环路补偿很容易

课程的目的

- 确定功率级特性
- 说明 **Type II** 补偿 **–** 电流模式
- 阐述 **Type III** 补偿 **–** 电压模式
- 补偿电流模式降压
- 找出交越频率和相位裕量
- 使用 **Excel** 补偿器设计工具

电源转换器拓扑

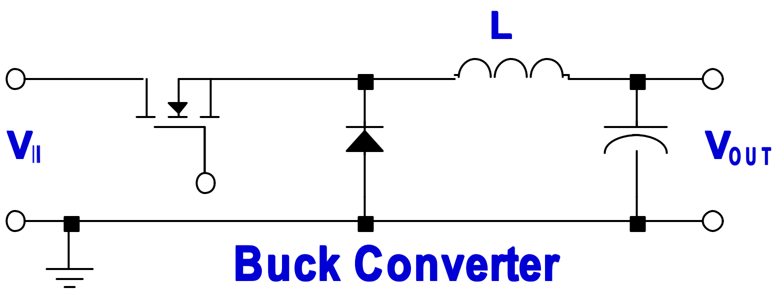
降压 / 正激式	• 降压 / 隔离
升压	• 升压
降压-升压 / 反激式	• 反转极性 / 隔离

电源转换器拓扑

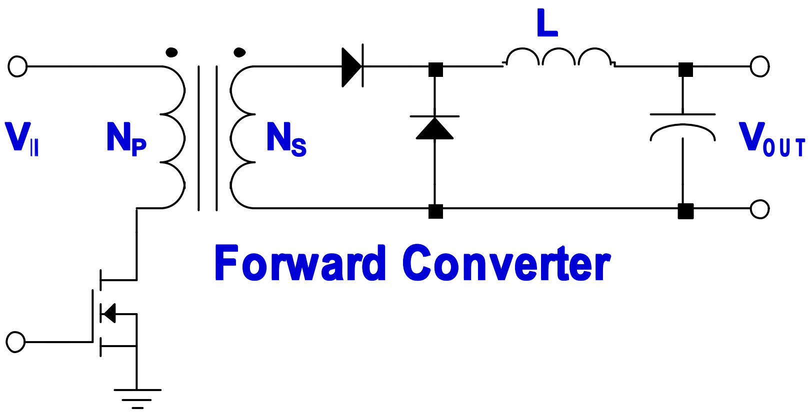
降压 /
正激式

升压

降压-升压 /
反激式



$V_{OUT} = V_{IN} \cdot D$



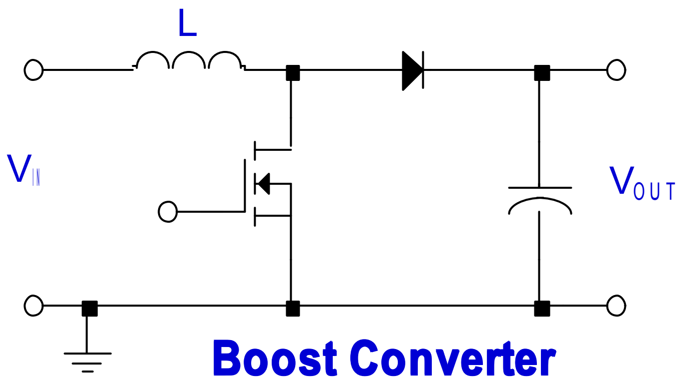
$$V_{OUT} = V_{IN} \cdot D \cdot \frac{N_S}{N_P}$$

电源转换器拓扑

降压 / 正激式

升压

降压-升压 / 反激式



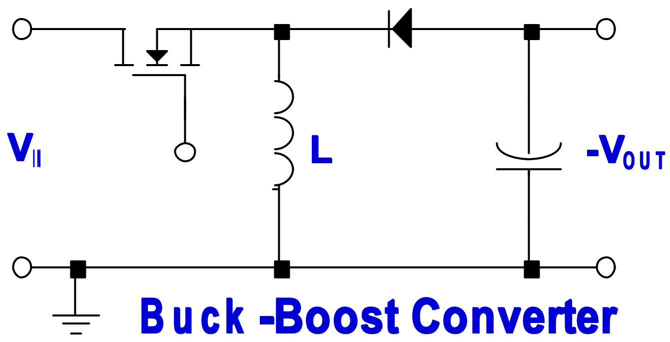
$$V_{OUT} = V_{IN} \cdot \frac{1}{1-D}$$

电源转换器拓扑

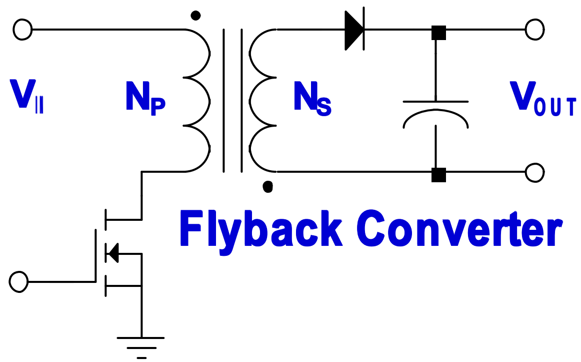
降压 /
正激式

升压

降压-升压 /
反激式



$$V_{OUT} = V_{IN} \cdot \frac{D}{1-D}$$



$$V_{OUT} = V_{IN} \cdot \frac{D}{1-D} \cdot \frac{N_S}{N_P}$$

极点/零点回顾

单个极点

单个零点

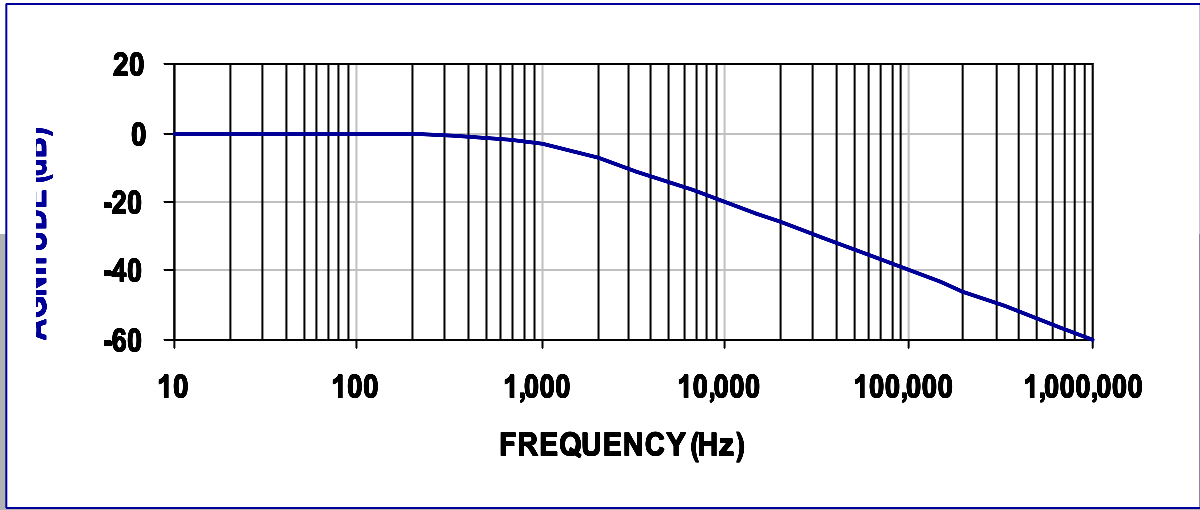
反相零点 (Inverted Zero)

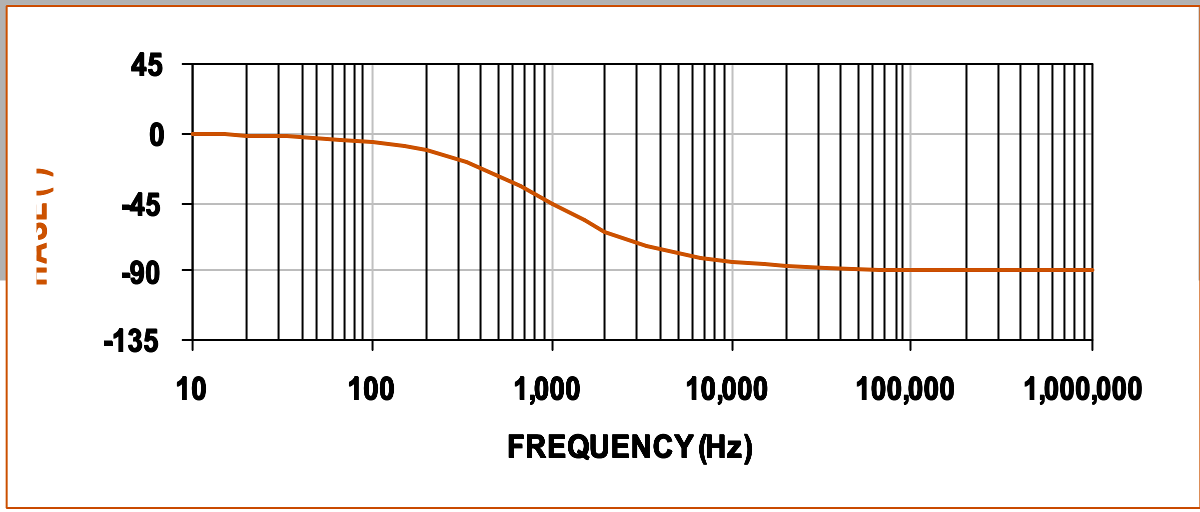
右半平面零点

共轭复极点

单个极点

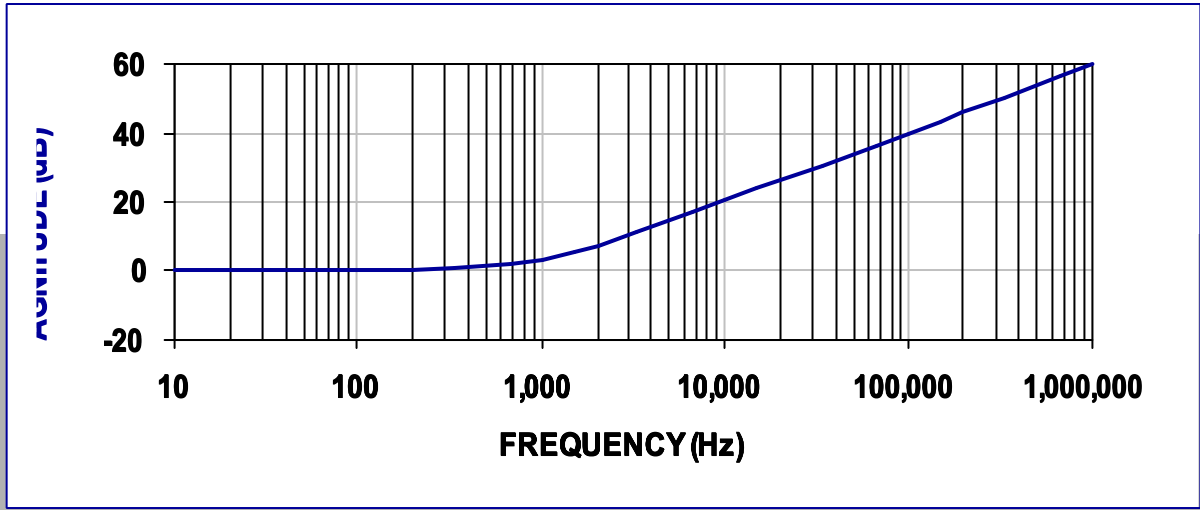
$$H(s) = \frac{1}{1 + \frac{s}{\omega_P}}$$

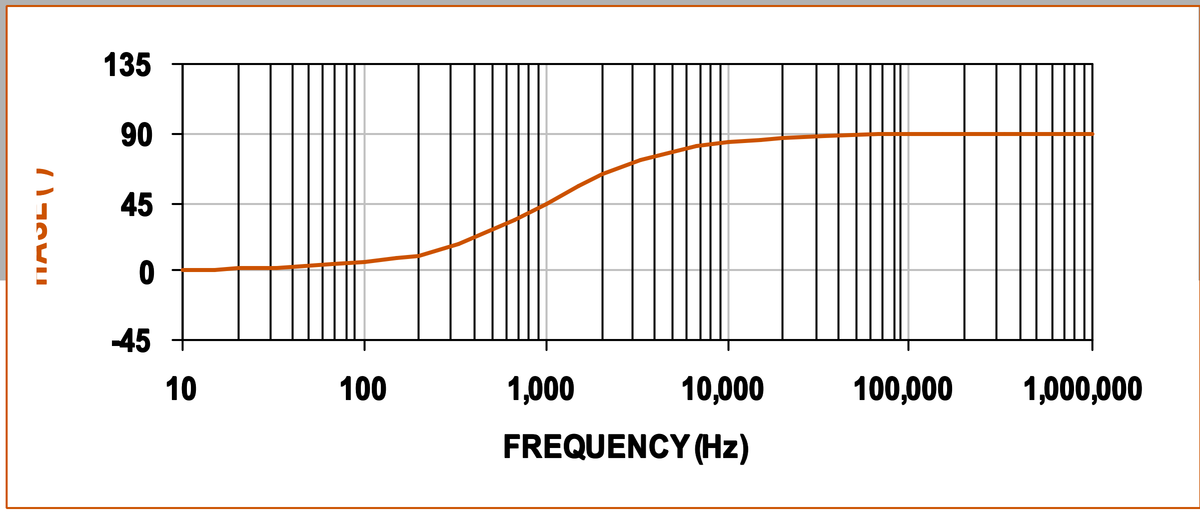




单个零点

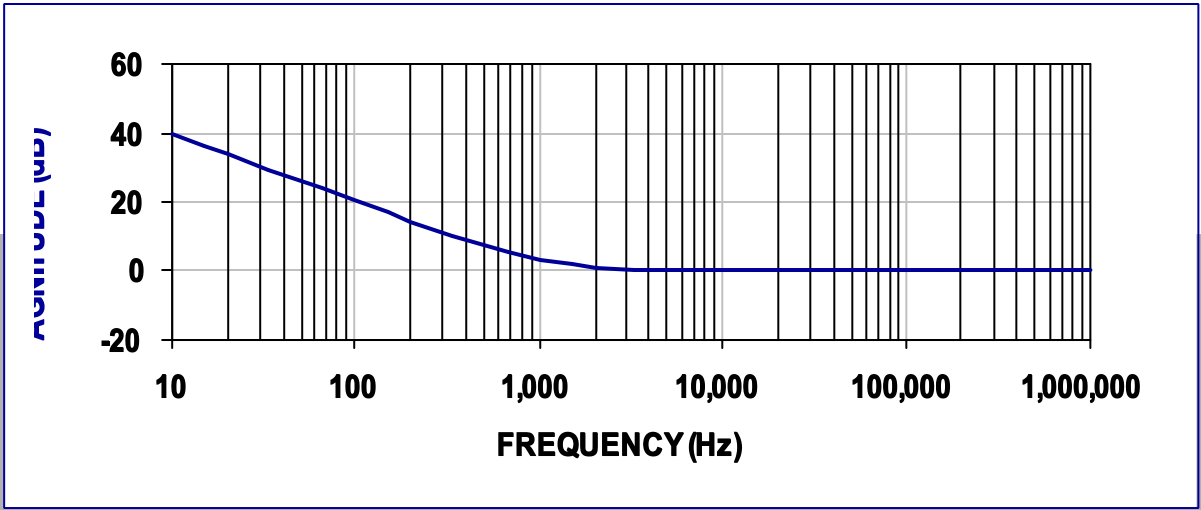
$$H(s) = \frac{1 + \dfrac{s}{\omega_Z}}{1}$$

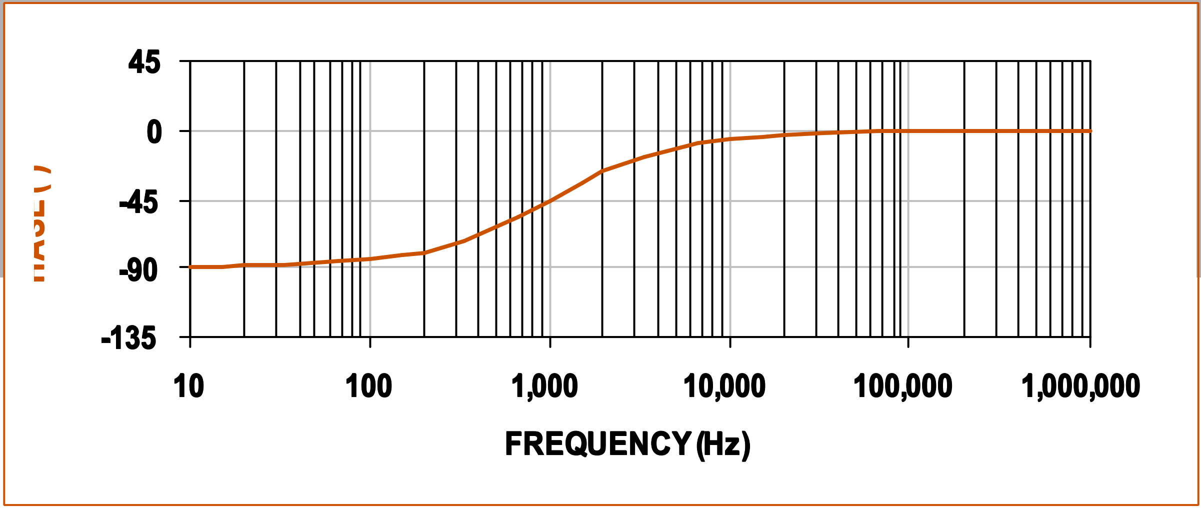




反相零点

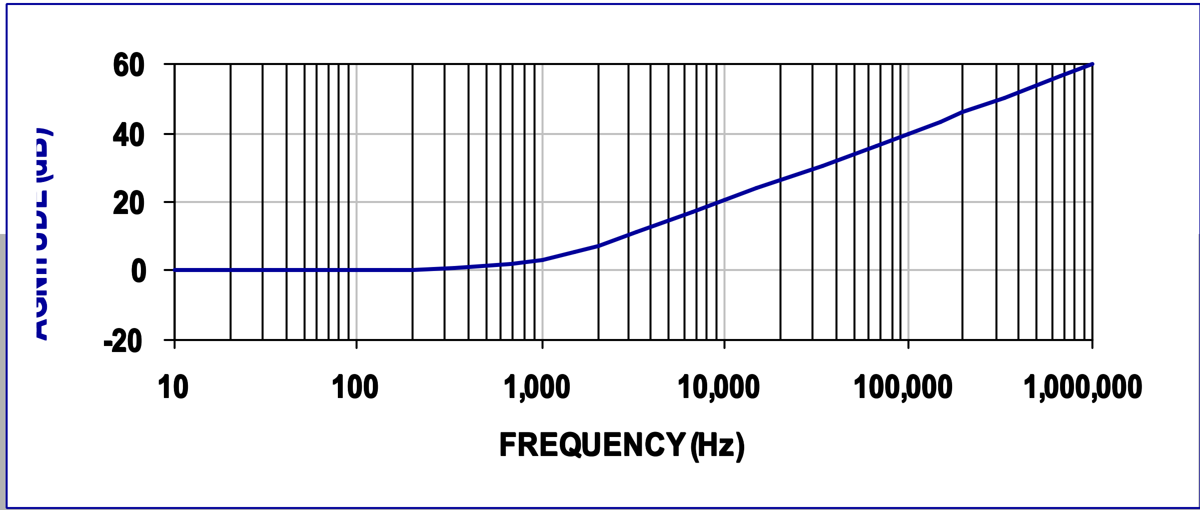
$$H(s) = \frac{1 + \dfrac{\omega_Z}{s}}{1}$$

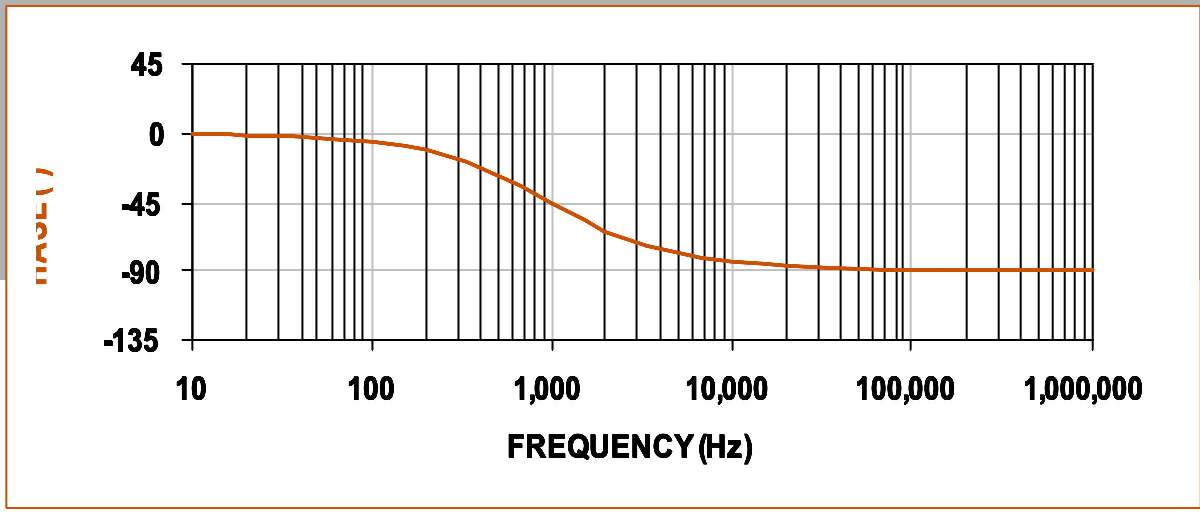




右半平面零点

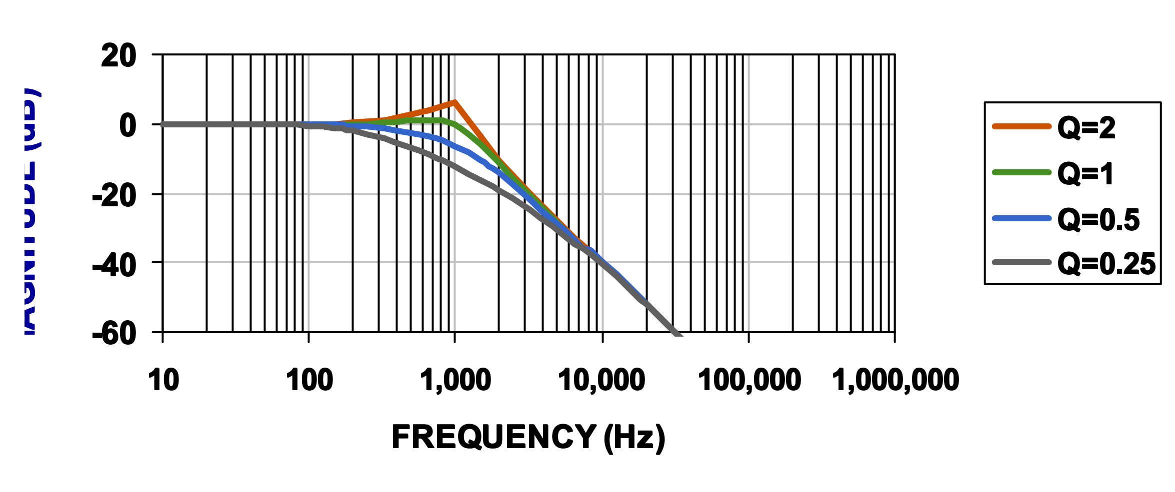
$$H(s) = \frac{1 - \dfrac{s}{\omega_Z}}{1}$$

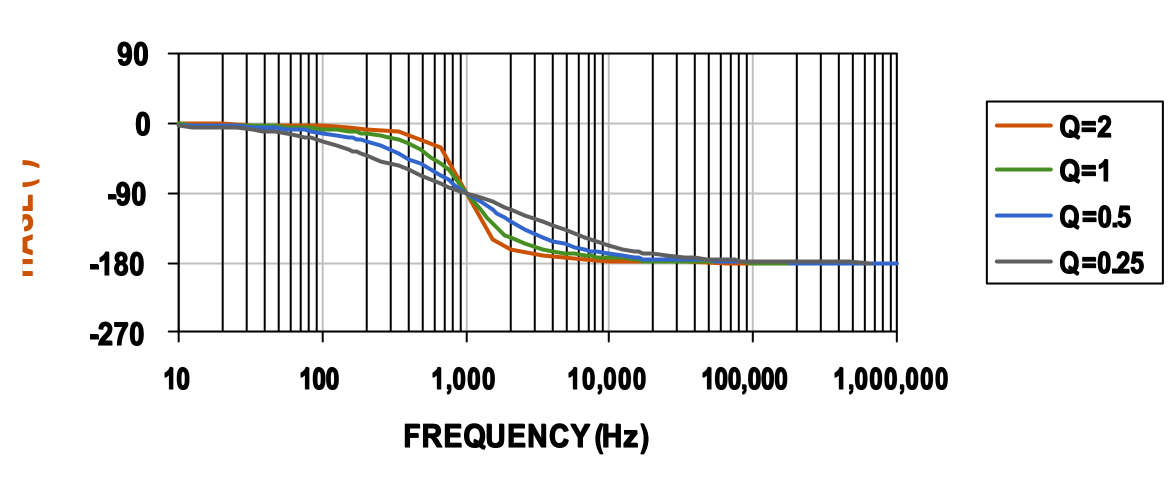




共轭复极点

$$H(s) = \frac{1}{1 + \frac{s}{Q_O \cdot \omega_O} + \frac{s^2}{\omega_O^2}}$$





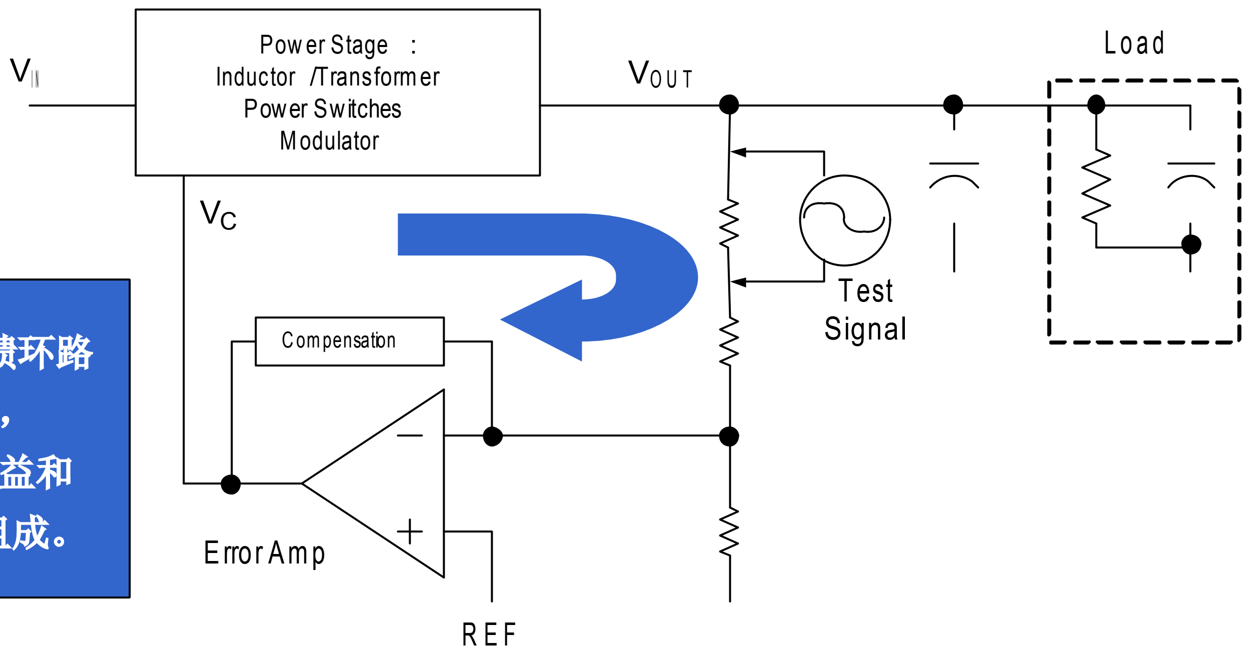
控制环路基础知识

环路补偿介绍

理想的控制环路

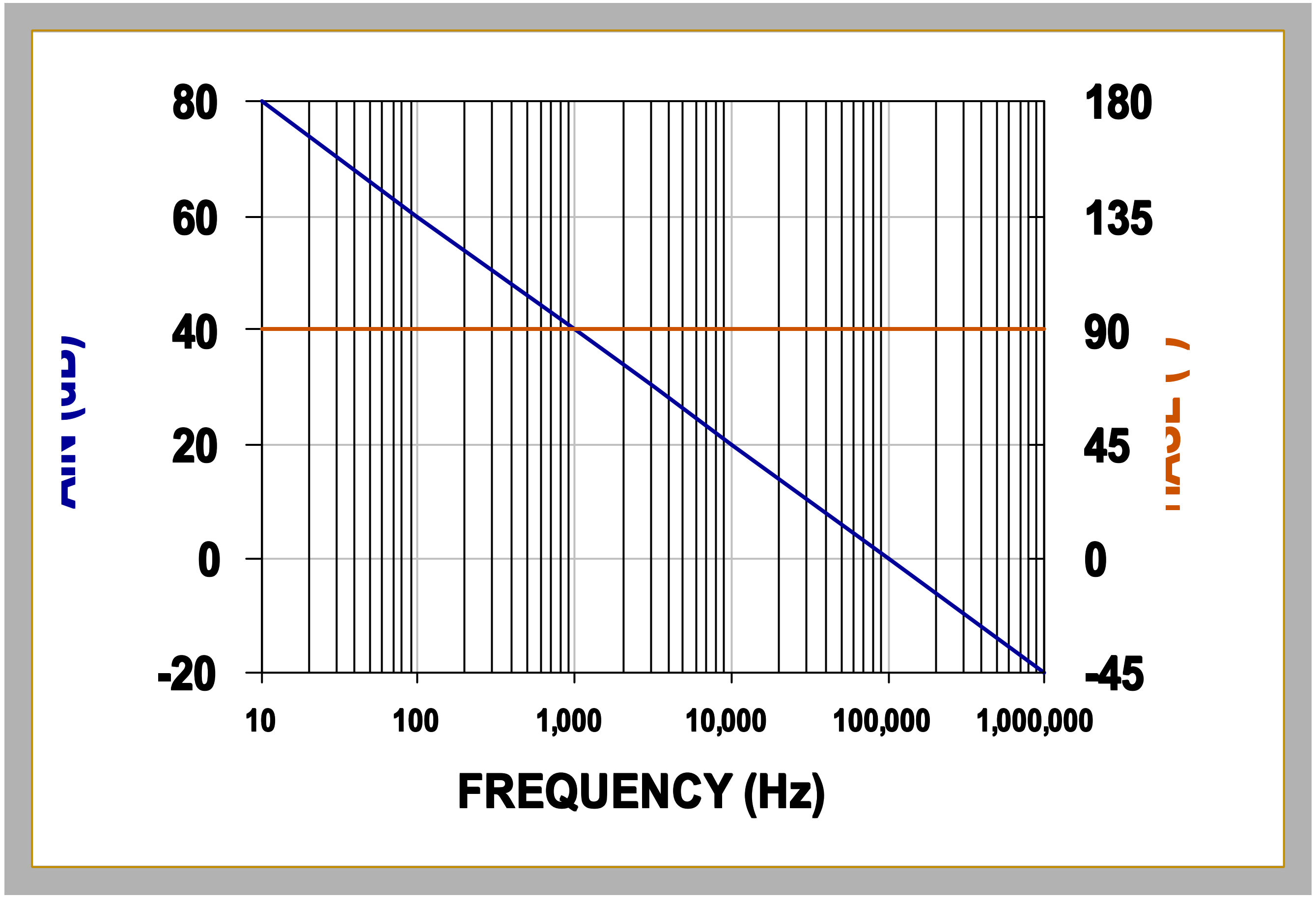
实用的反馈理论

环路补偿介绍



环路增益是以反馈环路为中心的增益，由误差放大器增益和功率级增益部分组成。

理想的控制环路


80
60
40
20
0
-20
180
135
90
45
0
-45
10
100
1,000
10,000
100,000
1,000,000
FREQUENCY (Hz)

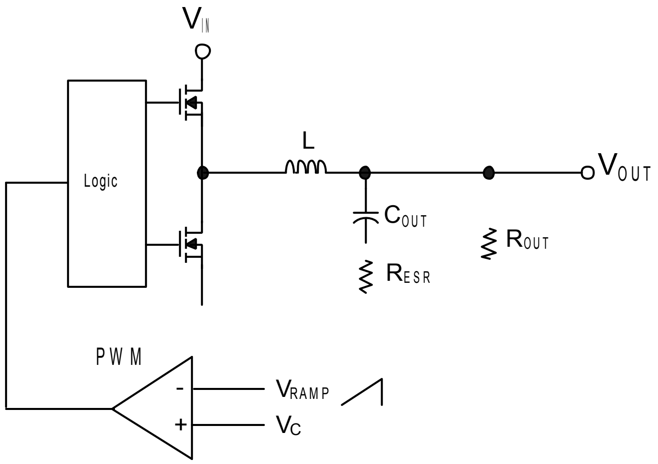
实用的反馈理论

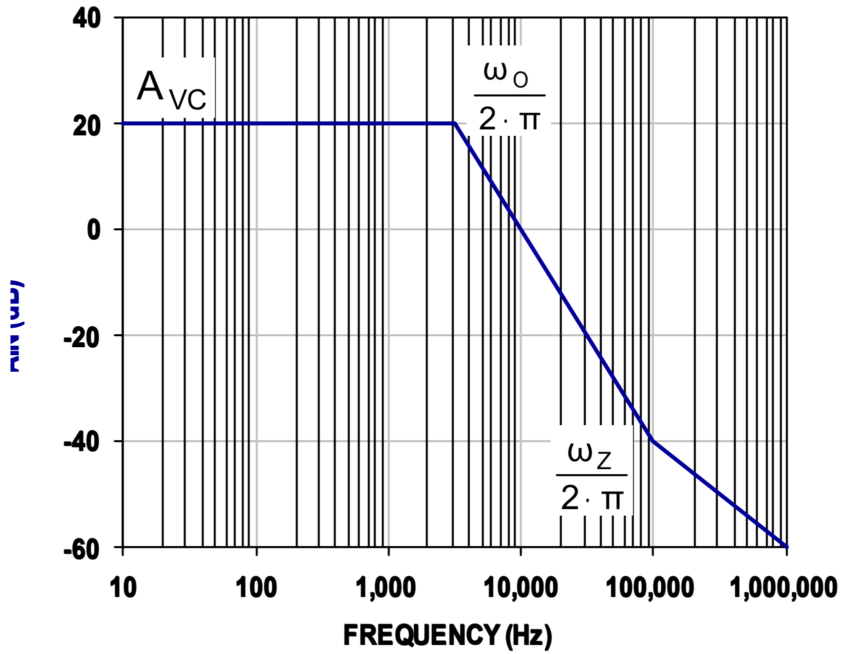
交越频率	相位裕量
• 控制环路的带宽决定了环路对于某种瞬态状况的响应速度 • 通常都会优先选择较高的交越频率，但存在着实际的限制。经验法则是将其设定为开关频率的 1/5 至 1/10 • 0°（增益裕量）时的衰减以及开关频率下的衰减也是很重要的	• 需要充足的相位裕量以避免发生振荡 • 最佳的相位裕量是 52° • 低相位裕量将导致欠阻尼的系统响应 • 较高的相位裕量则导致过阻尼的系统响应

功率级回顾

- 电压模式降压
- 电流模式降压
- 电流模式升压
- 电流模式降压-升压

电压模式降压功率级



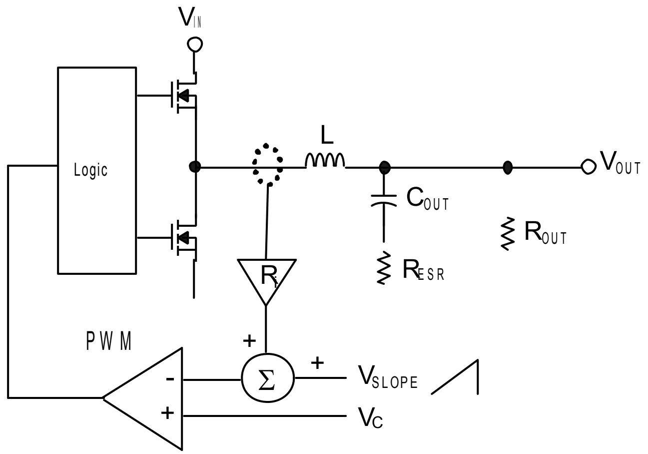


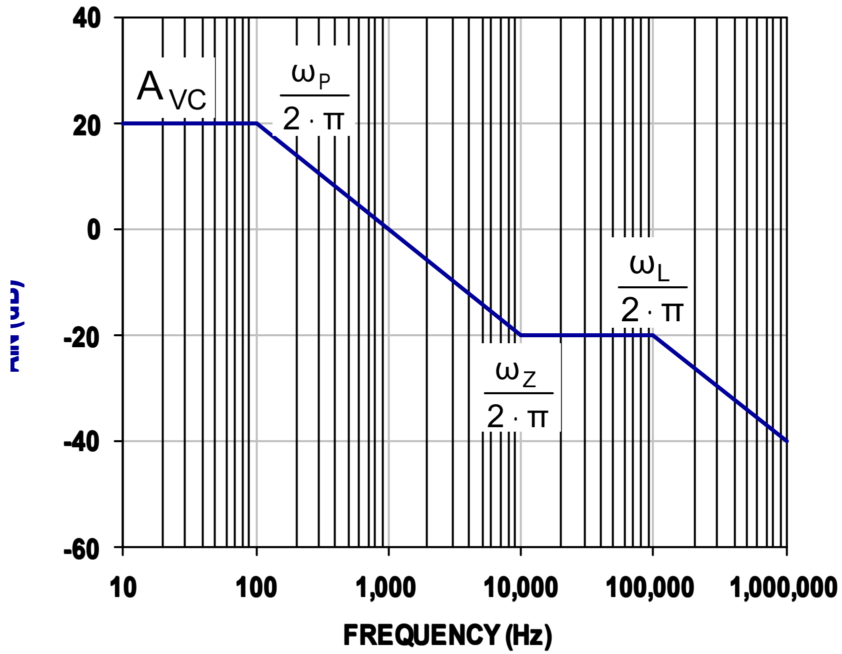
$$A_{VC} = \frac{V_{IN}}{V_{RAMP}} \qquad \omega_O = \frac{1}{\sqrt{L \cdot C_{OUT}}}$$

$$Q_O = \frac{R_{OUT}}{\sqrt{L / C_{OUT}}} \qquad \omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} = A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{1 + \frac{s}{Q_O \cdot \omega_O} + \frac{s^2}{\omega_O^2}}$$

电流模式降压功率级





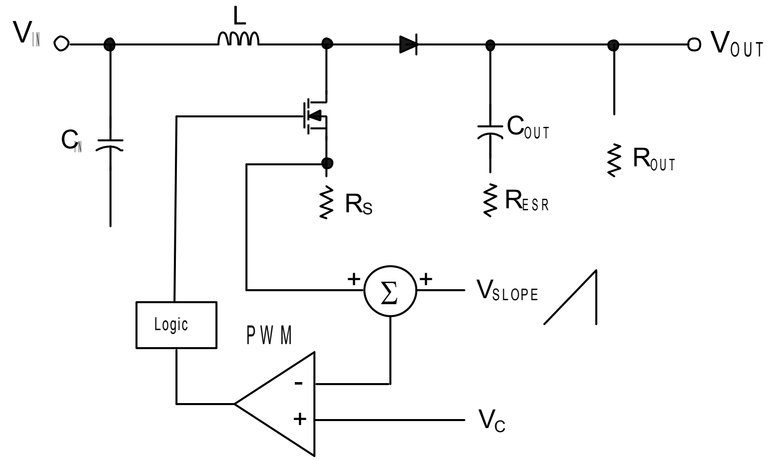
$$A_{VC} \approx \frac{R_{OUT}}{R_i}$$

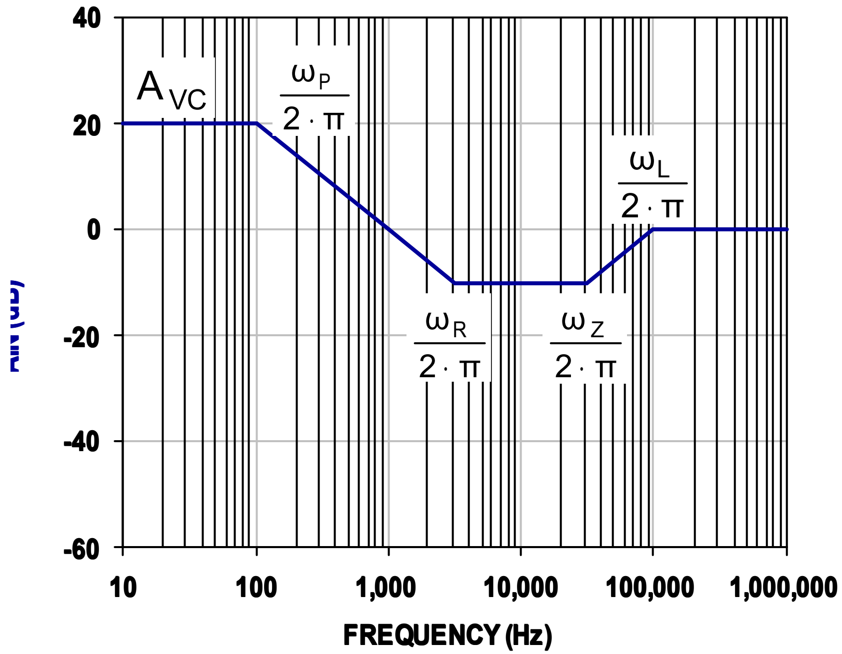
$$\omega_P \approx \frac{1}{C_{OUT} \cdot R_{OUT}} \qquad K_m \approx \frac{V_{IN}}{V_{SLOPE}}$$

$$\omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}} \qquad \omega_L = \frac{K_m \cdot R_i}{L}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{\left(1 + \frac{s}{\omega_P}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$

电流模式升压功率级





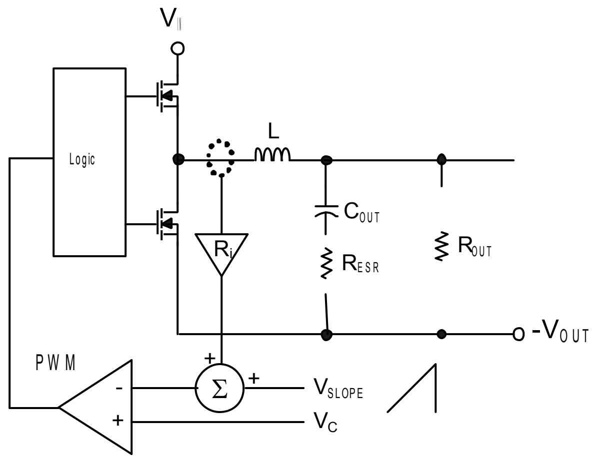
$$A_{VC} \approx \frac{R_{OUT}\cdot D'}{2\cdot R_i} \qquad \omega_R = \frac{R_{OUT}\cdot D'^2}{L}$$

$$\omega_P \approx \frac{2}{C_{OUT}\cdot R_{OUT}} \qquad K_m \approx \frac{V_{OUT}}{V_{SLOPE}}$$

$$\omega_Z = \frac{1}{R_{ESR}\cdot C_{OUT}} \qquad \omega_L = \frac{K_m\cdot R_i}{L}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC}\cdot\frac{\left(1-\frac{s}{\omega_R}\right)\cdot\left(1+\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{\omega_P}\right)\cdot\left(1+\frac{s}{\omega_L}\right)}$$

电流模式降压-升压功率级



$$A_{VC} \approx \frac{R_{OUT} \cdot D'}{(1+D) \cdot R_i}$$

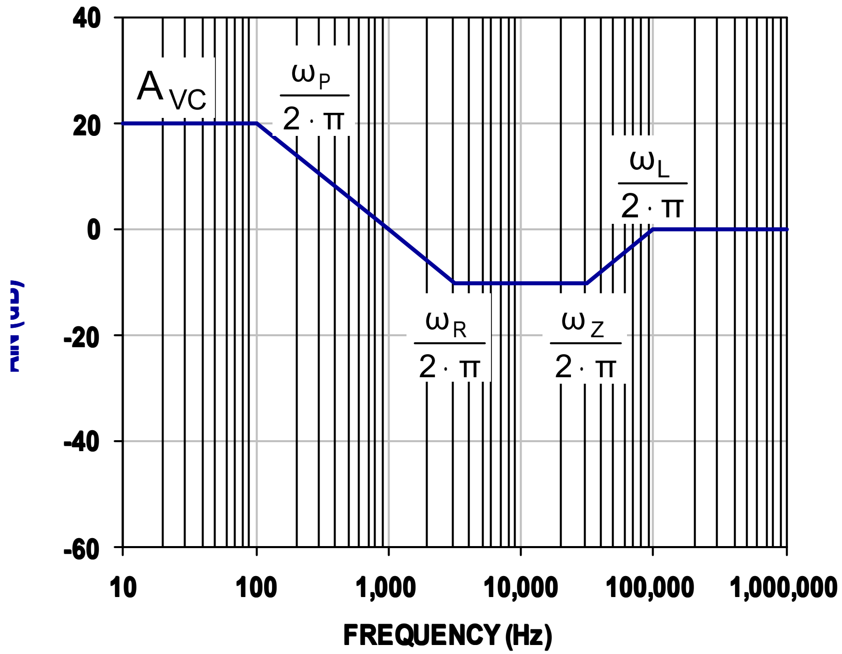
$$\omega_R = \frac{R_{OUT} \cdot D'^2}{L \cdot D}$$

$$\omega_P \approx \frac{1+D}{C_{OUT} \cdot R_{OUT}}$$

$$K_m \approx \frac{V_{IN} + V_{OUT}}{V_{SLOPE}}$$

$$\omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\omega_L = \frac{K_m \cdot R_i}{L}$$



$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{\left(1-\frac{s}{\omega_R}\right)\cdot\left(1+\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{\omega_P}\right)\cdot\left(1+\frac{s}{\omega_L}\right)}$$

误差放大器回顾

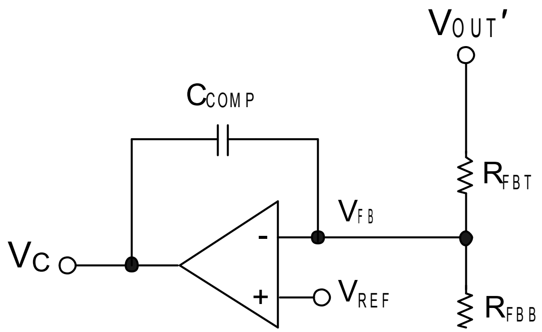
Type I 误差放大器

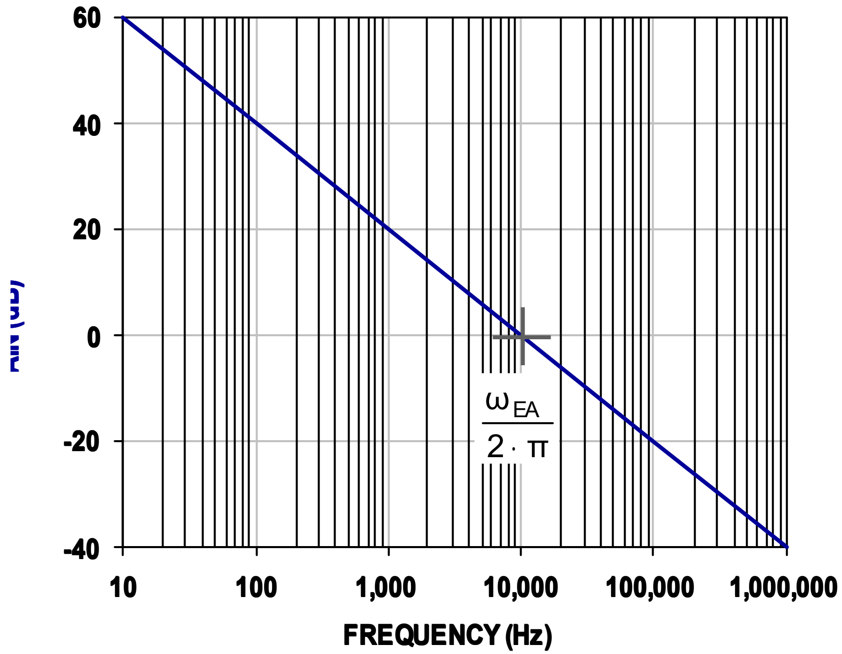
Type II 误差放大器

Type II 跨导放大器

Type III 误差放大器

Type I 误差放大器

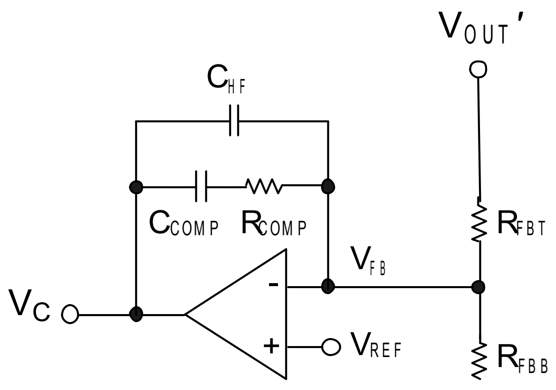


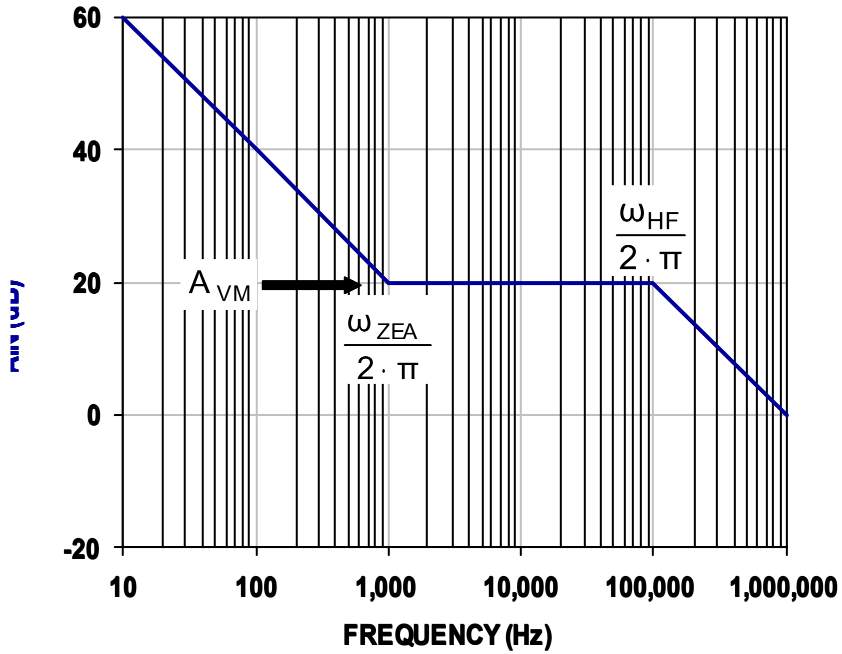


$$\omega_{EA} = \frac{1}{R_{FBT}\cdot C_{COMP}}$$

$$\frac{\hat{v}_C}{\hat{v}_{OUT}'} \approx -\frac{\omega_{EA}}{s}$$

Type II 误差放大器





$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}}$$

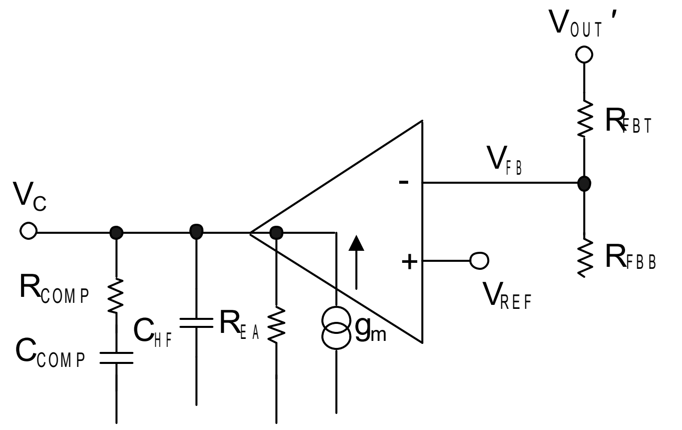
$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}}$$

$$\omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

假设：$C_{COMP} >> C_{HF}$

$$\frac{\hat{v}_C}{\hat{v}_{OUT}'} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}$$

Type II 跨导放大器

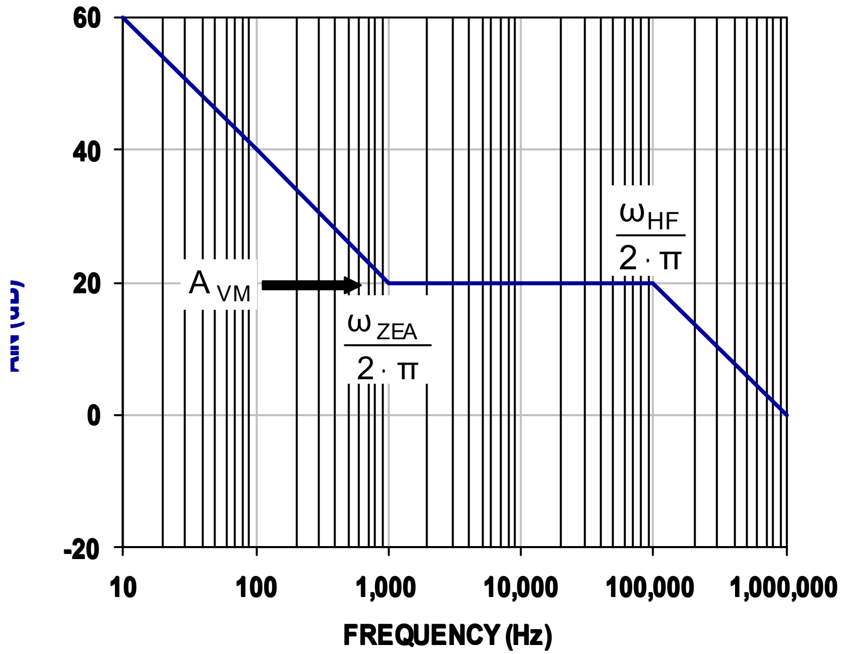


$$A_{VM} = K_{FB} \cdot g_m \cdot R_{COMP}$$

$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \qquad K_{FB} = \frac{R_{FBB}}{R_{FBB} + R_{FBT}}$$

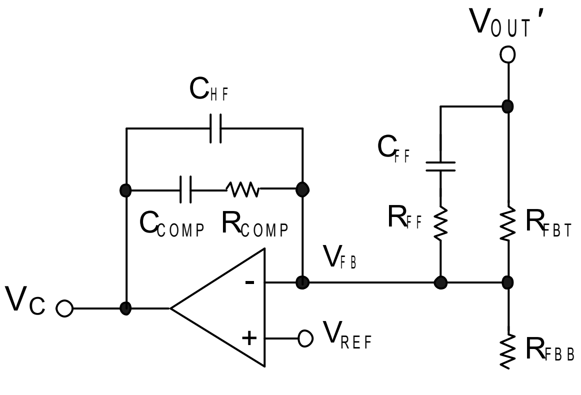
$$\omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}} \qquad A_{OL} = g_m \cdot R_{EA}$$

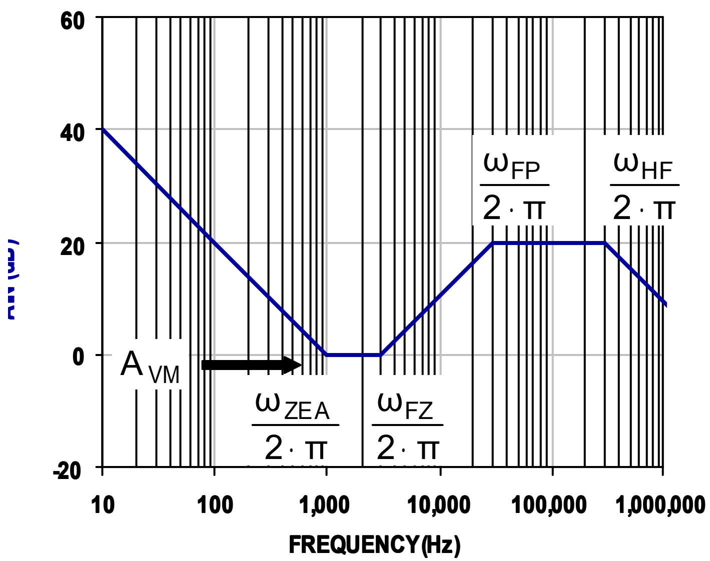
假设：$C_{COMP} >> C_{HF}$ & $R_{EA} >> R_{COMP}$



$$\frac{\hat{v}_C}{\hat{v}_{OUT}'} \approx -A_{VM} \cdot \frac{1 + \frac{\omega_{ZEA}}{s}}{1 + \frac{s}{\omega_{HF}}}$$

Type III 误差放大器





$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}}$$

$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \qquad \omega_{FZ} \approx \frac{1}{R_{FBT} \cdot C_{FF}}$$

$$\omega_{FP} = \frac{1}{R_{FF} \cdot C_{FF}} \qquad \omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

假设：$C_{COMP} >> C_{HF}$ & $R_{FBT} >> R_{FF}$

$$\frac{\hat{v}_C}{\hat{v}_{OUT}'} = -A_{VM} \cdot \frac{\left(1+\frac{\omega_{ZEA}}{s}\right) \cdot \left(1+\frac{s}{\omega_{FZ}}\right)}{\left(1+\frac{s}{\omega_{FP}}\right) \cdot \left(1+\frac{s}{\omega_{HF}}\right)}$$

开关稳压器补偿

电流模式降压 – **Type II** 补偿

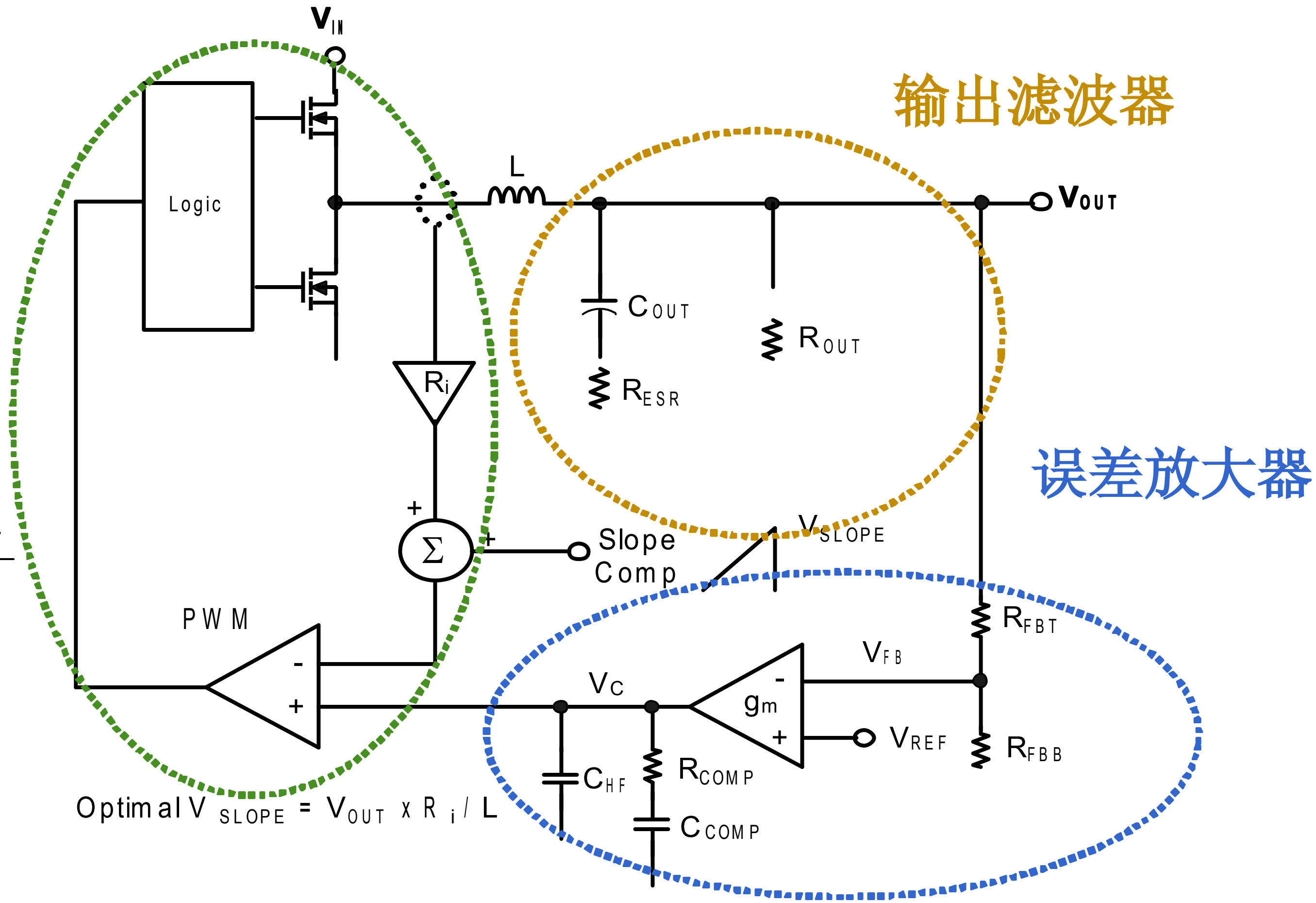
电流模式升压 – **Type II** 补偿

电流模式降压-升压 – **Type II** 补偿

电压模式降压 – **Type II** 补偿

电压模式降压 – **Type III** 补偿

电流模式降压模型



$$D = \frac{V_{OUT}}{V_{IN}}$$

$$D' = \frac{V_{IN} - V_{OUT}}{V_{IN}}$$

Optimal $V_{SLOPE} = V_{OUT} \times R_i / L$

电流模式降压 – **Type II** 补偿

- 选择一个大的 R_{FBT} 阻值，介于 2 kΩ 和 200 kΩ 之间
- 找出调制器跨导（单位： A/V）
- 选择一个目标带宽，通常为 $F_{SW}/10$
- 设定中频段增益 A_{VM} 以实现目标带宽： $\omega_C = 2\cdot\pi\cdot F_C$
- 设定 ω_{ZEA} = 1/10 目标交越频率： $\omega_{ZEA} = \omega_C/10$
- 设定 ω_{HF} = ESR 零点频率： $\omega_{HF} = \omega_Z$

$$G_m(\text{mod}) = \frac{1}{R_i} \qquad A_{VM} = \frac{\omega_C \cdot C_O}{G_m(\text{mod})}$$

$$R_{COMP} = A_{VM} \cdot R_{FBT}$$

或：

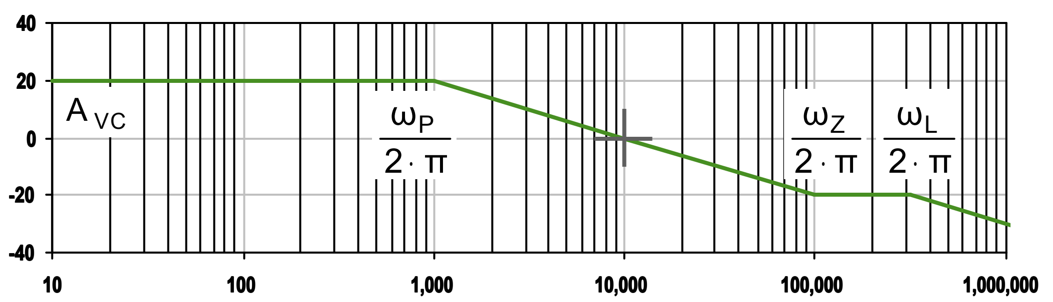
$$R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}}$$

$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}} \qquad C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}$$

电流模式降压控制环路

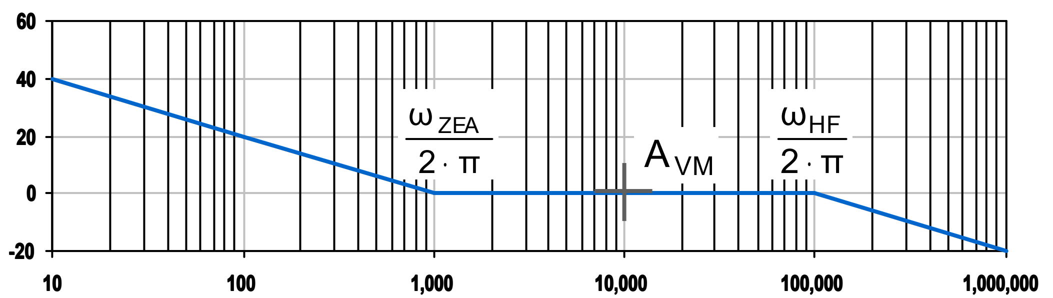
功率级

$$\frac{\hat{v}_{OUT}}{\hat{v}_{C}} \approx A_{VC} \cdot \frac{1+\frac{s}{\omega_Z}}{\left(1+\frac{s}{\omega_P}\right)\cdot\left(1+\frac{s}{\omega_L}\right)}$$



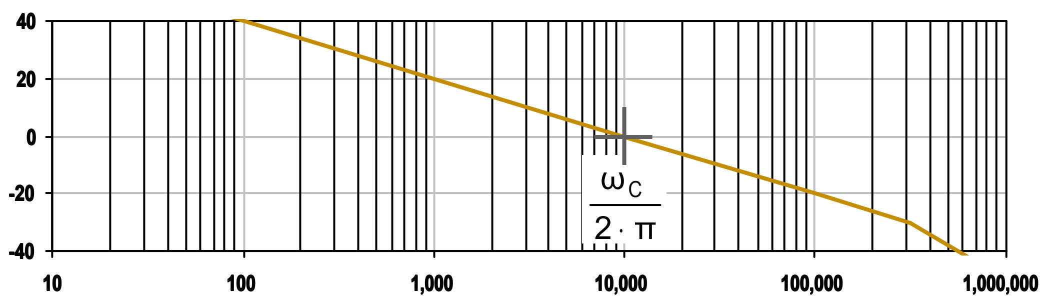
误差放大器

$$\frac{\hat{v}_{C}}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{1+\frac{\omega_{ZEA}}{s}}{1+\frac{s}{\omega_{HF}}}$$

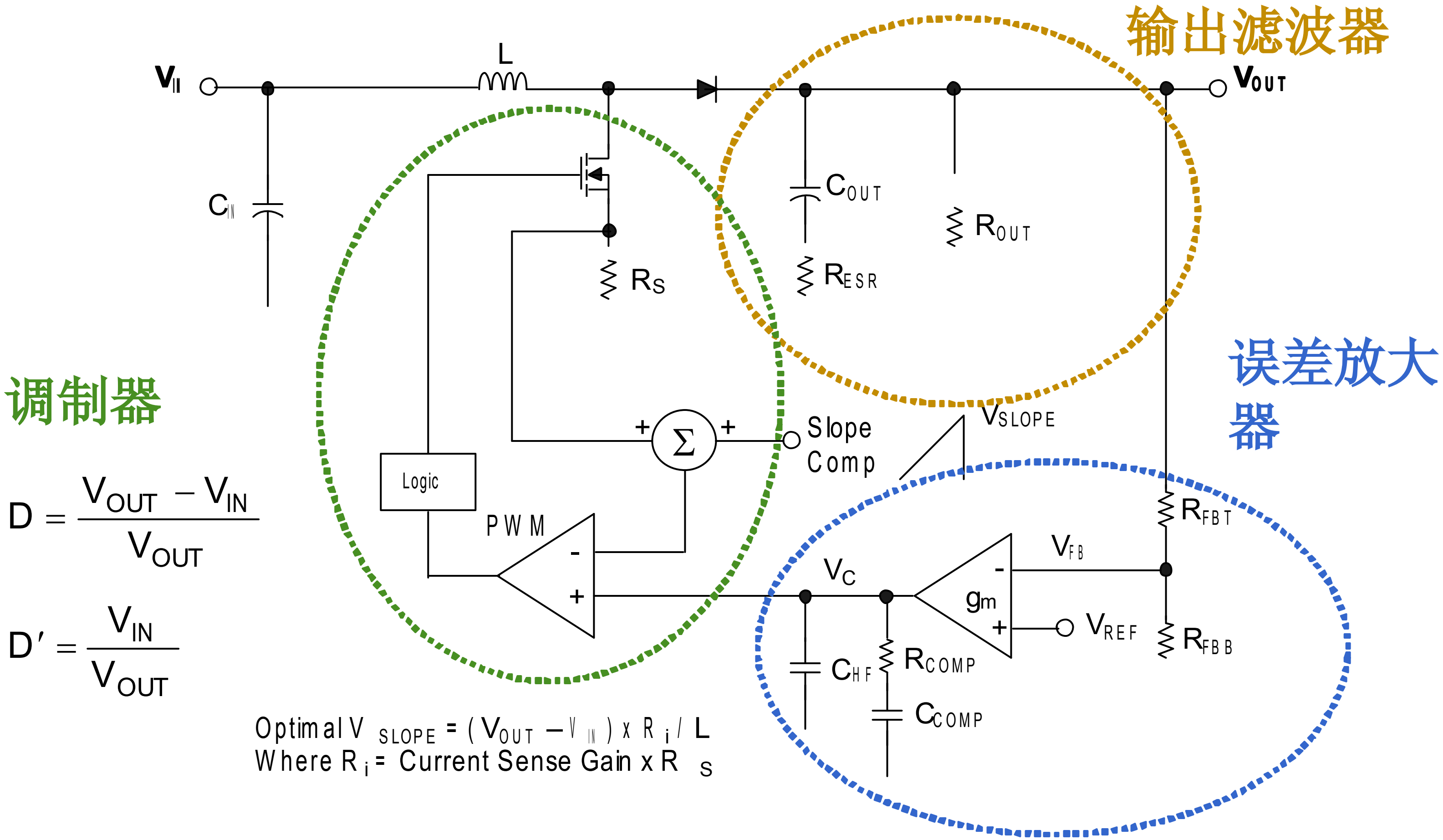


控制环路

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_{C}} \cdot \frac{\hat{v}_{C}}{\hat{v}'_{OUT}}$$



电流模式升压模型



$$D = \frac{V_{OUT} - V_{IN}}{V_{OUT}}$$

$$D' = \frac{V_{IN}}{V_{OUT}}$$

Optimal $V_{SLOPE} = (V_{OUT} - V_{IN}) \times R_i / L$
Where R_i = Current Sense Gain x R_S

电流模式升压 – Type II 补偿

- 选择一个大的 R_{FBT} 阻值，介于 2 kΩ 和 200 kΩ 之间
- 找出调制器跨导（单位：A/V）
- 找出最小输入电压和最大负载电流条件下的 RHPZ 频率
- 将目标带宽设定为 RHPZ 频率的 ¼：$\omega_C = \omega_R/4$
- 设定中频段增益 A_{VM} 以实现目标带宽：$\omega_C = 2 \cdot \pi \cdot F_C$
- 设定 ω_{ZEA} = 1/10 的目标交越频率：$\omega_{ZEA} = \omega_C/10$
- 设定 ω_{HF} = RHP 或 ESR 零点频率当中较低的那个：$\omega_{HF} = \omega_R$ 或 ω_Z

$$G_m(\text{mod}) = \frac{D'}{R_i} \qquad \omega_R = \frac{R_{OUT} \cdot D'^2}{L} \qquad A_{VM} = \frac{\omega_C \cdot C_O}{G_m(\text{mod})}$$

$$R_{COMP} = A_{VM} \cdot R_{FBT}$$

或：

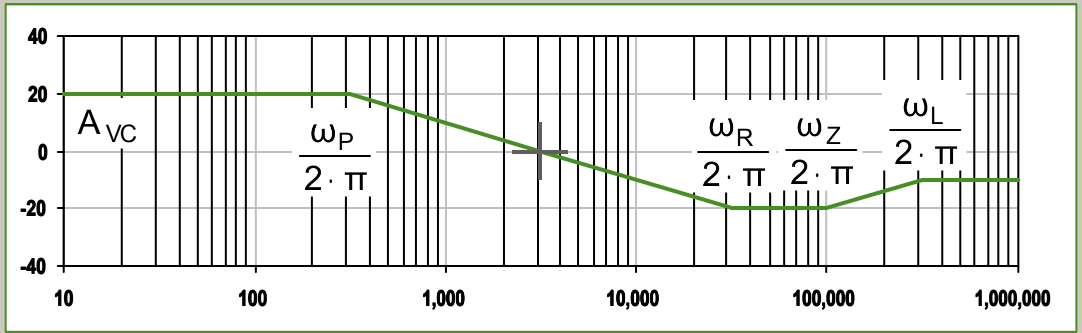
$$R_{COMP} = \frac{A_{VM}}{g_m \cdot K_{FB}}$$

$$C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}} \qquad C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}$$

电流模式升压控制环路

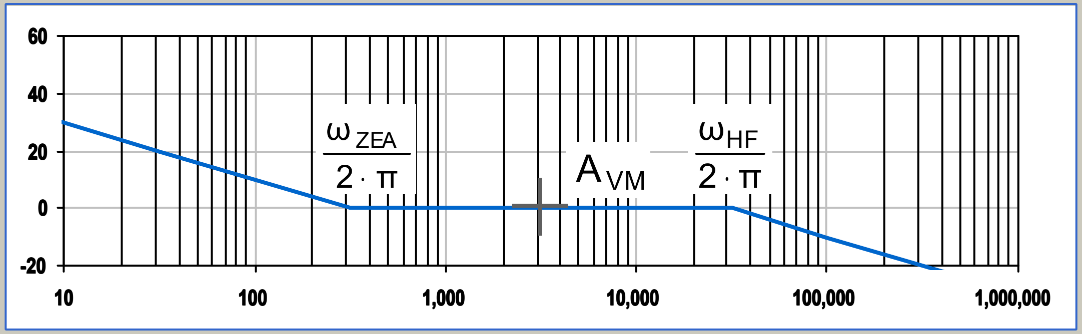
功率级

$$\frac{\hat{v}_{OUT}}{\hat{v}_{C}} \approx A_{VC} \cdot \frac{\left(1-\frac{s}{\omega_R}\right)\cdot\left(1+\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{\omega_P}\right)\cdot\left(1+\frac{s}{\omega_L}\right)}$$



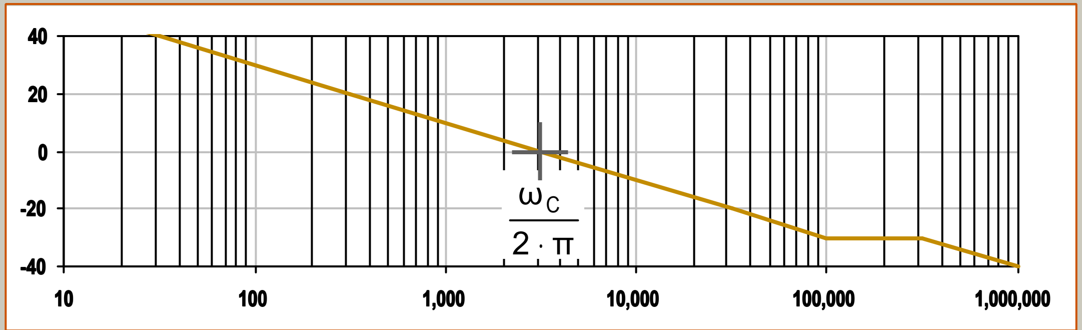
误差放大器

$$\frac{\hat{v}_{C}}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{1+\frac{\omega_{ZEA}}{s}}{1+\frac{s}{\omega_{HF}}}$$

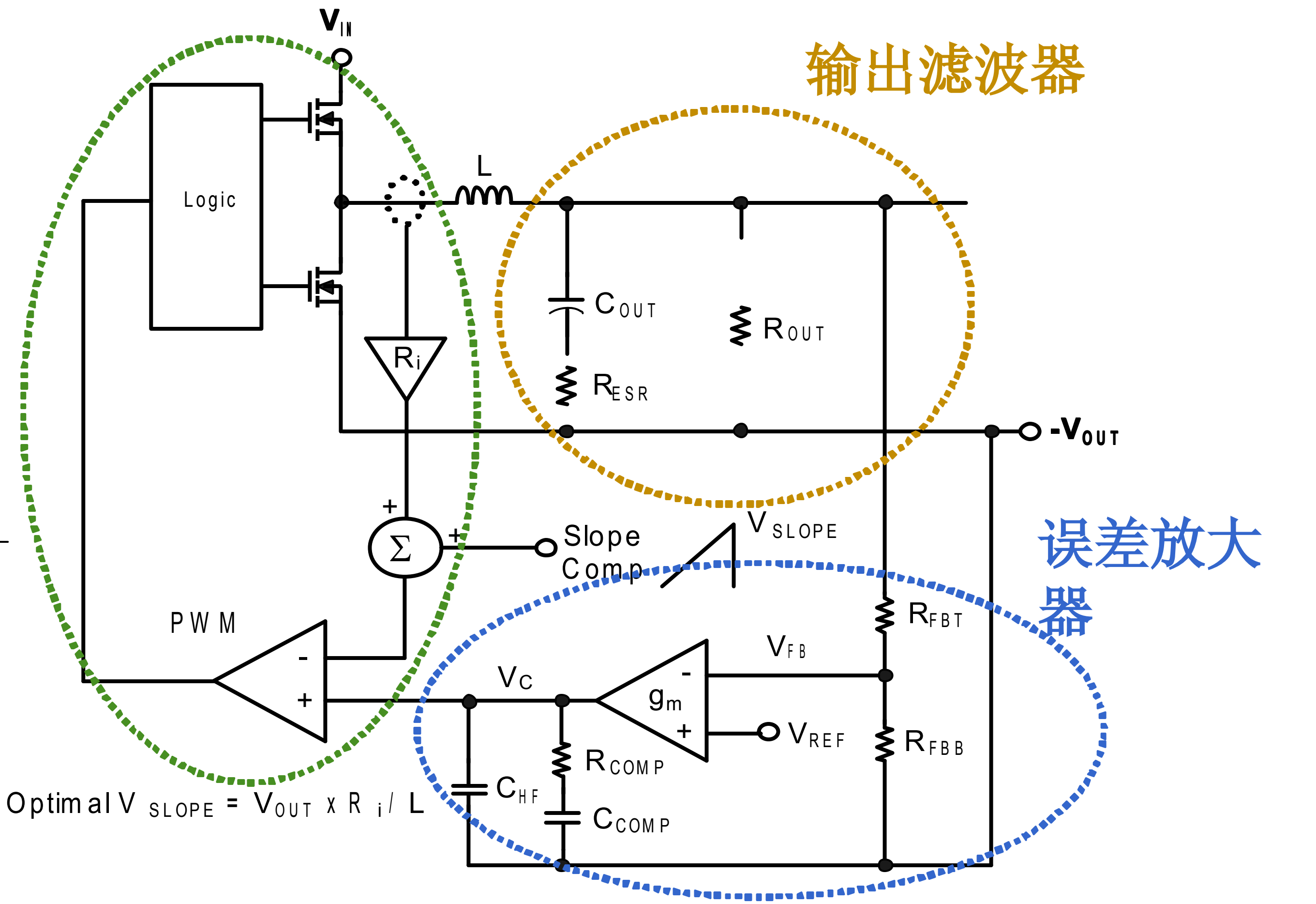


控制环路

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_{C}} \cdot \frac{\hat{v}_{C}}{\hat{v}'_{OUT}}$$



电流模式降压-升压模型



$$D = \frac{V_{OUT}}{V_{IN} + V_{OUT}}$$

$$D' = \frac{V_{IN}}{V_{IN} + V_{OUT}}$$

电流模式降压-升压 – Type II 补偿

- 选择一个大的 R_{FBT} 阻值，介于 2 kΩ 和 200 kΩ 之间
- 找出调制器跨导（单位：A/V）
- 找出最小输入电压和最大负载电流条件下的 RHPZ 频率
- 将目标带宽设定为 RHPZ 频率的 ¼： $\omega_C = \omega_R/4$
- 设定中频段增益 A_{VM} 以实现目标带宽： $\omega_C = 2\cdot\pi\cdot F_C$
- 设定 ω_{ZEA} = 1/10 的目标交越频率： $\omega_{ZEA} = \omega_C/10$
- 设定 ω_{HF} = RHP 或 ESR 零点频率当中较低的那个： $\omega_{HF} = \omega_R$ 或 ω_Z

$$G_m(\text{mod}) = \frac{D'}{R_i} \qquad \omega_R = \frac{R_{OUT}\cdot D'^2}{L\cdot D} \qquad A_{VM} = \frac{\omega_C\cdot C_O}{G_m(\text{mod})}$$

$$R_{COMP} = A_{VM}\cdot R_{FBT}$$

或：

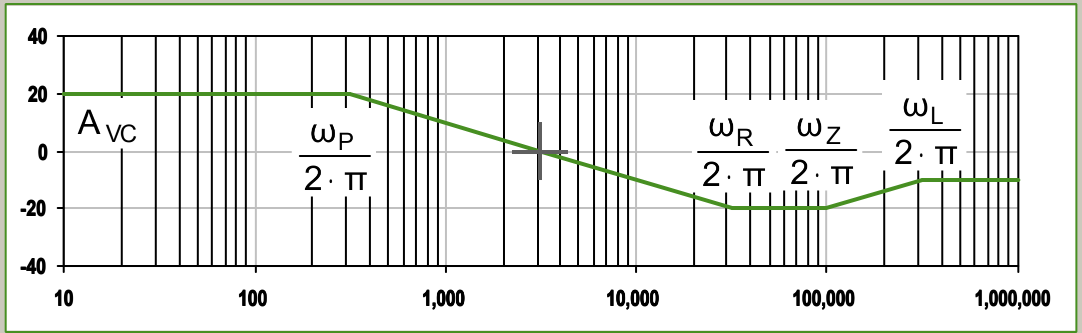
$$R_{COMP} = \frac{A_{VM}}{g_m\cdot K_{FB}}$$

$$C_{COMP} = \frac{1}{\omega_{ZEA}\cdot R_{COMP}} \qquad C_{HF} = \frac{1}{\omega_{HF}\cdot R_{COMP}}$$

电流模式降压-升压控制环路

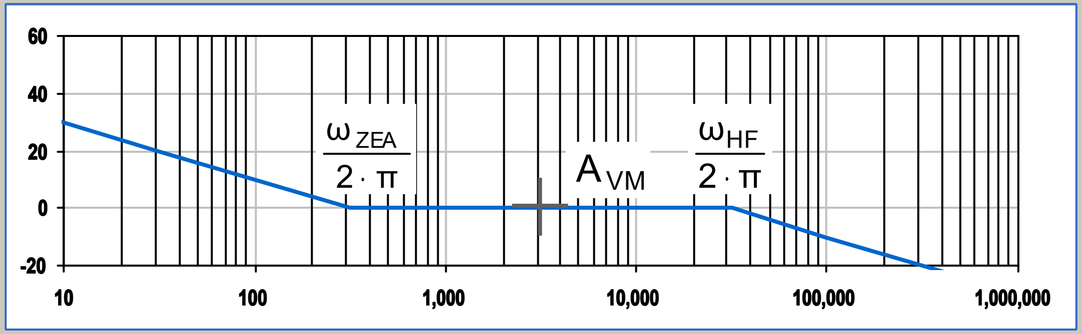
功率级

$$\frac{\hat{v}_{OUT}}{\hat{v}_{C}} \approx A_{VC}\cdot\frac{\left(1-\frac{s}{\omega_R}\right)\cdot\left(1+\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{\omega_P}\right)\cdot\left(1+\frac{s}{\omega_L}\right)}$$



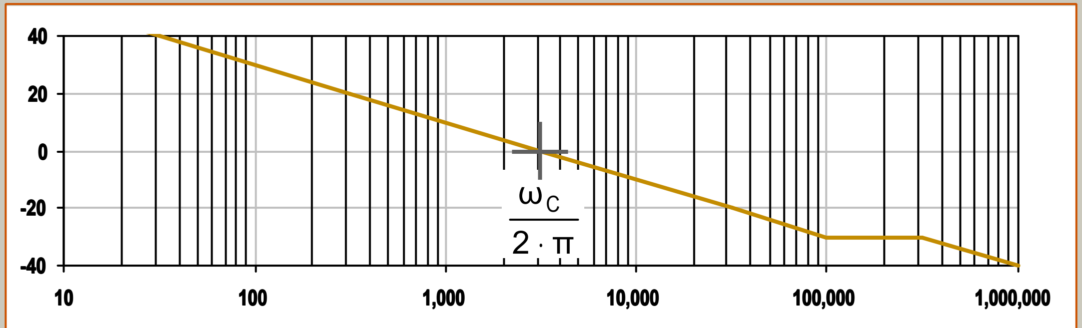
误差放大器

$$\frac{\hat{v}_{C}}{\hat{v}_{OUT}'} \approx -A_{VM}\cdot\frac{1+\frac{\omega_{ZEA}}{s}}{1+\frac{s}{\omega_{HF}}}$$

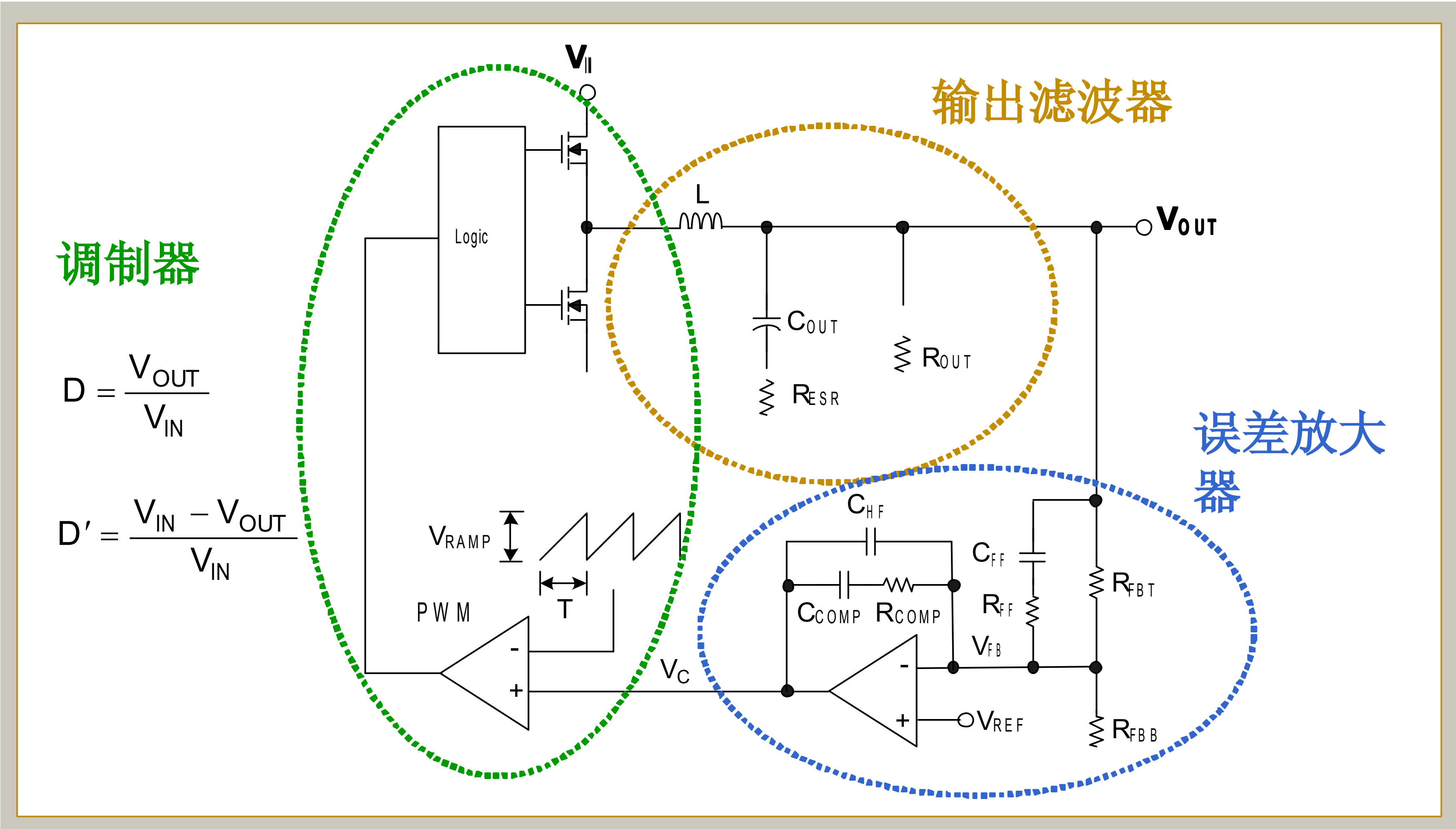


控制环路

$$\frac{\hat{v}_{OUT}}{\hat{v}_{OUT}'} = \frac{\hat{v}_{OUT}}{\hat{v}_{C}}\cdot\frac{\hat{v}_{C}}{\hat{v}_{OUT}'}$$



电压模式降压稳压器



调制器
$D = \frac{V_{OUT}}{V_{IN}}$
$D' = \frac{V_{IN} - V_{OUT}}{V_{IN}}$
Logic
V_{IN}
输出滤波器
L
V_{OUT}
C_{OUT}
R_{OUT}
R_{ESR}
误差放大器
V_{RAMP}
T
PWM
V_C
C_{HF}
C_{COMP}
R_{COMP}
C_{FF}
R_{FF}
V_{FB}
R_{FBT}
R_{FBB}
V_{REF}

电压模式降压 – **Type II** 补偿

- 与高 ESR 输出电容器配合使用
- 选择一个大的 R_{FBT} 阻值，介于 2 kΩ 和 200 kΩ 之间
- 设定中频段增益 A_{VM} 以获得期望的带宽
- 设定 ω_{ZEA} = 输出滤波器共轭复极点 ω_O
- 设定 $\omega_{HF} = ½$ 开关频率：$\omega_{HF} = 2 \cdot \pi \cdot F_{SW}/2$

$$R_{COMP} = A_{VM} \cdot R_{FBT} \qquad C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}} \qquad C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}$$

电压模式降压 – Type III 补偿

- 与低 ESR输出电容器配合使用
- 选择一个大的 R_{FBT} 阻值，介于 2 kΩ 和 200 kΩ 之间
- 设定中频段增益 A_{VM} 以实现目标带宽：$\omega_C = 2 \cdot \pi \cdot F_C$
- 设定 ω_{ZEA} 和 ω_{FZ} = 输出滤波器共轭复极点 ω_O
- 设定 ω_{FP} = 输出滤波器零点 ω_Z
- 设定 ω_{HF} = ½ 开关频率： $\omega_{HF} = 2 \cdot \pi \cdot F_{SW}/2$

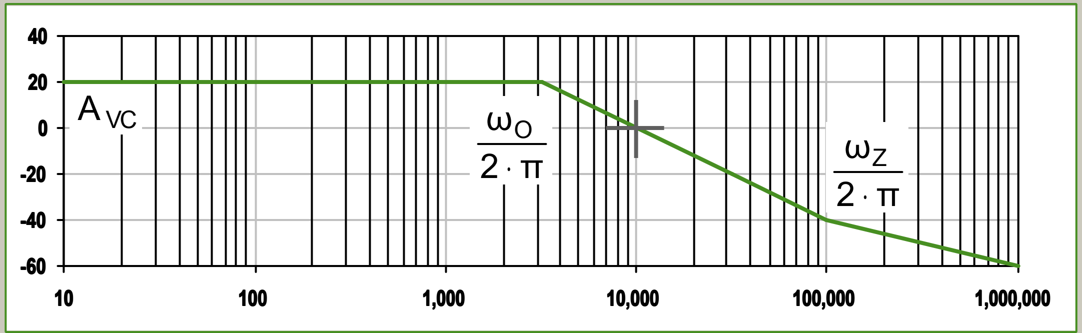
$$A_{VM} = \frac{\omega_C}{A_{VC} \cdot \omega_O} \qquad R_{COMP} = A_{VM} \cdot R_{FBT} \qquad C_{COMP} = \frac{1}{\omega_{ZEA} \cdot R_{COMP}}$$

$$C_{FF} = \frac{1}{\omega_{FZ} \cdot R_{FBT}} \qquad R_{FF} = \frac{1}{\omega_{FP} \cdot C_{FF}} \qquad C_{HF} = \frac{1}{\omega_{HF} \cdot R_{COMP}}$$

电压模式降压控制环路

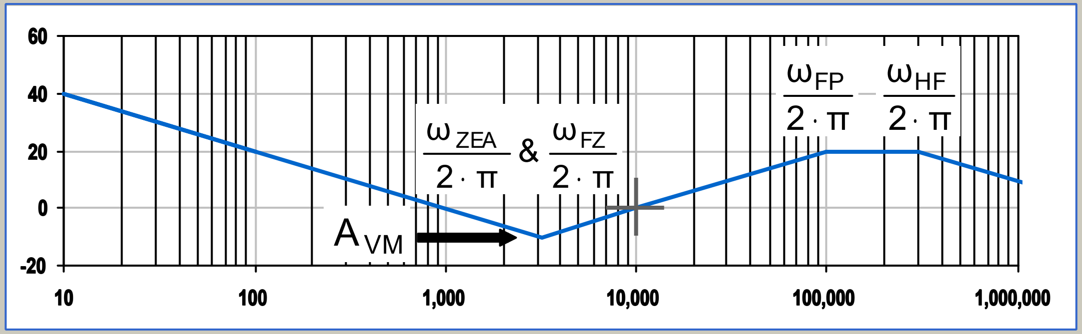
功率级

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1+\frac{s}{\omega_Z}}{1+\frac{s}{Q_O \cdot \omega_O}+\frac{s^2}{\omega_O{}^2}}$$



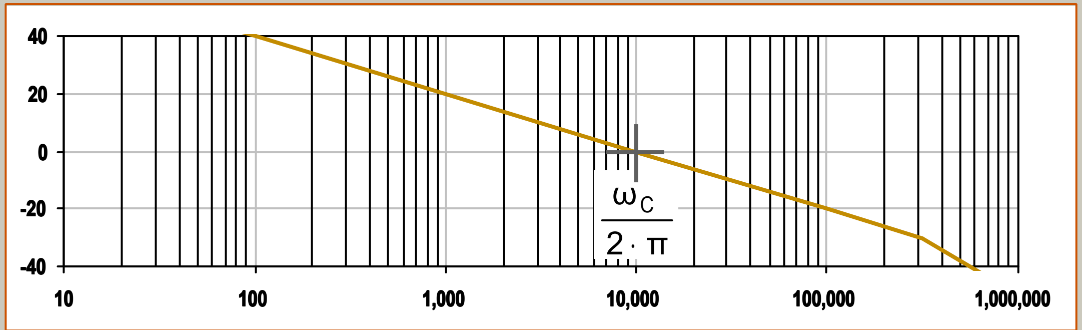
误差放大器

$$\frac{\hat{v}_C}{\hat{v}_{OUT}'} \approx -A_{VM} \cdot \frac{\left(1+\frac{\omega_{ZEA}}{s}\right)\cdot\left(1+\frac{s}{\omega_{FZ}}\right)}{\left(1+\frac{s}{\omega_{FP}}\right)\cdot\left(1+\frac{s}{\omega_{HF}}\right)}$$



控制环路

$$\frac{\hat{v}_{OUT}}{\hat{v}_{OUT}'} = \frac{\hat{v}_{OUT}}{\hat{v}_C} \cdot \frac{\hat{v}_C}{\hat{v}_{OUT}'}$$



误差放大器考虑因素

需要关注的是：

- 误差放大器必须驱动的阻抗
- 误差放大器的带宽
- 误差放大器的开环增益
- LC 滤波器的 Q 值

环路测量方法

测量选项

1: 瞬态响应测试

- 简单易行
- 无需专用设备

2: 伯德图

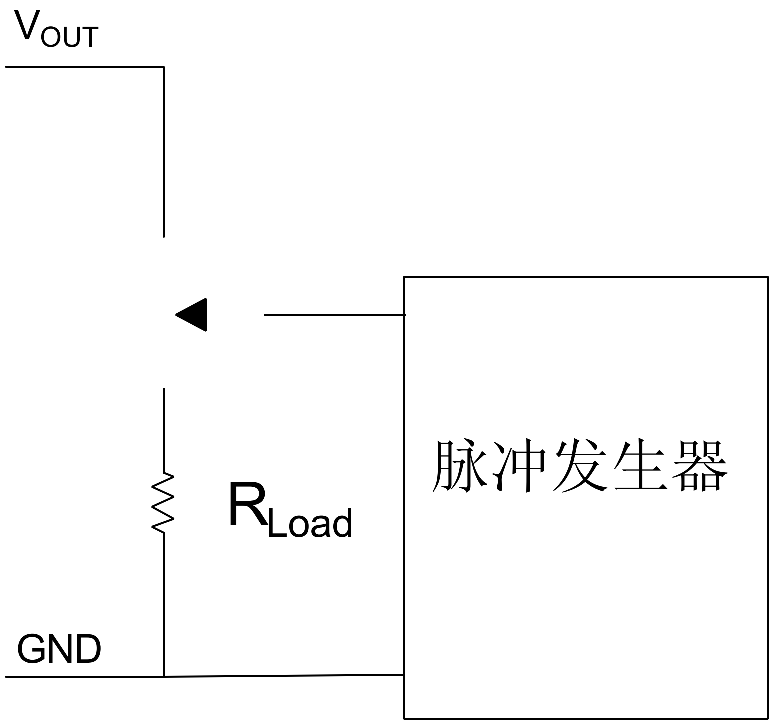
- 需要网络分析仪以获得完整的曲线图
- 可利用普通的测试设备获得关键性的数据点

负载阶跃分析

- 瞬态测试
- 负载阶跃实例
- 伯德图与瞬态

瞬态测试 – 负载阶跃

用于瞬态测试的简单电路

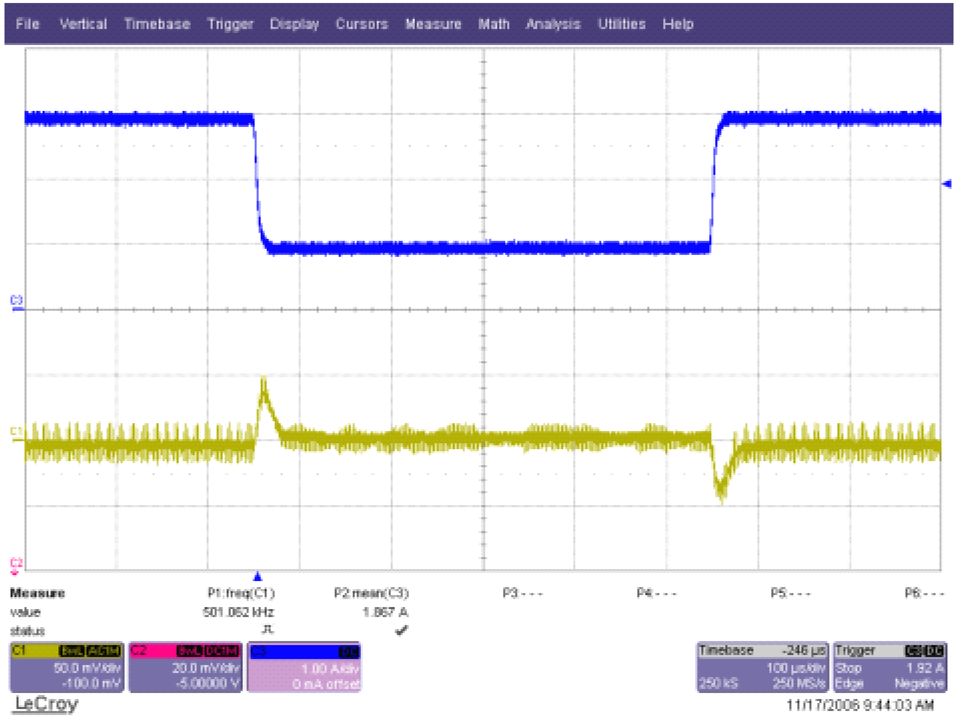


针对一个从 0V 至大约比 V_{OUT} 高 5V 的脉冲幅度及 100Hz 左右的频率来设置发生器。负载将跟随发生器的上升/下降时间。

增设用于设定最小负载的 DC 负载箱。V_{OUT}/R_{LOAD} 设定了 ΔI。

负载阶跃实例

典型的瞬态响应测试

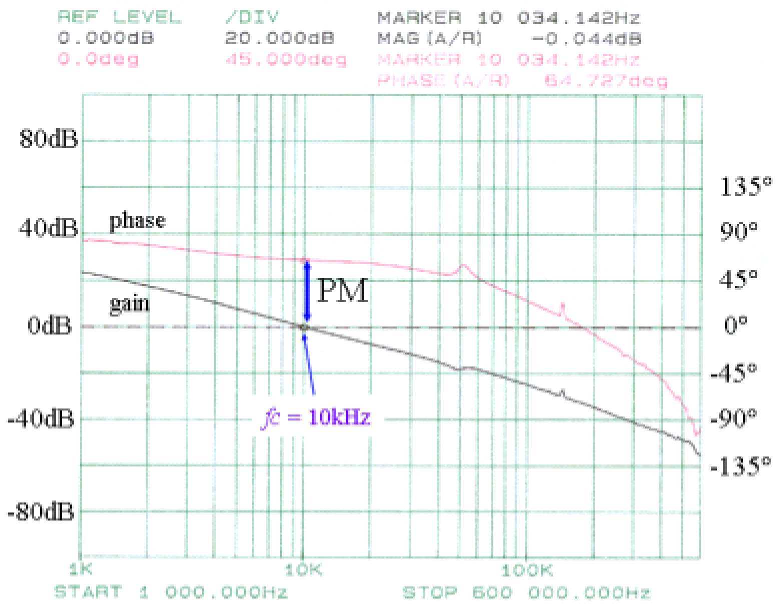
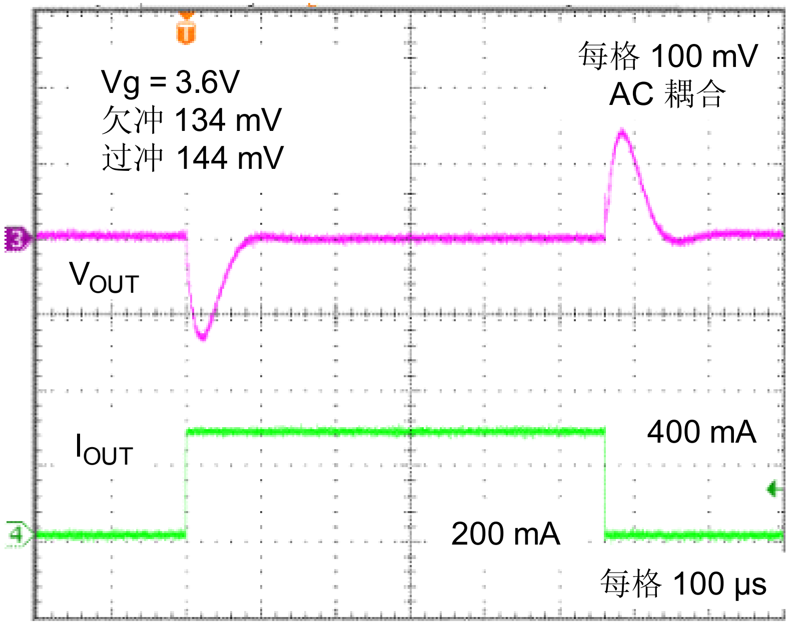


负载电流
每格 1A

输出电压
每格 50 mV

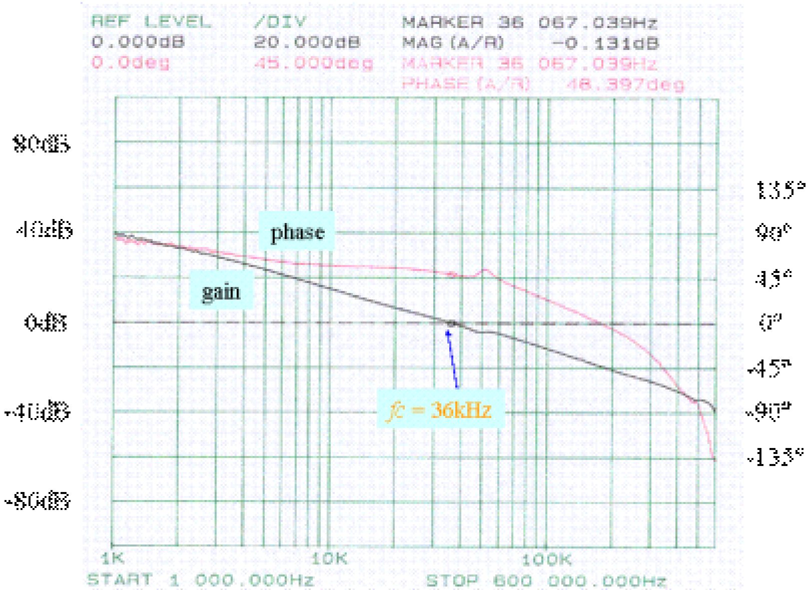
时标
每格 100 μ s

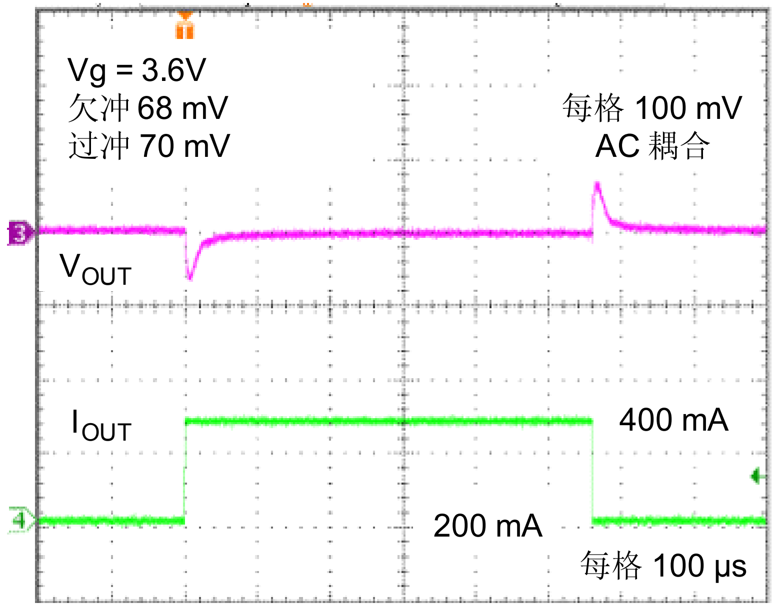
伯德图与瞬态响应对比案例一 – 稳定的稳压器

f_C = 10 kHz, PM = 65°	过阻尼
	

伯德图与瞬态响应对比案例二 – 稳定的稳压器

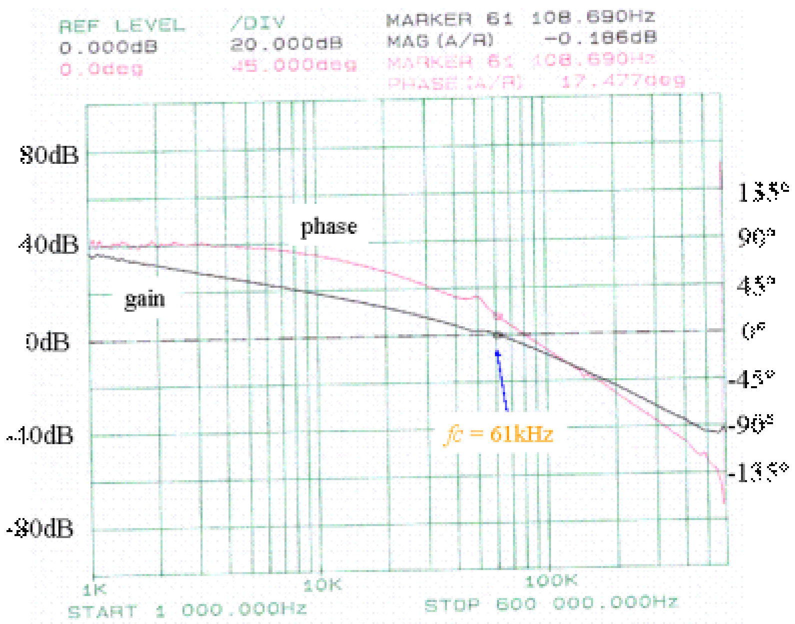
f_C = 36 kHz, PM = 48°	临界阻尼

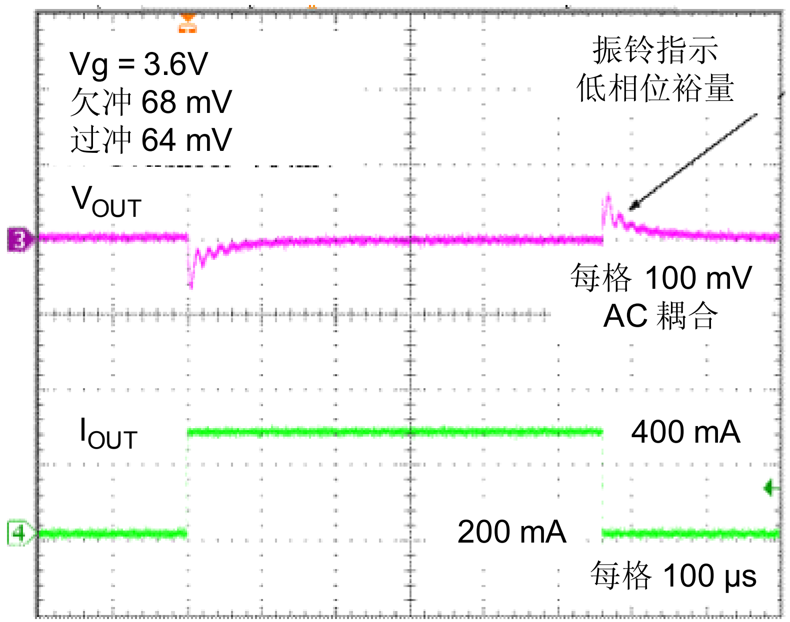




伯德图与瞬态响应对比案例三 – 边际稳定性

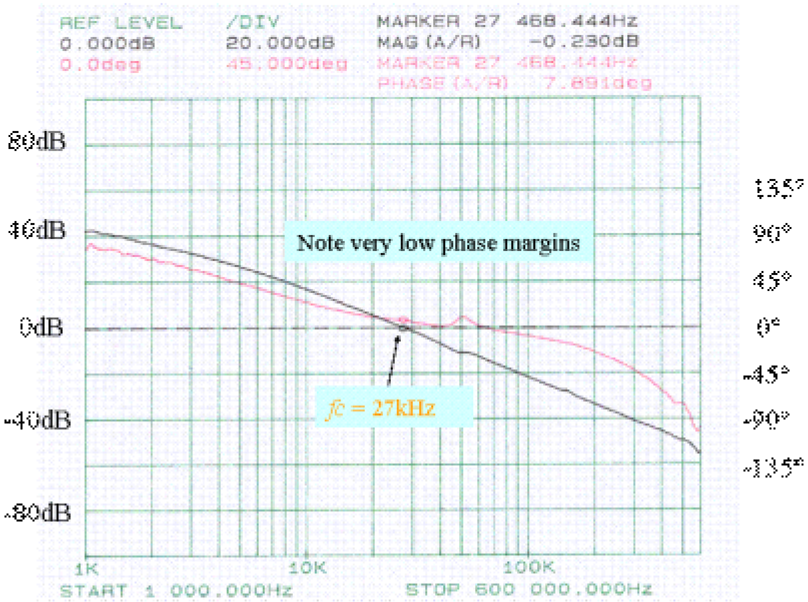
f_C = 61 kHz, PM = 17°	欠阻尼

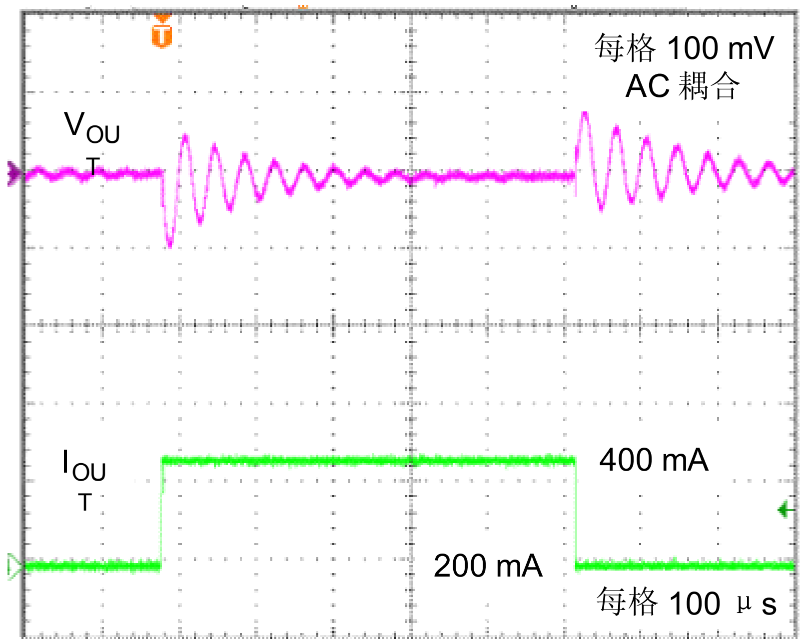




伯德图与瞬态响应对比案例四 – 不稳定的稳压器

f_C = 27 kHz, PM = 8°	不稳定的稳压器





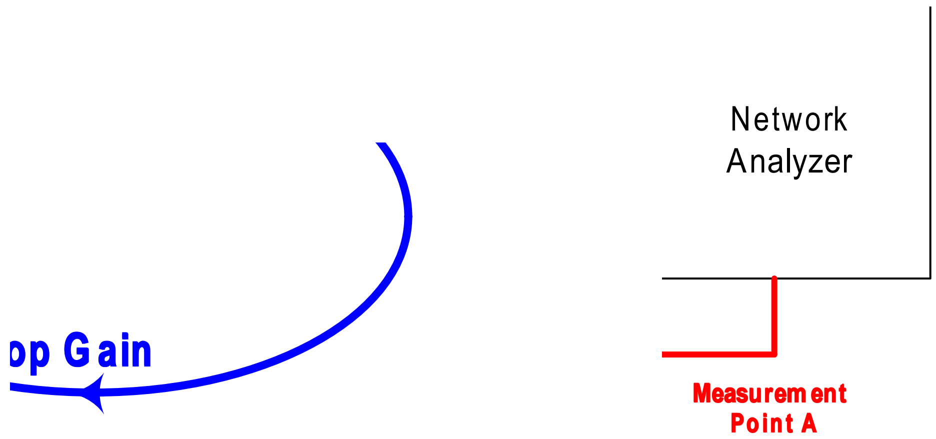
环路测量

网络分析仪测量

正弦波注入

穿越频率和相位裕量

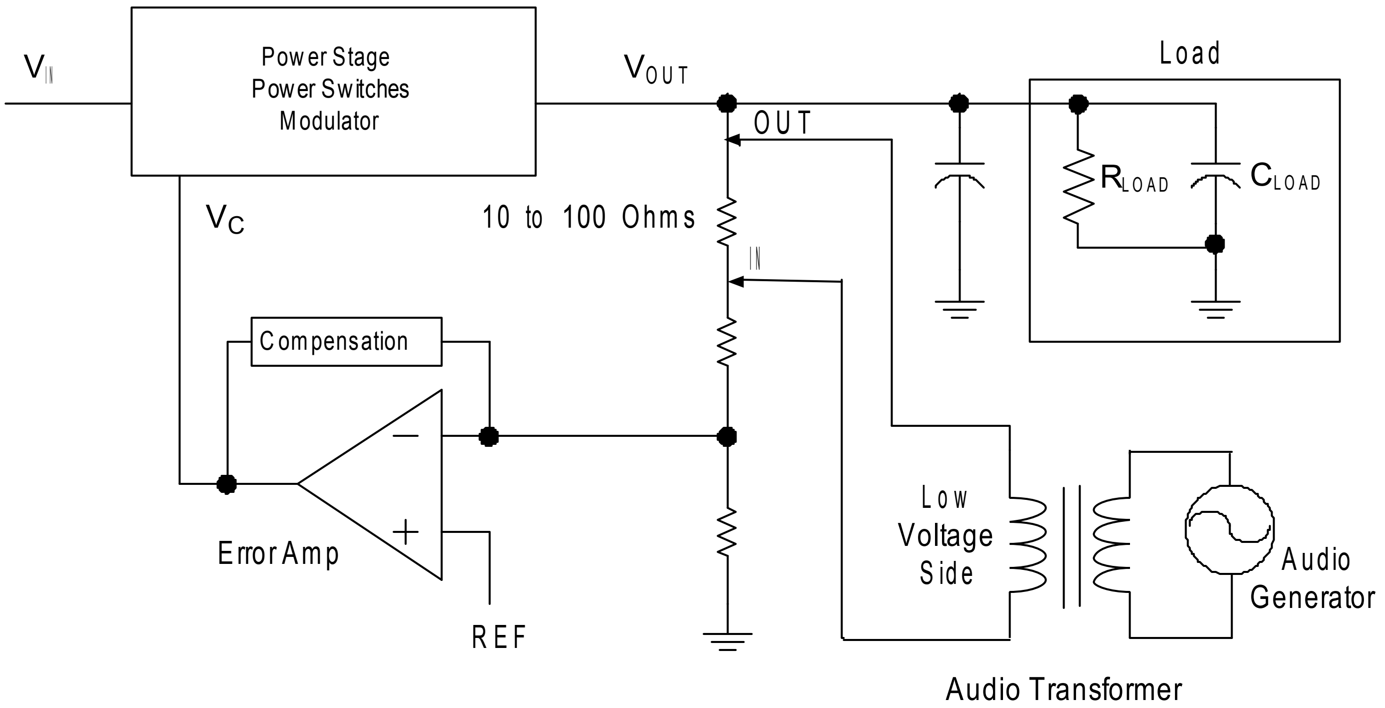
网络分析仪测量



$$\text{环路增益} = 20 \cdot \log_{10}\left(\frac{v(B)}{v(A)}\right)$$

$$\text{相位} = \text{phase}\left(\frac{v(B)}{v(A)}\right)$$

正弦波注入



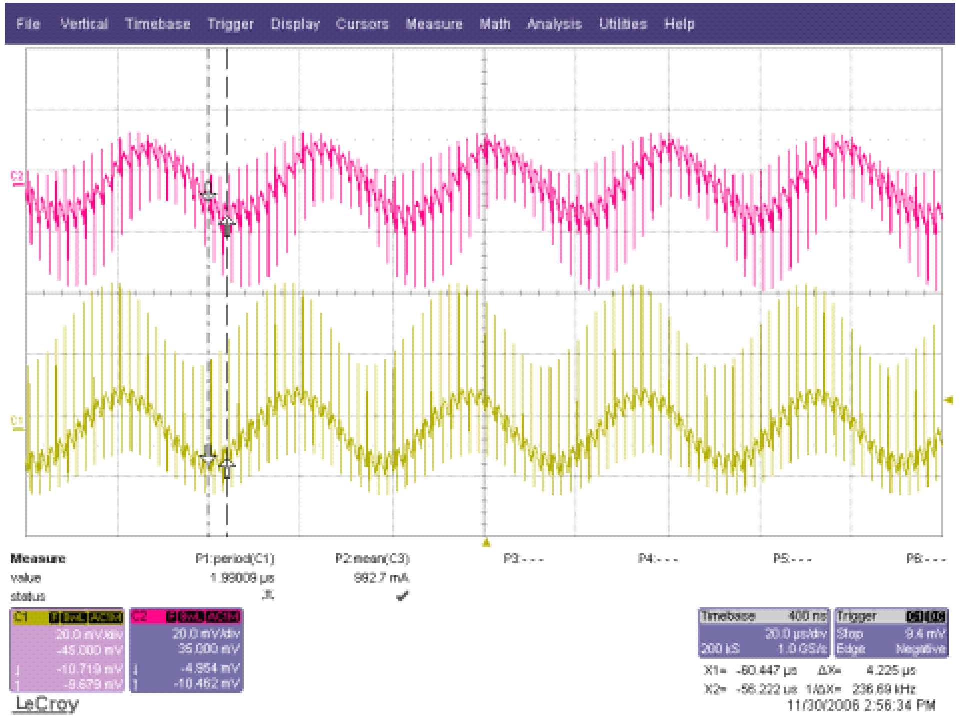
Connect oscilloscope channel 1 to OUT , channel 2 to IN . Both relative to the local controller ground .

穿越频率和相位裕量

LM5576 – 500 kHz 开关频率

输出

输入



24V V_{IN} 5V V_{OUT}
1A 负载
幅度 120 mV pk-pk
26.5 kHz 交越频率
相位裕量 = 40.5°

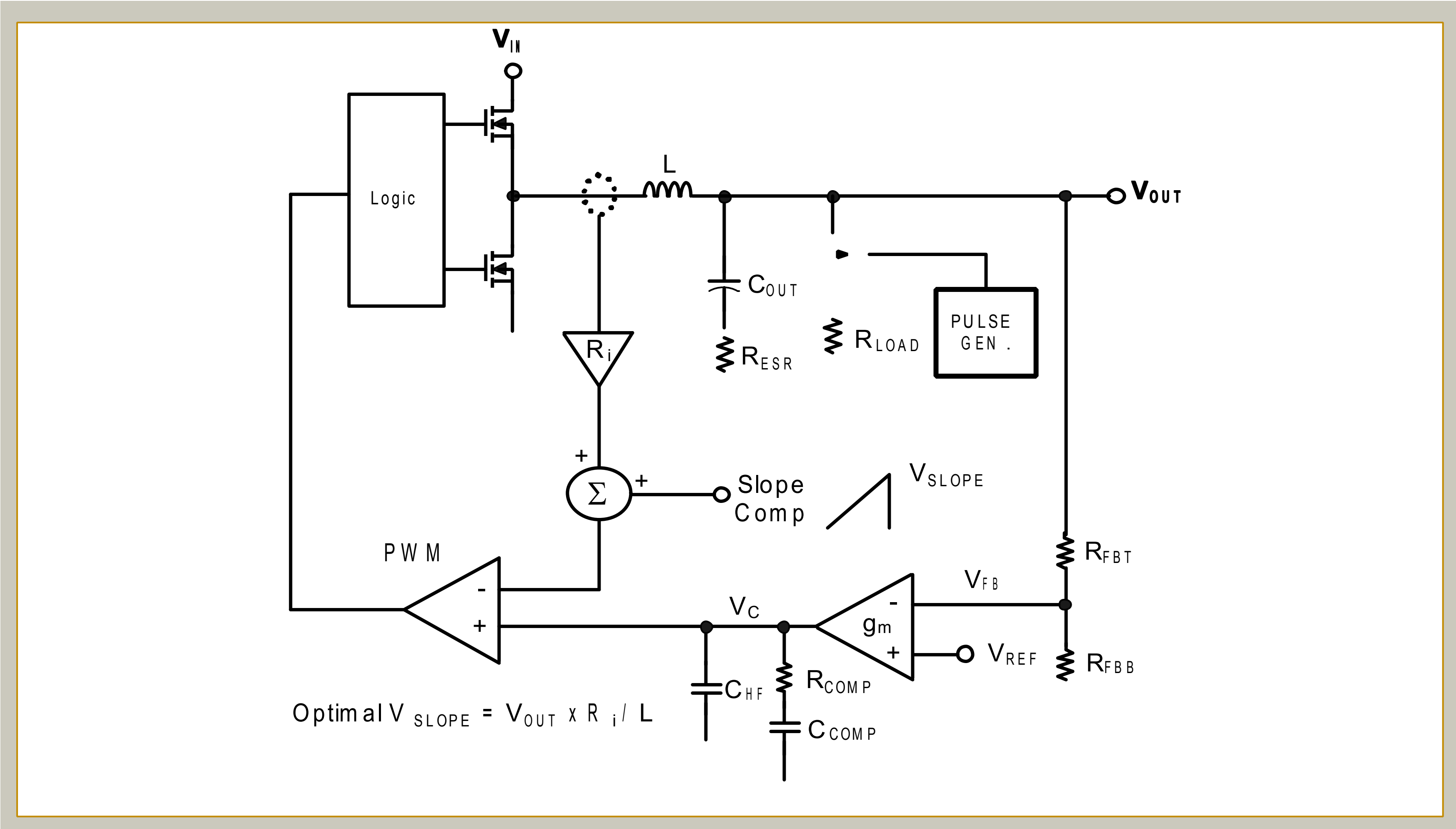
注意光标
时间差 = 4.225 μs
在 26.5 kHz，周期为
37.7 μs。
(4.225/37.7)*360
= 40.5

动手实验

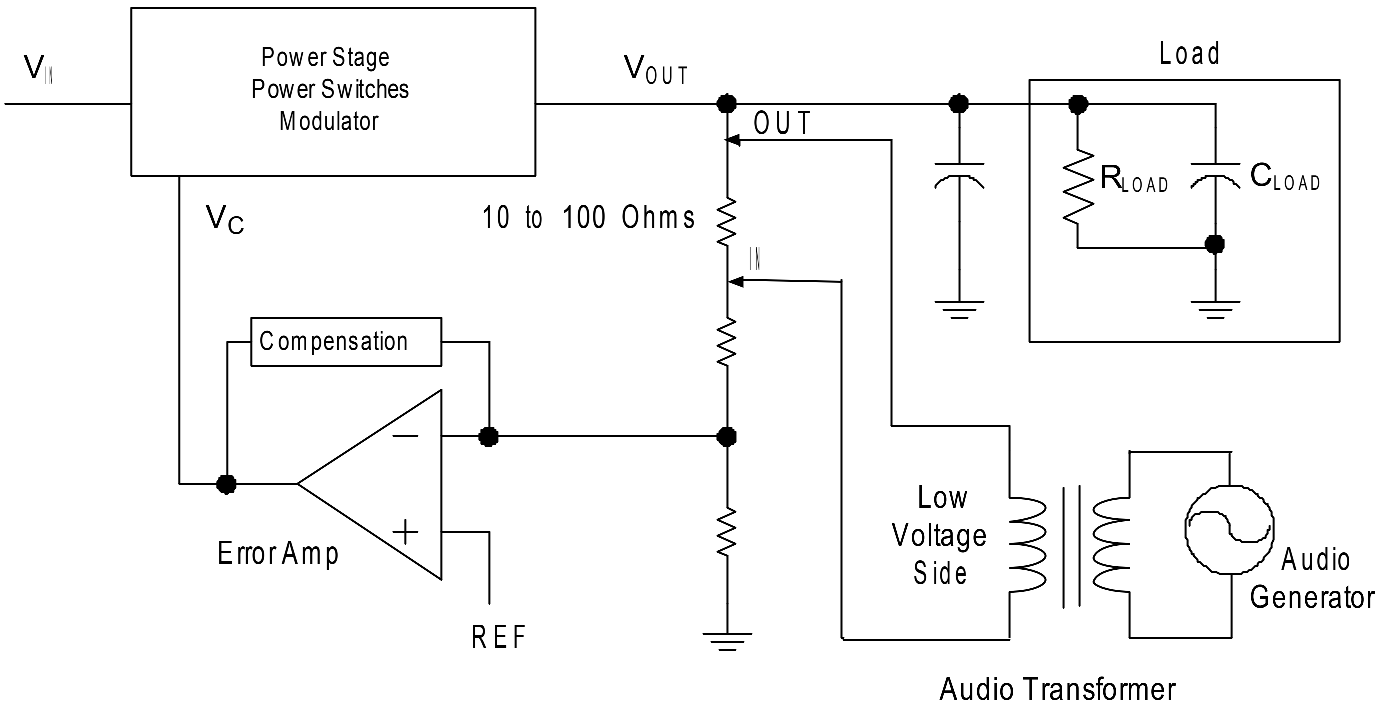
采用负载阶跃补偿降压稳压器

运用信号注入得到穿越频率和相位裕量

带负载阶跃的电流模式降压



单位增益和相位测量



Connect oscilloscope channel 1 to OUT, channel 2 to IN. Both relative to the local controller ground.

Excel 补偿器设计工具

峰值电流模式降压 – **Type II** 跨导放大器

峰值电流模式控制 – **Type II** 电压放大器

电压模式降压 – **Type III** 电压放大器

电流模式简化频率补偿

电流模式降压 – Type II 跨导放大器

Compensator Design - Peak Current-Mode Buck - Transconductance Amplifier

Enter parameters in shaded cells

Version 2.0

Revision date: 9 May 2010

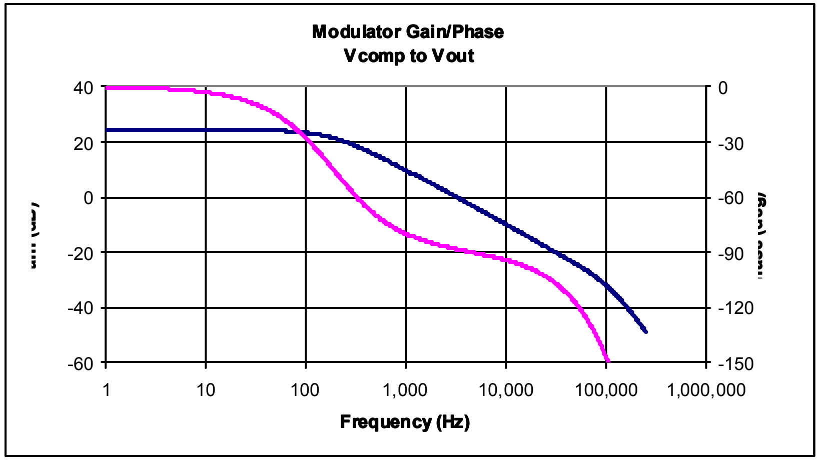
Vin (V)	10
Vout (V)	5
Load Current Iout (A)	1
Switching Frequency Fsw (kHz)	250
Current Sense Resistor Rs (mΩ)	10.0
Current Sense Gain A (V/V)	10
Slope Comp Multiplier SLM (V/V)	1
Output Inductor L (μH)	5.0
Output Capacitor Cout (μF)	500
Output Capacitor ESR (mΩ)	1.0
Error Amplifier gm (μA/V)	1,000
Error Amplifier Rea (kΩ)	1,000

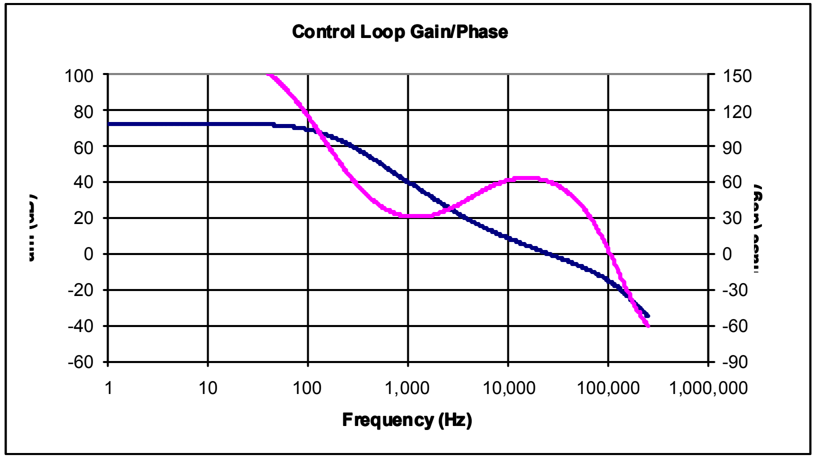
PCM1 Frequency Compensation Parameters

Error Amplifier - Single Pole Transconductance Amplifier

Reference Voltage Vref (V)	1.25
Bottom Feedback Divider Rfbb (Ω)	1,250
Top Feedback Divider Rfbt (Ω)	3,750
Modulator Scale Factor SFM (V/V)	1.00
Modulator Gain Gm(mod) (A/V)	10.00
Modulator Crossover Fc(mod) (kHz)	3.18
Error Amp Zero (kHz)	4.02
Target Loop Bandwidth Fc (kHz)	25.00
Error Amplifier Aol (V/V)	1,000
Error Amplifier UGB (MHz)	10.0
Error Amplifier Cbw (pF)	16

Modulator		Error Amp	
D =	0.5000	Kfb =	0.2500
Rout =	5.00	Avm =	8.250
Ri =	0.1000	khf =	1.010
Vsl =	0.4000	wzea =	25,253
Km =	25.00	whf =	2,550,505
Kd =	3.000	wbw =	62,831,853
Av =	16.667	**Slope Comp**	
wp =	1,200	Se =	100000
wz =	2,000,000	Sn =	100000
wc =	157,080	wn =	785,398
		Q =	0.6366





电流模式降压 – Type II 电压放大器

Compensator Design - Peak Current-Mode Buck - Voltage Amplifier

Enter parameters in shaded cells

Version 2.0

Revision date: 9 May 2010

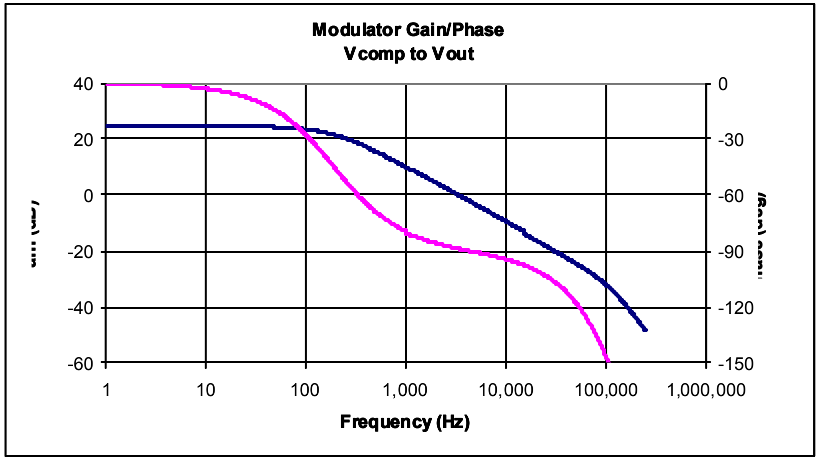
Vin (V)	12
Vout (V)	5
Load Current Iout (A)	1
Switching Frequency Fsw (kHz)	250
Current Sense Resistor Rs (mΩ)	10.0
Current Sense Gain A (V/V)	10
Slope Comp Multiplier SLM (V/V)	1
Output Inductor L (μH)	5.0
Output Capacitor Cout (μF)	500
Output Capacitor ESR (mΩ)	1.0
Error Amp Aol (V/V)	10,000
Error Amp UGB (MHz)	10.0

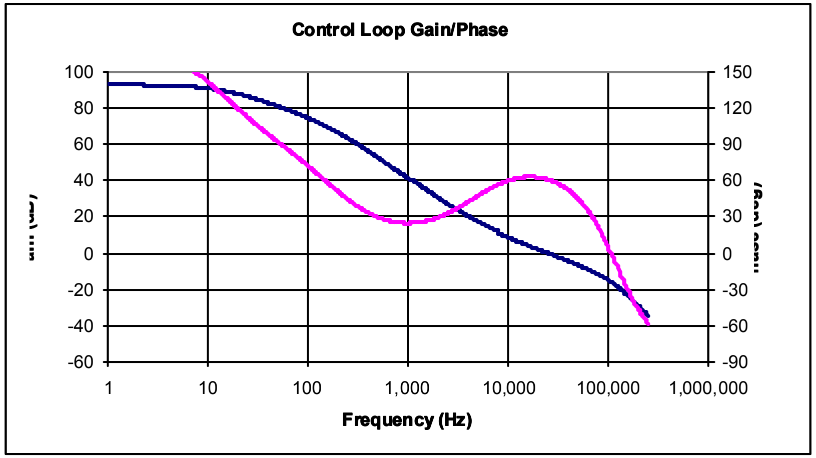
PCM1 Frequency Compensation Parameters

Error Amplifier - Single Pole Operational Amplifier

Reference Voltage Vref (V)	1.25
Bottom Feedback Divider Rfbb (Ω)	1,250
Top Feedback Divider Rfbt (Ω)	3,750
Modulator Scale Factor SFM (V/V)	1.00
Modulator Gain Gm(mod) (A/V)	10.00
Modulator Crossover Fc(mod) (kHz)	3.18
Error Amp Zero (kHz)	4.42
Target Loop Bandwidth Fc (kHz)	25.00

Modulator		**Error Amp**	
D =	0.4167	Kfb =	0.2500
Rout =	5.00	Rth =	937.5
Ri =	0.1000	Avm =	8.000
Vsl =	0.4000	khf =	1.008
Km =	25.00	wzea =	27,778
Kd =	3.000	whf =	3,361,111
Av =	16.667	wbw =	62,831,853
wp =	1,200	**Slope Comp**	
wz =	2,000,000	Se =	100000
wc =	157,080	Sn =	140000
		wn =	785,398
		Q =	0.6366





电压模式降压 – **Type III** 电压放大器

Compensator Design - Voltage-Mode Buck - Voltage Amplifier

Enter parameters in shaded cells

Version 2.1

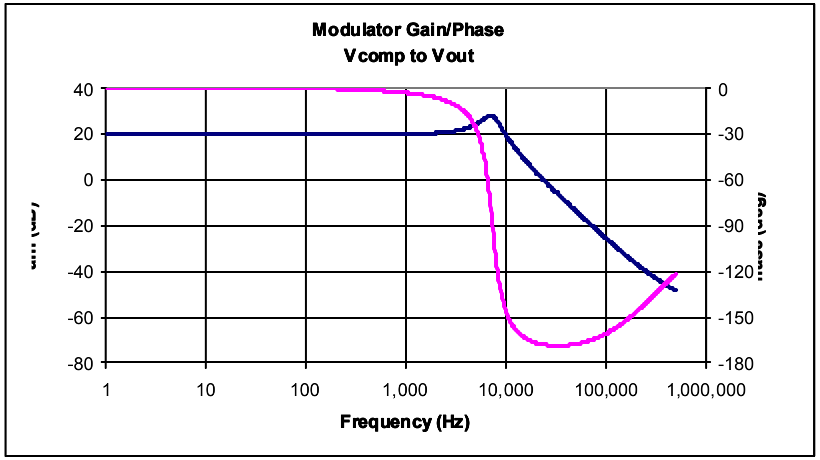
Revision date: 10 May 2010

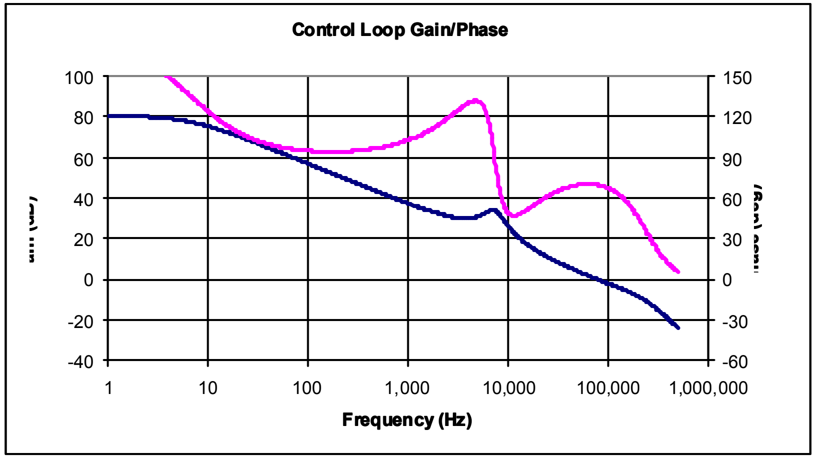
Frequency Compensation Parameters

Error Amplifier - Single Pole Operational Amplifier

Vin (V)	12	Input Voltage Feed-Forward Kff (V/V)	0.100
Vout (V)	1.8	Equivalent Ramp Voltage Vramp (V)	1.200
Load Current Iout (A)	10	Reference Voltage Vref (V)	0.600
Switching Frequency Fsw (kHz)	500	Bottom Feedback Divider Rfbb (Ω)	1,500
		Top Feedback Divider Rfbt (Ω)	3,000
Output Inductor L (μH)	1.0		
Output Capacitor Cout (μF)	500	Error Amp Aol (V/V)	3,300
Output Capacitor ESR (mΩ)	1.0	Error Amp UGB (MHz)	15.0
Modulator Scale Factor SFM (V/V)	1.00	Target Loop Bandwidth Fc (kHz)	75.00

Modulator		**Error Amp**	
D =	0.1500	Kfb =	0.3333
Rout =	0.18	Rth =	1000.0
Km =	10.00	Avm =	1.069
Gc =	1.054	khf =	1.014
wp =	44,721	wfz =	44,721
wc =	471,239	wzea =	44,721
wz =	2,000,000	wfp =	2,000,000
wsw =	3,141,593	whf =	3,141,593
		wbw =	94,247,780





电流模式简化频率补偿

Word 文档	嵌入式 Excel

Current-Mode Simplified Frequency Compensation

Peak Current-Mode Buck – Voltage Amplifier

Ri = Gi*Rs

Figure 1. Current-mode buck switching model.

freq / Hertz

Figure 2. Control-to-output gain and phase.

- 降压（采用理想运算放大器）
- 降压（采用理想跨导放大器）
- 升压（采用理想运算放大器）
- 升压（采用理想跨导放大器）
- 降压-升压（采用理想运算放大器）
- 降压-升压（采用理想跨导放大器）

结论

概要/行动倡议

1	• 采用 **Excel** 补偿器设计工具
2	• 运用瞬态负载验证性能
3	• 采用信号注入进行单位增益和相位测量