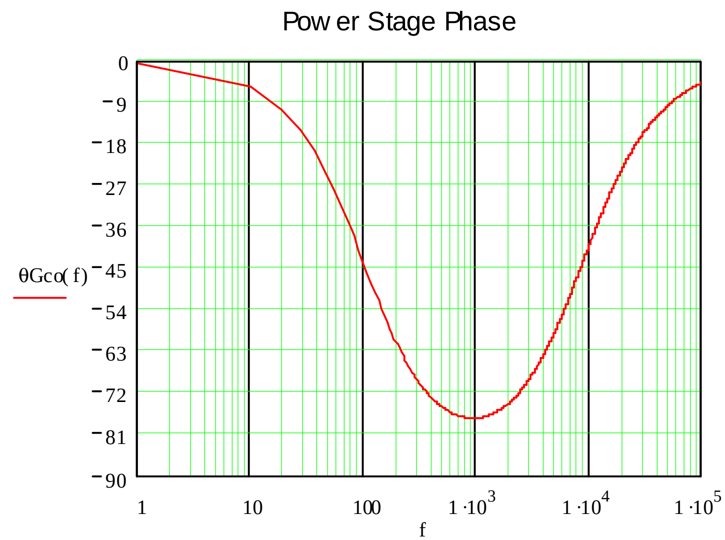
$$K = \frac{\Delta Iout}{\Delta Iin} = \frac{\Delta Vout}{\Delta Vc} = \frac{a * RL}{Rsense}$$

$$Gf(s) = \frac{(s * Cout * ESR + 1)}{(s * RL * Cout + 1)}$$

$$Gco(s) = \frac{\Delta Vout}{\Delta Vc} = \frac{a * RL}{Rsense} \frac{(s * Cout * ESR + 1)}{(s * RL * Cout + 1)}$$

$$GcodB(s) = 20 \log\left(\frac{a * RL}{Rsense} \frac{(s * Cout * ESR + 1)}{(s * RL * Cout + 1)} \right)$$





Peak current mode control makes the filter inductor (Lout) look like a current source.

•The Gco(s) becomes a first order filter which is much easier to compensate

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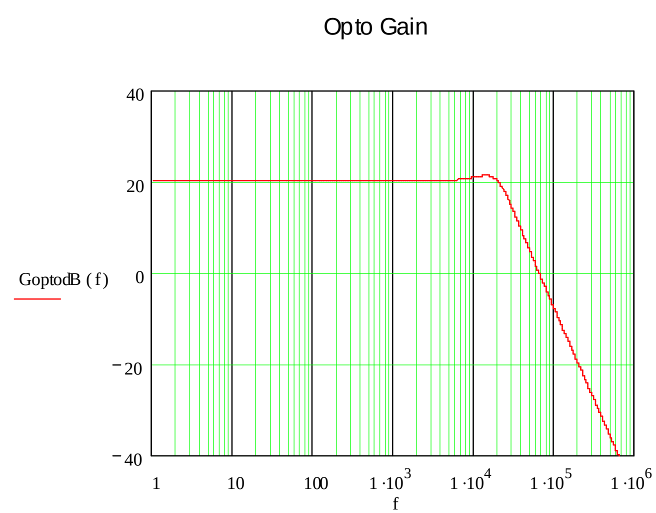
Gopto(f) Gain Block

- The opto isolator small signal characteristics (Gopto(f)) are over looked in many designs and can cause problems
  - The opto isolator small signal response looks similar to an LCR filter
  - When designing a control loop the opto isolator will limit the amount of bandwidth that can be designed in the voltage loop T(s).
    - The voltage loop needs to be designed to crossover before the double pole of the opto isolator
    - These specifications are not generally given in the opto data sheet and should be measured

$$\mathrm{Gopto}(f) = \frac{\Delta Vc}{\Delta V1} = \frac{\frac{R1}{R2}}{1 + \frac{s}{2j\pi fp * Q} + \left(\frac{s}{2j\pi fp}\right)^2}$$

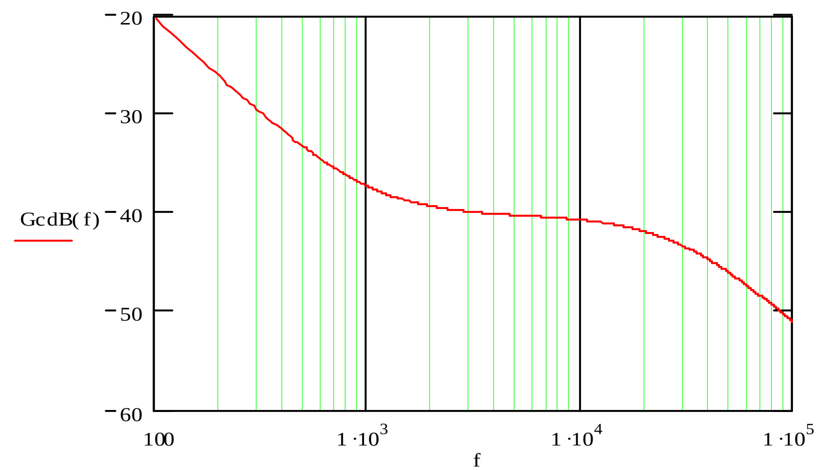


Type 2 Compensation Feed Back (Gc(s))

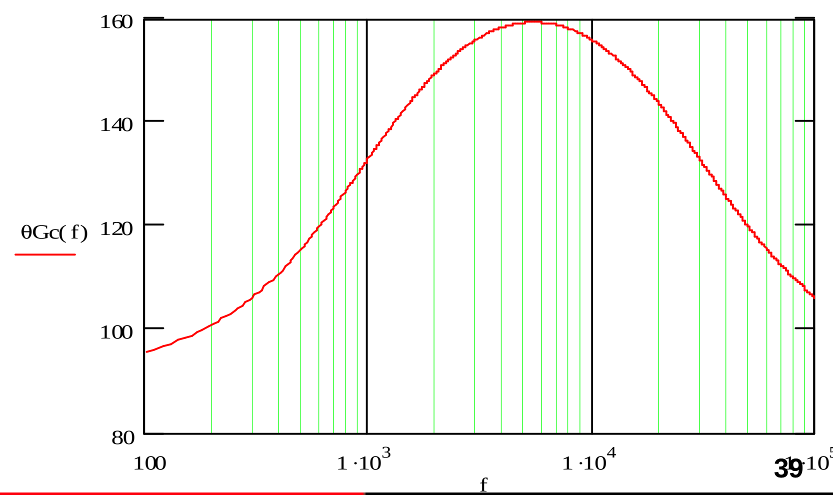
A type 2 compensation is generally used to compensate peak mode control converters
- A type 3 amplifier can also be used

$$Gc(f) = \frac{\Delta V1}{\Delta Vout} = \frac{(s*Rf*Cz+1)}{s*Ri*(Cp+Cz)((s*Rf*Cp+1)}$$

Gain of Gc(s)



Phase of Gc(s)



Date 2004

Peak Current Mode (PCM) Control Forward Converter Design Example

- Power Converter Specifications
  - Vin = 300 to 400V
  - Vout = 24 V
  - Vref = 2.5 V
  - Switching Frequency fs = 200 kHz
  - Lout = 50 uH
  - Cout = 270 uF with an ESR of 68 mohm
  - Pout = 100W / Load Impedance (RL) =5.76ohm
  - PWM Ramp (Vramp) = 5V
  - a=Np/Ns=5.98
  - Opto pole fp = 20 kHz
  - Loop crossover fc = 10 kHz < fp < fs/6

Gopto(s)

- The opto used for this design was an HP11A with the following characteristics
  - Resistors R1 and R2 were selected to give the opto a DC gain of 20dB

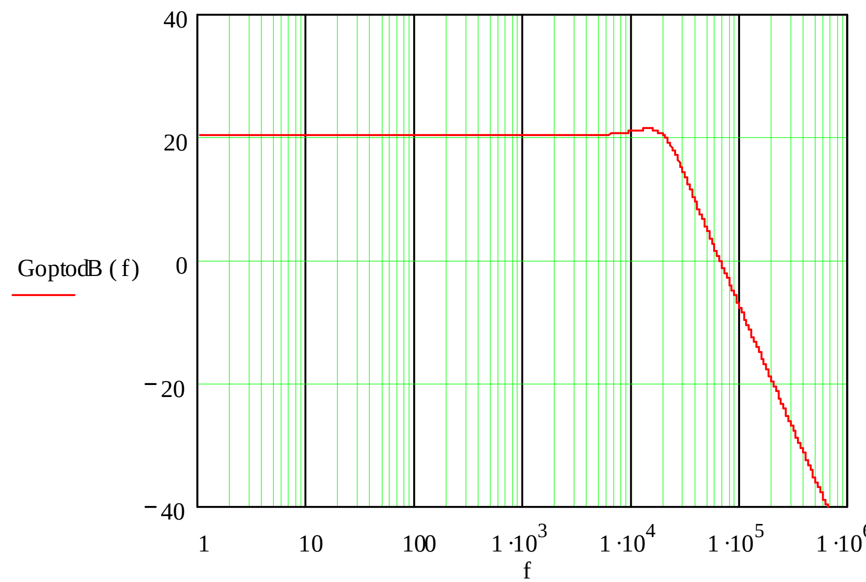
$R1 = 1kohm$

$R2 = 100ohm$

$fp = 20kHz$

$$Gopto(f) = \frac{\Delta Vc}{\Delta V1} = \frac{\frac{R1}{R2}}{1 + \frac{s}{2 j\pi fp * Q} + \left(\frac{s}{2 j\pi fp}\right)^2}$$

Opto Gain



Setting up Type 2 Gc(s) for PCM Forward Converter in CCM Mode

•The voltage divider Ri/(Ri+R) sets up the DC output voltage

$$Ri = \frac{R*(Vout - Vref)}{Vref} = \frac{1k(24V - 2.5V)}{2.5V} \approx 8.66K$$

•Rf is sized to adjust the loop crossover at 0dB

-This should be calculated base on maximum load conditions when RL is at its smallest value to ensure loop stability

$$Rf = 10^{\frac{-GcodB(fc) - Gopto(fc)}{20}} \approx 1.45k$$

$$Rf = 1.43k$$

Choose a standard resistor for Rf of 1.43k ohm

Setting up Type 2 Gc(s) for VM Buck Converter

- A zero of the compensation scheme will be set to give the feedback loop a phase boost at the crossover frequency

$$fz = fc = 10kHz \qquad Cz = \frac{1}{2\pi fc * Rf} \approx 10nF$$

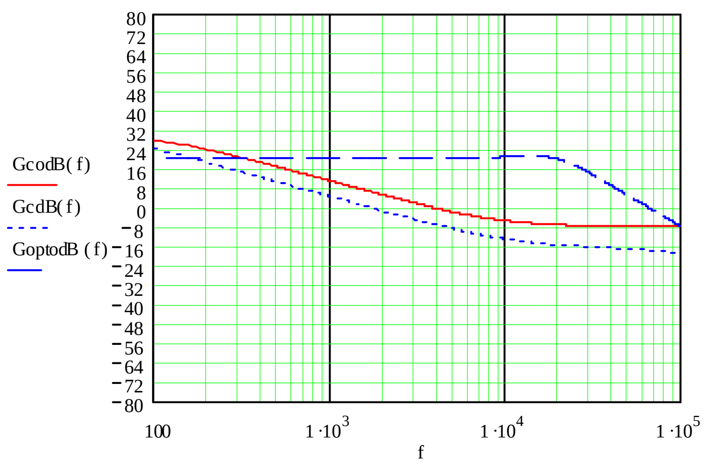
- A pole will be added to roll off the gain at one half the switching frequency

$$Cp = \frac{1}{2\pi \frac{fs}{2} Rf} = 1nF$$

Bode Plots of The VM Buck Converter Design Example

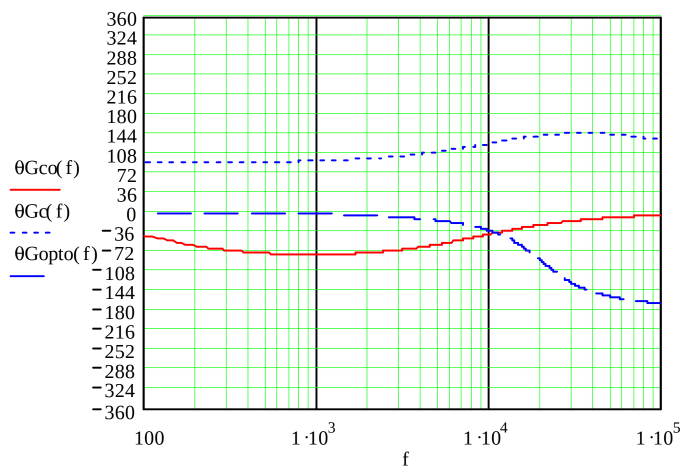
•The sum of GcodB(f), GcdB(f) and GoptodB(f) is the loop gain Tdb(s)

Gain of GcodB(f), GcdB(f) and GoptodB(f)



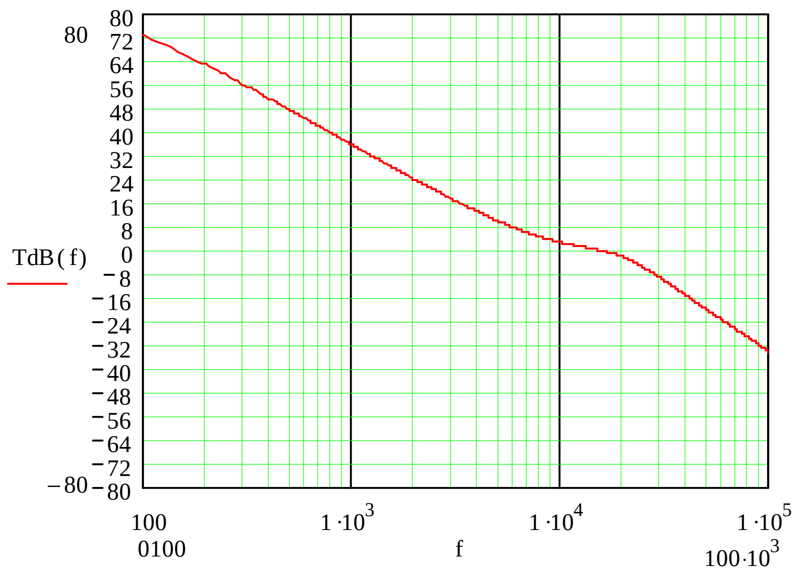
•The sum of ΘGco(f), ΘGco(f) and ΘGopto(f) is the loop phase ΘT(f)

Phase of Gco(f), Gc(f) and Gopto(f)

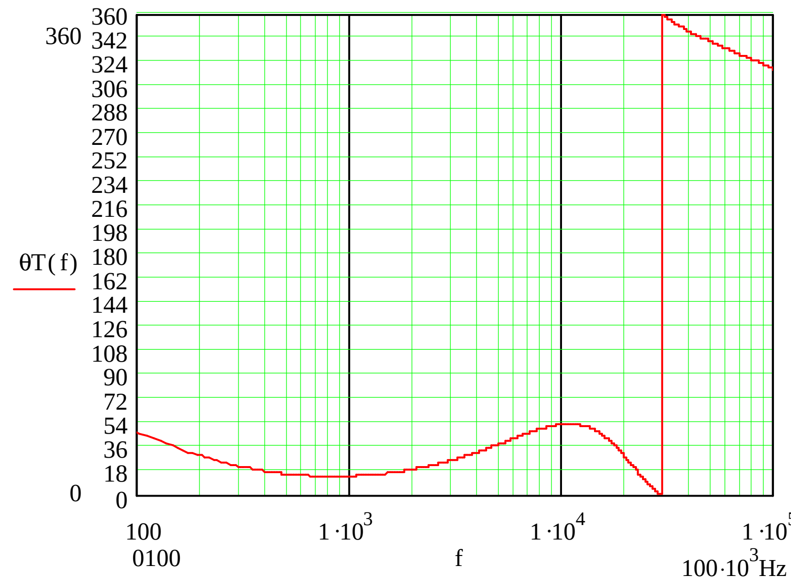


Evaluate The Voltage Feedback Loop T(f)
Peak Current Mode Forward Converter

Loop Gain TdB(f)



Loop Phase ΘT(f)



From the bode plots of the voltage loop (T(f)) it can be observed that the loop was stable

- -The loop crossover occurred at roughly 15kHz
- -The PM was roughly 54 degrees at crossover

Recap

- Bode plots can be used to compensate feedback loops
- Most power supply control loops can be compensated using a type 2 or type 3 compensation scheme
- Voltage Mode Control
  - is mostly used with buck converters
  - can be done with flyback and Boost converters but is very complicated and should be avoided
  - is typically compensated with a type 3 compensation scheme (Gc(f))
- Current Mode Control
  - simplifies the transfer function by making the filter inductor look like a current source
  - is typically compensated with a type 2 compensation network (Gc(f))
- Opto Isolators have a small signal response that affects loop gain

Gco(f) Transfer Functions of Different Type of Power Converters

Voltage Mode Control, Buck/Forward, Continuous Conduction Mode (CCM)

$$Gco(s) = \frac{1}{a}\frac{Vin}{Vramp}\frac{(s * ESR * Cout + 1)}{1 + \frac{s}{wp * Q} + \left(\frac{s}{wp}\right)^2}$$

Voltage Mode Control, Buck/Forward, Continuous Conduction Mode (CCM) with VFF

$$Gco(s) = \frac{1}{a}\frac{R1t + R2t}{R1t}\frac{(s * ESR * Cout + 1)}{1 + \frac{s}{wp * Q} + \left(\frac{s}{wp}\right)^2}$$

Current Mode Control, Buck/Forward, Continuous Conduction Mode (CCM)

$$Gco(s) = \frac{a * RL}{Rsense}\frac{(s * Cout * ESR + 1)}{(s * RL * Cout + 1)}$$

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Gco(f) Transfer Functions of Different Type of Power Converters

Voltage Mode Control, Flyback, Continuous Conduction Mode (CCM)
*This technique is complex and easier methods are available

$$wp = \frac{1-D}{\sqrt{LC}}$$

$$Gco(s) = \frac{1}{a}\frac{Vin}{Vramp}\left(1+\frac{Vout}{Vin}\right)^2 \frac{(s*ESR*Cout+1)}{1+\frac{s}{wp*Q}+\left(\frac{s}{wp}\right)^2}\left(1-\frac{s*L}{RL}\frac{Vout(Vout+Vin)}{Vin}\right)$$

Current Mode Mode Control, Flyback, Continuous Conduction Mode (CCM)
*Need to roll off the gain extremely early due to the RHP Zero

$$Gco(s) = a\frac{Ro}{Rsense}\frac{Vin}{(Vout+Vin)}\frac{(s*ESR*Cout+1)}{(s*RL*Cout+1)}\left(1-\frac{s*L}{RL}\frac{Vout(Vout+Vin)}{Vin}\right)$$

Current Mode Control, Flyback, Discontinuous Conduction Mode (DCM)
*The right half plane zero is not present in DCM flyback converters
*This technique is more popular and easier to compensate

$$Gco(s) = a\frac{Ro}{Rsense}\frac{Vin}{(Vout+Vin)}\frac{(s*ESR*Cout+1)}{(s*RL*Cout+1)}$$

Gco(f) Transfer Functions of Different Type of Power Converters

Voltage Mode Control, Boost, Continuous Conduction Mode (CCM)
*This technique is complex and easier methods are available

$$wp = \frac{1-D}{\sqrt{LC}}$$

$$Gco(s) = \frac{1}{a}\frac{Vin}{Vramp}\left(\frac{Vout}{Vin}\right)^2 \frac{(s*ESR*Cout+1)}{1+\frac{s}{wp*Q}+\left(\frac{s}{wp}\right)^2}\left(1-\frac{s*L}{RL}\left(\frac{Vout}{Vin}\right)^2\right)$$

Current Mode Control, Boost, Continuous Conduction Mode (CCM)
*Need to roll off the gain extremely early due to the RHP Zero

$$Gco(s) = a\frac{Ro}{Rsense}\frac{Vin}{Vout}\frac{(s*ESR*Cout+1)}{(s*RL*Cout+1)}\left(1-\frac{s*L}{RL}\left(\frac{Vout}{Vin}\right)^2\right)$$

Current Mode Control, Boost, Discontinuous Conduction Mode (DCM)
*The right half plane zero is not present in DCM flyback converters
*This technique is more popular

$$Gco(s) = a\frac{Ro}{Rsense}\frac{Vin}{Vout}\frac{(s*ESR*Cout+1)}{(s*RL*Cout+1)}$$

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Home Work

- Use bode plot to compensate a forward converter with the following specifications
- Power Converter Specifications
  - Vin = 300 to 400V
  - Vout = 24V
  - Vref = 2.5V
  - Switching Frequency fs = 200 kHz
  - Lout = 50 uH
  - Cout = 270 uF with an ESR of 68 mohm
  - Pout = 100W / Load Impedance (RL) =5.76ohm
  - PWM Ramp (Vramp) = 5V
  - a=Np/Ns=5.98
  - Opto pole fp = 20 kHz, R1 = 1K, R2 =100 ohm
  - Loop crossover fc = 10 kHz < fp < fs/6

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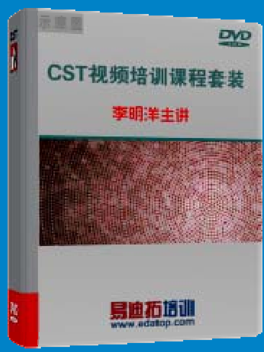

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