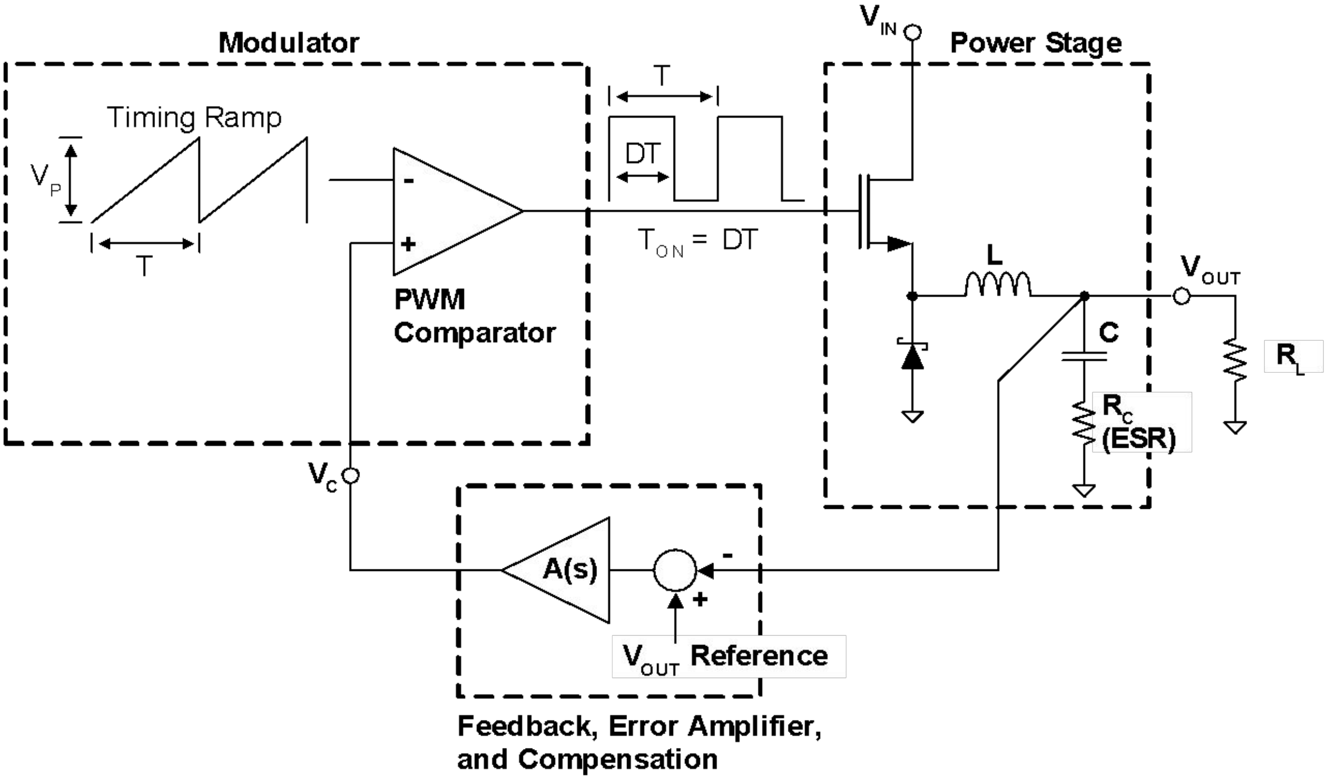
Switching Power Supplies A to Z

Basic Switcher Architectures

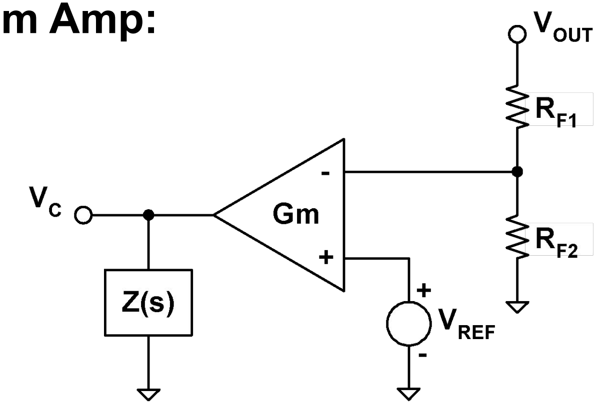
Thanks to John Bittner

Voltage Mode Buck Regulator Basic Architecture



Feedback, Error Amplifier, and Compensation – Two Types

Gm Amp:

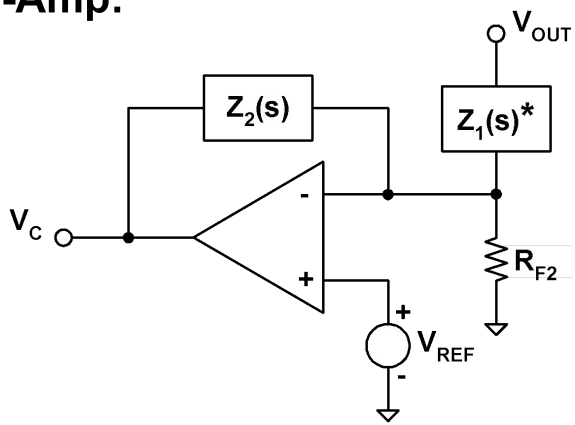


$$\frac{V_C}{V_{OUT}} = -\frac{R_{F2}}{R_{F1}+R_{F2}} \bullet Gm \bullet Z(s)$$

$$= -\frac{V_{REF}}{V_{OUT}} \bullet A(s) \qquad A(s) = Gm \bullet Z(s)$$

Gain is a function of the feedback ratio, so regulator loop gain increases inversely with V_{OUT}. Gain is also affected by changes in A(s).

Op-Amp:



$$\frac{V_C}{V_{OUT}} = -\frac{Z_2(s)}{Z_1(s)}$$

Loop gain is independent of op-amp's open loop gain and the feedback ratio.

$^*\,Z_1(s) = R_{F1}$ at DC:

$$\therefore V_{OUT}(DC) = V_{REF}\,\frac{R_{F1}+R_{F2}}{R_{F2}}$$

Voltage Mode Buck Regulator Loop Gain

- **Modulator and Power Stage gain:**

$$\frac{V_{OUT}}{V_C} = \frac{V_{IN}}{V_P} \bullet \frac{1 + sR_C C}{1 + s(R_C C + L/R_L) + s^2 LC}$$

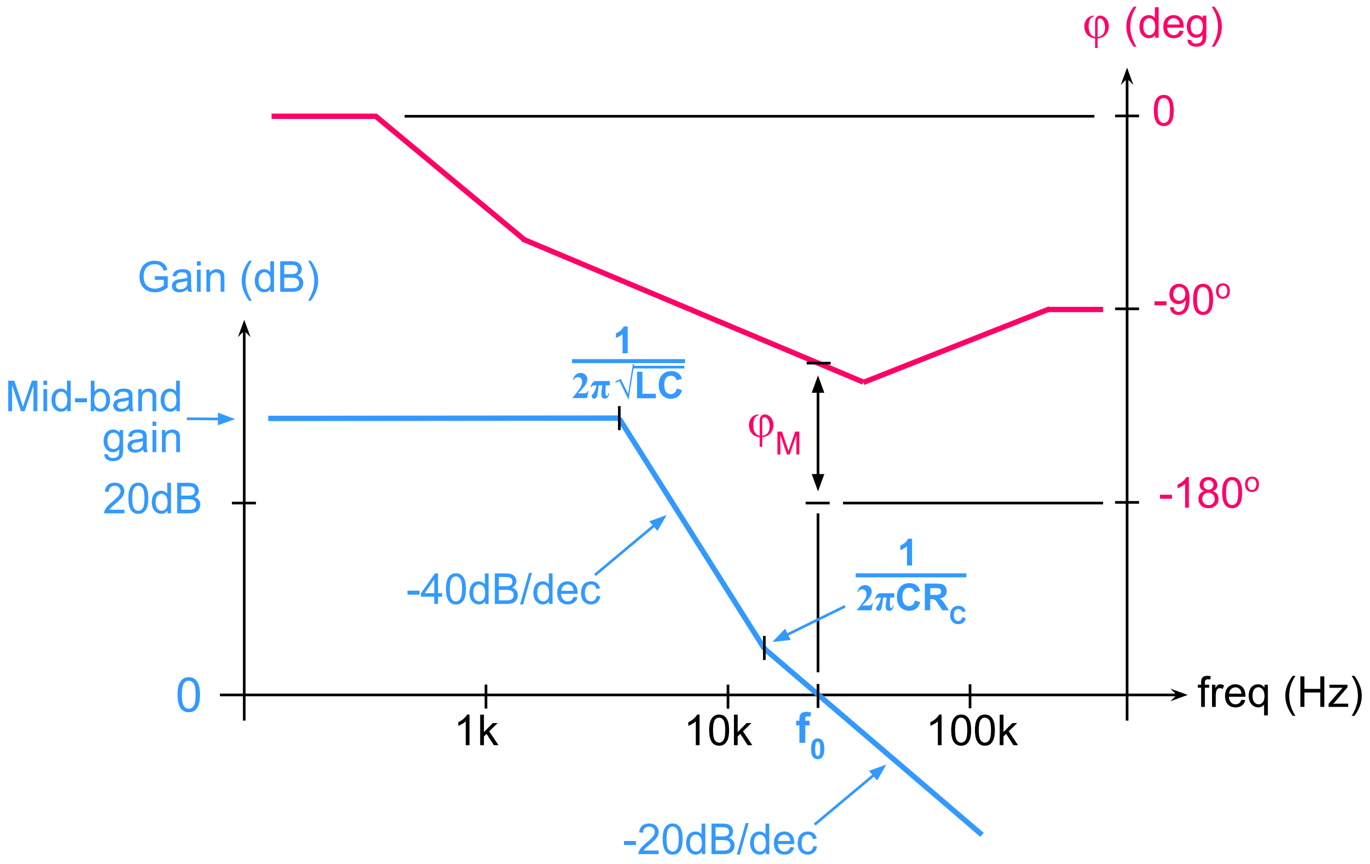
- **Feedback, Error Amplifier, and Compensation gain (Gm-type Error Amp):**

$$\frac{V_C}{V_{OUT}} = -\frac{V_{REF}}{V_{OUT}} \bullet A(s)$$

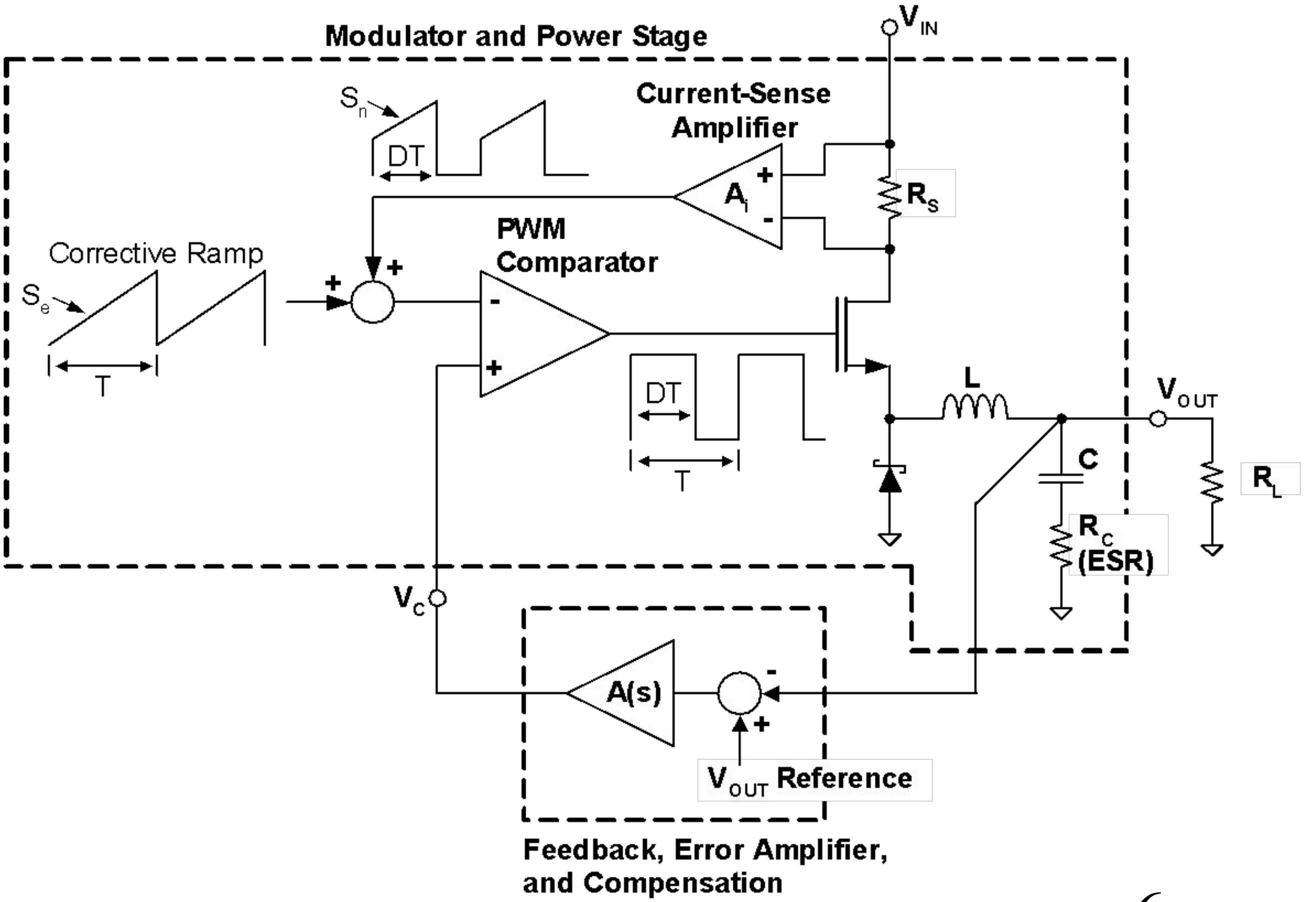
- **Regulator loop gain, H(s):**

$$H(s) = \frac{V_{REF}}{V_{OUT}} \bullet A(s) \bullet \frac{V_{IN}}{V_P} \bullet \frac{1 + sR_C C}{1 + s^2(R_C C + L/R_L) + s^2 LC}$$

Voltage-Mode Buck Regulator Frequency Response



Current Mode Buck Regulator Basic Architecture



Current Mode Buck Regulator Loop Gain

- **Gain of Modulator and Power Stage:**

$$\frac{V_{OUT}}{V_C} = \frac{R_L}{R_i} \bullet \frac{1}{1+\frac{R_L T}{L}(m_C D' - 0.5)} \bullet \frac{1+sR_C C}{1+\frac{s}{\omega_P}} \bullet \frac{1}{1+\frac{s}{\omega_N Q_P}+\frac{s^2}{\omega_N^2}}$$

$$R_i = A_i \bullet R_S \qquad D' = 1 - D$$

$$m_C = 1 + \frac{S_e}{S_n}$$

S_e = corrective ramp slope

S_n = positive slope current-sense waveform

$$\omega_P = \frac{1}{CR_L} + \frac{T}{LC}(m_C D' - 0.5)$$

$$\omega_N = 2\pi \bullet \left(\frac{f_{SW}}{2}\right) = \frac{\pi}{T}$$

$$Q_P = \frac{1}{\pi(m_C D' - 0.5)}$$

Current Mode Buck Regulator Loop Gain

- **Feedback, Error Amplifier, and Compensation gain (Gm-type Error Amp):**

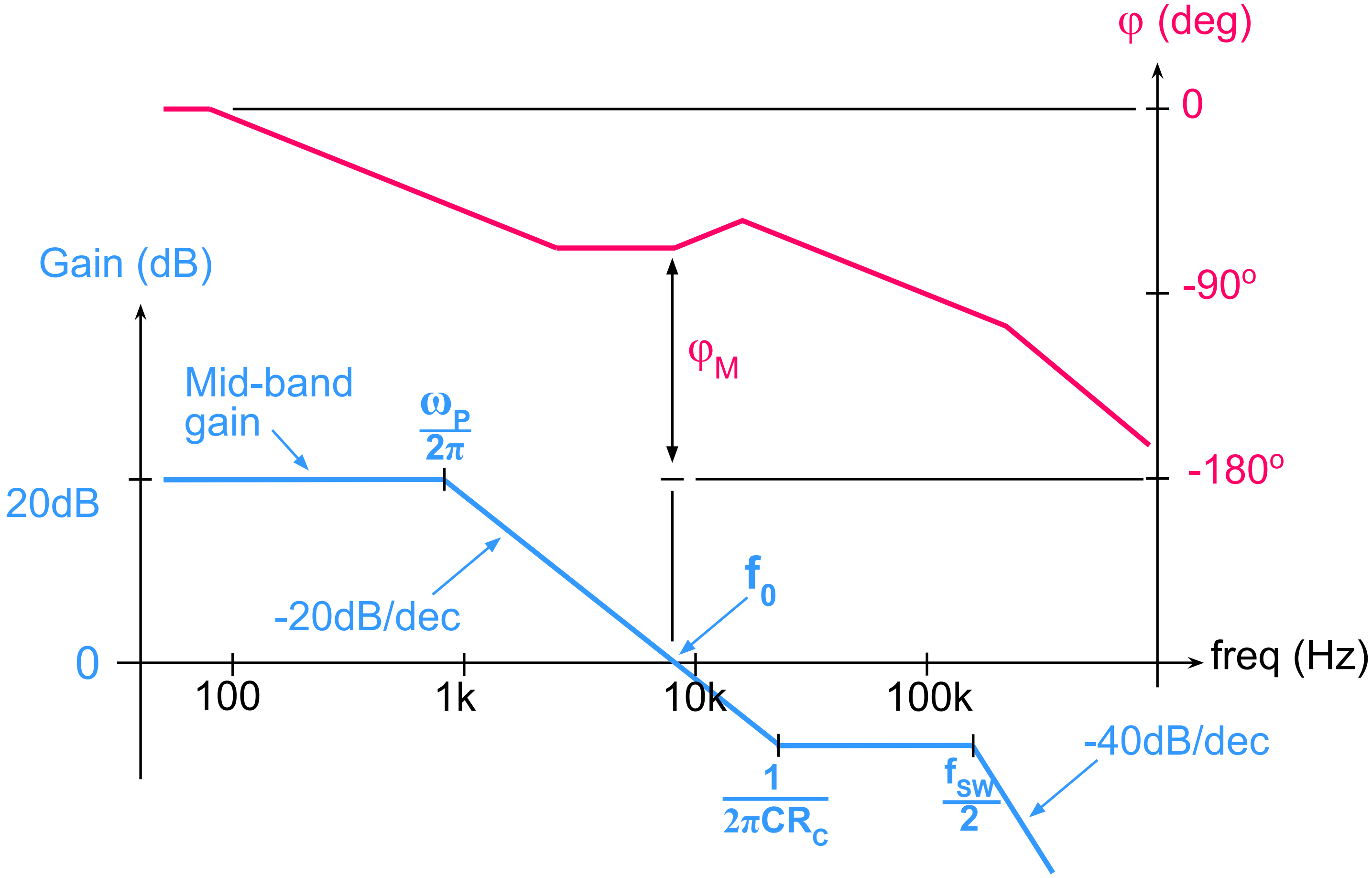
$$\frac{V_C}{V_{OUT}} = -\frac{V_{REF}}{V_{OUT}} \bullet A(s) \qquad A(s) = Gm \bullet Z(s)$$

- **Regulator loop gain:**

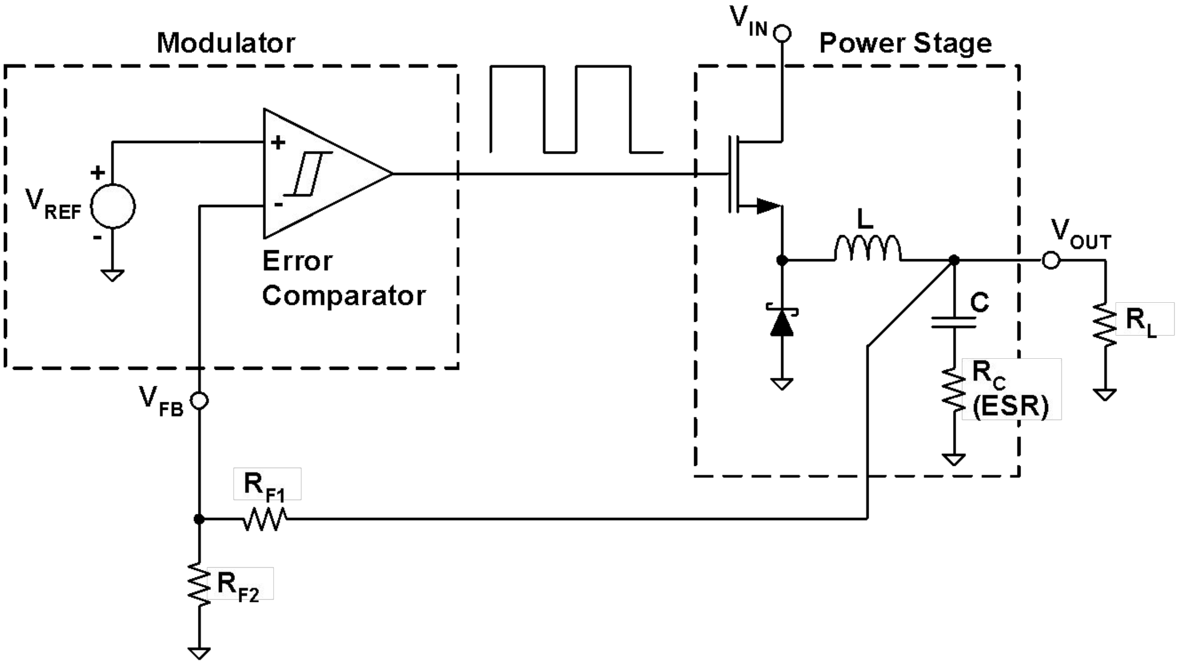
$$H(s) = -\frac{V_{REF}}{V_{OUT}} \bullet A(s) \bullet \frac{R_L}{R_i} \bullet K \bullet \frac{1 + sR_C C}{1 + \frac{s}{\omega_P}} \bullet Fh(s)$$

$$K = \frac{1}{1 + \frac{R_L T_{SW}}{L}(m_C D' - 0.5)} \qquad Fh(s) = \frac{1}{1 + \frac{s}{\omega_N Q_P} + \frac{s^2}{\omega_N^2}}$$

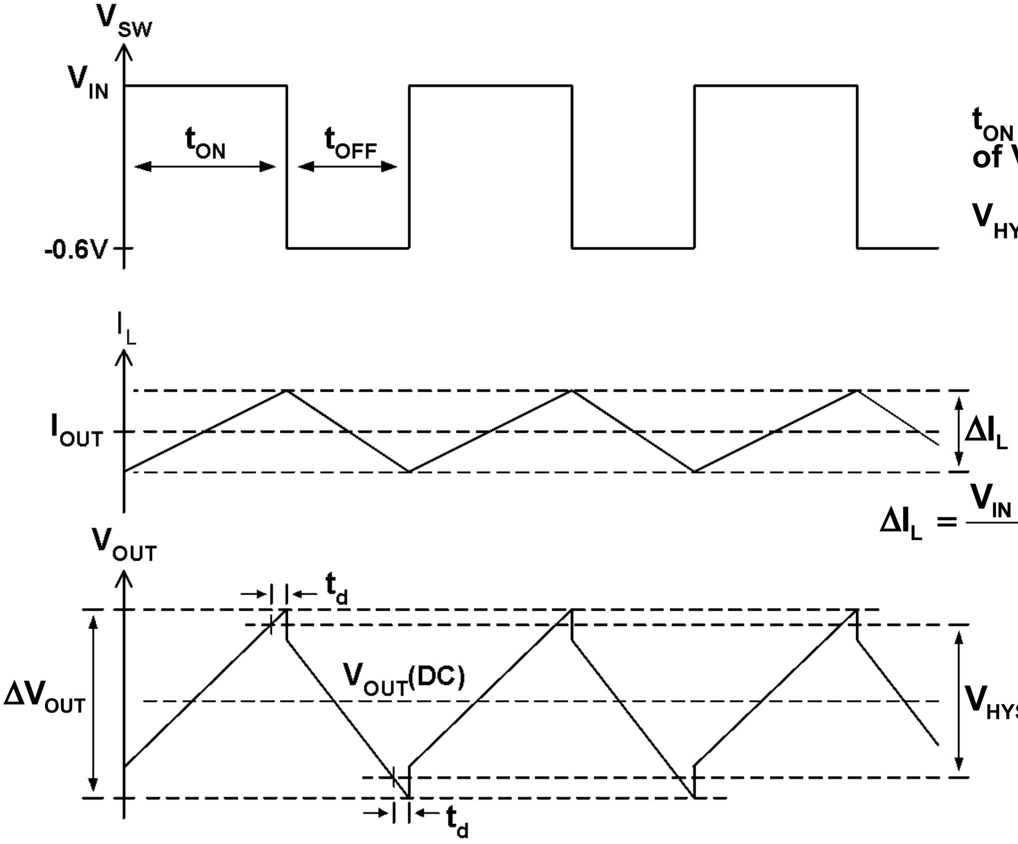
Current-Mode Buck Regulator Frequency Response



Hysteretic Buck Regulator Basic Architecture



Hysteretic Buck Regulator Switching Waveforms



t_{ON} and t_{OFF} are functions of V_{IN}, V_{OUT}, L, ESR, ESL, $V_{HYS}*(R_{F1}+R_{F2})/R_{F2}$, and t_d

$$\Delta I_L = \frac{V_{IN} - V_{OUT}}{L} \bullet t_{ON} = \frac{V_{OUT}}{L} \bullet t_{OFF}$$

$$V_{HYS} \bullet \frac{R_{F1} + R_{F2}}{R_{F2}} \quad (V_{HYS} \approx 15\text{mV})$$

Calculating Hysteretic Regulator Switching Frequency

- In most cases, switching frequency is determined by output ripple voltage (ΔV_{OUT}) resulting from ESR. Amplitude of ΔV_{OUT} is described by the following two equations:

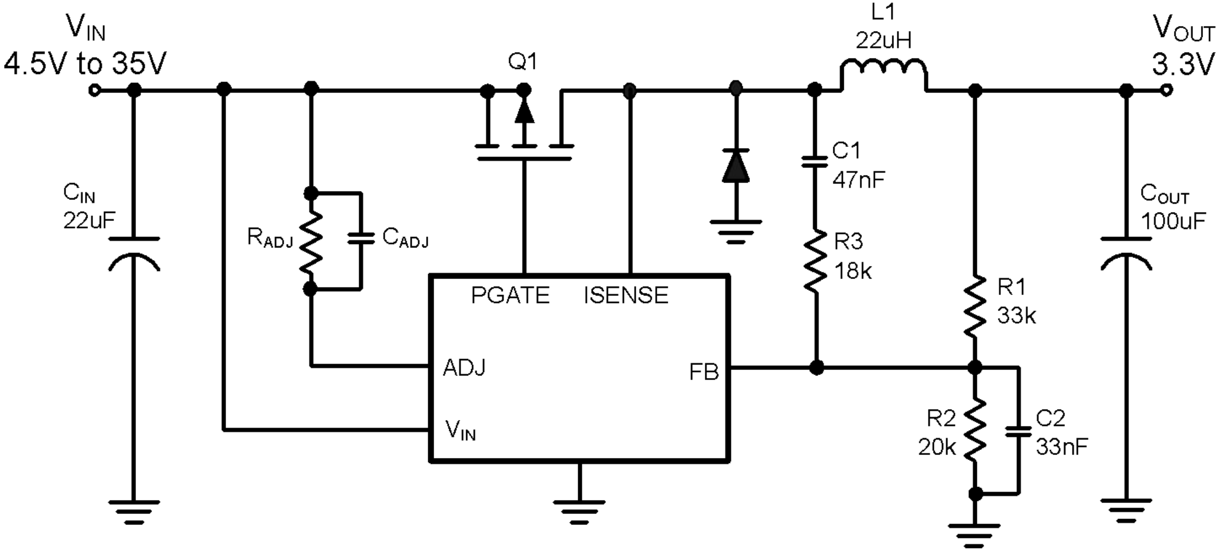
$$\Delta V_{OUT} = \frac{V_{IN} - V_{OUT}}{L} \bullet DT \bullet ESR \qquad DT = t_{ON} \qquad D = \frac{V_{OUT}}{V_{IN}}$$

$$\Delta V_{OUT} = V_{HYS} \bullet \frac{R_{F1} + R_{F2}}{R_{F2}} + \left[ESR \bullet \left(\frac{V_{IN} - V_{OUT}}{L} + \frac{V_{OUT}}{L} \right) \bullet t_d \right]$$

- Combining these two equations yields an expression for the switching frequency

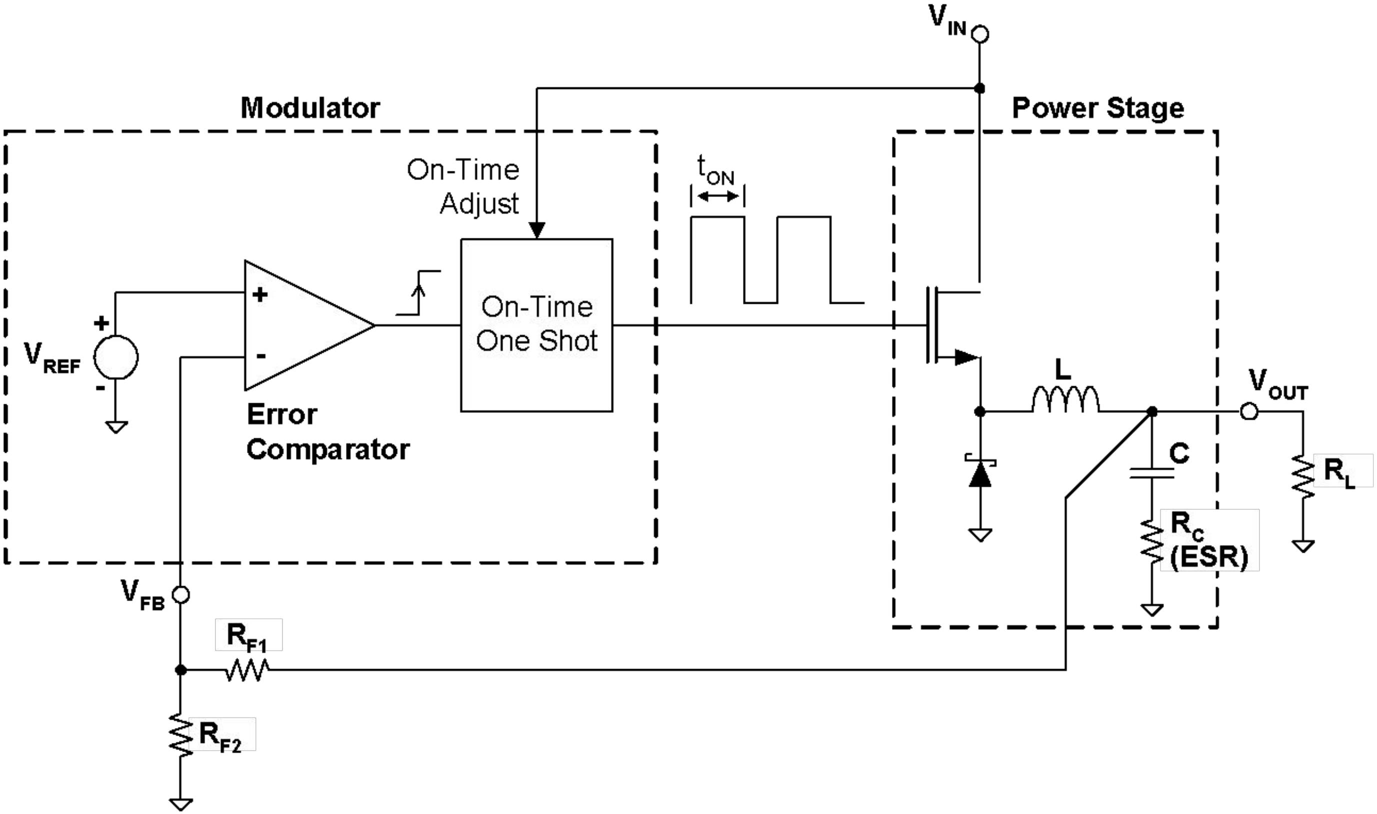
$$f_{SW} = \frac{V_{OUT}}{V_{IN}} \bullet \frac{(V_{IN} - V_{OUT}) \bullet ESR}{\left(V_{HYS} \bullet \frac{R_{F1} + R_{F2}}{R_{F2}} \bullet L \right) + (V_{IN} \bullet ESR \bullet t_d)}$$

Compensating for excessive ESL in output capacitor

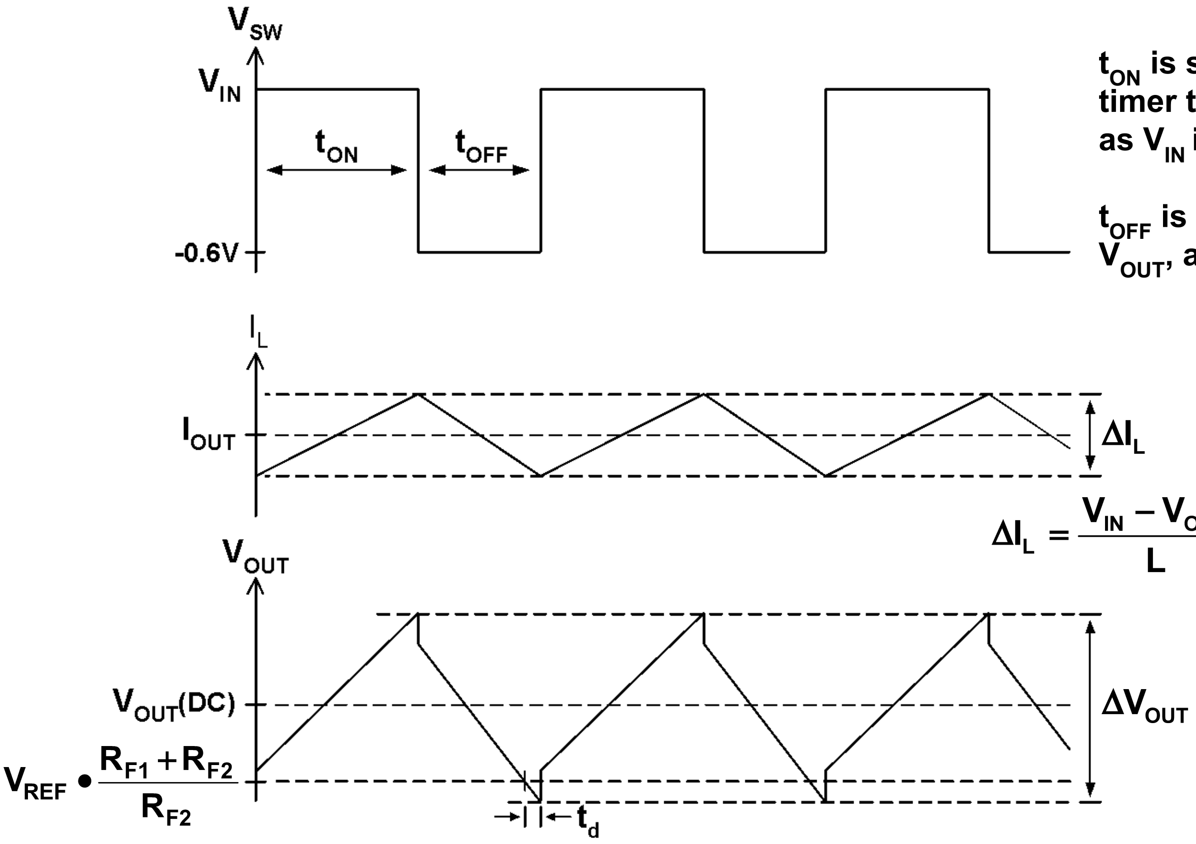


C_{OUT} has excessive ESL, so ΔV_{OUT} has large voltage steps that result in erratic switching. C2 filters-out ESL voltage step at FB pin. C1, C3 and R3 generate triangle waveform that determines the switching frequency.

Constant On-Time Buck Regulator Basic Architecture



Constant On-time Buck Regulator Switching Waveforms



t_{ON} is set by a one-shot timer that decreases t_{ON} as V_{IN} increases.

t_{OFF} is a function of V_{IN}, V_{OUT}, and t_{ON}

$$\Delta I_L = \frac{V_{IN} - V_{OUT}}{L} \bullet t_{ON} = \frac{V_{OUT}}{L} \bullet t_{OFF}$$

Calculating Constant On-Time Regulator Switching Frequency

- t_{ON} is a constant, so the regulator must adjust t_{OFF} to the value necessary to maintain charge balance in the inductor. This is expressed by the following equation:

$$\frac{V_{IN} - V_{OUT}}{L} \bullet t_{ON} = \frac{V_{OUT}}{L} \bullet (T - t_{ON}) \qquad t_{OFF} = (T - t_{ON})$$

- Solving this equation for 1/T yields an expression for the switching frequency:

$$f_{SW} = \frac{V_{OUT}}{t_{ON} \bullet V_{IN}}$$