# WEBENCH® Power Designer

# Power Supply Design Made Easy

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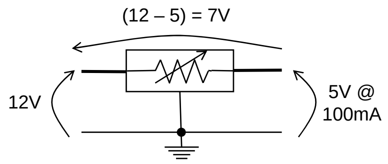
## Introduction to Power Management

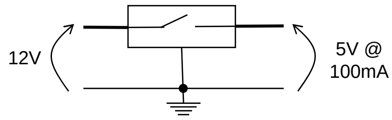
- The voltage of the power supply and/or battery feeding our PCB is seldom at the correct level that we need for our circuitry:
  - Example: A standard desktop PC in Europe is fed with 230V but the motherboard needs: +12V, -12V, +5V and +3.3V
- We need to step up and step down (convert) our voltage levels 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 Vin = 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

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# 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 Vin 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 (Vout) and automatically changing this variable resistor value such that Vout remains constant
- Advantages:
  - Cheap & easy, quiet, small
- Disadvantages:
  - Very inefficient, low current only, limited Vin and Vout ranges




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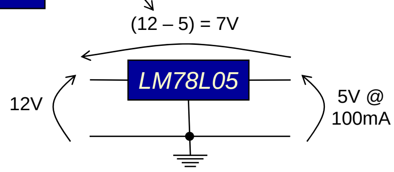
# So What is Wrong with Linear Regulators?

- 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*

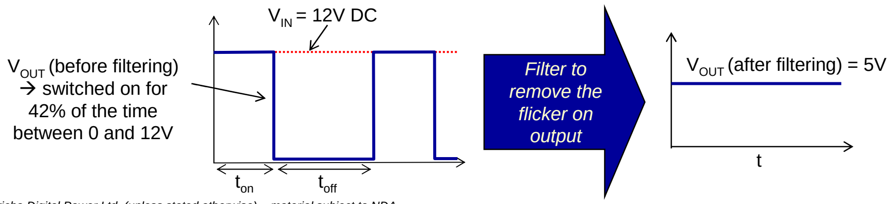



- Output Power = 5V x 100mA = 500mW
- Power Loss in regulator = 7V x 100mA = 700mW
- Efficiency = 500mW / (1200mW) = 41.6% !

*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

*WEBENCH® to the rescue!*

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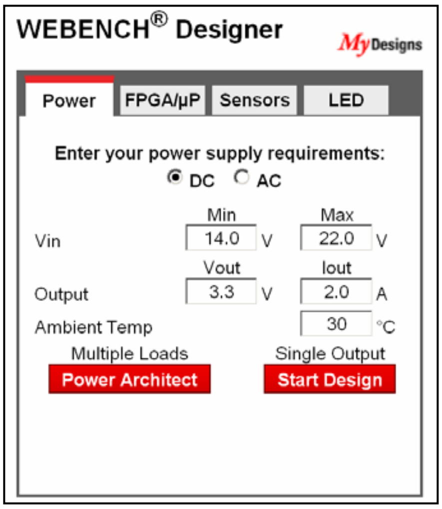
# Introduction to WEBENCH

- WEBENCH is a free, automatic tool that allows engineers to create reliable power supply circuits over the internet in minutes
- The user inputs circuit performance requirements and specifications and the WEBENCH toolset designs all the necessary circuitry
- Currently the following tools are available:
  - WEBENCH Power Designer
  - WEBENCH LED Designer
  - WEBENCH Sensor Designer
  - WEBENCH Active Filter Designer
  - WEBENCH Amplifier Designer
  - WEBENCH EasyPLL




*In this session we will concentrate on WEBENCH Power Designer*





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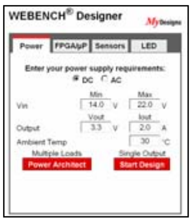
# Designing with WEBENCH

Input Spec

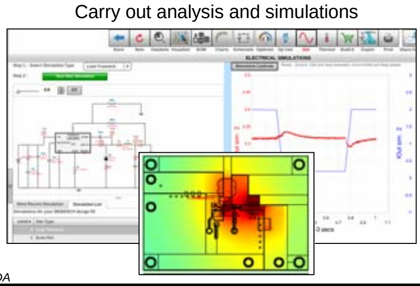


Filter and choose a Part

Optimize Design

Order parts and Build It!

Carry out analysis and simulations



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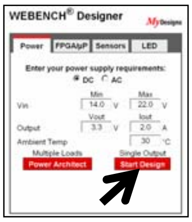
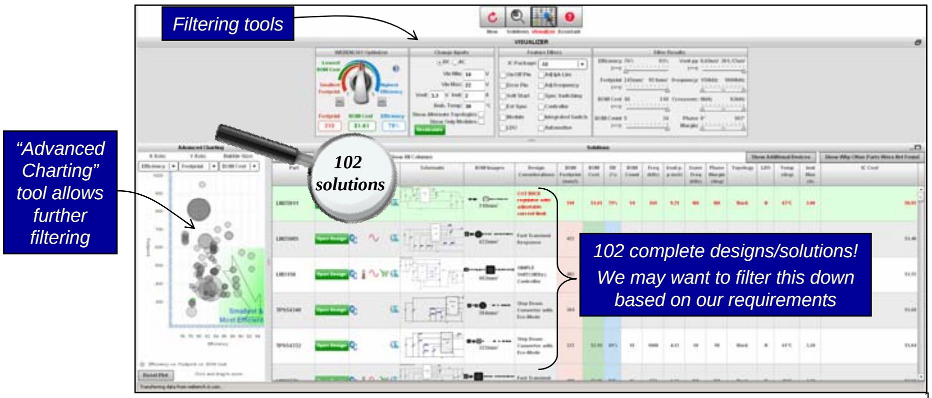
TEXAS INSTRUMENTS

# Design Using WEBENCH

- Input your specification and then press Start Design
  - WEBENCH will then open the “Visualizer” which provides you with a list of possible designs (sometimes over 100 designs) using different parts and topologies




WEBENCH Visualizer



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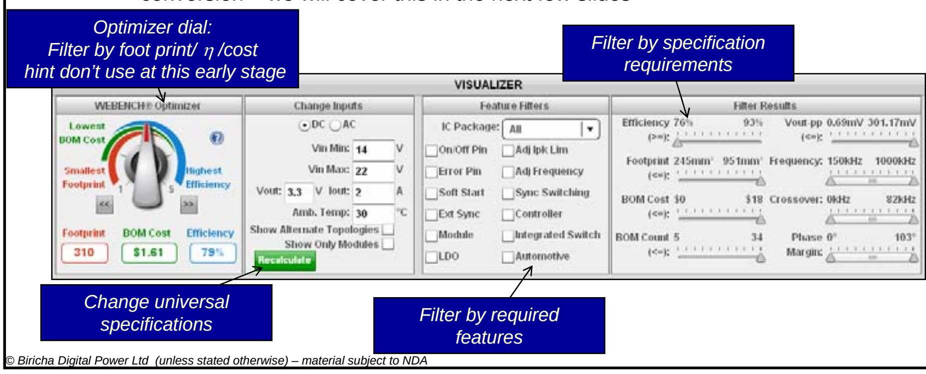
TEXAS INSTRUMENTS

# Design Using WEBENCH

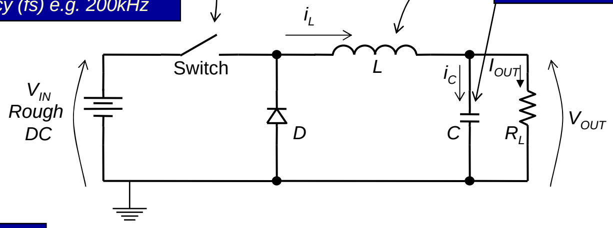
- Using the Visualizer’s filtering tools we will narrow down the designs to a smaller subset that will fit our requirements and then choose a part
  - WEBENCH will present you with many possible designs (sometimes over 100); so we have a few different filtering tools to help us narrow down the list
  - Before we can make an informed decision on how to select the best design for our application, we need to understand some basic fundamentals of power conversion – we will cover this in the next few slides



# Simple Buck Converter and Basic Terminology

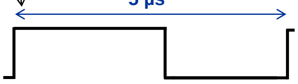
*The switch is usually a MOSFET and we switch it on and off at our switching frequency (fs) e.g. 200kHz*

*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 Ts of 1/200kHz = 5 µs*



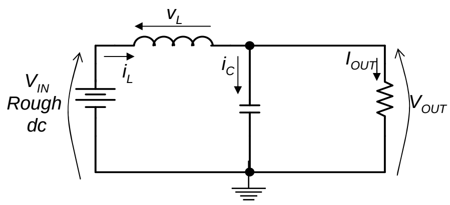

$$D = \frac{\text{"On" time of switch}}{\text{Switching Period}} = \frac{t_{on}}{T_S}$$



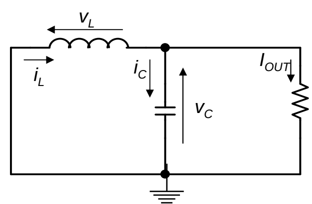



# Simple Buck Converter and Basic Terminology

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

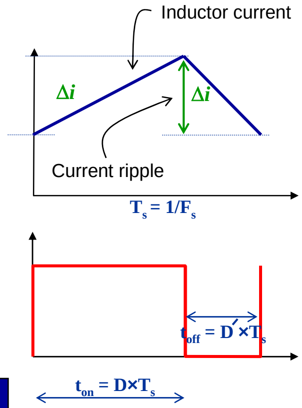



- When the switch is OFF
  - Replace switch with open circuit
  - Diode is forward biased (replace with short circuit)
  - Inductor current will fall linearly



# 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*

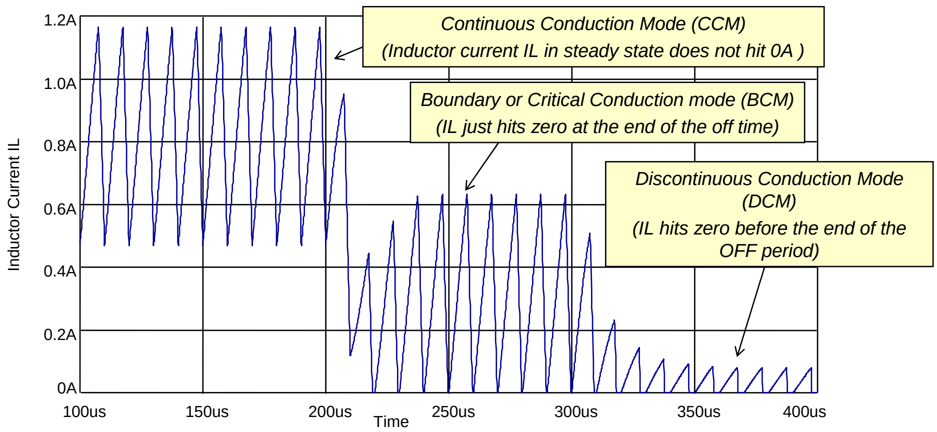
*If we switch faster we can use a smaller inductor*

*(we will talk about switching losses later)*






# What Do We Mean by Conduction Mode?




*Whether or not the inductor current at steady state is in DCM or CCM will have implications on how our power supply behaves*

*WEBENCH will look after this for us but we need to understand the terminology used*

## WEBENCH Power Designer*

- You can use WEBENCH to create customized power supplies or DC-DC converters for your circuits
  - This environment gives you end-to-end power supply designs and prototyping tools
- WEBENCH tools enable you to solve switching-power-supply design problems before you build your prototype
  - This alleviates the time and trouble associated with traditional power supply design methods
- Included in the WEBENCH toolset is a device selection tool
  - This tool helps you find the best switching regulator or MOSFET controller for your power supply circuit. It even selects the most appropriate passive components

* Taken from http://www.ti.com/lsds/ti/analog/webench/power.page





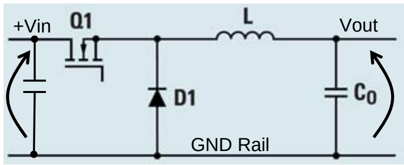

## Topologies Used in WEBENCH

- WEBENCH supports the following topologies
  - Buck
  - Boost
  - Inverting Buck-Boost
  - SEPIC
  - Flyback
- These topologies cover almost all your point of load (POL) needs
  - There are other topologies not supported by WEBENCH but these are for very high power off-line power supplies and rarely used for POL power distribution within a PCB
- WEBENCH automatically recommends the most suitable topology for you
  - But we will compare these topologies so that you have a better insight as to which topology is most suitable for your application

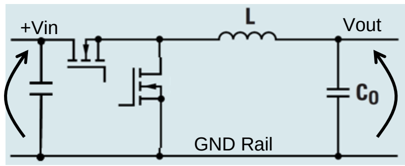
# Topology Selection Guide

$$Vout = Vin \times D$$

- 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




Normal buck




Synchronous buck

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



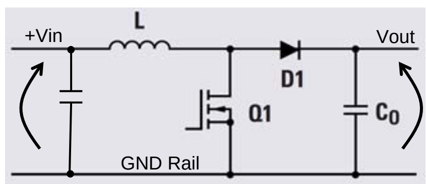




# Topology Selection Guide

- 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!)

$$Vout = Vin \times \frac{1}{(1 - D)}$$

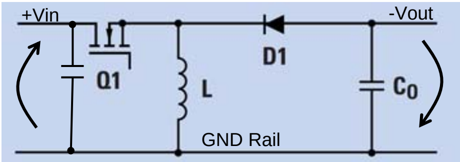



* Image taken from www.ti.com/lit/sg/sluw001e/sluw001e.pdf

## 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 Vout always has a reverse polarity with respect to the Vin
    - 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

$$Vout = Vin \times \frac{D}{(1-D)}$$




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

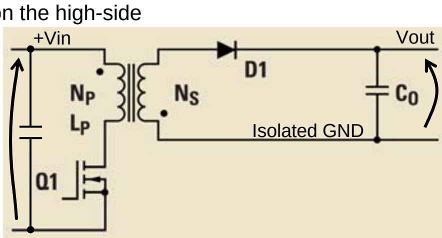




## Topology Selection Guide

- 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

$$Vout = Vin \times \frac{N_S}{N_P} \frac{D}{(1-D)}$$

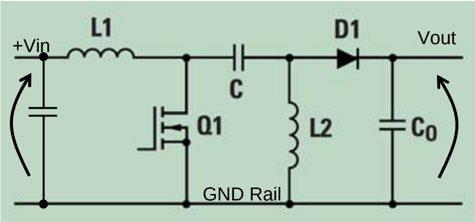



* Image taken from www.ti.com/lit/sg/sluw001e/sluw001e.pdf

# 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

$$Vout = Vin \times \frac{D}{(1-D)}$$




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







# Control Method Selection Guide

- WEBENCH uses the following control methods
  - 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 (Fs) 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

*WEBENCH can optimize your design for efficiency or size or cost depending on your requirements*






# Choosing the Right Part/Device for Your Application

- There are 4 major categories of ICs that WEBENCH designs with:
  - LDOs
    - Not recommended for good efficiency, output current above 500mA or large voltage drops
  - Switching Power Modules
  - Switching Regulators
  - Switching Controllers
- Within seconds WEBENCH calculates over 100 designs with this parts
- Which one is the most suitable for your application?
  - We will now quickly go through these categories
  - Once you know what the differences are you can very quickly use WEBENCH's filtering tools to narrow down these 100 designs to just a handful most suitable for your application

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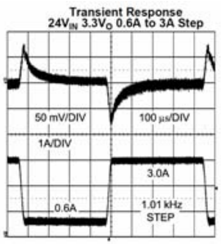
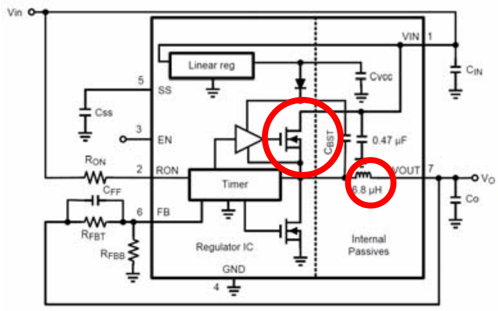
# Which Device is Best for Your Application


- **<u>Switching Modules</u>** (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









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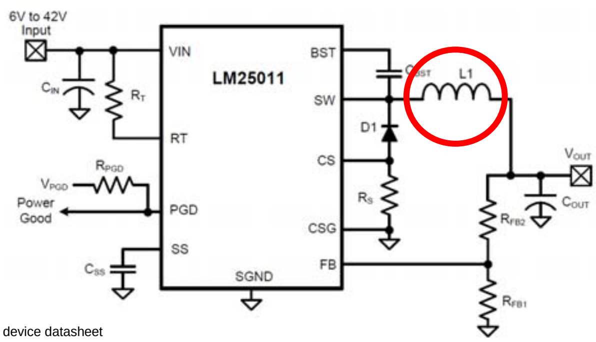
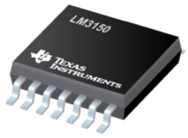
# Which Device is Best for Your Application

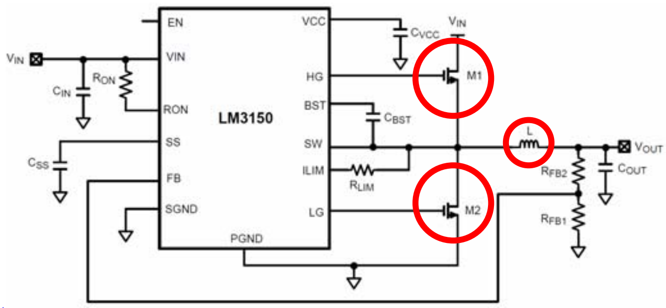

- **<u>Switching Regulators</u>** (e.g. LM25011)
  - Complete solution with internal switch but external inductor
  - Small foot print + switch drive circuitry optimized (but not as small as a module)
  - Much cheaper than power modules but need an inductor
  - Can have some more flexibility due to external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



# Which Device is Best for Your Application




- **<u>Switching Controllers</u>** (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

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TEXAS INSTRUMENTS

# Quick Summary to Selection Guide

- Selecting the switching frequency
  - The higher our Fs, the smaller the PSU but the poorer the efficiency
  - The higher the Fs 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

*We are now ready to move on to Step 3 of designing with WEBENCH*





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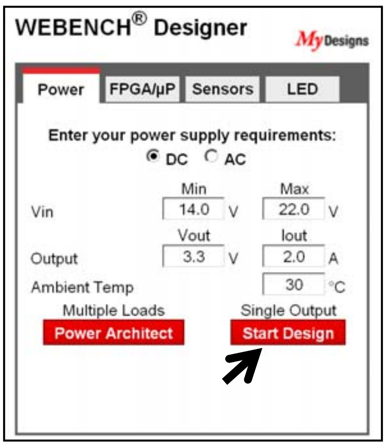
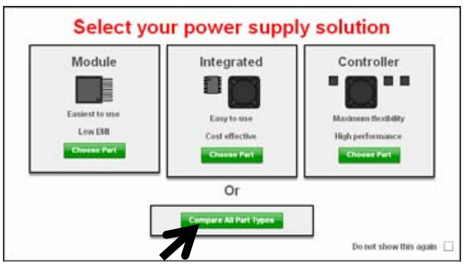
TEXAS INSTRUMENTS

# Hands-On Demo 1 - Fundamentals

- Step 1: Input your specification:
  - Vin = 22V, Vout = 3.3V, Iout = 2A, Ambient Temp = 30º



# Hands-On Demo 1 - Fundamentals

- Step 2: WEBENCH will create many solutions (~102) and display all of them in the Visualizer
  - We now need to filter these ~102 designs to a smaller subset that meets our design objectives



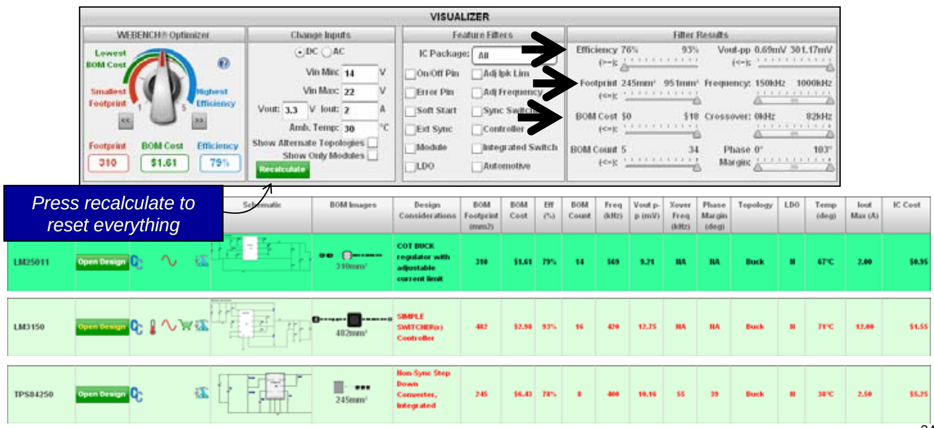




*Note your results may be different*

# Hands-On Demo 1 - Fundamentals

- Using the filtering tools of the Visualizer let us first see best case scenarios for:
  - Lowest Cost → LM25011 – total BoM Cost = 1.61 USD
  - Highest efficiency → LM3510 - $\eta$ = 93%
  - Smallest footprint → TPS84250 – Total footprint = 245mm² (i.e. ~1.5cm x 1.5cm)



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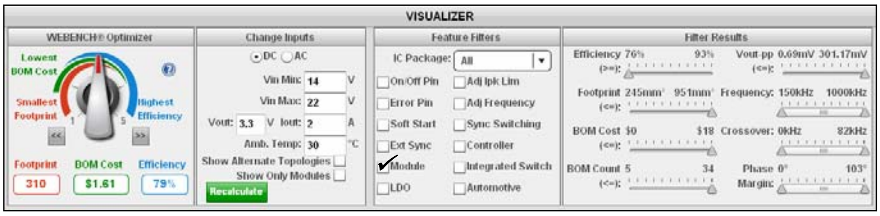
## Hands-On Demo 2 - Fundamentals

- Let us design a new power supply
  - WEBENCH starts with around 102 designs
  - We are going to assume that for this design, we are short of space and time, but cost is not a big issue
    - Therefore we would like the quickest and smallest possible solution → use "Switching Modules"
  - When we filter down to Switching Modules only, the number of solutions will fall from 102 to 11 (next slide)





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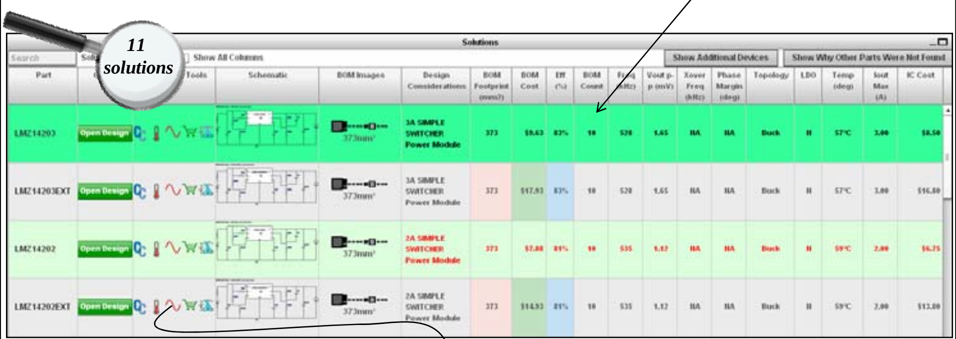
## Hands-On Demo 2 - Fundamentals

*The first (in green) on the list is WEBENCH's top choice*




*WEBENCH will do Circuit Calculations*

*WEBENCH will do Thermal Simulations*

*Circuit Simulations*

*Can export schematic to CAD package*

*Buy it option: can buy an entire kit including PCB from Digikey*

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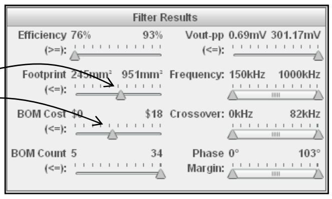
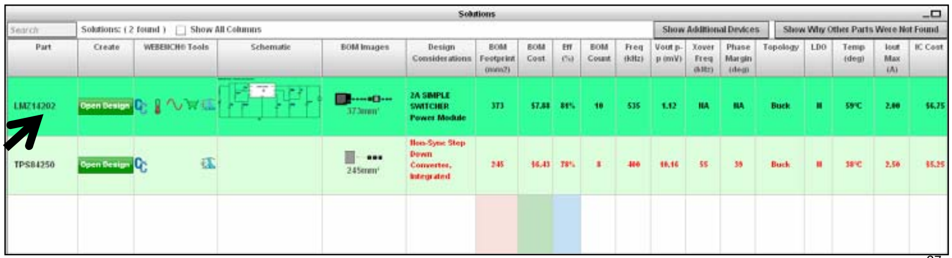
# Hands-On Demo 2 - Fundamentals




- Let us now filter down with 2 more requirements:
  - Max PCB footprint = 2.5cm x 2.5cm = 625mm$^2$
  - Total cost (for 1k units) less than 8.5 USD
- We now see that we have narrowed down our solutions to only 2:
  - LMZ14202 & TPS84250
  - LMZ part is being recommended. It has all the simulations tools and Buy It tools available so we could select this design → Let us look at the datasheet first
  - **IMPORTANT: Please DO NOT press Open Design yet; we will do this shortly**



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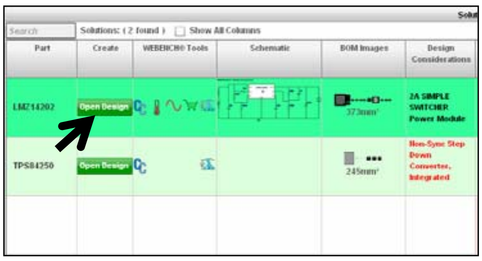
# Hands-On Demo 2 - Fundamentals

- Step 3: "Open Design" (you may have to log in)
  - In Steps 1 & 2 we typed in our specification and then filtered down our solutions to just one or two
  - Now we select the most appropriate by pressing "Open design"
  - We can now optimize our selected design even further to make find a best fit solution for our application



# Hands-On Demo 2 - Fundamentals

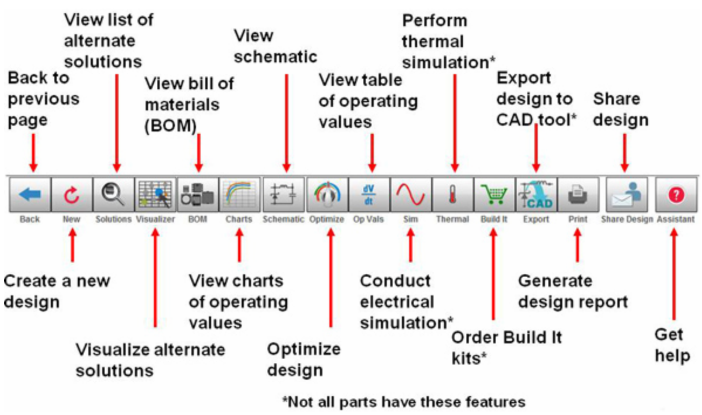
- Step 4: Modifying/Optimising our Design using WEBENCH Dashboard
  - Depending on the device used some of the options on this page will be different
  - We are using a fully integrated "Module" so we don't have that many options, but this is a good start; we will explore more complicated designs later





# WEBENCH Dashboard and Controls

- Dashboard navigation icons after opening the design




Taken from: http://www.ti.com/lsds/ti/analog/webench/help-overview.page#start

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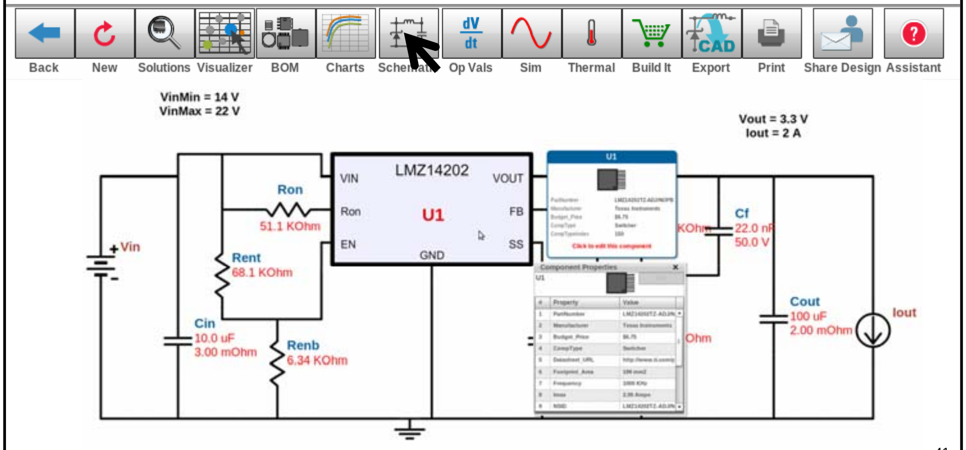
# Hands-On Demo 3 – The Schematic

- Let us look at the Schematic first
  - From the navigation icons on top of the page click on the schematic
    - If you further click on a component you will get more information





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# Hands-On Demo 4 – Operating Values


*You can change the operating point and WEBENCH will recalculate all these values*

Modify Operating Point

Vin: 22 Iout: 2.0 Recalculate

| Name | Value | Category | Description |
|---|---|---|---|
| Vout p-p | 1.12mV | Op_Point | Peak-to-peak output ripple voltage |
| Vout OP | 3.3V | Op_Point | Operational Output Voltage |
| VIN_OP | 22V | Op_Point | Vin operating point |
| Total Pd | 1.51W | Power | Total Power Dissipation |
| Total BOM | 7.88$ | | Total BOM Cost |
| Pout | 6.6W | General | Total output power |
| Mode | CCM | General | Conduction Mode |
| M1 Irms | 0.98A | Current | Q Iavg |
| M Vds Act | 0.12V | General | Voltage drop across the MosFET |
| Iin Avg | 0.36A | Current | Average input current |
| IOUT_OP | 2A | Op_Point | Iout operating point |
| ICThetaJA | 19.3degC/W | Op_Point | IC junction-to-ambient thermal resistance |
| IC Tolerance | 0.02V | General | IC Feedback Tolerance |
| IC Tj | 59.0degC | Op_Point | IC junction temperature |
| IC Ipk | 2.28A | Current | Peak switch current in IC |
| Frequency | 535KHz | General | Switching frequency |
| FootPrint | 373mm2 | General | Total Foot Print Area of BOM components |
| Efficiency | 81.4% | Op_Point | Steady state efficiency |
| Duty Cycle | 16.2% | Op_Point | Duty cycle |

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## Hands-On Demo 4 – Operating Values

- What is the efficiency, duty and conduction mode if we run at 14V?

Modify Operating Point

Vin: 14 Iout: 2.0 Recalculate

| Name | Value | Category | Description |
|---|---|---|---|
| Vout p-p | 1.00mV | Op_Point | Peak-to-peak output ripple voltage |
| Vout OP | 3.3V | Op_Point | Operational Output Voltage |
| VIN_OP | 14V | Op_Point | Vin operating point |
| Total Pd | 1.20W | Power | Total Power Dissipation |
| Total BOM | 7.88$ | | Total BOM Cost |
| Pout | 6.6W | General | Total output power |
| Mode | CCM | General | Conduction Mode |
| M1 Irms | 1.20A | Current | Q Iavg |
| M Vds Act | 0.12V | General | Voltage drop across the MosFET |
| Iin Avg | 0.55A | Current | Average input current |
| IOUT_OP | 2A | Op_Point | Iout operating point |
| ICThetaJA | 19.3degC/W | Op_Point | IC junction-to-ambient thermal resistance |
| IC Tolerance | 0.02V | General | IC Feedback Tolerance |
| IC Tj | 53.2degC | Op_Point | IC junction temperature |
| IC Ipk | 2.25A | Current | Peak switch current in IC |
| Frequency | 535KHz | General | Switching frequency |
| FootPrint | 373mm2 | General | Total Foot Print Area of BOM components |
| Efficiency | 84.6% | Op_Point | Steady state efficiency |
| Duty Cycle | 25.4% | Op_Point | Duty cycle |





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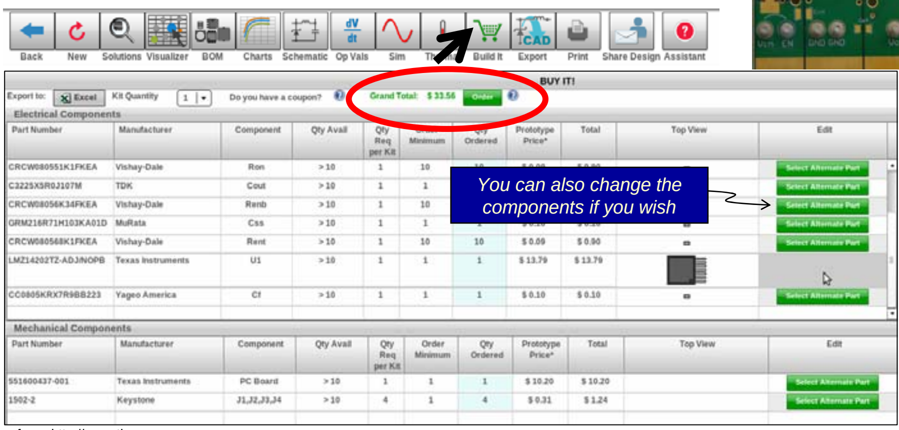
TEXAS INSTRUMENTS

## Hands-On Demo 5 – Built It® Tool

- We will talk about simulation capabilities of WEBENCH in another design example
  - For now let us finalize our design and order a custom prototype based on our design (including the PCB) with just one click!




Taken from: http://www.ti.com

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TEXAS INSTRUMENTS

# WEBENCH Optimization Tips and Tricks

- In the previous slides we designed a Buck converter starting from a specification to a prototype within minutes
- In the process we became familiar with some of the most important WEBENCH tools
  - Designer, Visualizer, filtering tools and Dashboard
  - Within Dashboard we used
    - Schematic tool
    - Operating Values
    - Built it tool
- We will now design a more complicated power supply and become familiar with the Optimization tools available within WEBENCH




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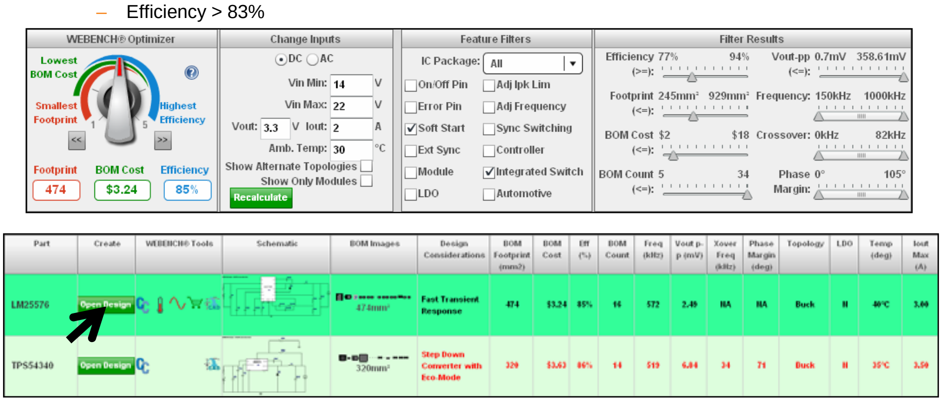
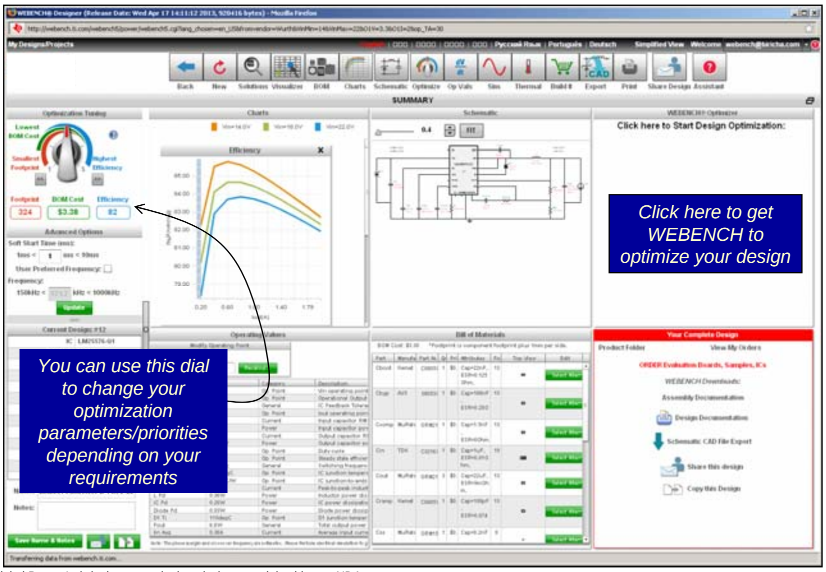
# Hands-On Demo 6 - Optimization Tips and Tricks

- Let us design a power supply with the following requirements:
  - Vin 14 – 22V; Vout 3.3 @ 2A
  - Must have Soft Start & integrated switch and full WEBENCH simulation capability
  - Foot print <270 mm$^2$
  - Max BoM cost < 3.50 USD
  - Efficiency > 83%



# Hands-On Demo 6 - Optimization Tips and Tricks

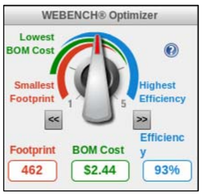




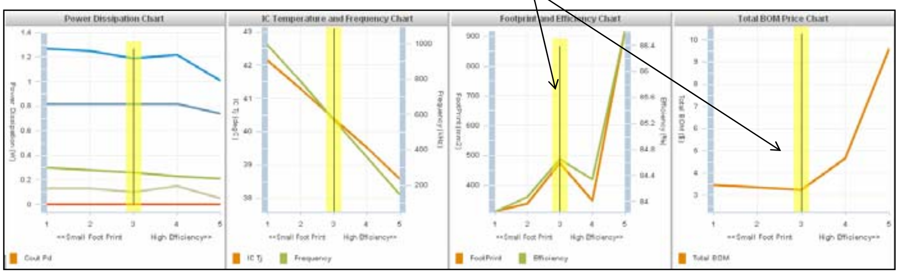


# Hands-On Demo 6 - Optimization Tips and Tricks

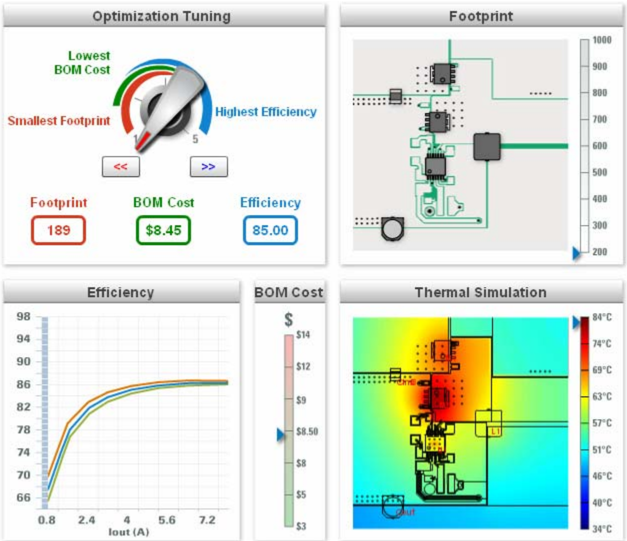
- WEBENCH calculates many different designs based on the selected part (LM25576) and displays the top 5 based on the position of the Optimizer dial
  - Dial set to 3 usually gives the best compromise between efficiency and size (Pls. Don't change from this position for this exercise)




*The yellow line represents the position of the dial; we can see that by setting the dial to 5 we will get a significant improvement in efficiency but a much larger footprint*



# Optimizer Dial




Images taken from www.ti.com





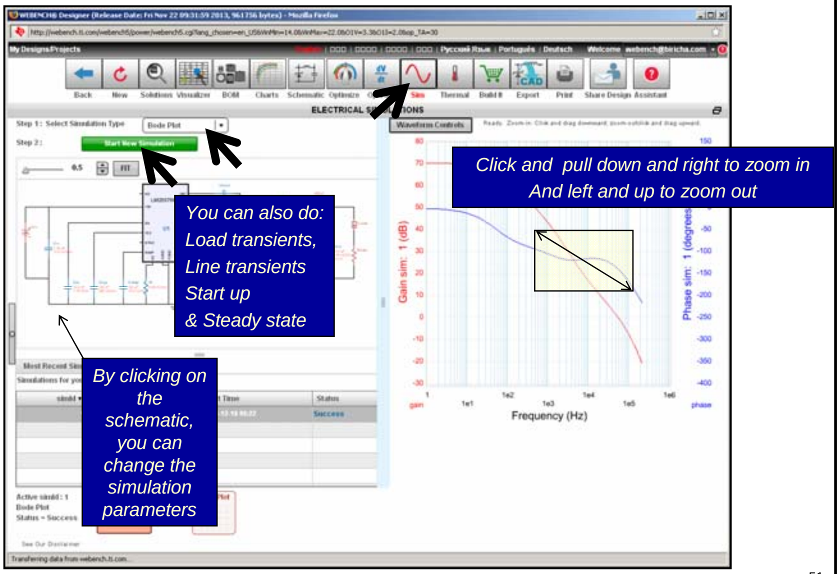


# Optimizer Dial

| Optimization Setting | Frequency | Component Selection | Summary |
|---|---|---|---|
| 1 – Smallest footprint | Highest | • Smallest footprint<br>• Don't care about cost | Smallest size but lowest efficiency |
| 2 – Lowest cost | High | • Lowest cost | High frequency means smaller / cheaper components |
| 3 – Balanced | Medium | • In stock<br>• Low cost | Balanced approach using IC's middle frequency |
| 4 – High efficiency | Low | • Low DCR, ESR, Vf<br>• Low cost | Higher efficiency, with low cost but larger parts |
| 5 – Highest efficiency | Lowest | • Low DCR, ESR, Vf<br>• Don't care about cost | Highest efficiency but largest parts |

Table taken from http://www.ti.com/lsds/ti/analog/webench/optimizer.page

## Hands-On Demo 7 – Simulation Tool – Bode Plots









## Understanding Bode Plots

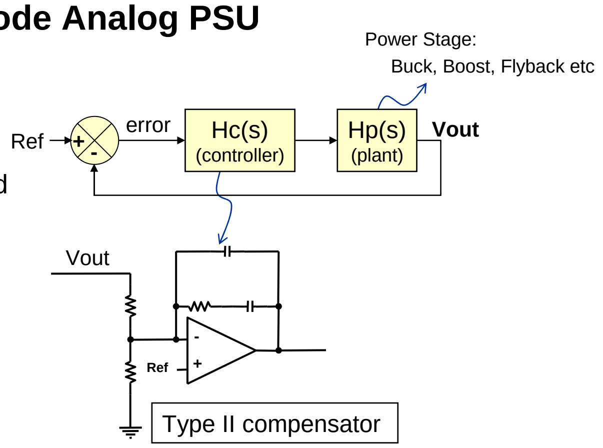
- Analog PSUs are (almost) always designed in the frequency domain
  - We modulate our PWM duty with a small sinusoid of a certain frequency (say 10 Hz) and we measure how the gain and phase of this sinusoid is modified by the time it goes through our plant (i.e. PSU)
  - We increase the frequency of our injected sinusoid and measure again, we repeat this for all frequencies of interest (say 1Hz to ½ 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 Hc(s) & Hp(s)




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

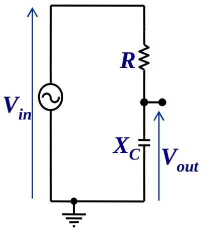





## Quick Review of Analog Transfer Functions H(s)

- 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 Hp(s) is our plant's transfer function (i.e. the power stage) and Hc(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




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

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

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

- **Observations:**
  - Laplace is only a "mathematical trick" used to help us analyze circuits
  - $s$ is a function of frequency $\omega$ 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 $\infty$. 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 → $H(s) = \frac{1}{(1 + j\,2\pi f\,RC)}$

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

- 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

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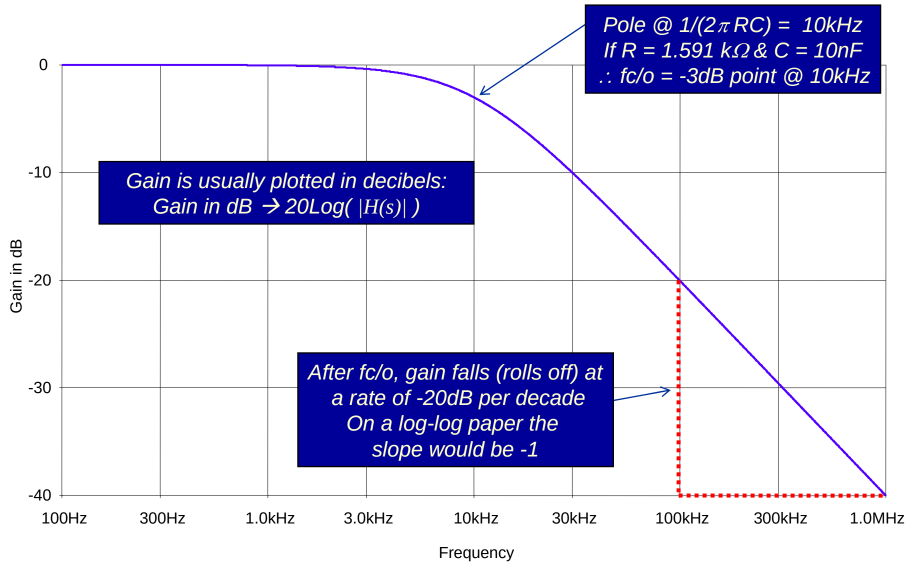
## Gain Plot of the 1st Order (single pole) RC Circuit





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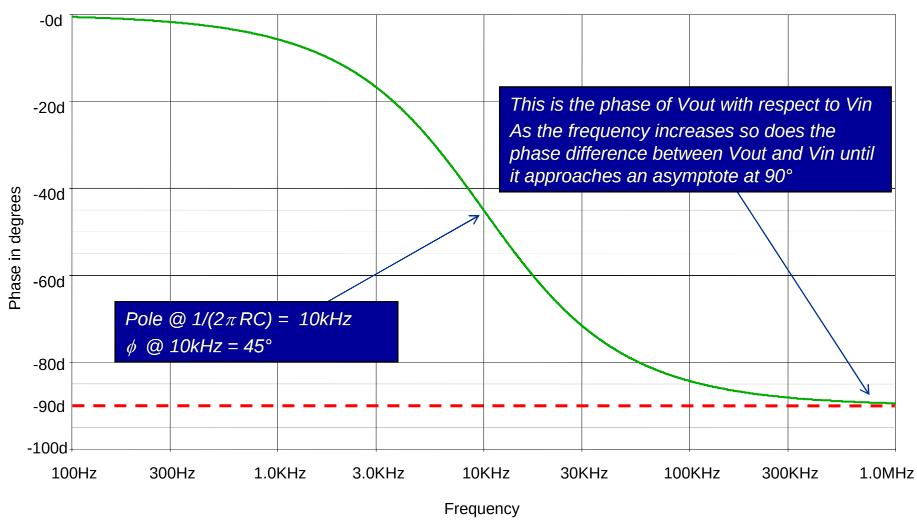
## Phase Plot of the Simple 1st Order RC Circuit



# 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) → 0
  - This would lead to the numerical value of H(s) → ∞
    - 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 @ -$\beta$**

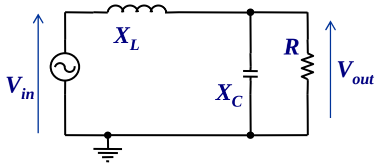
- Every zero in our system (located at a negative value of $s$) causes the gain to rise at a rate of 20dB per decade and
- Introduces a phase lead of 90º






# 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!



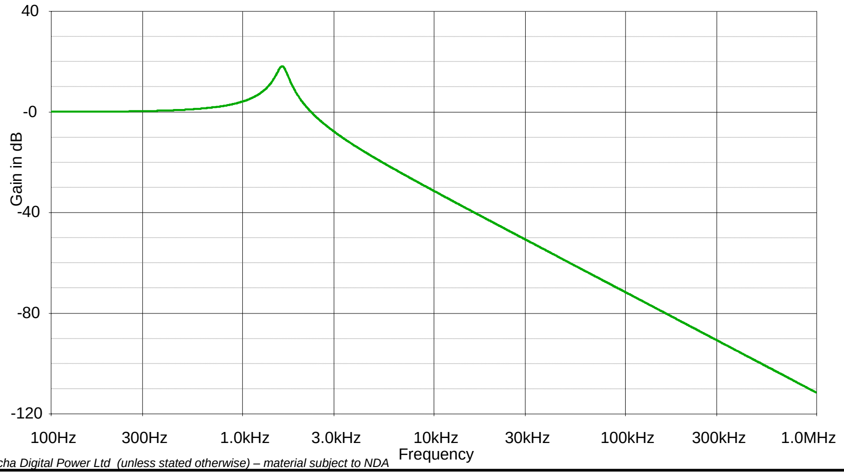

  - Transfer Function Hp(s):

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

  - 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

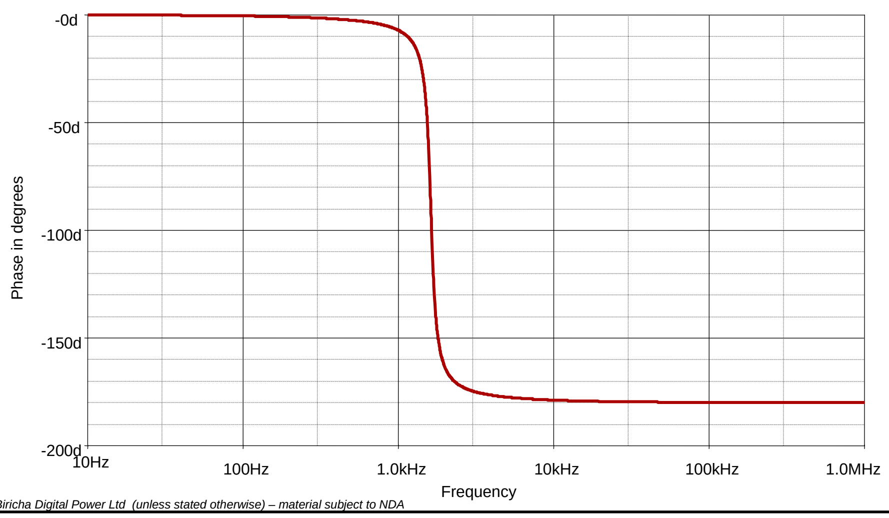
- **Exercise:** Calculate $F_r$ + estimate "roll-off" in dB/decade after $F_r$
- What is the maximum phase? Is it leading or lagging?







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



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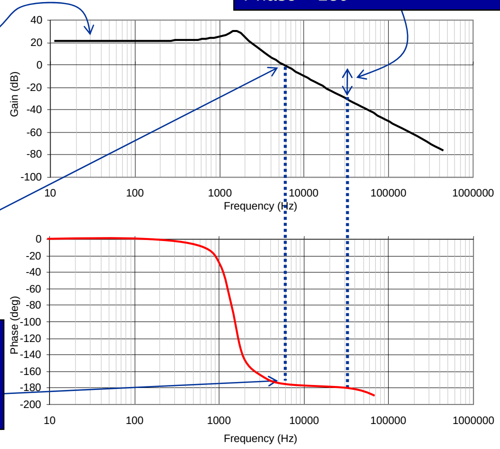
## Gain Margin, Phase Margin and Crossover Frequency

- 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 Fx*
*i.e. frequency at which gain crosses 0 dB ≅ 6kHz*
*Important:*
*Slope @ Fx = -40 dB/decade*

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



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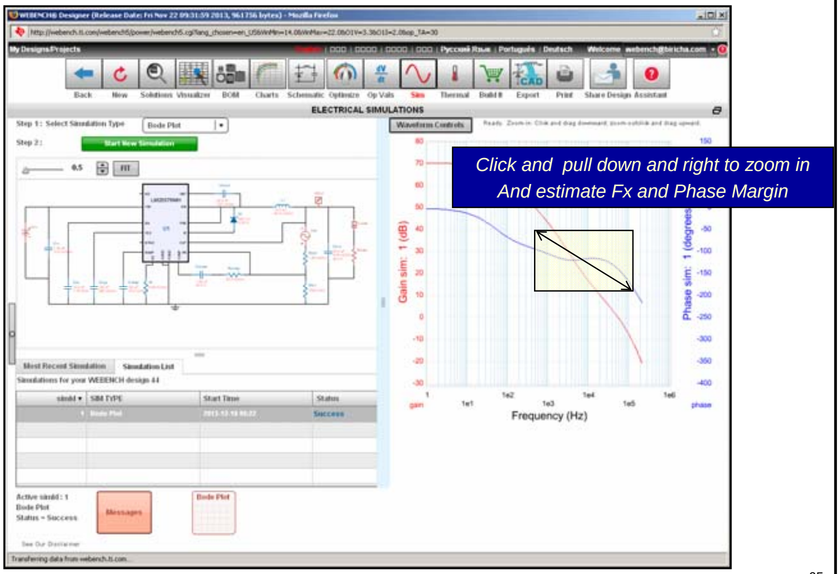
## Power Supply Stability Criterion

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

# Hands-On Demo 7 – Simulation Tool – Bode Plots

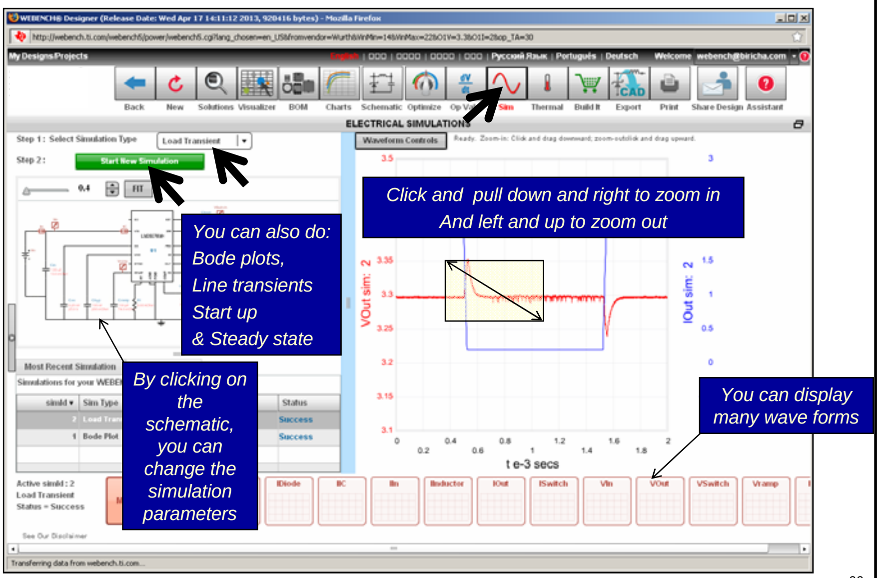








# Hands-On Demo 7 – Simulation Tool – Load Transients



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# Thermal Simulation with WebTHERM™

- WebTHERM™ online tool simulates the thermal behavior of an electronic printed circuit board
  - Using validated thermal models for the components and the reference PCB
  - The user defines the environment, air flow, copper thickness, presence of fan/heat sink, etc
  - Takes into account the thermal interaction of different components adjacent to each other
  - The WebTHERM tools helps the user identify heat problems on the printed circuit board
    - i.e. the board goes into production.
  - A simulation typically takes two to three minutes to complete,
  - After the simulation is complete, the user can view the result, a full colour plot of the temperature across the board
  - The temperature of each component is also listed in an accompanying table
  - If desired, the user can adjust the parameters and resubmit the job for simulation

Taken from: www.ti.com/lsds/ti/analog/webench/thermal-simulation.page





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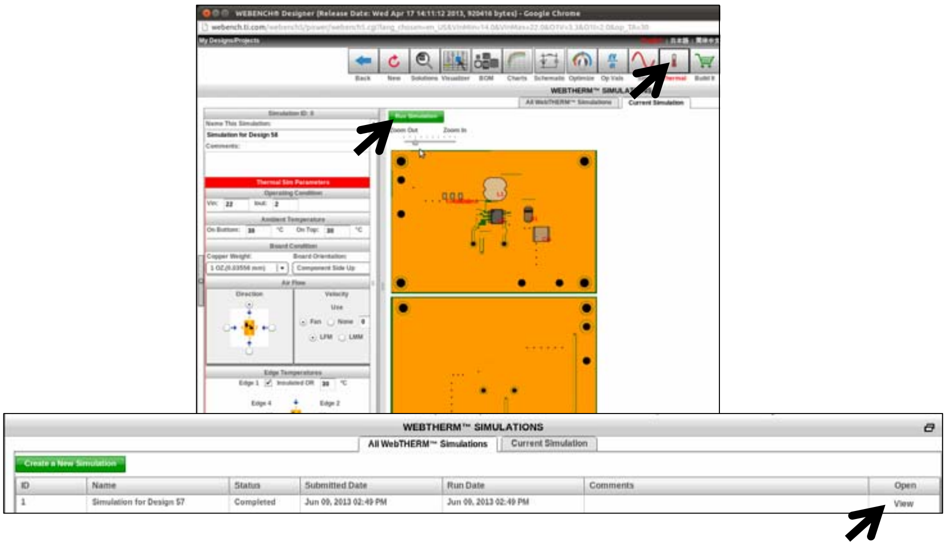
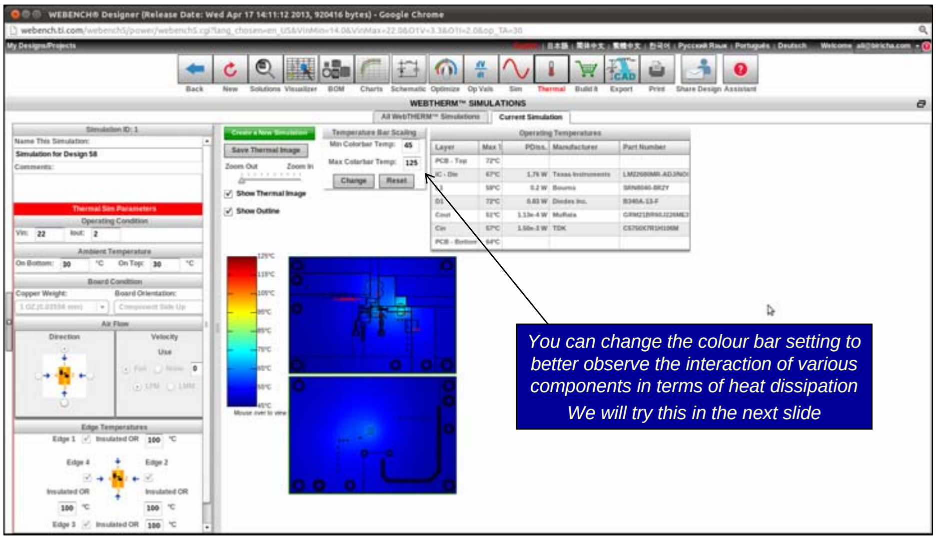
# Hands-On Demo 8 – Thermal Simulation



# Hands-On Demo 8 – Thermal Simulation

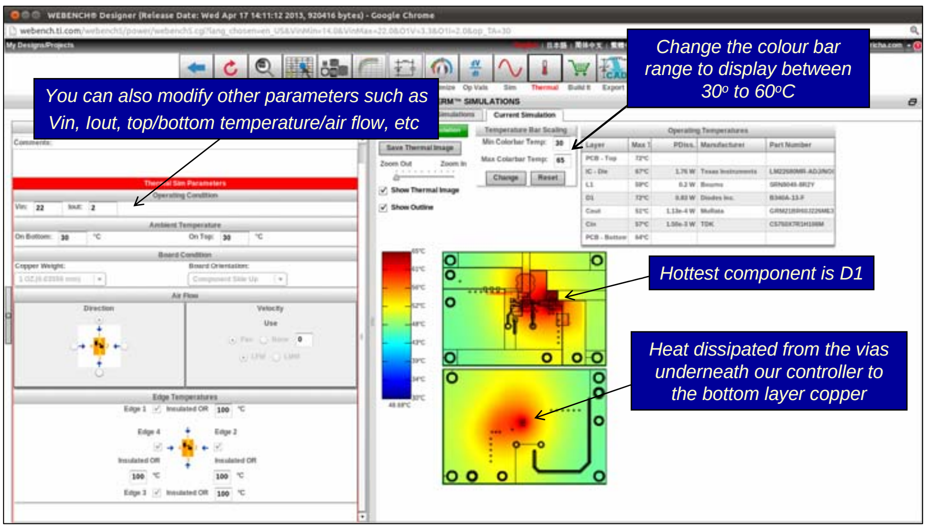








# Hands-On Demo 8 – Thermal Simulation



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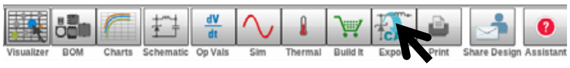
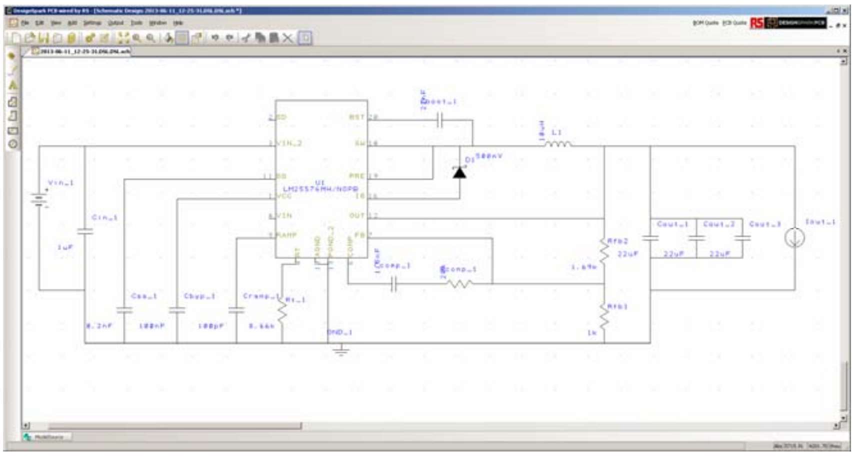
# Hands-On Demo 9 – CAD Export





- Example export to Design Spark







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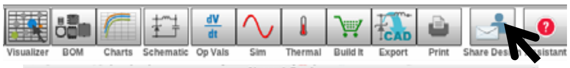
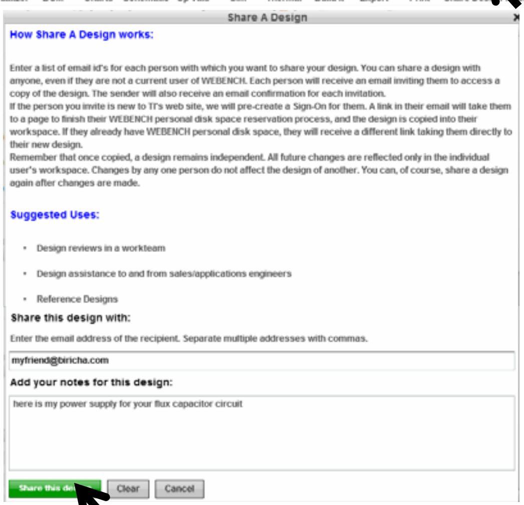
# Hands-On Demo 10 – Share you Design



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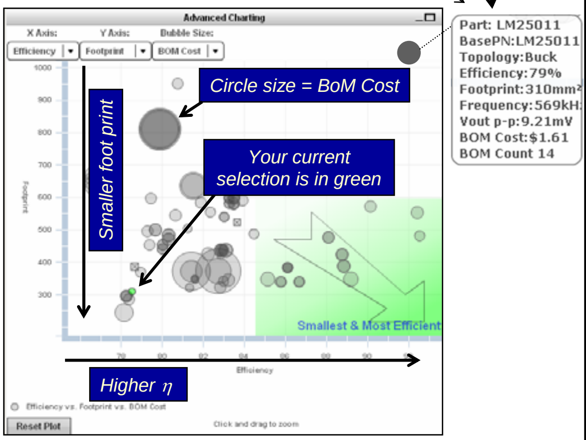
# Advanced Optimization with Charting Tools

- You can further optimize your design using the “Advanced Charting Tool”
  - In its most basic form it allows you to graphically select a design that you want open based on TI part number
  - If used before opening a design, it is simply a graphical alternative to using the sliders that we have used so far
  - **IMPORTANT:** However *after* opening a design, it can be used as a *very* powerful tool to optimize and select each individual component
  - We will now use this tool to select an alternative inductor for our design

*If you hover your mouse over any of the circles you will see the details of the design*





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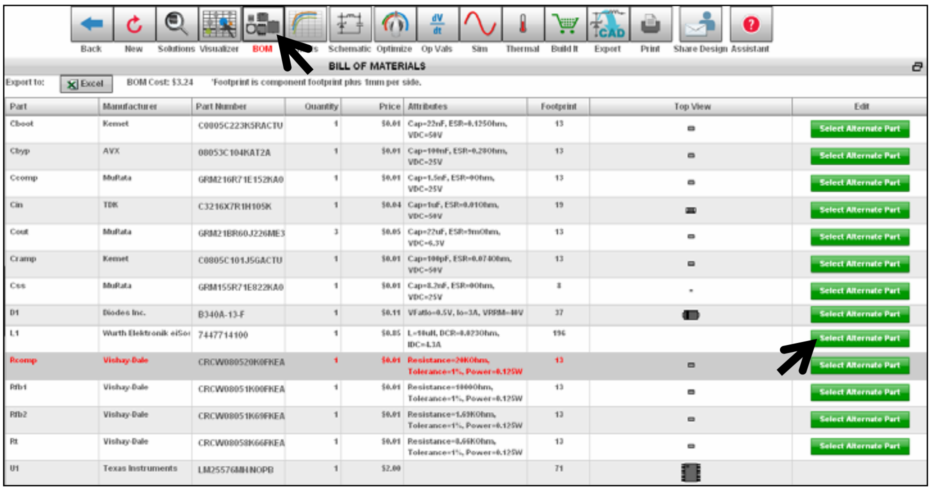
# Hands-On Demo 11 – Alternative Component Selection




| Part | Manufacturer | Part Number | Quantity | Price | Attributes | Footprint | Top View | Edit |
|---|---|---|---|---|---|---|---|---|
| Cboot | Kemet | C0805C223K5RACTU | 1 | $0.01 | Cap=22nF, ESR=0.125Ohm, VDC=50V | 13 | | Select Alternate Part |
| Cbyp | AVX | 08053C104KAT2A | 1 | $0.01 | Cap=100nF, ESR=0.28Ohm, VDC=25V | 13 | | Select Alternate Part |
| Ccomp | MuRata | GRM216R71E152KA01 | 1 | $0.01 | Cap=1.5nF, ESR=0Ohm, VDC=25V | 13 | | Select Alternate Part |
| Cin | TDK | C3216X7R1H105K | 1 | $0.04 | Cap=1uF, ESR=0.010Ohm, VDC=50V | 19 | | Select Alternate Part |
| Cout | MuRata | GRM21BR60J226ME3 | 3 | $0.05 | Cap=22uF, ESR=9mOhm, VDC=6.3V | 13 | | Select Alternate Part |
| Cramp | Kemet | C0805C101J5GACTU | 1 | $0.01 | Cap=100pF, ESR=0.074Ohm, VDC=50V | 13 | | Select Alternate Part |
| Css | MuRata | GRM155R71E822KA01 | 1 | $0.01 | Cap=8.2nF, ESR=0Ohm, VDC=25V | 3 | | Select Alternate Part |
| D1 | Diodes Inc. | B340A-13-F | 1 | $0.11 | VFatIo=0.5V, Io=3A, VRRM=40V | 37 | | Select Alternate Part |
| L1 | Wurth Elektronik eiSo | 7447714100 | 1 | $0.85 | L=10uH, DCR=0.023Ohm, IDC=4.3A | 196 | | Select Alternate Part |
| Rcomp | Vishay-Dale | CRCW080520K0FKEA | 1 | $0.01 | Resistance=20KOhm, Tolerance=1%, Power=0.125W | 13 | | Select Alternate Part |
| Rfb1 | Vishay-Dale | CRCW08051K00FKEA | 1 | $0.01 | Resistance=1000Ohm, Tolerance=1%, Power=0.125W | 13 | | Select Alternate Part |
| Rfb2 | Vishay-Dale | CRCW08051K69FKEA | 1 | $0.01 | Resistance=1.69KOhm, Tolerance=1%, Power=0.125W | 13 | | Select Alternate Part |
| Rt | Vishay-Dale | CRCW08058K66FKEA | 1 | $0.01 | Resistance=8.66KOhm, Tolerance=1%, Power=0.125W | 13 | | Select Alternate Part |
| U1 | Texas Instruments | LM25576MH/NOPB | 1 | $2.00 | | 71 | | |

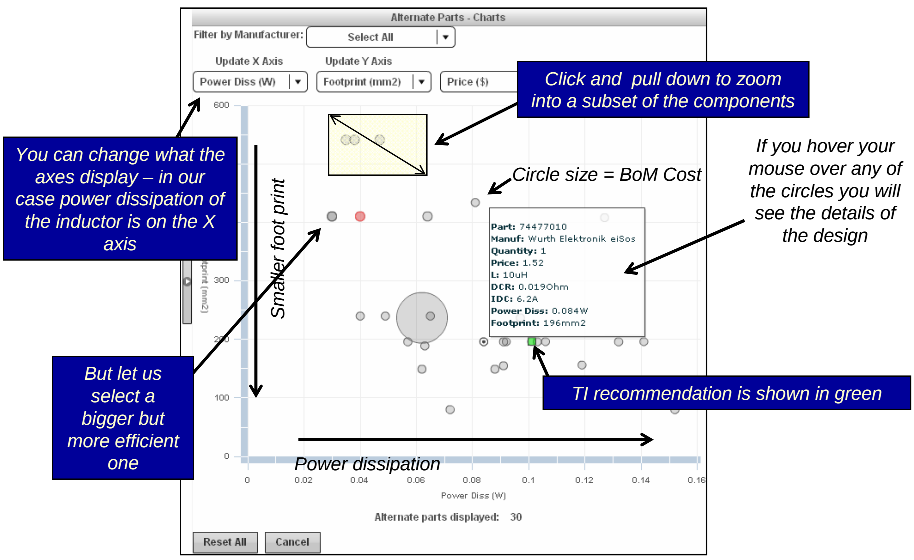
## Hands-On Demo 11 – Alternative Component Selection

- Using the advanced charting tools we can select a more suitable inductor for our power supply






## Hands-On Demo 11 – Alternative Component Selection



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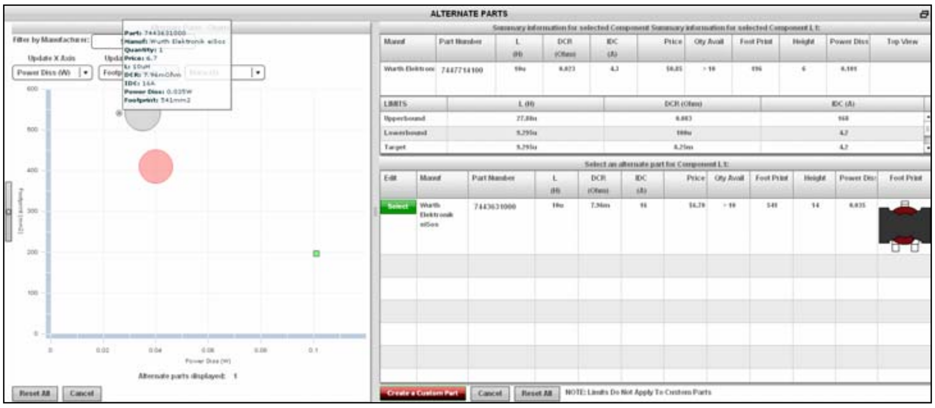
## Hands-On Demo 11 – Alternative Component Selection

- Note that a new more efficient but larger component has now been selected
  - We can now run our simulation and analysis based on this new component
  - When we are happy we can finalize our design and print the final report





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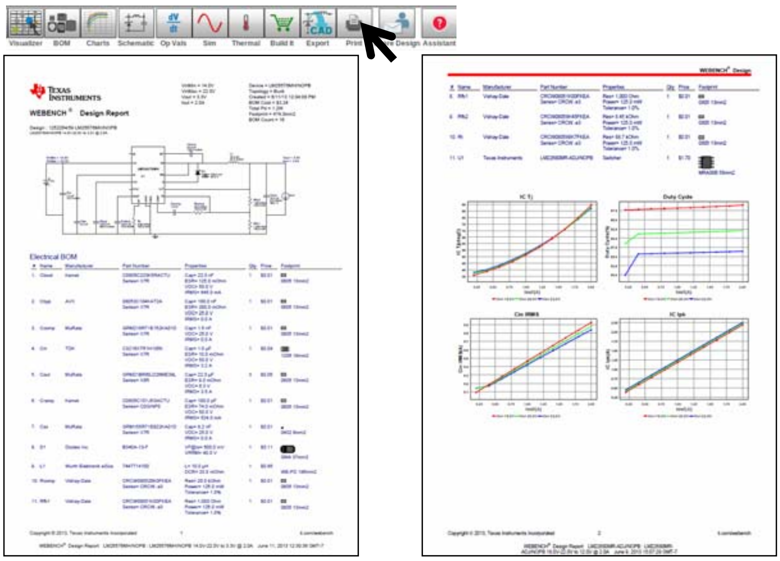
## Hands-On Demo 12 - Automatic Report Generation



# Concluding Remarks and Summary

- WEBENCH is a very powerful tool to assist you in your PoL PSU Designs
  - Based on your specifications, it automatically designs 100+ of PSUs
- We've learned how to:
  - Filter down our designs and select the most appropriate part based on your efficiency/footprint/cost requirements
  - Optimize our design and carry out electrical and thermal simulations
  - Change components within your BoM
  - Create schematics and import to CAD packages
  - Print the final report and order BoM including the PCB within a few clicks
- In this seminar we only covered Power Designer; there is also:
  - WEBENCH Power Architect
  - WEBENCH LED Designer
  - WEBENCH Sensor Designer
  - WEBENCH Active Filter Designer
  - WEBENCH Amplifier Designer
  - WEBENCH EasyPLL

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*www.surveymonkey.com/s/webench-ch*






*End of Seminar*

*Thank you for attending*