

A close-up photograph of several copper coils on a printed circuit board, with a large orange waveform graphic overlaid on the left side of the image.

Introduction to Power Management

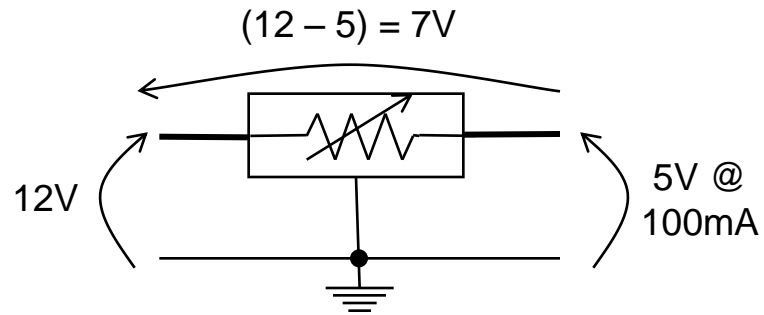
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Introduction to Power Management

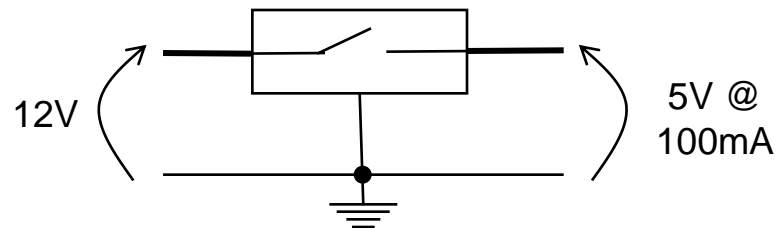
- The voltage of the power supply and/or battery feeding our PCB is seldom at the correct level that we need for our circuitry:
 - Example: A standard desktop PC in Europe is fed with 230V but the motherboard needs: +12V, -12V, +5V and +3.3V
- We need to step up and step down (convert) our voltage levels ALL THE TIME depending on the voltage available to us at our input connector and what the circuitry actually needs
 - There are two major methods to do this:
 - Linear Regulators (also known as series pass regulator, series regulator or LDOs) and
 - Switching Regulators (known as switch mode power supplies, or switching power supplies and power “converters”)
 - Note that (beyond very low currents) zener diodes or potential dividers are not good choices for this purpose!

Introduction to Power Management

- LDO



- Switching Regulator



Why Do We Need a Converter/Regulator

- Of course the first job of the converter/regulator is to convert our input voltage to the output voltage level that our circuit requires
 - e.g. Input voltage $V_{in} = 12V$ but we actually need 5V for our ICs
- The second job is to regulate!
 - If there is a increase/decrease in the amount of current that we draw, the output voltage should not fall/rise
 - This is called *Load Regulation*
 - If there is a change in the input voltage of our power supply the output voltage should not change
 - This is called *Line Regulation*
- There are other desirable characteristics such as: transient response, efficiency, EMI, cost, size, etc but we will talk about these later

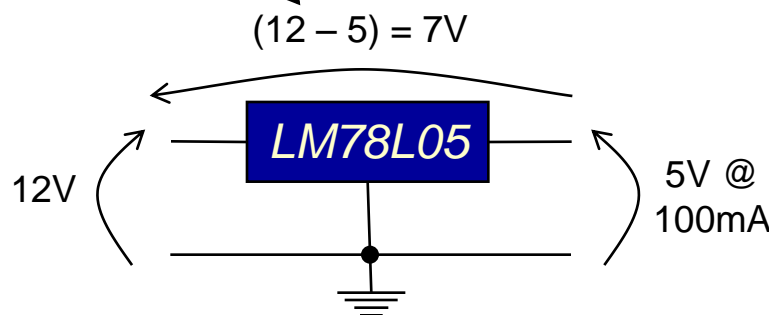
Linear Regulators

- Two major types (even though many people call all of them LDOs):
 - Standard
 - e.g. LM78LXX
 - Requires higher input voltage of around 2V; e.g. LM78L05 will give you a regulated output of 5V @100mA but V_{in} must be $> 7V$
 - Low Drop Out (LDO):
 - e.g. TPS793xx
 - Requires less dropout voltage than “standard type”. The input voltage typically needs to be only 0.6V higher than the output voltage
- They work by operating a transistor in the linear region (i.e. like a variable resistor), sensing the output voltage (V_{out}) and automatically changing this variable resistor value such that V_{out} remains constant
- Advantages:
 - Cheap & easy, quiet, small
- Disadvantages:
 - Very inefficient, low current only, limited V_{in} and V_{out} ranges

So What is Wrong with Linear Regulators?

- Let's say our input voltage is 12V and we need a 5V, 100mA supply
 - Ignoring the ground current, we will have 7V drop across our regulator

Head for Linear Regulator ~ 2V
Head needed for LDO ~ 0.6V

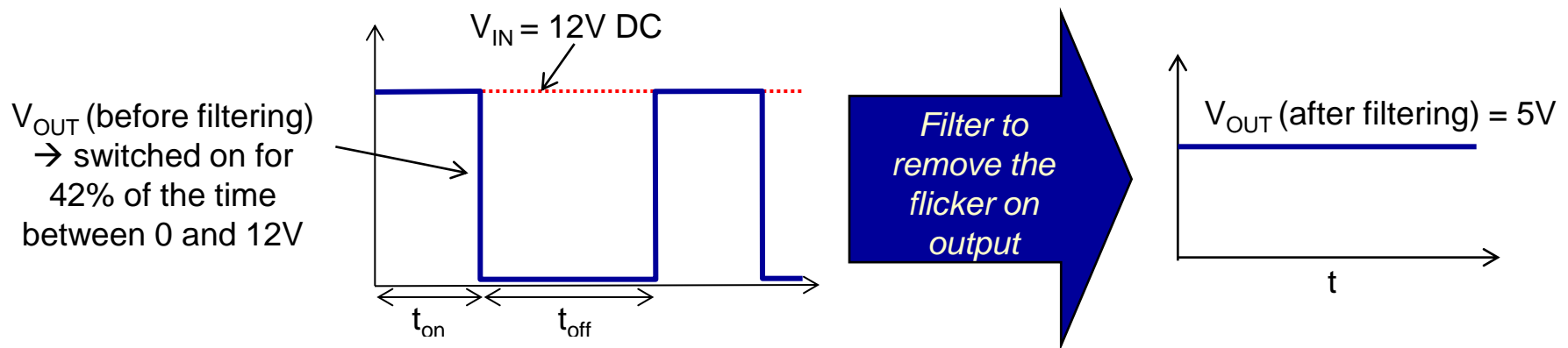


- Output Power = $5V \times 100mA = 500mW$
- Power Loss in regulator = $7V \times 100mA = 700mW$
- Efficiency = $500mW / (1200mW) = 41.6\%$!

A switching regulator can be MUCH MORE efficient (+90%)

Switching Regulators (Power Converters)

- Imagine that we want to dim an old fashioned incandescent light bulb whereby the switch is on 100% of the time,
 - if we place a resistor in series with it and keep the switch on all the time then we dim the light but we waste energy in the resistor (this is like the linear regulator)
 - If instead of the resistor if we turn the switch off for 50% of the time and then turn it on for 50% of the time then we will dim the light by 50%
 - Obviously if we switch at a slow rate (once per second) then we would see the light flicker, but if we switch at a very fast rate then we would not see the flicker
 - This is the basic principle by which step down switching power supplies work



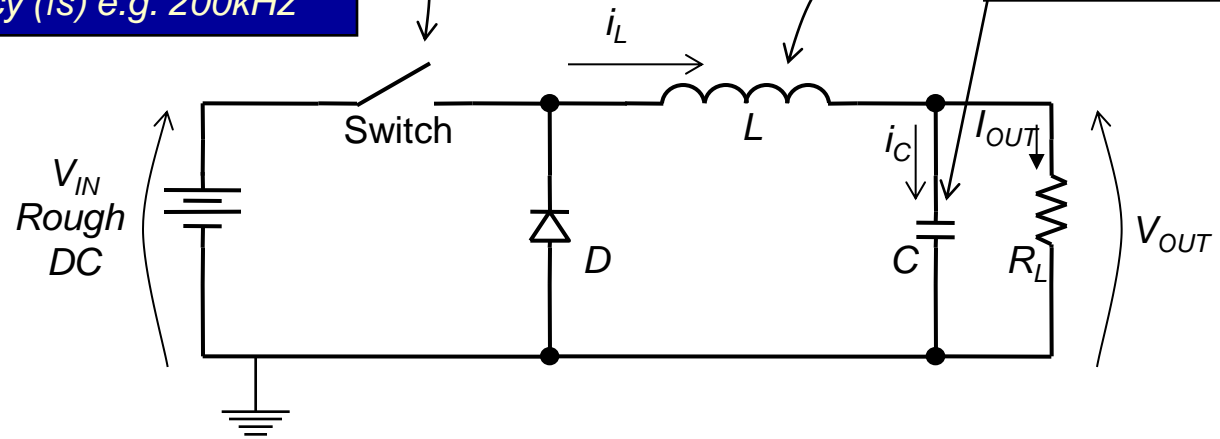
Switching Regulator Design Challenges

- Designing switch mode power supplies without software tools is HARD!
 - Need an understating of power electronics
 - Good understanding of control theory is essential for stability
 - There are many things that can go wrong... usually with a bang!
 - Need to understand the effect of parasitics and thermal management
 - Component selection is difficult and must be chosen so that they can tolerate the worse case scenario
 - Switching regulators are very noisy (from an EMI stand point) and good PCB layout is essential
 - Custom magnetic design is necessary for isolated power supplies
 - Engineers specialising in power can have most of these skills but, for the vast majority of us, all we need is power for our boards

Simple Buck Converter and Basic Terminology

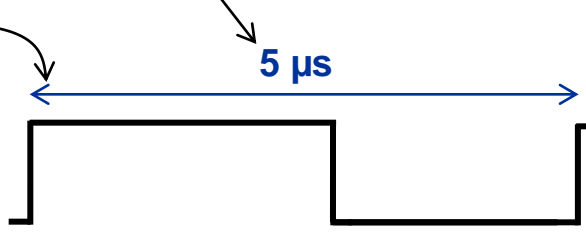
The switch is usually a MOSFET and we switch it on and off at our switching frequency (f_s) e.g. 200kHz

The inductor L & the capacitor C form a filter to smooth the output (remove the flicker)



The percentage of time that we keep the switch on in one switching period is called Duty (D) and determines our output voltage

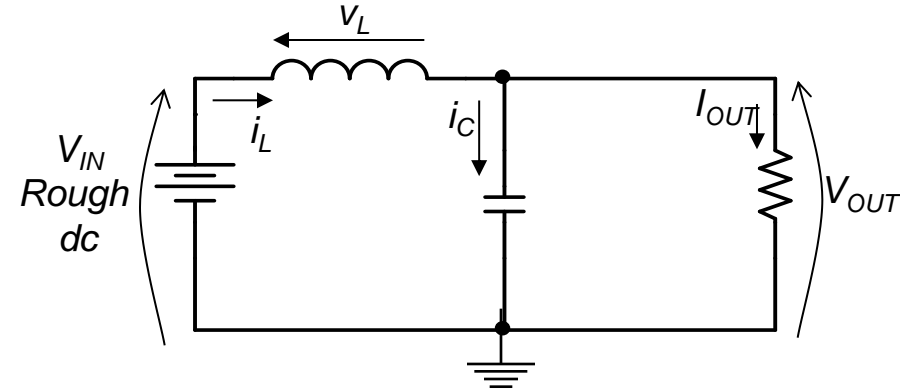
200kHz will give a switching period T_s of $1/200\text{kHz} = 5 \mu\text{s}$



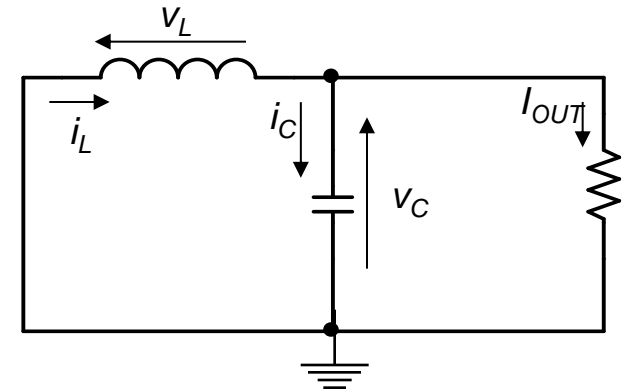
$$D = \frac{\text{"On" time of switch}}{\text{Switching Period}} = \frac{t_{on}}{T_s}$$

Simple Buck Converter and Basic Terminology

- When the switch is ON
 - Replace the switch with a short
 - Diode is reverse biased (replace with open circuit)
 - Inductor current will rise linearly

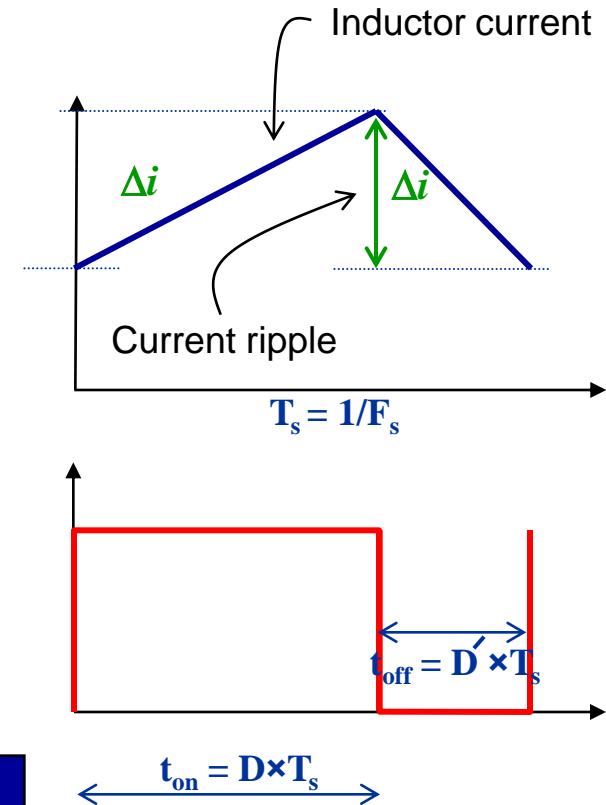


- When the switch is OFF
 - Replace switch with open circuit
 - Diode is forward biased (replace with short circuit)
 - Inductor current will fall linearly



Simple Buck Converter and Basic Terminology

- Observations:
 - At turn on inductor current rises linearly
 - At turn off it falls linearly
 - Inductor current ripple is proportional to how long the switch is on and off
 - If we have a longer turn on period and turn off period, (i.e. slower switching frequency) we will have a larger ripple
 - Inductor Ripple Current is one of the most important design parameters → we will talk about this in more detail later but for now:



The faster the switching frequency, the smaller the inductor current ripple

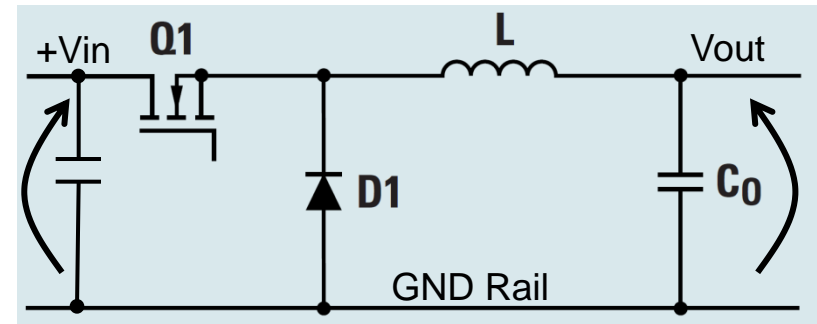
OR

*If we switch faster we can use a smaller inductor
(we will talk about switching losses later)*

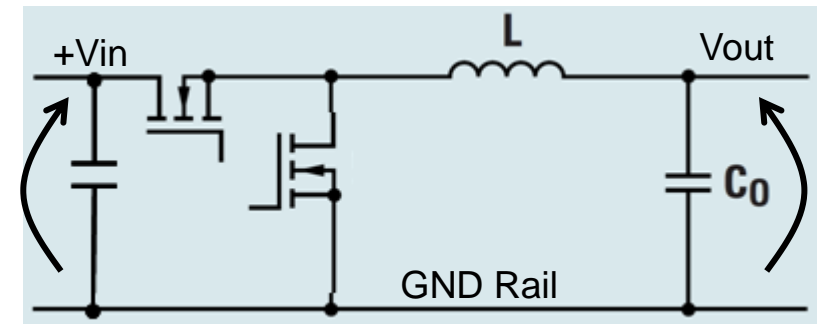
Topology Selection Guide

- Buck Converters
 - Standard Buck (as shown)
 - Step down only
 - Most popular converter for PoL
 - Switch is not referenced to ground
 - high-side switch i.e. more expensive gate driver
 - Synchronous Buck
 - Replaces or complements the diode with an extra switch (and a low side gate driver) to improve efficiency
 - But efficiency is not that great if converter is operated under discontinuous conduction mode (DCM)
 - Synchronous Buck with Diode Emulation
 - Similar to Synchronous Buck but solves the DCM efficiency performance issue
 - But more expensive IC

$$V_{out} = V_{in} \times D$$



Normal buck



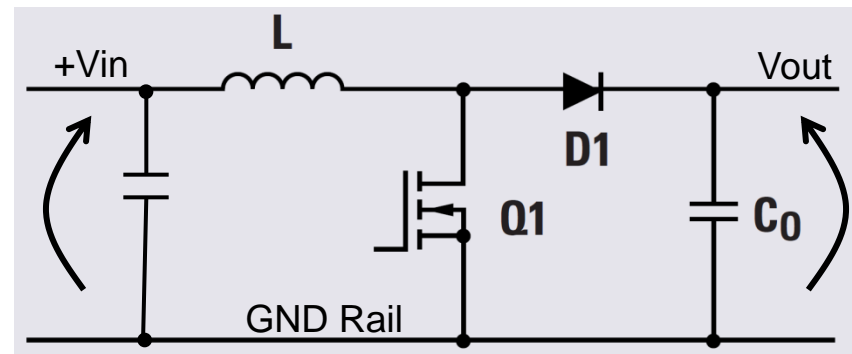
Synchronous buck

* Image taken from www.ti.com/lit/sq/sluw001e/sluw001e.pdf

Topology Selection Guide

- Boost
 - Step up only
 - Switch is referenced to ground (low-side switch)
 - Can use a cheaper gate driver
 - Used when the voltage you need on your PCB needs to be higher than the input voltage
 - Better used with current mode control as opposed to voltage mode if operated in continuous conduction mode
 - We will talk about conduction modes and control methods soon
 - Major draw back is that there is no ability to limit the current (i.e. can't turn off the switch to stop the current!)

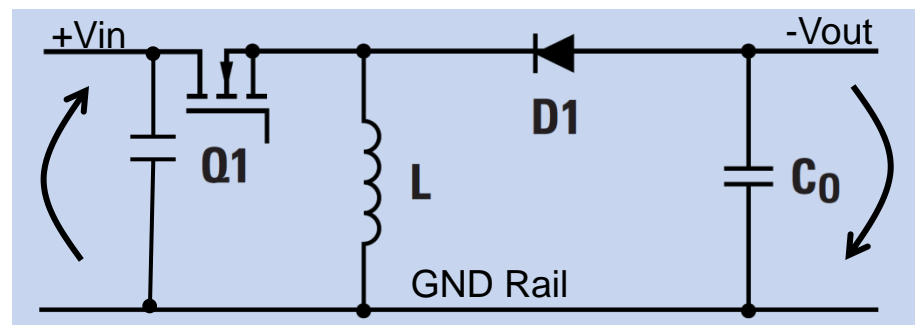
$$V_{out} = V_{in} \times \frac{1}{(1 - D)}$$



Topology Selection Guide

- Inverting Buck-Boost
 - Can step both up and down
 - Common in battery operated devices where, depending on the battery charge, you may want to either buck or boost
 - But V_{out} always has a reverse polarity with respect to the V_{in}
 - Most popular when you have a positive voltage on your input but on your PCB you need a negative voltage
 - Best used with current mode control when in CCM
 - Very noisy from an EMI point of view
 - The switch can be either on the high side or on the low side
 - High side switch needs a more expensive gate driver
 - Low side switch is cheaper but the load is then referenced to ground

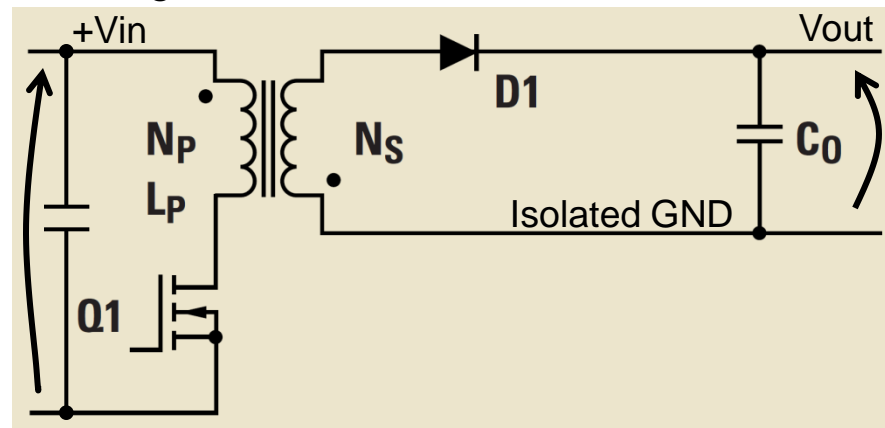
$$V_{out} = V_{in} \times \frac{D}{(1 - D)}$$



Topology Selection Guide

- Flyback
 - Transformer isolated version of Inverting Buck-Boost
 - Depending on how the transformer is wound it can have both positive and negative output voltage
 - Because of the transformer can buck down from much higher input voltage rails
 - Can have multiple output voltage of different polarities (e.g. +- 12V) by having more than one secondary winding - but only one voltage rail can be controlled
 - For DC/DC conversion it is most commonly used with current mode control in CCM
 - Very noisy but cheap
 - The switch is usually placed on the low side so that a cheaper gate driver can be used but it can also be placed on the high-side

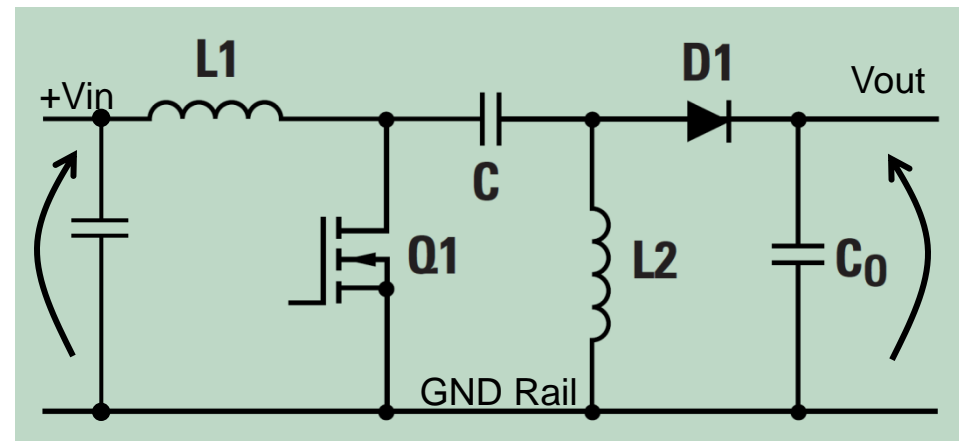
$$V_{out} = V_{in} \times \frac{N_s}{N_p} \frac{D}{(1-D)}$$



Topology Selection Guide

- SEPIC (Single Ended Primary Inductor Converter)
 - Can step up and down (like buck boost) but does not invert the polarity
 - Common in battery operated devices, where depending on the battery charge you may want to either buck or boost
 - Unlike Boost it can be shut-down
 - Transfer function is complex (use WEBENCH for stable design)
 - Therefore typically used when fast transient response is not required
 - Needs just a single low-side switch

$$V_{out} = V_{in} \times \frac{D}{(1 - D)}$$



Control Method Selection Guide

- Voltage mode
 - Cheap and simple; works well for Buck but not suitable for CCM Boost, Buck-Boost, Flyback or SEPIC
 - Poor/slow transient performance under DCM conditions
- Current mode
 - Faster transient response than voltage mode during line voltage transients
 - Good performance in both DCM and CCM
 - Ideal for Boost, Buck-Boost, Flyback and SEPIC in CCM
 - Poor performance when duty is small (e.g. if you step-down too much)
 - Needs slope compensation and leading edge blanking (i.e. bit of a pain!)
- Emulated current mode
 - Similar to current mode but can operate under low duties
 - But based on a mathematic model which will not be perfect
- Constant On Time
 - Cheap and easy and always stable with fast response
 - Better efficiency under low loads (unless pulse skipping used in other control methods)
 - But will have more ripple than other control methods
 - Variable frequency so unpredictable EMI spectrum + harder to design EMI filter

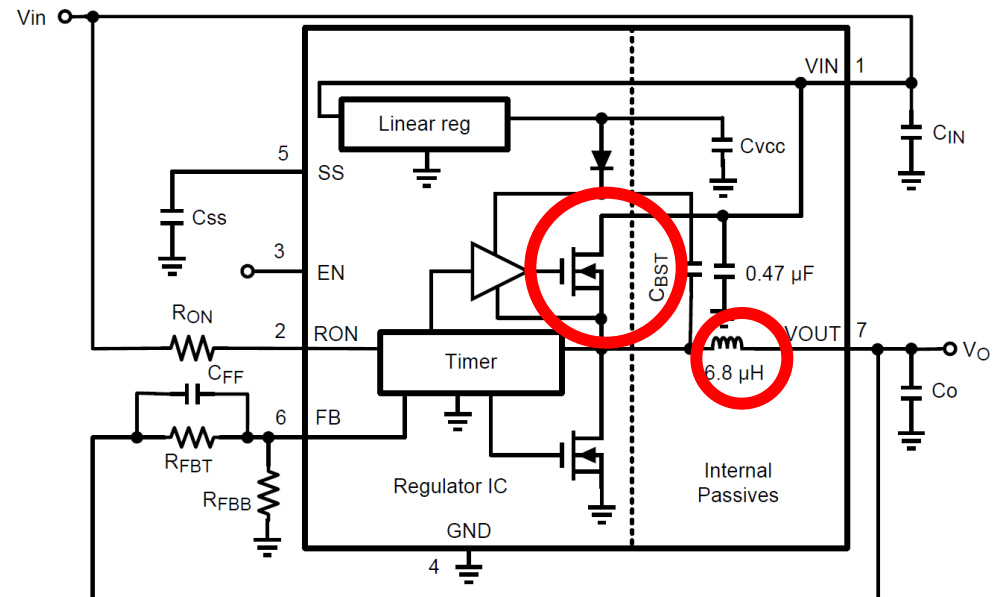
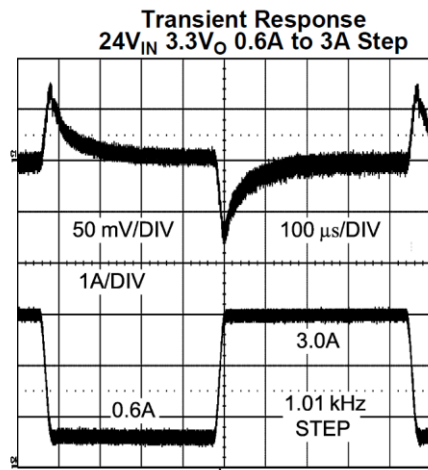
Choosing the Right Switching Frequency

- Our switching frequency (F_s) directly impacts the size of our power supply
 - We saw earlier that the higher the switching frequency the smaller the current ripple on our inductor
 - i.e. the higher the switching frequency, the smaller the inductor
 - This also applies to our output capacitor, so the entire power supply will get smaller
 - This is why the switching frequency of the PSU for small hand held devices needs to be so high
 - There is a limit as to the ripple we can have on our inductor as you must not saturate the inductor → WEBENCH automatically selects a correctly sized inductor
- Our switching frequency directly impacts our efficiency
 - The higher the switching frequency the poorer the efficiency
 - Every time we turn a switch on or off we will waste some energy; these are called Switching Losses → if we switch faster we will have higher switching losses
 - Every time we magnetize and de-magnetize our inductor we will lose some energy in the magnetic material of our inductor; these are called Core Losses → if we switch faster we will have higher core losses
- Of course both of the above will have an impact on cost

Which Device is Best for Your Application



- **Switching Modules** (e.g. LMZ14203)
 - Complete solution with internal switch and inductor in one package
 - Very small foot print + everything optimized
 - Some come with EMC compliance
 - But:
 - more expensive (~ 1.5 to 8 USD)
 - More limited as the value of the inductor is fixed
 - Max current delivery of 20A

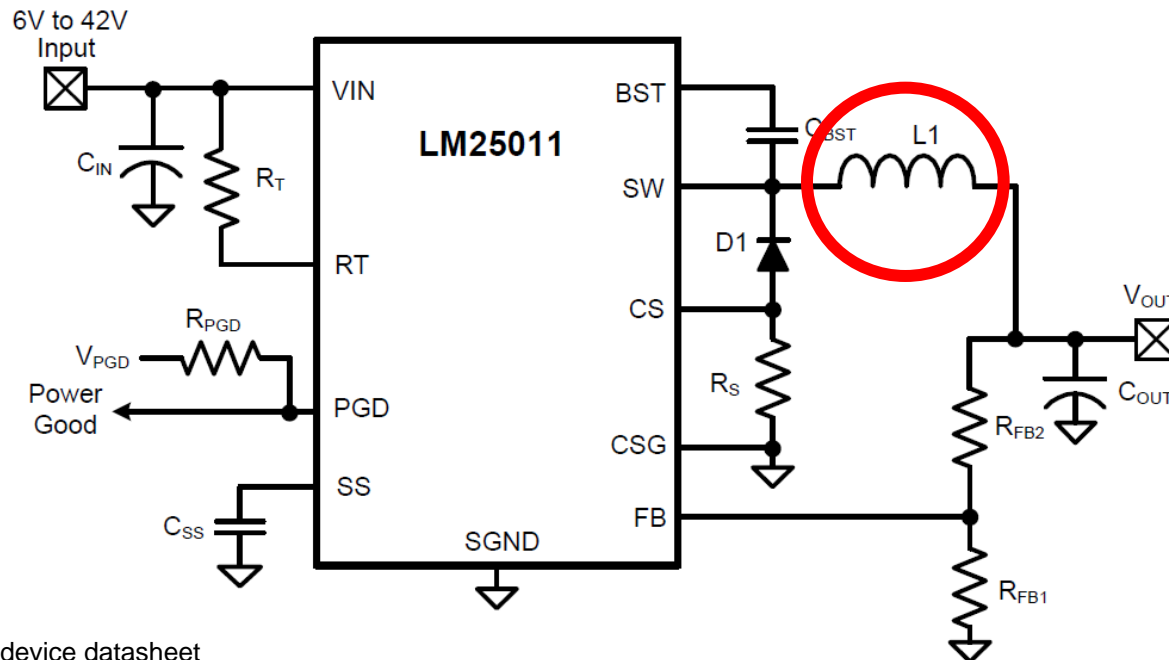


* Images taken from www.ti.com & device datasheet

Which Device is Best for Your Application



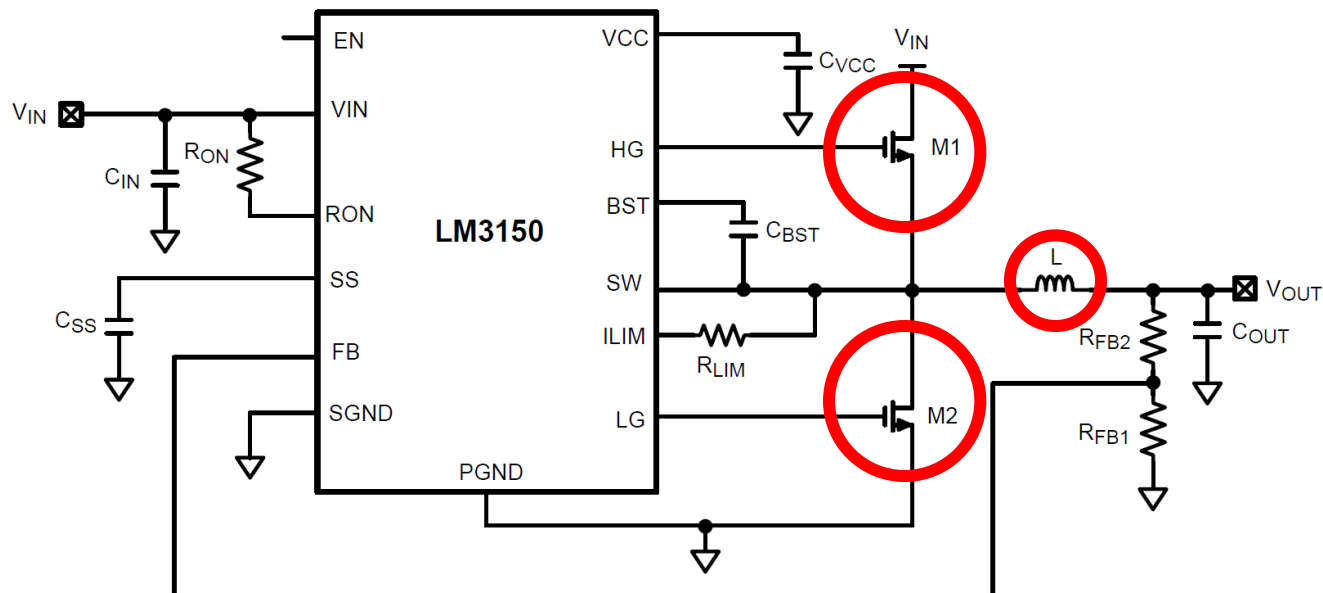
- **Switching Regulators** (e.g. LM25011)
 - Complete solution with internal switch but external inductor
 - Small foot print + switch drive circuitry optimized (but not as small as a module)
 - Much cheaper than power modules but need an inductor
 - Can have some more flexibility due to external components



Which Device is Best for Your Application



- **Switching Controllers** (e.g. LM3150)
 - Just the PWM chip; i.e. no internal switch or inductor
 - Largest foot print + most have gate driver inside but not optimized with the switch
 - You have to select the right switch yourself (or use WEBENCH)
 - V cheap but need an extra switch/inductor/compensation etc
 - Gives you complete flexibility in terms of your design at the expense of more development time, larger foot print, extra components & routing etc



* Images taken from www.ti.com & device datasheet

Quick Summary to Selection Guide

- Which topologies to use for various applications:
 - LDOs → Small currents and limited/fixed voltages, poor efficiency
 - Buck → most common step down
 - Boost → most common step up
 - Buck-Boost/SEPIC → most common for battery operation / step up and down
 - Flyback → when you need multiple voltage or need to step down from large input voltage
- Which control mode to use for various applications?
 - COT → cheap and easy, always stable but variable frequency & ripple
 - Voltage mode → most common in Buck, cheap and easy low component count
 - Current mode → most common for CCM in Boost, Buck-Boost, SEPIC, Flyback, very good performance but needs slope compensation and leading edge blanking (a bit of a pain), not great if duty is very small
 - Emulated Current Mode → like current mode but solved the low duty issue, but model based so it all depends on how accurate the model is

Quick Summary to Selection Guide

- Selecting the switching frequency
 - The higher our F_s , the smaller the PSU but the poorer the efficiency
 - The higher the F_s the smaller the ripple on the inductor → large ripple on inductor could cause saturation and a blown up power supply
 - WEBENCH[®] allows you to automatically optimize this
- Which Device to Select?
 - Switching Modules → (almost) everything internal, smallest foot print, quickest and easiest to set up but more expensive
 - Switching Regulators → Internal switch but external inductor, larger foot print than a module, more flexible due to external components, cheaper (if you don't count the price of the inductor)
 - Switching Controllers → just a PWM controller, so almost everything else is external, largest foot print, largest BoM, development time and routing but most flexible

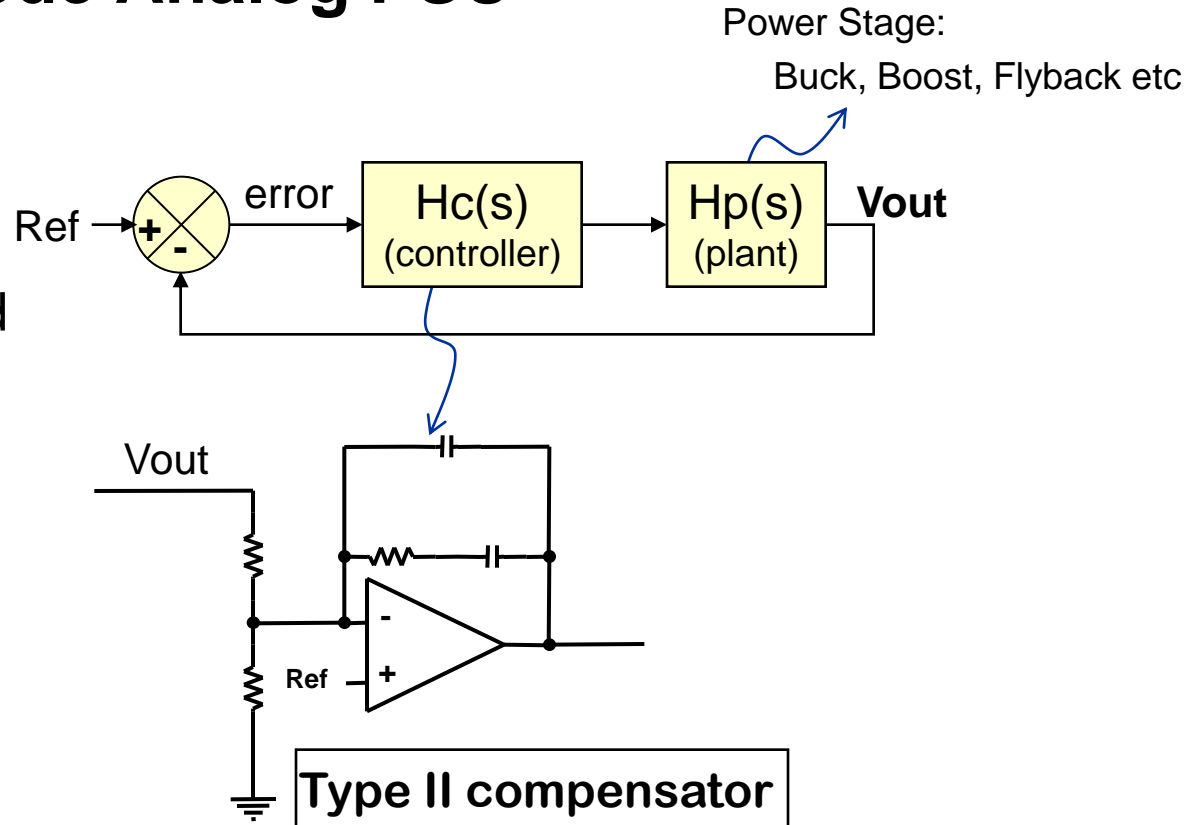
Understanding Bode Plots

- Analog PSUs are (almost) always designed in the frequency domain
 - We modulate our PWM duty with a small sinusoid of a certain frequency (say 10 Hz) and we measure how the gain and phase of this sinusoid is modified by the time it goes through our plant (i.e. PSU)
 - We increase the frequency of our injected sinusoid and measure again, we repeat this for all frequencies of interest (say 1Hz to $\frac{1}{2}$ Fs) and plot the Bode plot

In short we plot the “open loop” gain and phase of the PSU (i.e. its Bode plot) and design the compensator such that we get appropriate gain and phase margins

Typical Voltage Mode Analog PSU

- Typically we tune the compensator by selecting the position of poles and zeros so as to achieve the desirable gain and phase margins
- To do this we need the Transfer Functions $H_c(s)$ & $H_p(s)$

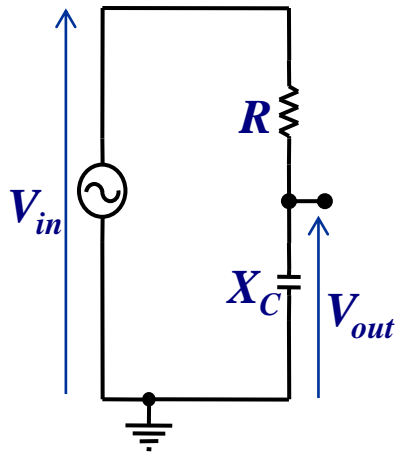


Open loop gain = Gain of the compensator x Gain of the Boost Power stage

Quick Review of Analog Transfer Functions $H(s)$

- Transfer function $H(s)$:
 - Is a mathematical representation of the relationship between the input and the output of our continuous time system
 - In our case $H_p(s)$ is our plant's transfer function (i.e. the power stage) and $H_c(s)$ is our compensator's transfer function
 - For both of the above, we are interested in the relationship between the output voltage and the input voltage:
$$H(s) = \frac{Y(s)}{X(s)} = \frac{V_{out}}{V_{in}}$$
 - It follows, therefore, that if we have the transfer function for our system, then for any given input we can calculate the output
$$Y(s) = X(s) H(s)$$
 - In our case, our inputs will be sinusoidal voltages of various frequencies so that we can plot the Bode plot

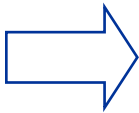
Example: A Simple 1st Order Transfer Function



$$s = \text{Laplace Operator} = j\omega = j2\pi f$$

$$V_{out} = V_{in} \frac{X_c}{(X_c + R)} \quad \text{Where: } X_c = \frac{1}{j\omega C} = \frac{1}{sC}$$

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{\frac{1}{sC}}{\left(\frac{1}{sC} + R\right)}$$



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

• **Observations:**

- Laplace is only a “mathematical trick” used to help us analyze circuits
- s is a function of frequency ω in rad/s or $2\pi f$ in Hz
- As we vary s from $-\infty \rightarrow \infty$ the “numerical value” of $H(s)$ varies
- When $s = -1/RC$ “Numerical Value” of $H(s)$ will become ∞ . This value of s is called the “POLE” of our system
 - IMPORTANT: this does not necessarily mean that the output of our system becomes infinite. This only means that the “numerical value” of our transfer function will become infinite
 - To find the amplitude of the output of our system we need to calculate our “gain”. We will do this next
 - For a stable system all poles must always have a negative value i.e. be on the left hand side of the s-plane

Calculating Gain and Phase from H(s)

- Transfer function \rightarrow
$$H(s) = \frac{1}{(1 + j 2\pi f RC)}$$

- Gain: $\sqrt{\text{Re}^2 + \text{Im}^2} \rightarrow$
$$|H(s)| = \frac{1}{\sqrt{(1^2 + (2\pi f RC)^2)}}$$

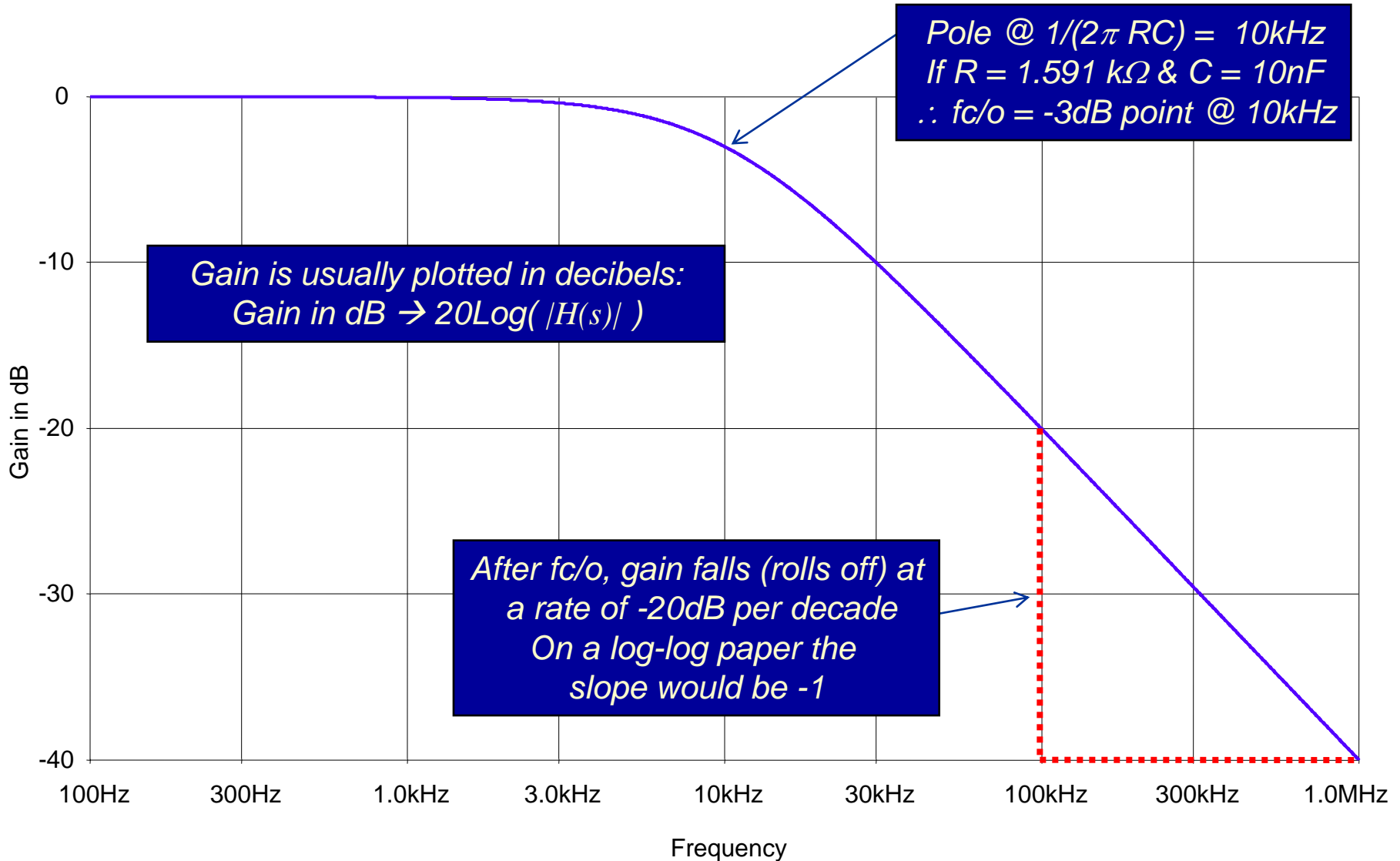
- Phase:

$$\phi = \tan^{-1}\left(\frac{\text{Im}}{\text{Re}}\right) \quad \&$$

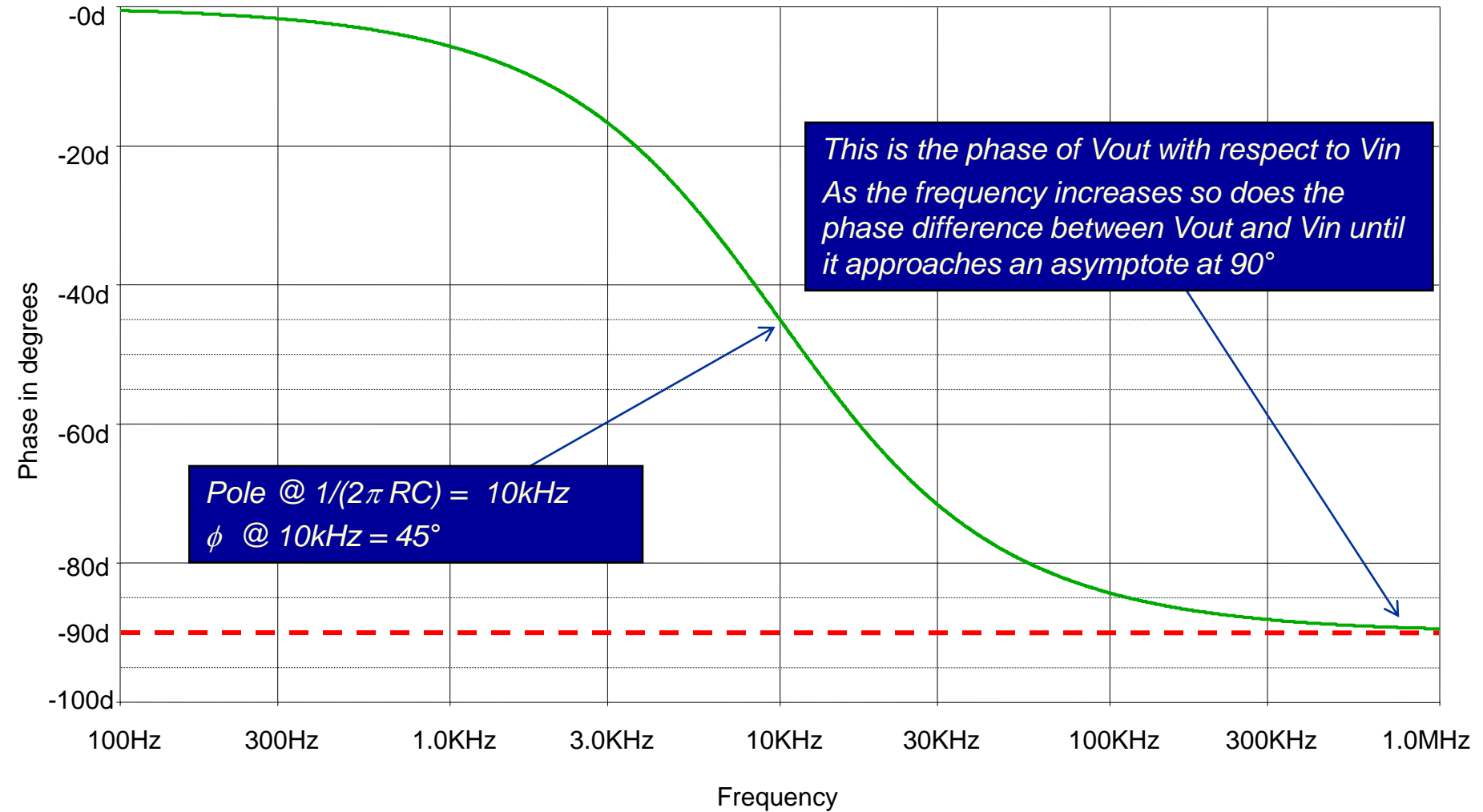
$$\tan^{-1}\left(\frac{Z_1}{Z_2}\right) = \tan^{-1}(Z_1) - \tan^{-1}(Z_2) \rightarrow \tan^{-1}\left(\frac{0}{1}\right) - \tan^{-1}\left(\frac{2\pi f RC}{1}\right) = -\tan^{-1}(2\pi f RC)$$

- We can now plot Gain and Phase with respect to the frequency

Gain Plot of the 1st Order (single pole) RC Circuit



Phase Plot of the Simple 1st Order RC Circuit



Poles and Zeros

- The circuit in the previous slide had a single pole
 - Where “pole” was defined as the value of s where the **denominator** of $H(s) \rightarrow 0$
 - This would lead to the numerical value of $H(s) \rightarrow \infty$
 - Every pole in our system (located at a negative value of s) causes the gain to fall (roll-off) at a rate of -20dB per decade and
 - Introduces a phase lag of 90 degree
- If we have a transfer function such that its “**numerator**” can become 0 for a certain value of s then we have a “**zero**” on our transfer function:

$$H(s) = \frac{(s + \alpha)}{(s + \beta)}$$

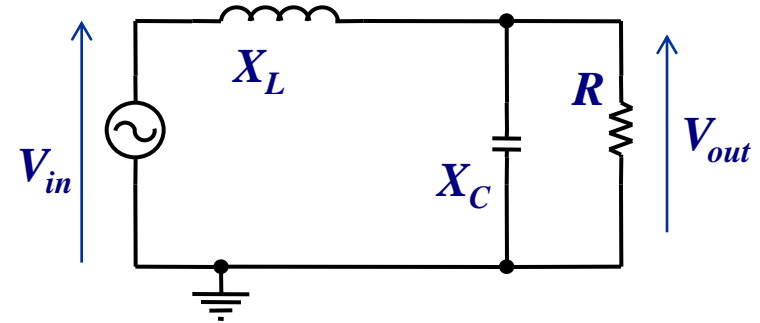
← Zero @ $-\alpha$ &
← Pole @ $-\beta$

- Every zero in our system (located at a negative value of s) causes the gain to rise at a rate of 20dB per decade and
- Introduces a phase lead of 90°

H(s) of a 2nd Order System

- For BDP-106 @ full load:
 - L = 22μH C = 440μF & R = 1.8Ω
 - ESR is assumed to be 0 for now!
 - Transfer Function Hp(s):

$$H_p(s) = \frac{1}{s^2 LC + s\left(\frac{L}{R}\right) + 1}$$



- The denominator of Hp(s) is a 2nd Order Polynomial

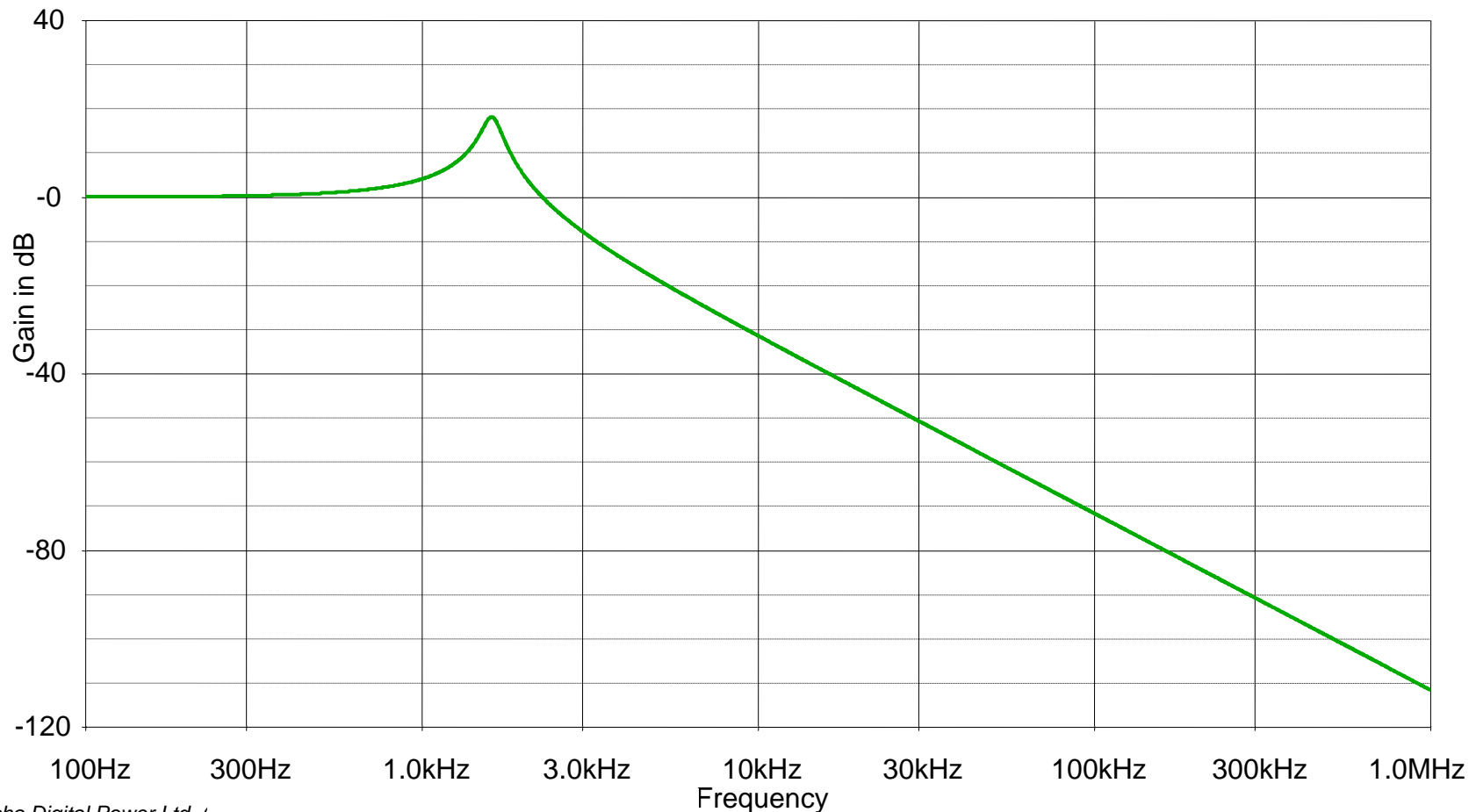
- It has 2 poles @

$$\frac{1}{2\pi\sqrt{LC}}$$

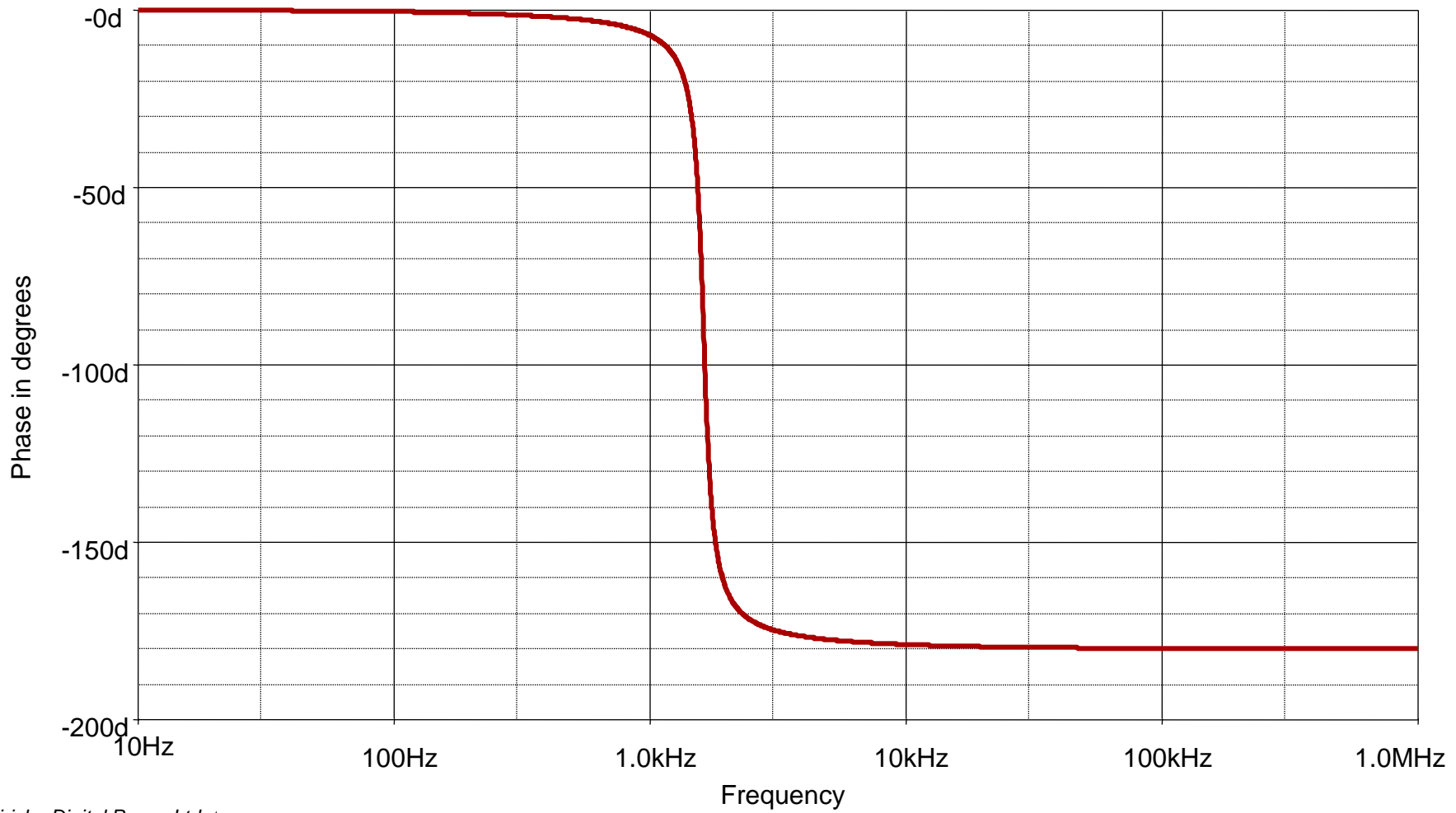
- This is the resonance frequency F_r of our system
- At resonance we “may” see a bump on our gain plot. The size of the bump is dependant on the load resistor (as well as other things)
- We have two poles so we call this a 2nd order system

Gain Plot of the 2nd Order (2 pole) LC Circuit

- **Exercise:** Calculate F_r + estimate “roll-off” in dB/decade after F_r
- What is the maximum phase? Is it leading or lagging?



Phase Plot of the 2nd Order (2 pole) LC Circuit

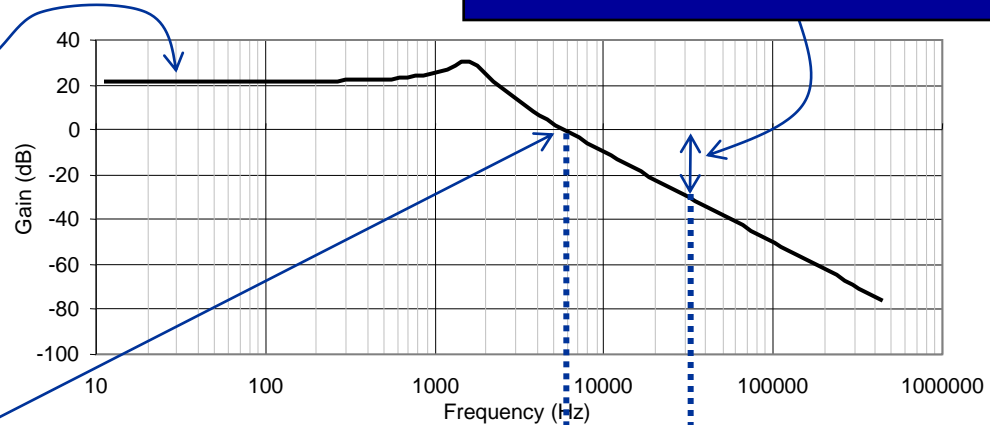


Gain Margin, Phase Margin and Crossover Frequency

- We need to define a few variables to allow us to design a stable power supply

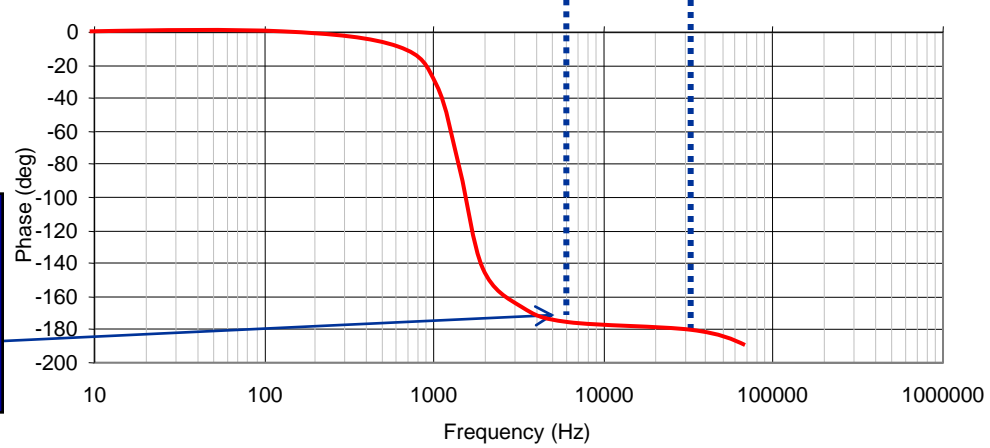
Gain Margin (GM) = How much the gain is below 0 dB when Phase = 180°

DC Gain = say 21dB



*Crossover frequency F_x
i.e. frequency at which gain crosses 0 dB \cong 6kHz
Important:
Slope @ F_x = -40 dB/decade*

*Phase Margin (ϕ_M)
i.e. Phase left before reaching -180°
when the gain = 0 dB
In this case \cong 10°*



Power Supply Stability Criterion

- When considering the **Open loop** frequency response:
 - 1 - At crossover frequency (F_x), the Phase Margin (ϕ_M) must be more than 40° to 45°
 - $\phi_M \rightarrow$ the amount by which the phase shift is less than 180° at F_x
 - The lower the phase margin, the faster the transient response (in time domain) but the higher the risk of instability
 - 2 - At F_x , the slope of the open loop gain plot should be no more than -20 dB/decade
 - PSU jargon
 - -20 dB/decade \rightarrow -1 slope
 - -40 dB/decade \rightarrow -2 slope
 - 3 - Gain Margin G_M should be at least 10 dB
 - $G_M \rightarrow$ The amount by which the gain is lower than 0 dB when the phase = 180°

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