Power Beginner's Hands-on Workshop

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Power Basics

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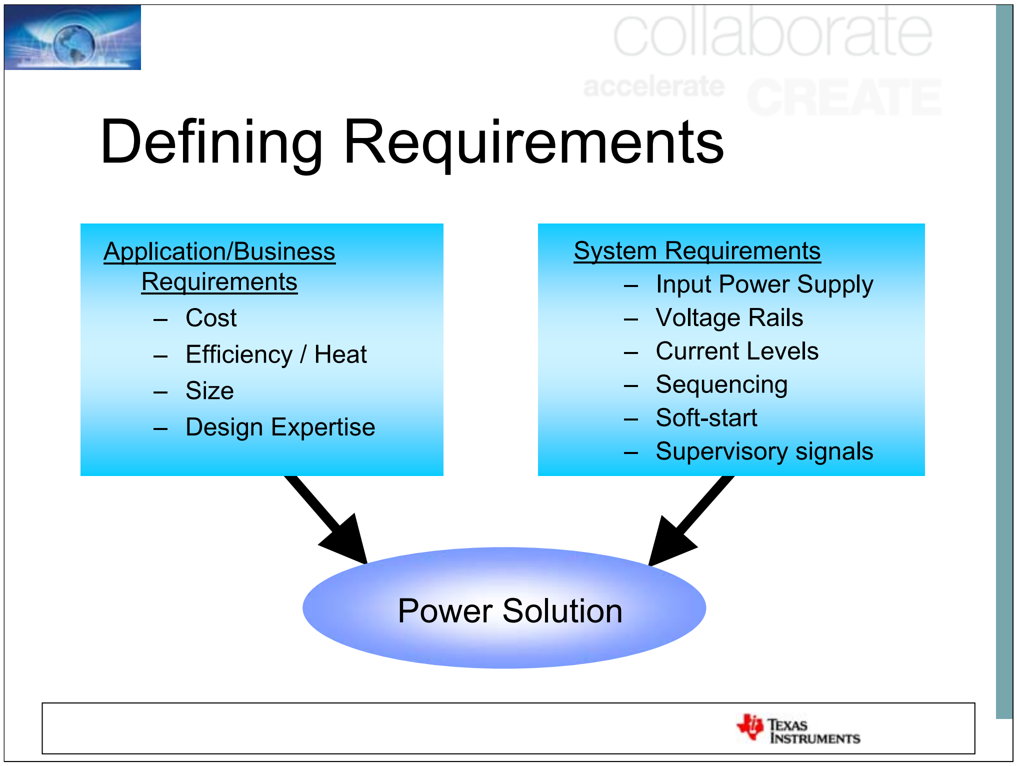
Agenda

- Linear Regulator Basics
- Switching Power Supply Basics
- Component Selection Careabouts
  - Input Caps
  - Output Caps
  - Inductor
  - FETs
  - Phase & Gain Plots



System level/application specific requirements drive the overall dc/dc power supply design

Cost vs. Size vs. Efficiency in a portable vs. PC system application

- Cost includes not only component cost but also time involved in designing the supply
- Size of the complete solution (i.e., board space allocated to the power supply) is typically a major concern in portable systems
- Efficiency
  - Portable app might have low power mode thus requiring high efficiency over a wide load rang to prolong battery life
  - System application may have higher currents in a closed and therefore need higher efficiency and/or additional heat sinking to accommodate power dissipation

Noise sensitive application?

- Are they some ICs that would be sensitive to noise?
  - Digital rails, e.g. “core” and I/O rails, use switcher or linear reg because they are not sensitive to noise
  - Analog rails, e.g. for powering audio ICs, need low noise linear regulators
- May require special layout and/or shielding
- Hysteretic vs. constant frequency controller?

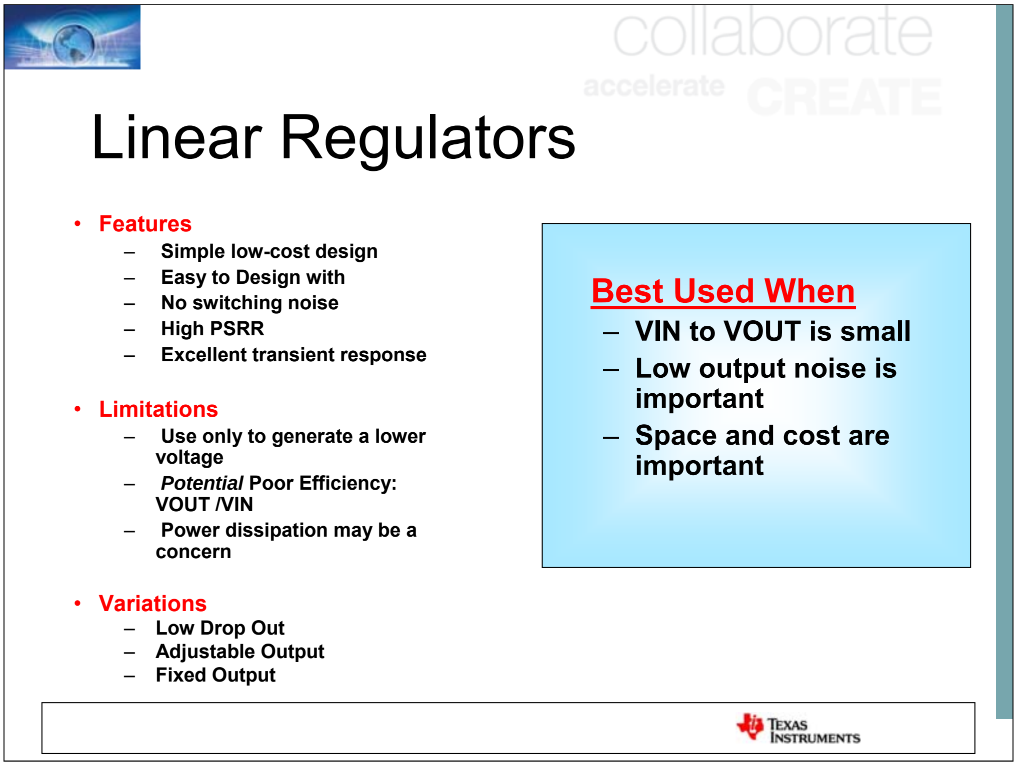
Which FPGA?

- Different families have different rails and power requirements

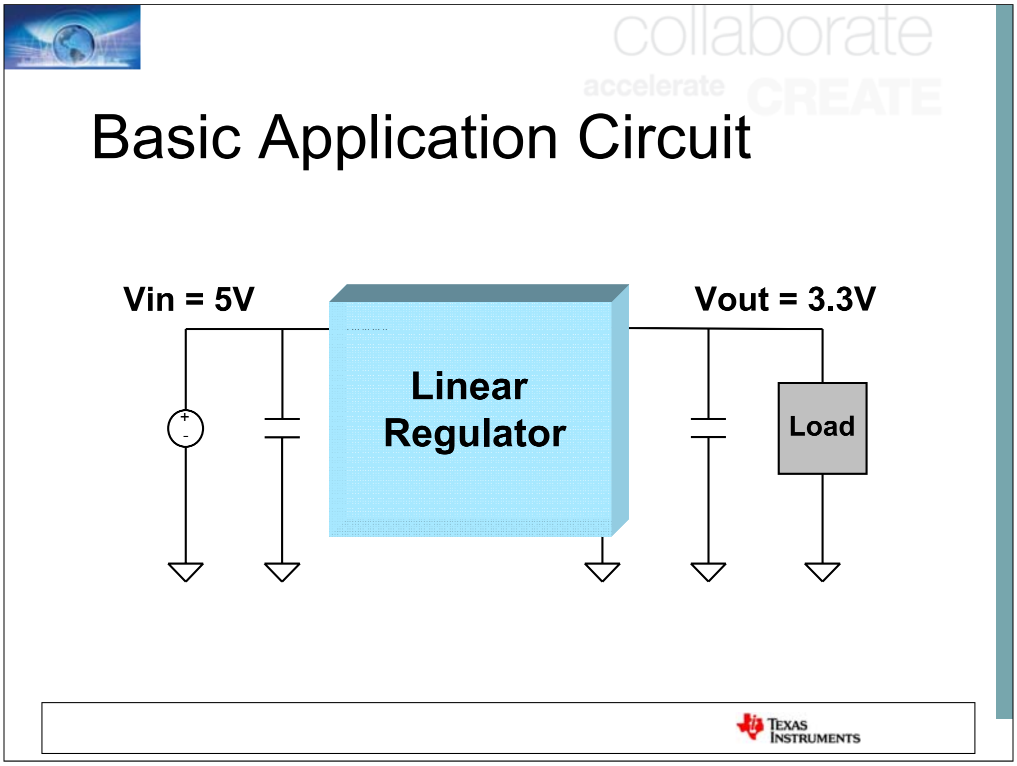
Other components with power needs

- DDR memory needs power a power supply and a termination voltage
- Any boosted voltages necessary

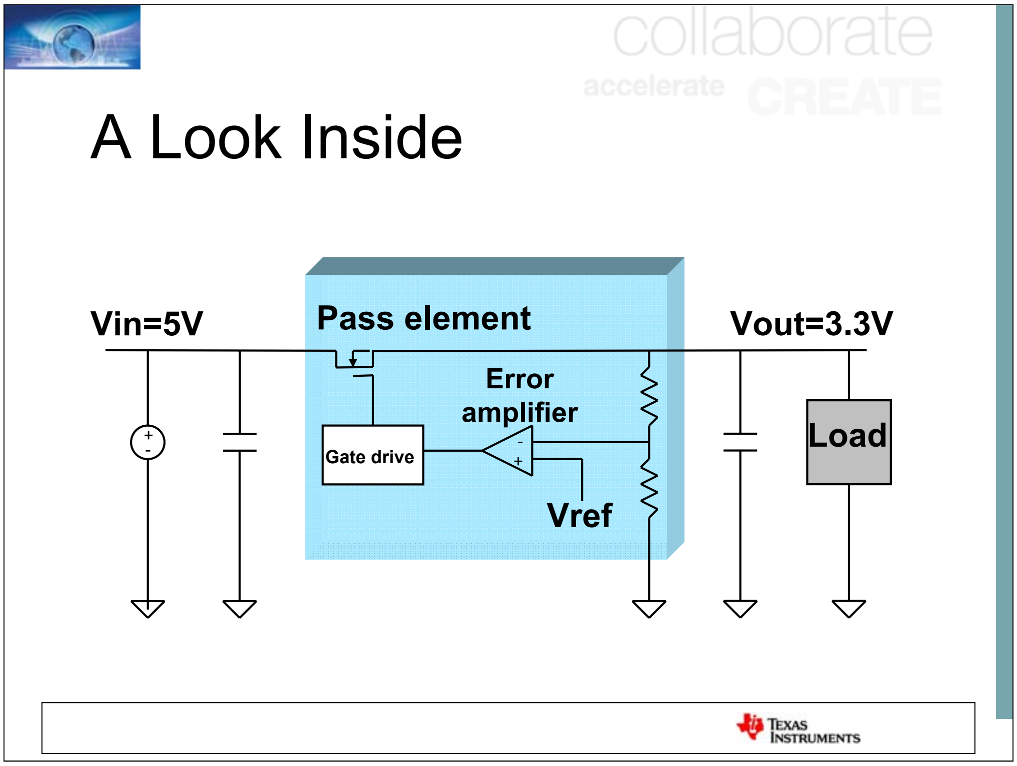
Basic Theory
of
Linear Regulators



These reasons are why they are used whenever possible.



This is a typical application. Note that there are only two external capacitors and no inductors. Very easy and simple design.



The pass element reduces the input voltage and regulates it to the output voltage. The pass element operates in the linear region and dissipates power unlike the FETs in a switching power supply that are either on or off. The feedback network and the gate drive circuit close the feedback path to modulate the pass element to provide the regulated output.

Regulator dropout classification:

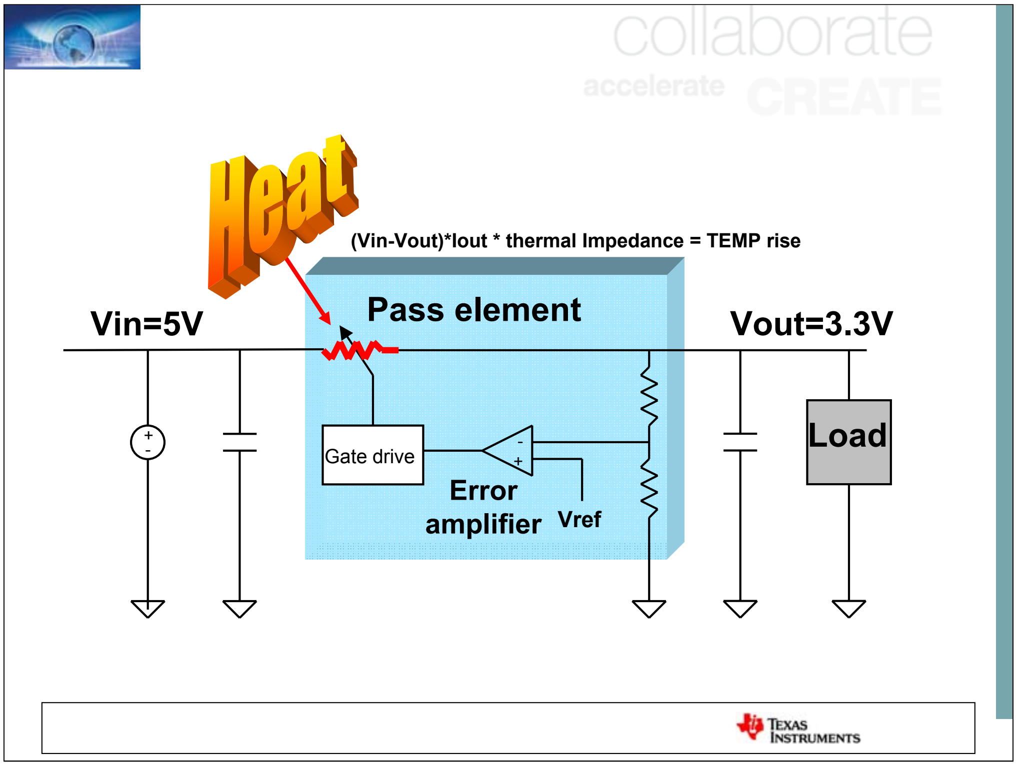
Standard dropout: >1V

Low dropout: < 1V

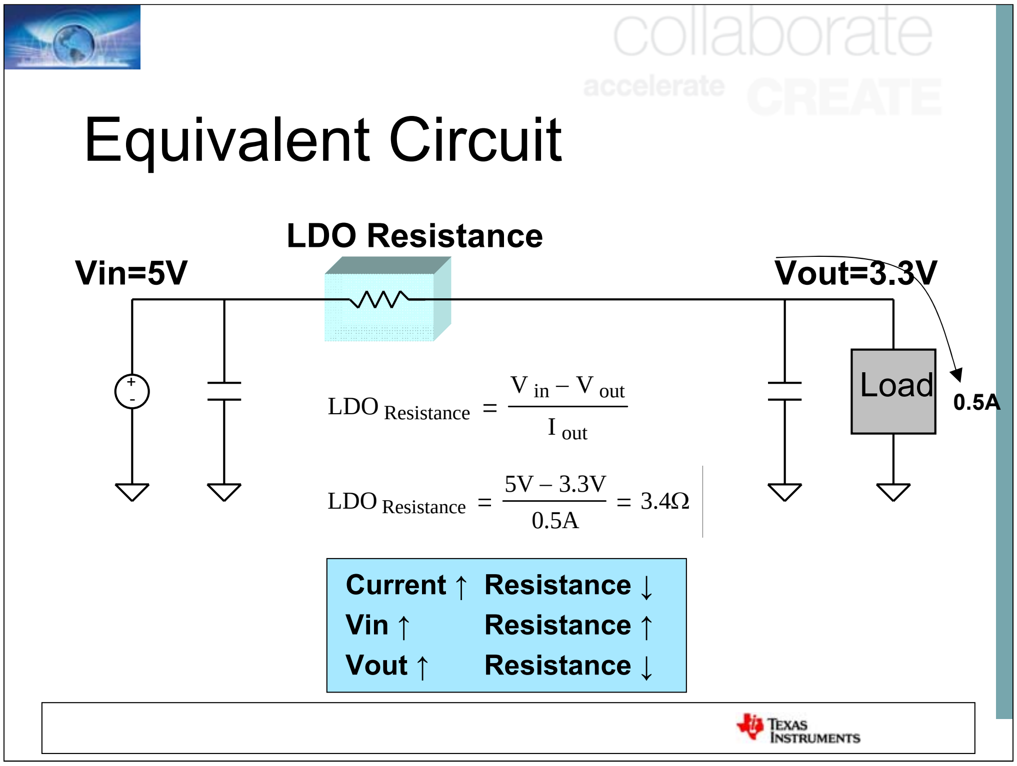
Pass element:

STD regulator darlington or NPN

LDO: PMOS, NMOS or sometimes a PNP



Since the pass element is in operated in the linear region, it acts as a voltage variable resistor. The feedback network drives the gate of the pass element to make it the correct resistor value to compensate for changes in Vin, Vout, or Iout.



Under steady state conditions, an LDO can be replaced by a discrete resistor. However, no system operates at a single operating point (Vin & Io = constant) so the equivalent resistance must change.

Voltage Dropout

- **A linear regulator is in dropout when its output voltage falls out of regulation because the regulator can not adjust its resistance any lower**

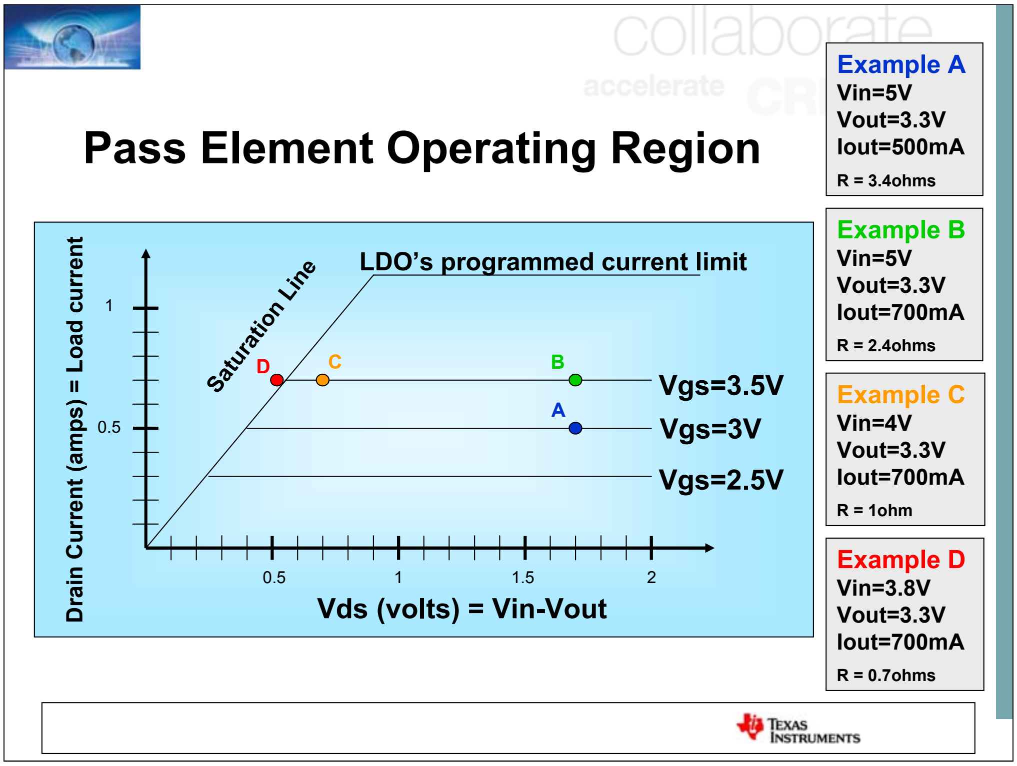
- **Dropout voltage is defined as the differential voltage across the regulator when it enters dropout.**

Why Do We Care?

(Vin-Vout)*Iout * thermal Impedance = TEMP rise

we'd like to minimize

The LDO pass element has a minimum resistance when fully enhanced, and when the circuit requires the LDO resistance to be lower than this value, the LDO goes into dropout. In the system, this happens when the output voltage drops out of regulation. The term “dropout voltage” is used to define the differential voltage across the LDO when the LDO goes into dropout.

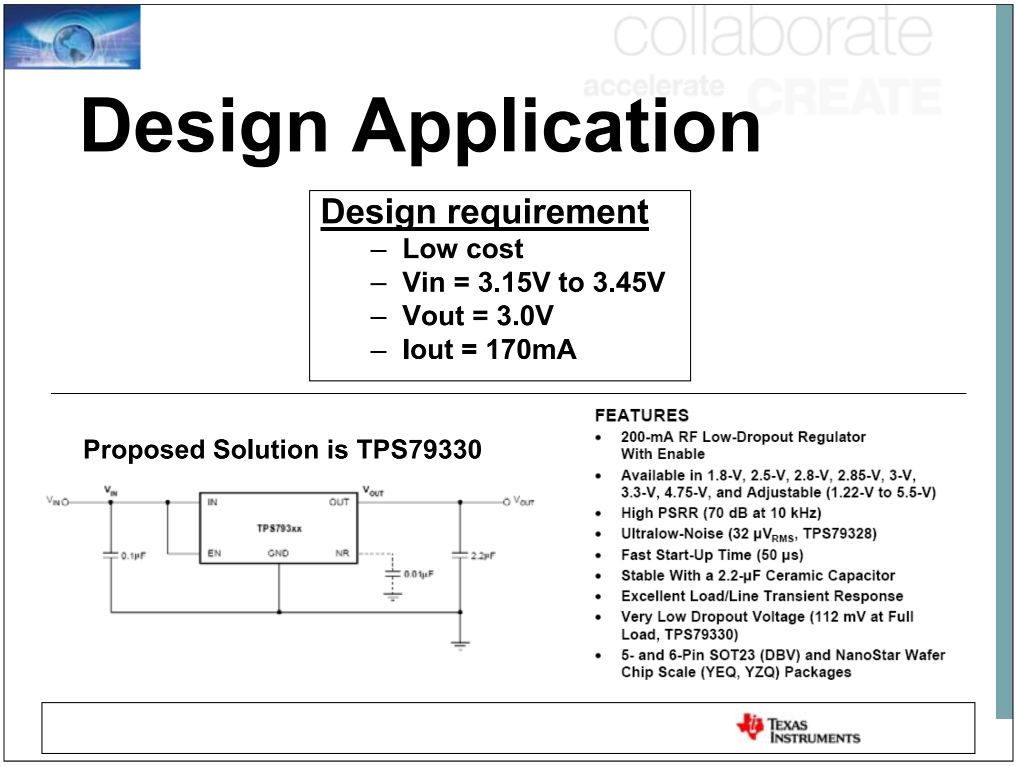


The graph illustrates the V-I characteristics of a FET pass element. Each point represents the operating point of the FET under the specified conditions. The FET must operate on these curves. The FETs resistance is defined by the line from the origin to the operating point. The FET can NOT operate at point D. Example D puts the LDO into dropout. The actual operating point of example D is on the saturation line.

A. 1.7V / 0.5A = 3.4ohms B. 1.7V / 0.7A = 2.4ohms C. 0.7V / 0.7A = 1ohm

Range of operation:

Limited by the saturation region of the pass element or the devices programmed current limit.



Will this LDO meet the customer's requirements. Note that the front page of the datasheet provides typical values only.

Will it Work?

- **Parametric Data**
  - **Ensured**
  - **One operating point**

TPS79301

			MIN	TYP	MAX	UNIT
Dropout voltage[2] ($V_{IN} = V_{OUT(nom)}$ - 0.1V)	TPS79328	I_{OUT} = 200 mA		120	200	mV
	TPS793285	I_{OUT} = 200 mA		120	200	
	TPS79330	I_{OUT} = 200 mA		112	200	
	TPS79333	I_{OUT} = 200 mA		102	180	
	TPS793475	I_{OUT} = 200 mA		77	125	

200mV is more than the required dropout voltage of 150mV, but this number is specified at 200mA. We only need 170mA.

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Will it Work?

- Datasheet Graphs
  - Typical data
  - Not ensured over all conditions
  - Many operating points

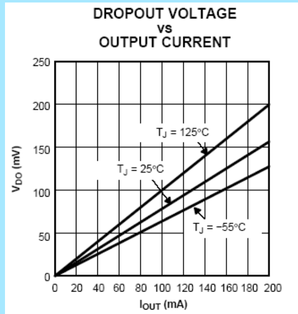

Figure 18.

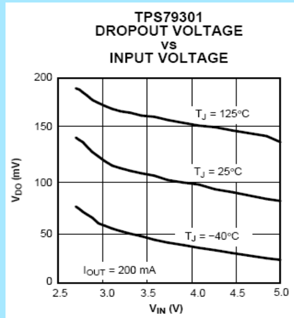

Figure 19.

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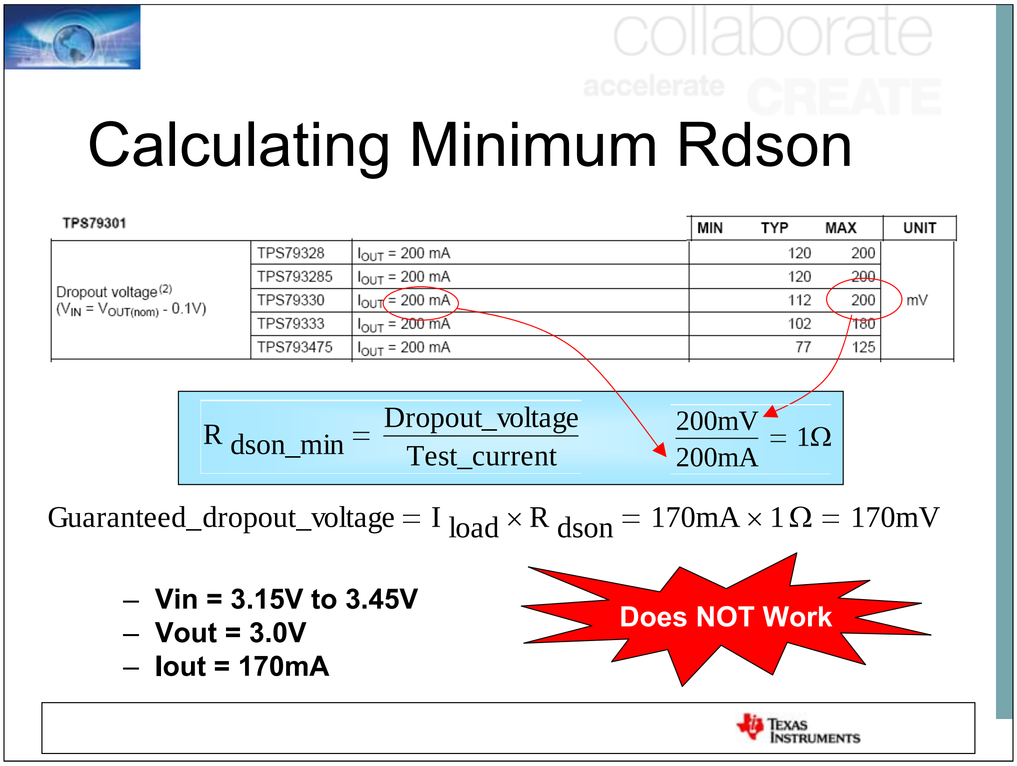
Will it Work?

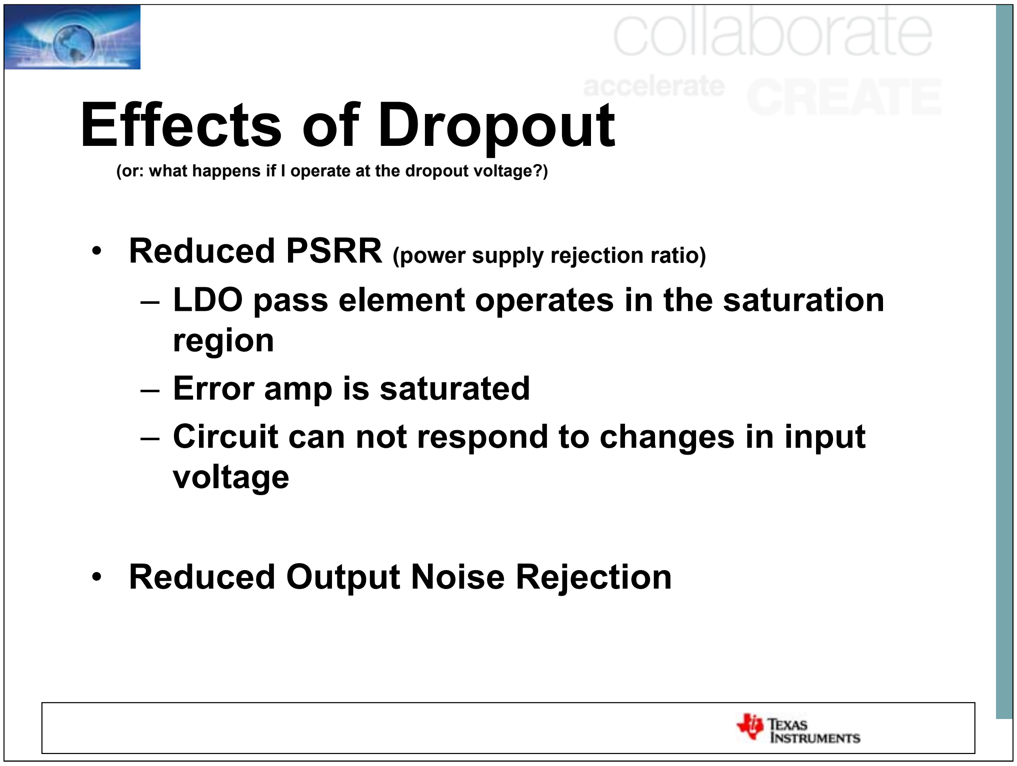
– **Parametric table does not assure performance @ 170mA**
– **Typical graphs do not assure performance over temperature**

FET minimum Rdson

The answer to whether or not this LDO works for the customer can be found by calculating the LDOs minimum resistance.



Guaranteed minimum resistance can be calculated from the parametric table. Be sure to use the maximum dropout voltage. 1st calculate the resistance at the test current. Then use this number to calculate the guaranteed dropout voltage at the customer's specific operating current. Note that the LDO has 170mV of dropout, which is higher than the 150mV requirement. This LDO does not work for the customer application, even though the front page of the datasheet implied that it would.

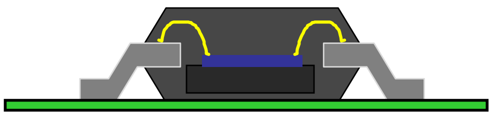


Operating in dropout reduces the PSRR of the LDO since the error amp is saturated and can't respond to voltage changes on the input. Most LDO PSRR data is taken with Vin = Vout + 1V.

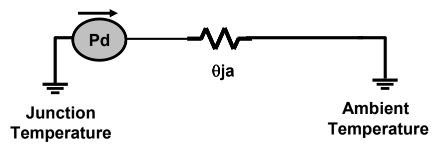
When the LDO is in dropout the attenuation at Vout can be modeled as a single pole response due to the RDSon of the pass element and the output capacitance.

Thermal Considerations

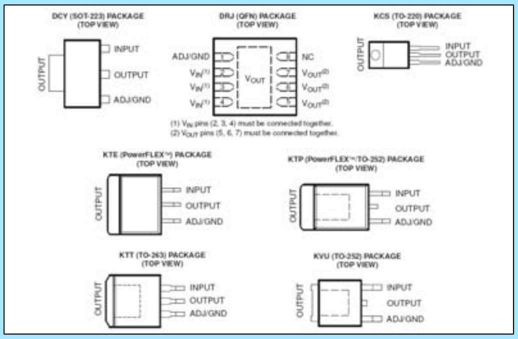
- Must consider package thermal characteristics
  - Different packages have different capabilities to handle heat dissipation



Junction Temperature



Package Power Dissipation



PACKAGE	BOARD	θ_{JP} (2)	θ_{JC}	θ_{JA}
PowerFLEX (KTE)	High K, JESD 51-5	2.7°C/W	11.6°C/W	23.3°C/W
PowerFLEX/TO-252 (KTP)	High K, JESD 51-5	1.4°C/W	19.2°C/W	27.6°C/W
QFN (DRJ)	High K, JESD 51-5	1.78°C/W		46.5°C/W
SOT-223 (DCY)	High K, JESD 51-7		30.6°C/W	52.8°C/W
TO-252 (KVU)	High K, JESD 51-5			30.3°C/W
TO-220 (KCS)	High K, JESD 51-5	3°C/W	17°C/W	19°C/W
TO-263 (KTT)	High K, JESD 51-5	1.94°C/W	18°C/W	25.3°C/W

Max Power Dissipation

- Tj : Max Junction Temp
- Ta : Max Ambient Temp

$$P_d = (T_j - T_a) / \theta_{ja}$$

Lowest θja can dissipate the most heat.

Trade-offs between package size and thermal properties

Linear Regulators : What We Learned

- LDO regulates output by changing it's equivalent resistance
- Minimum resistance sets dropout voltage
- LDO datasheets can't specify all operating conditions.
- User can interpolate the dropout specs to any specific operating condition
- Operating in dropout affects PSRR and Noise performance
- Proper design involves thermal calculations and proper package selection

Switching Regulators

- **Features**
  - Boost, Buck or Inverting Types
  - Wide range of VIN and IOUT
  - Very Efficient
  - Good Transient Response
  - Limited Power Dissipation
- **Limitations**
  - Larger solution size
  - More expensive to implement
  - Noise
- **Variations**
  - Buck
  - Boost
  - Buck-Boost
  - SEPIC
  - Flyback

Best Used When

- Need best efficiency for battery life
- Higher currents are needed
- V_{IN} and V_{OUT} are wide

These reasons are why they are used whenever possible.

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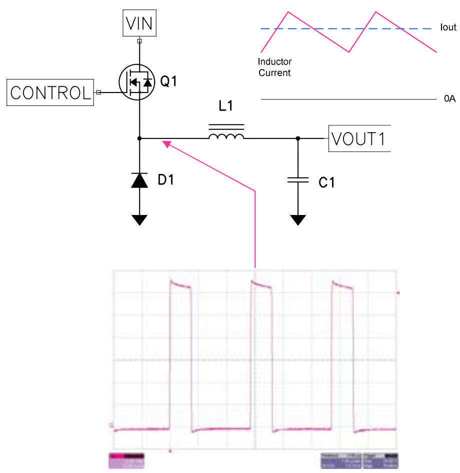
Topologies – Buck Regulator



Used When?
- Non-isolated
- Vin > Vo

Variations
- Module/Swift/Discrete
- Continuous/Discontinuous Current
- N/P Channel FET
- Synchronous/not
- Multiphase

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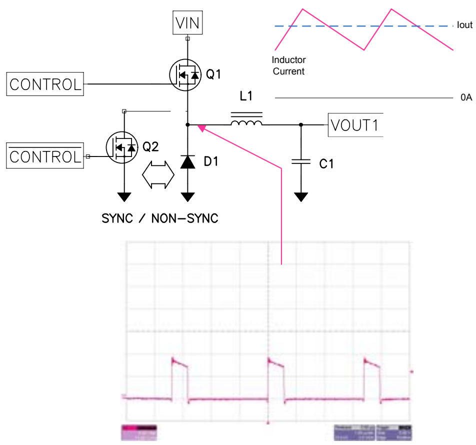
Topologies – Sync vs Non-sync Buck



Used When?
- Sync for Highest Efficiency
- Non-sync for lowest cost

Sync ICs
- TPS40190 (Single)
- TPS51020 (Dual)
- TPS54310 (SWIFT)

Non-Sync ICs
- TPS40200 (Ext. P-FET)
- TPS5430 (SWIFT)

Design Considerations

Inductor Considerations

- Benefits of low L values
  - Lower DCR
  - Higher Isat
  - Higher di/dt
    - Transient response improves
    - Less output capacitance required for given transient performance
- Benefits of high L values
  - Lower ripple current
    - Lower AC losses (skin effect, hysteresis)
    - Lower RMS current in MOSFETs
    - Lower RMS capacitor current (mainly output)
    - Continuous inductor current over broader load range
    - Less C required for equivalent output ripple

Inductor Types





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Power MOSFET Selection

- Compare different MOSFETs in each position
- In general higher F and higher input voltage require lower Qg to cut switching losses in switch MOSFET
- For rectifier MOSFET, low $R_{DS(on)}$ is most important, but don't ignore gate power

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No known method for calculating a “best” Qg & RDSon in a given situation.

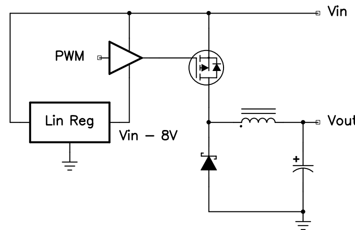
Limited by the data the MOSFET manufacturers provide- inconsistent format, etc.

Mention spreadsheet that allows examination of predicted system losses with changing MOSFET parameters.

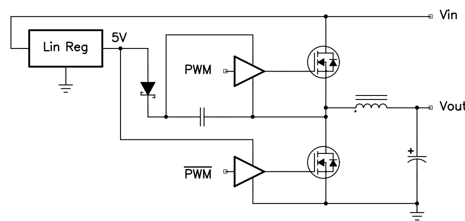
For SW MOSFET, lower Qg does give faster switching time, but this contributes to more parasitic turn-on of the rectifier MOSFET. There is a happy medium somewhere.

Buck Regulator – P Ch vs. N Ch FET

- **P Channel**
  - Lower Cost Controller
  - Higher Vin operation
  - Fewer pins required



- **N Channel**
  - Greater Selection
  - Lower cost than P-Ch (same Rds on)
  - Higher Efficiency
  - Typically implemented as synchronous buck



P-CH - Fewer pins required (SW node deleted)

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Power Capacitors Selection

- Power Dissipation
  - ESR
- Ripple Performance
  - ESR
- Transient Performance
  - ESL
  - Capacitance
  - ESR
- Cost
- Size
- Reliability

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Relative Capacitor Characteristics

	ESR	Cost	Current Rating	Reliabilit y
Std Al Electrolytic	high	low	low	low
OSCON	low	medium	high	High
Solid Polymer (SP)	low	very high	medium	high
POSCAP	low	high	medium	high
Tantalum	medium	medium	medium	medium
Ceramic	very low	very high	high	high

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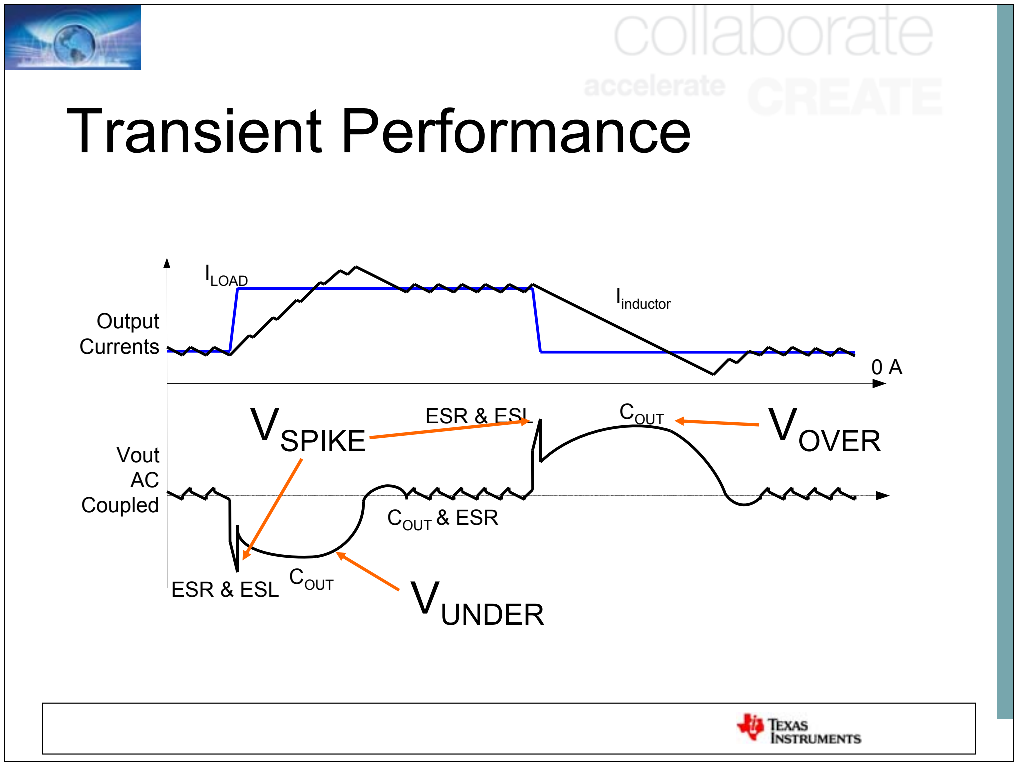
Choosing Capacitor Size

- Input Filter
  - Sized for AC current handling
- Output Filter
  - Transient events on load
  - Output voltage ripple

Output Capacitor Selection Criteria

- Transient performance
  – Bulk capacitance
  – ESR
  – ESL
- Output Ripple
  – ESR
  – Bulk value
  – ESL has minor effect

Just a listing of what parameters are important in selecting the output cap



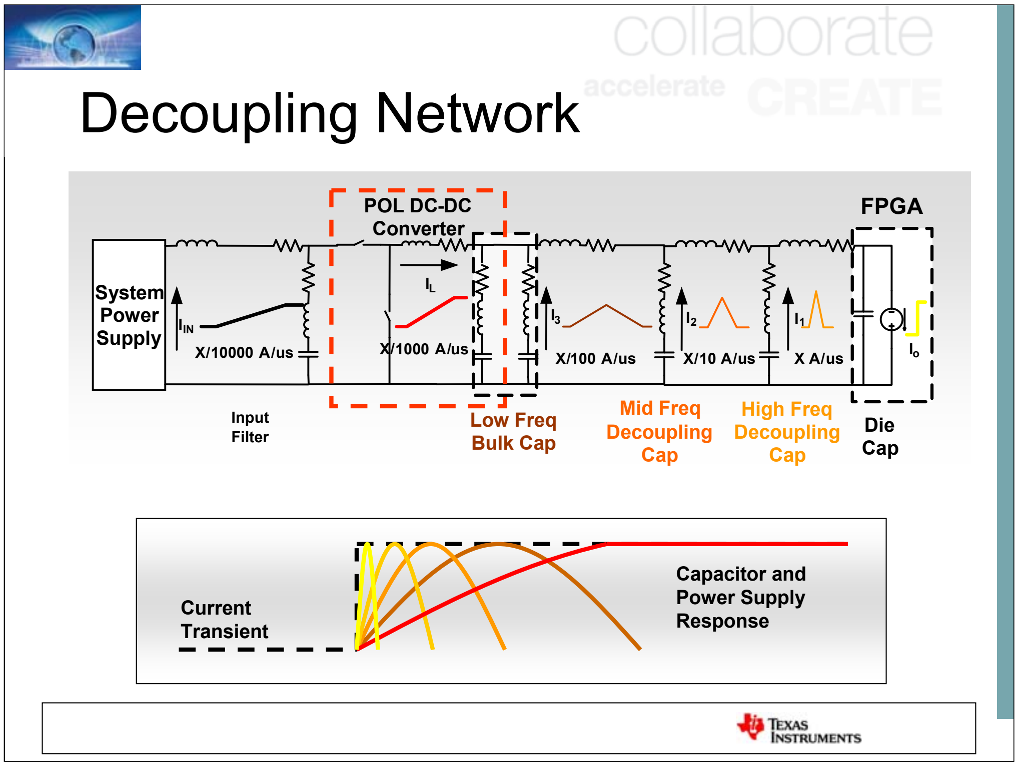
An idealized picture showing contributions of output capacitor characteristics and where they occur in a load transient event.

Note the di/dt of the load causing the ESL spiking.

Note fixed inductor current slopes causing the bulk of the transient event disturbance.

Recovery from load step increase depends on energy stored in output capacitor and voltage loop response time

Recovery from load step decrease depends on energy stored in output inductor, output capacitor size, and voltage loop response time.



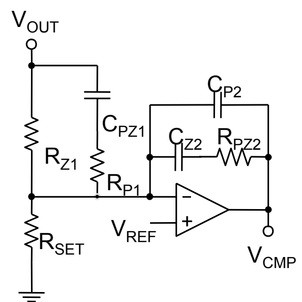
All POL dc/dc converters have finite response time, whether the converter has a traditional feedback loop with a bandwidth set by the loop's crossover frequency or a hysteretic converter with fixed on or off time. Therefore, additional capacitance is almost always required on a power rail to assist the converter in handling the transient step. As shown in the figure, a decoupling network is used to handle the different frequency components of the transient so that the POL dc/dc converter, and ultimately its input power supply, only see the small low frequency component of the load step.

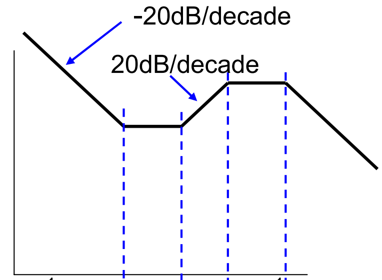
Small pf to 1 uf range capacitors handle the high frequency component of the load step. Capacitors from 1 uF to 22 uF handle the mid-frequency component of the load step. Low ESR bulk capacitors from 47 uF to 1000 uF handle the low frequency portion of the transient. A common method for optimizing the decoupling network (i.e., minimizing the amount of capacitance) is the target impedance method, as explained more fully in SLUA110. This method requires that worst case load transient step of the device being powered (e.g., from 200 mA to 2.2 A in 0.5 us or 4A/us for 10us) be known as well as some idea of the transient response capabilities of the POL converter. If the POL converter is not close to the load and the board layout requires that the power rail use small traces and/or vias to get to the load, then approximations of the board resistance and inductance may be necessary for the model as illustrated in the figure.

For most FPGA and DSP applications, the worst case load transient is rarely known and it is simpler to use rules of thumb to design the decoupling network. For example, it is not uncommon to allocate a certain amount or percentage of each type of capacitor (high-, mid-, and low-frequency) per the number of power pins used in total or per section of the digital IC. While effective, this method tends to overdesign the decoupling network, resulting in underutilization of the dc/dc converter's transient response capabilities as well as recommending more capacitors than absolutely necessary be placed around the IC, taking up board space.

In this example, the 1.5V supply for the Virtex-II device supplies VCCO for banks 1 and 6, and VCCINT. There are 44 VCCINT pins on this device. Banks 1 and 6 were previously calculated to use two pins each. Adding the 44 VCCINT pins and the four VCCO pins for Banks 1 and 6 equals 48 pins. Therefore, there should be 48 capacitors total on the 1.5V supply.

Compensation Networks





$$f_{Z1} = \frac{1}{2\pi \times R_{Z1} \times C_{PZ1}} \qquad f_{P1} = \frac{1}{2\pi \times R_{P1} \times C_{PZ1}}$$

$$f_{Z2} = \frac{1}{2\pi \times R_{PZ2} \times C_{Z2}} \qquad f_{P2} = \frac{1}{2\pi \times R_{PZ2} \times C_{P2}}$$

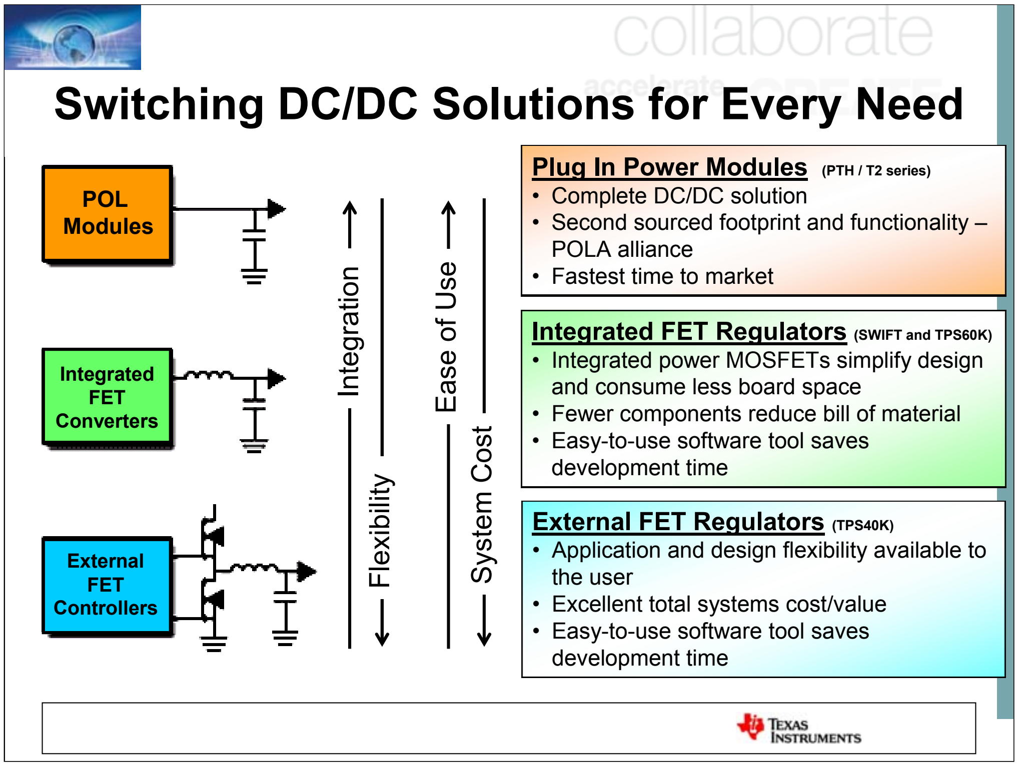
Type 3

- Three poles one at origin, one set by R_{PZ2} & C_{P2} and one by R_{P1} & C_{PZ1}
- Two zeros one set by C_{Z2} & R_{PZ2} and one by R_{Z1} & C_{PZ1}

Power Supply Stability Considerations

- Phase/gain margin critical for stability of closed-loop feedback systems.

- Computer simulation helpful but inadequate
  - Device models unavailability or inaccurate
  - Parasitic/stray elements play a role
  - Mechanical decisions affect models
  - “Proof” is in final measurements



Plug In Power Modules - PTH series

Modules – these are a complete DC/DC solution. Minimal design effort is needed, and customer can get into production fastest. Typically, these are the most expensive of the single output converters. Complete DC/DC solution

Second sourced footprint and functionality – POLA alliance

Fastest time to market

Integrated FETs (SWIFTTM

Integrated power MOSFETs simplify design and consume less board space

Fewer components reduce bill of material

Easy-to-use software tool saves development time
2) SWIFT and TPS6xxxx DC/DC Converters –The emphasis of these products has been to integrate as much of the power solution as possible into a single IC – including the power FETs. As few as 6 external components are all that is needed to develop a solution – newer designs enable up to 14A of output current from a 3.3V supply. These parts are ‘simple discrete’ solutions for the customer

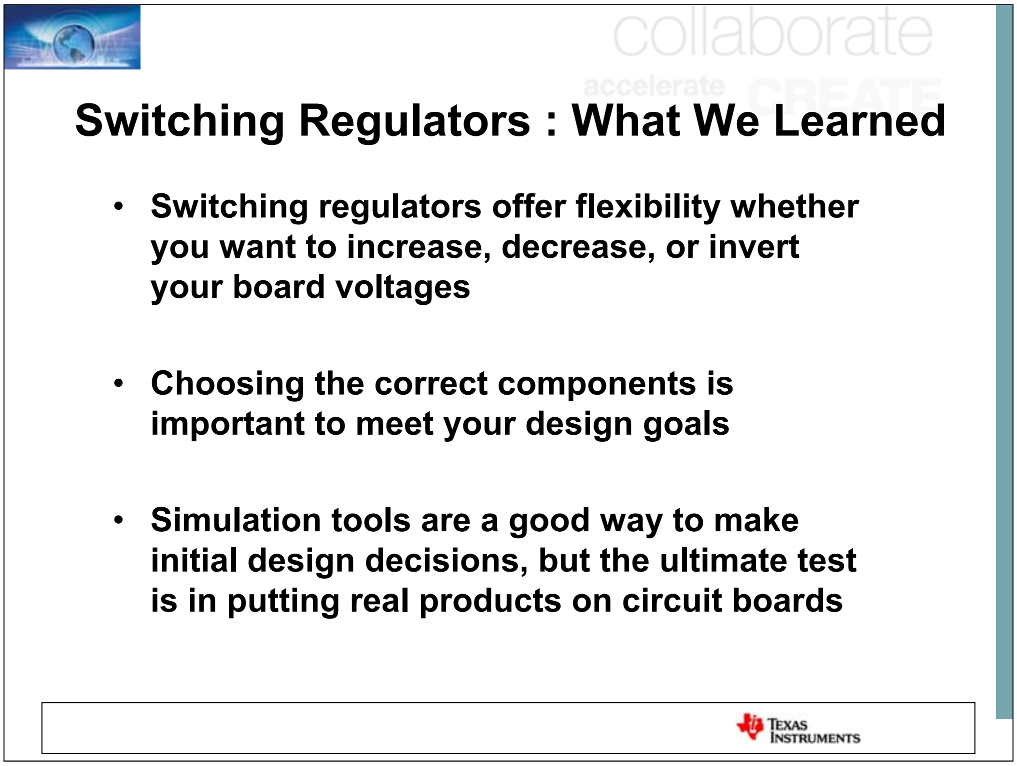
External FETs (DC/DC Controllers)

Application and design flexibility available to the user

Excellent total systems cost/value

Easy-to-use software tool saves development time
3) In many applications, using a standalone controller, TPS40k, TPS5xxxx without the on board FETs offers customers the most flexibility – and the ability to provide higher output currents. The customer has higher levels of design flexibility, and the ability to optimize performance and cost. The trade-off is that typically, this solution will require more design work and board space. So, if system cost includes not only component cost but board space and design time, then IFET converters for low to medium current applications are lower cost than controllers with external FETs.

The modules and the IFET products are available in various current steps: PTH from 2A to 30A, SWIFT from 1.5A to 14A.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Switching Regulators : What We Learned
• Switching regulators offer flexibility whether you want to increase, decrease, or invert your board voltages
• Choosing the correct components is important to meet your design goals
• Simulation tools are a good way to make initial design decisions, but the ultimate test is in putting real products on circuit boards
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Questions?

SwitcherPro™

Heath Gallimore

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SwitcherPro ™

- SwitcherPro is a complete on-line design tool for non-isolated switching DC/DC converter designs
- Access SwitcherPro from the ti.com website
  - Keyword search for “SwitcherPro”
  - Select “Power Management” (upper left)
    - “Tools and Software”
    - SwitcherPro is one of the listed items
- Log in using my.TI.com user account

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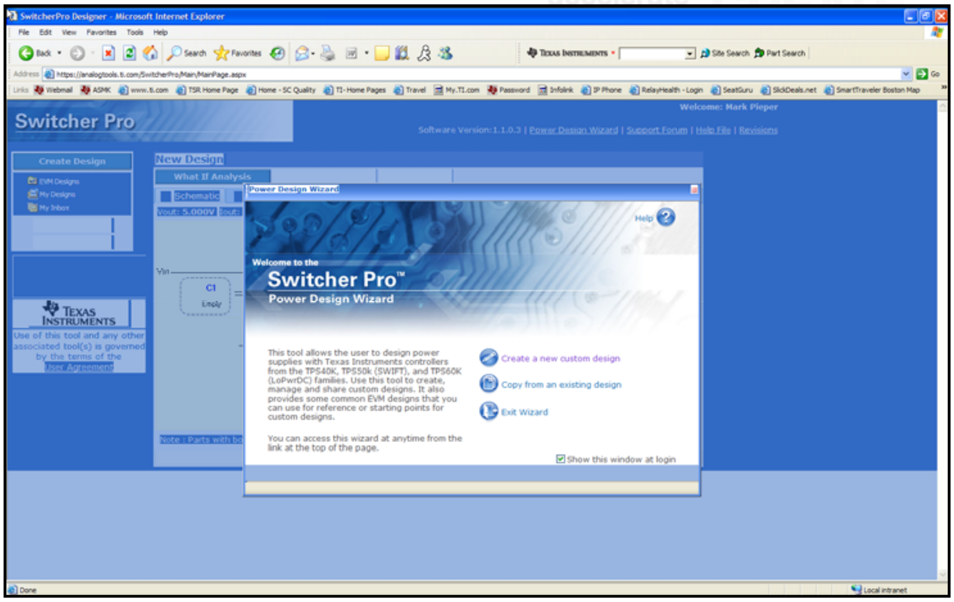
Switcher Pro™ Startup Screen



SwitcherPro Startup Screen

The **Power Design Wizard** can be used to start a design, or it can be closed and the design can be created using the Create Design file folder at the left. The **Design Wizard** and the **Create Design** button both access the same design utilities. We will use the **Design Wizard** to create our custom design.

Select: **Create a new custom design**

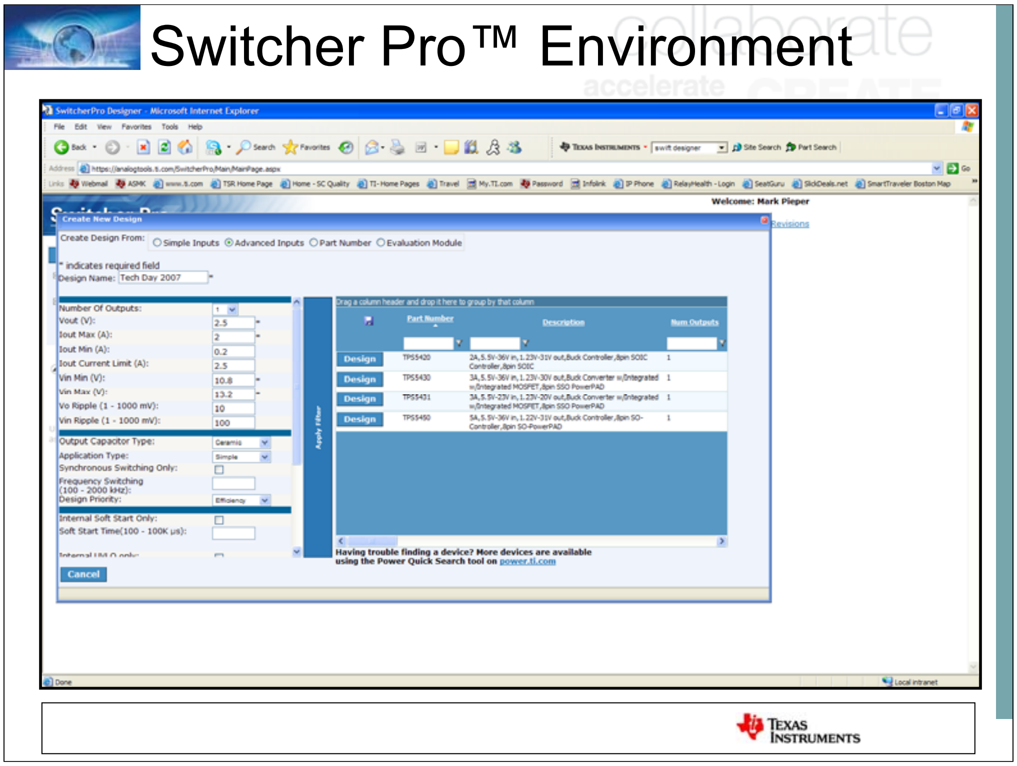
Start by entering specifications

Advanced Inputs button

Switcher Pro™ Example

- DC Design Parameters
  - Vin = 12.0V ±10%
  - Vout = 2.5V ±2%
  - Iout = 2.0A max. 0.2A min
  - Optimize for size
  - SMD, shielded inductor, ceramic output caps
- AC Design Parameters
  - Vout ripple voltage: 10mV p-p
  - Vin ripple voltage: 100 mV p-p

These are the design parameters for our example. This data is entered into the **Advanced Inputs** tab in the **Create New Design** window. After entering this data and Enter on the keyboard, the selection of parts narrows to those that are capable of fulfilling the requirements.

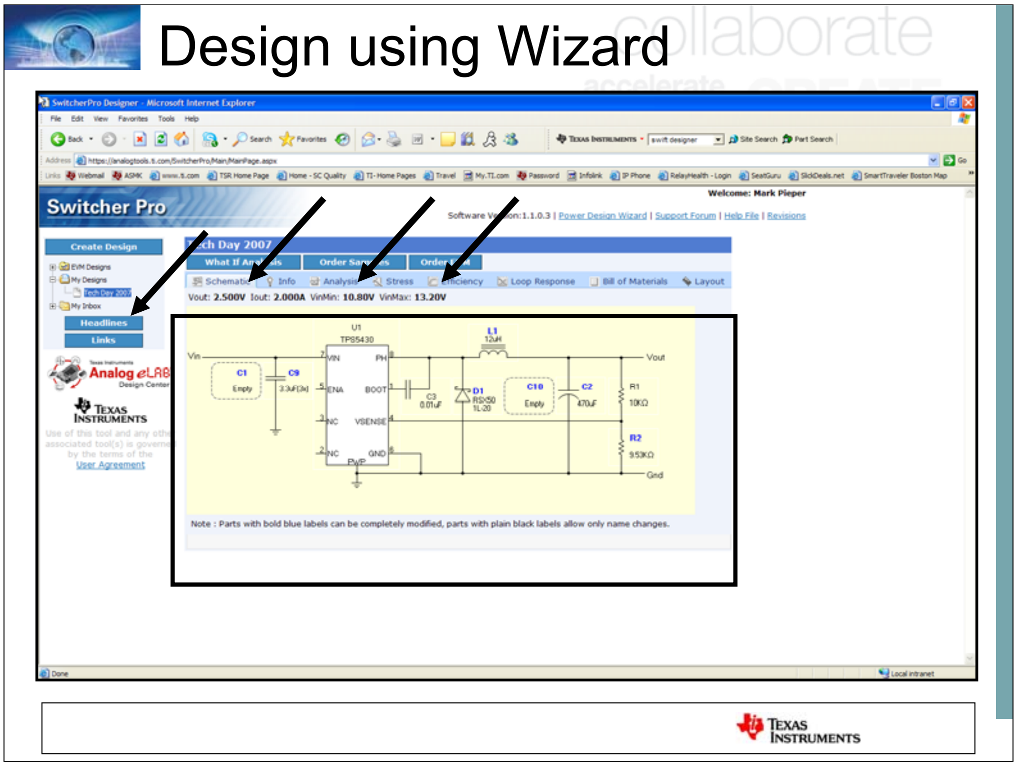


Enter the design requirements into the list at left.

Select **Apply Filter**

Applicable components are displayed.

Since we are interested in a TPS5430 SWIFT design, select **Design** next to the **TPS5430**.



The design is displayed <click> and shows up as an entry under the **My Designs** folder <click>.

The main window has three buttons:

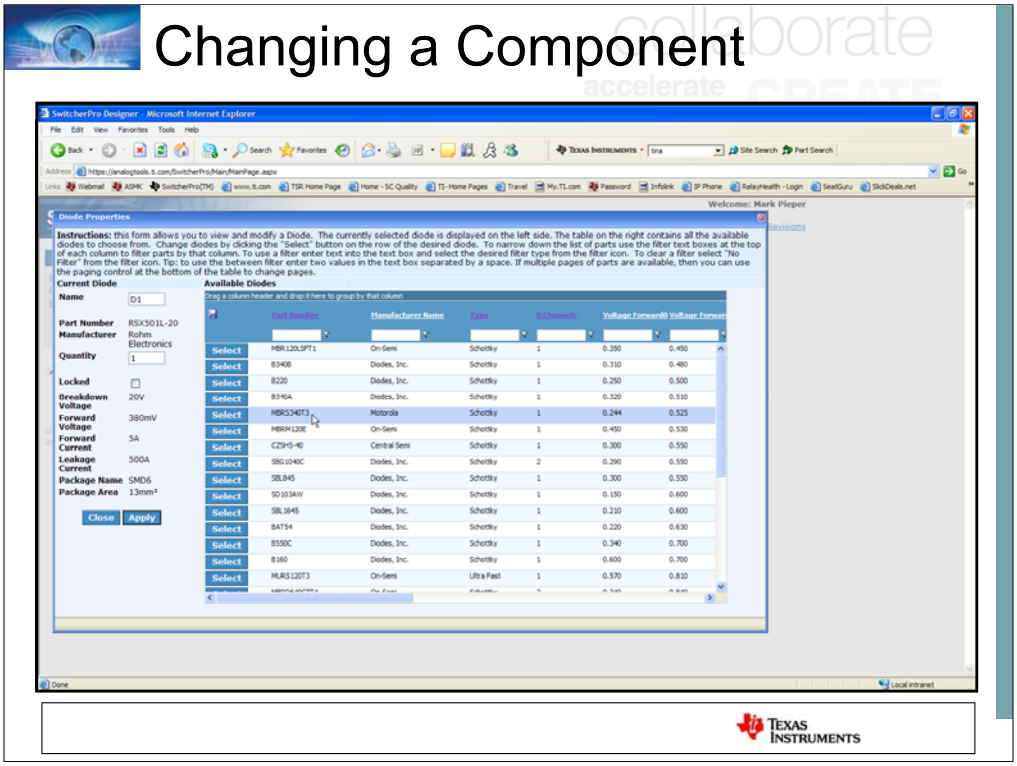
What if Analysis: <click> Allows examining the impact of various component changes to the performance of the design (more on this later).

Order Samples: <click> Is a link to the product page where samples can be ordered.

Order EVM: <click> Is a link to the Tools and Software section of the product pae where evaluation modules can be ordered.

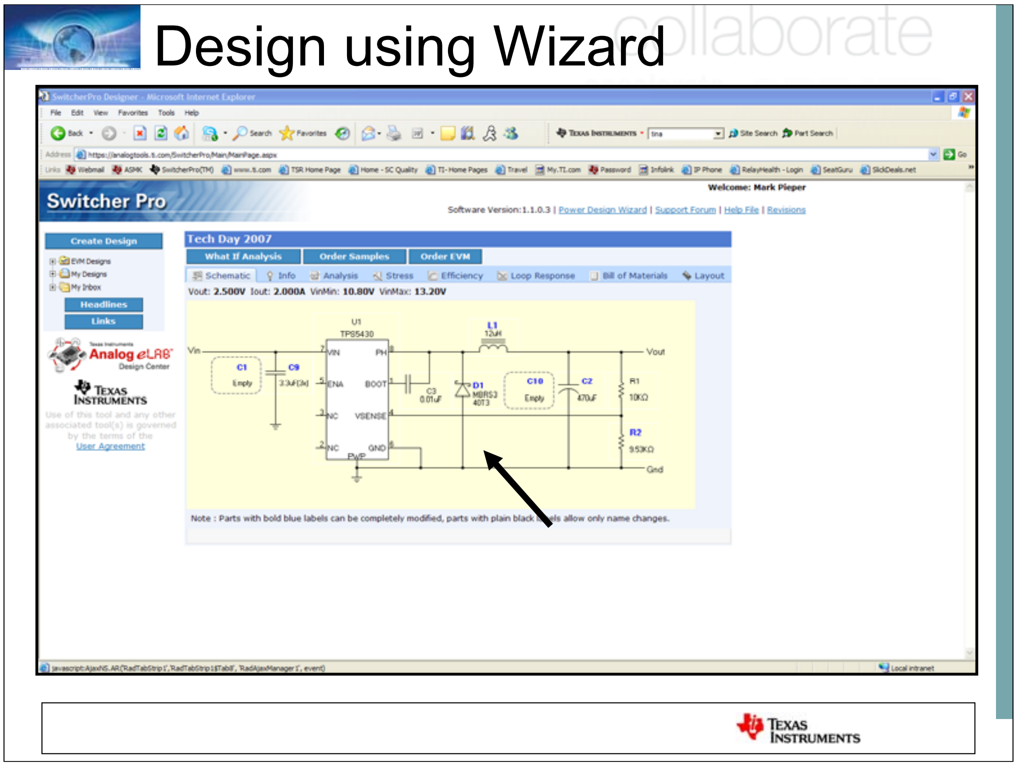
Schematic components with blue Ref Des can be selected and changed to a different component. Also note that when the mouse hovers over a component, information about that component is displayed. Balloons that have components that are labeled “empty” are optional components that you may choose to add. Examples are bulk input capacitors, additional output capacitors, and sometimes snubber networks.

Select D1 and evaluate alternatives. Change D1 to a MBRS340T3

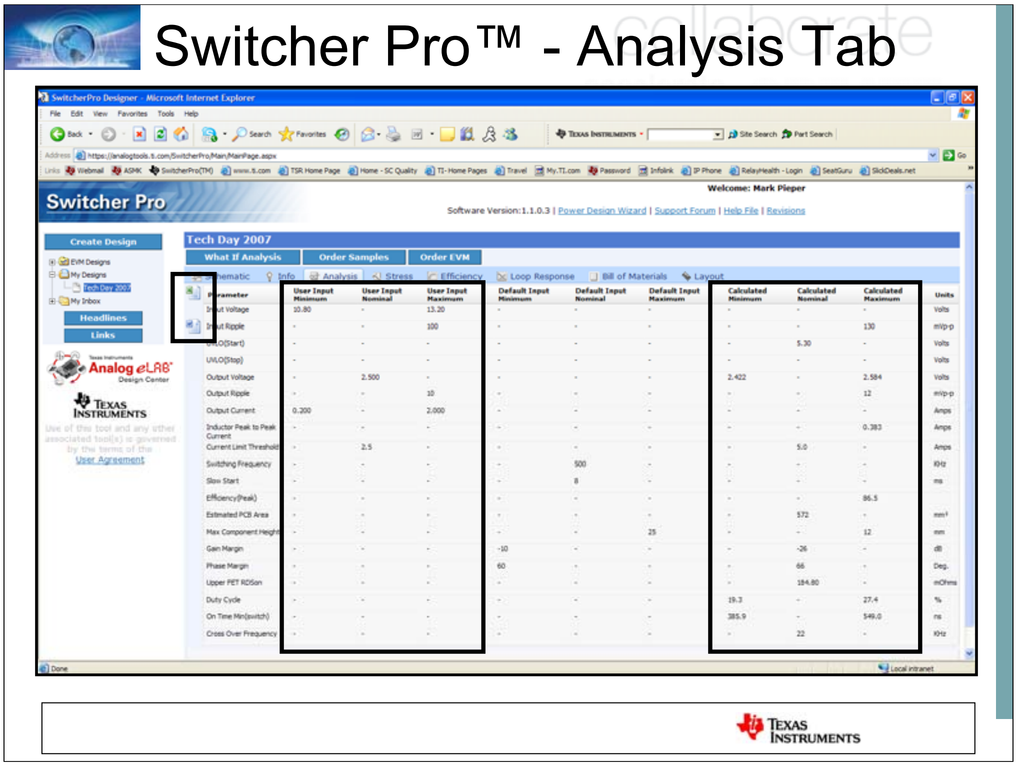


Changing D1 to MBRS340T3:

Select the button next to the **MBRS340** <click>

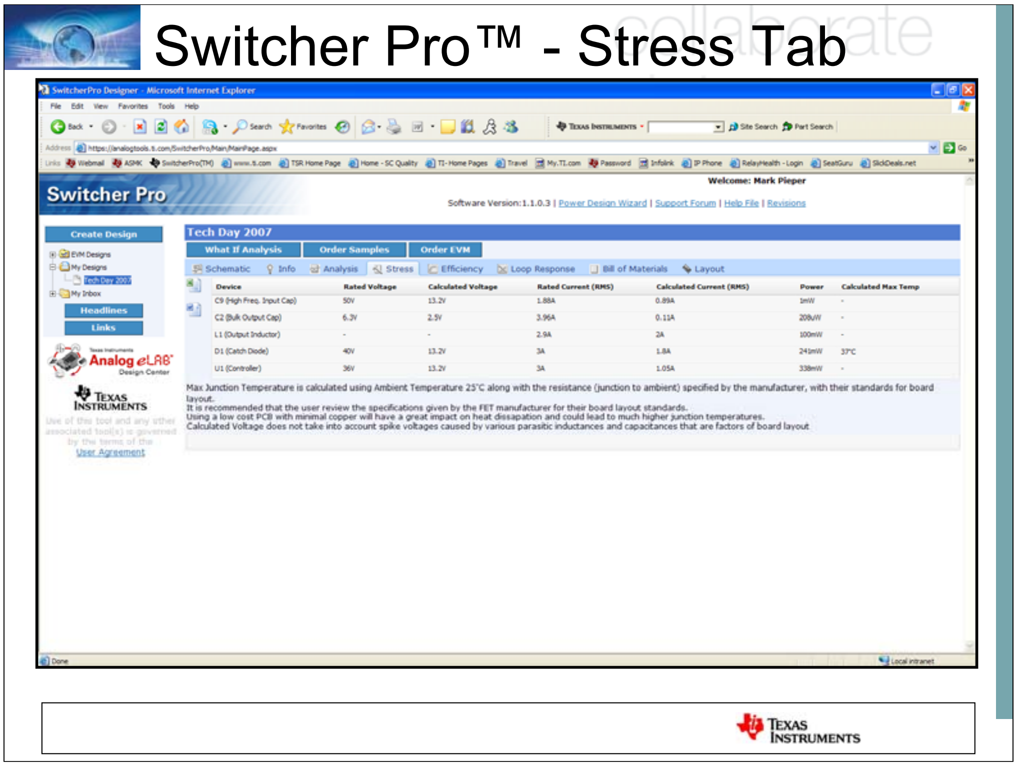


D1 is changed to a MBRS340T3 on the schematic page



The Switcher Pro Analysis tab provides a comparison between the specified design requirements (**User Inputs**) <click> and the anticipated performance (**Calculated**) <click>.

The Analysis table can be exported to either Excel or Word documents by selecting the appropriate icon in the upper left <click>.

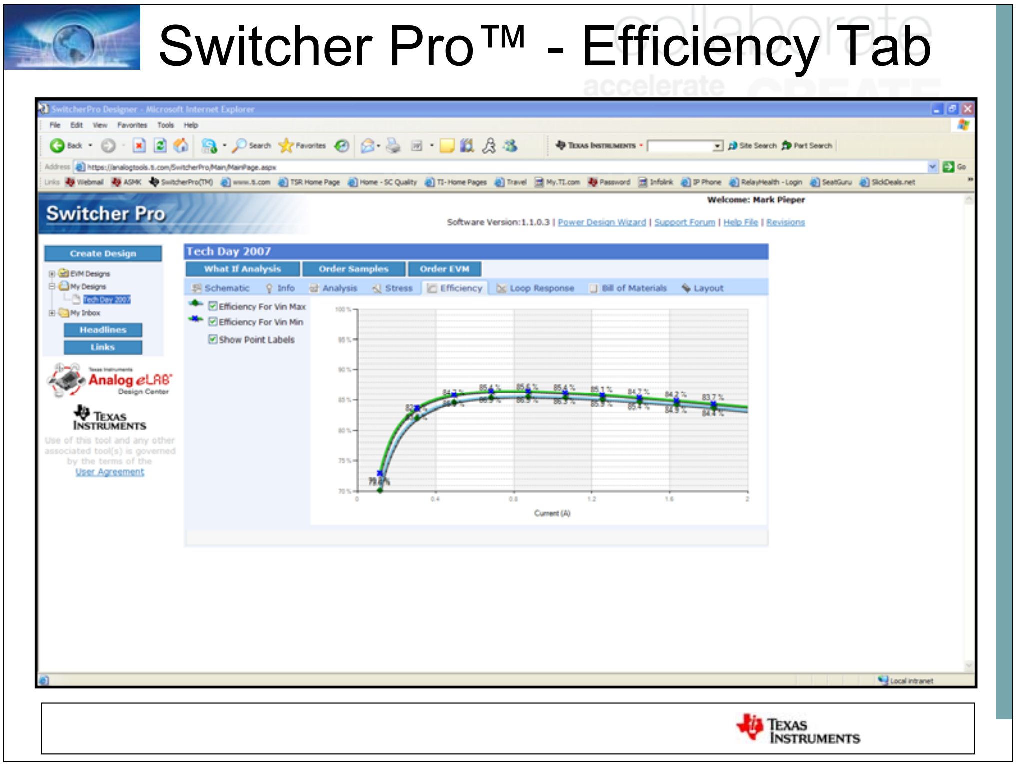


The Switcher Pro Stress tab provides stress analysis for the critical components in the design.

It compares component rated voltage and current to the calculated value in the design.

It calculates the power dissipation for each component, and if a thermal impedance is associated with that component it calculates the max temperature for that component.

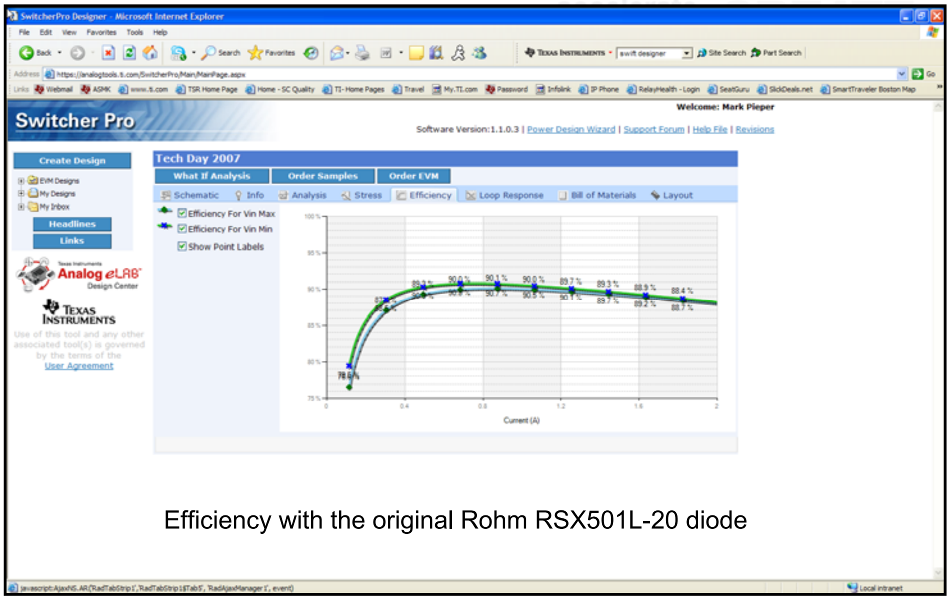
The Stress table can be exported to either Excel or Word documents by selecting the appropriate icon in the upper left.



The Switcher Pro Efficiency tab displays the calculated efficiency curves for the design for both Vin min and Vin max.

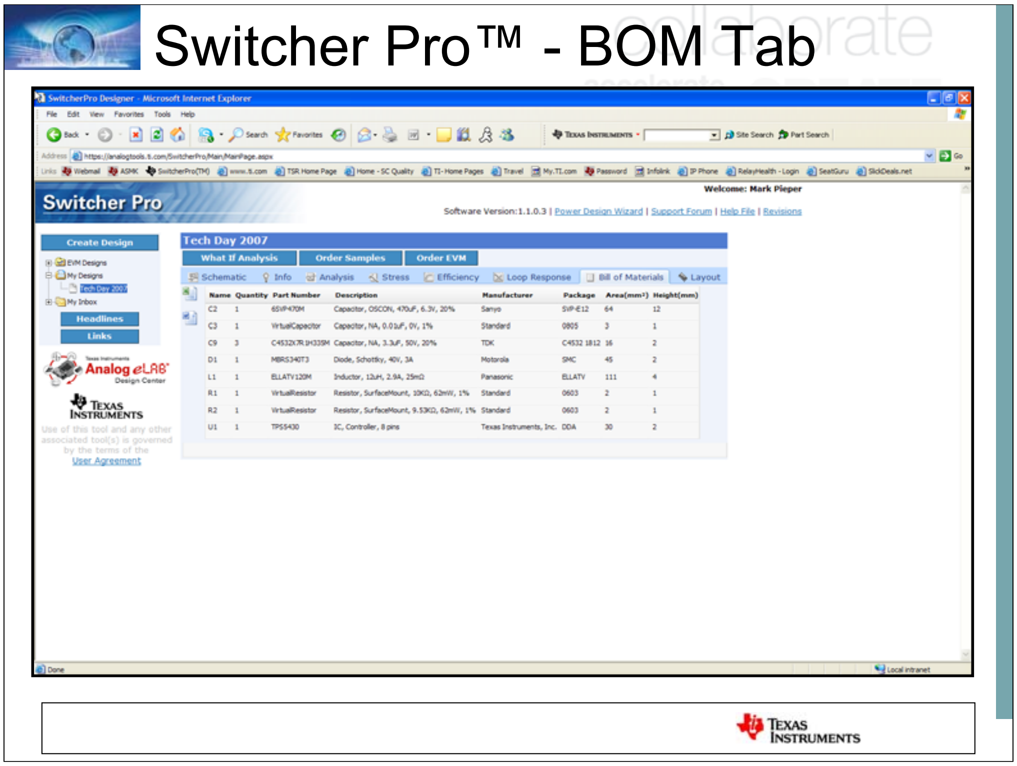
The buttons allow customizing the graph to show or hide data.

Switcher Pro™ - Efficiency Tab



Efficiency with the original Rohm RSX501L-20 diode

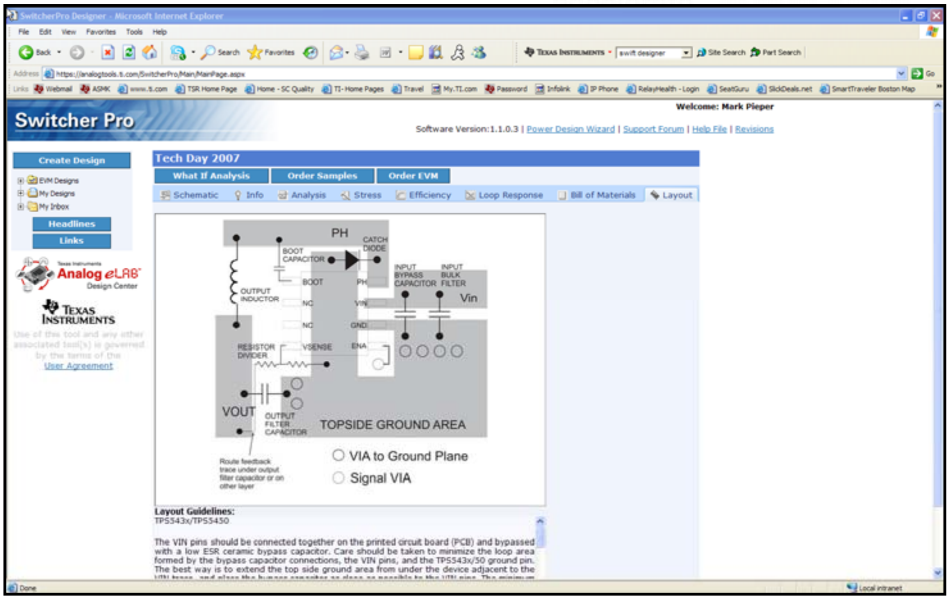
This is the efficiency curve for the original design before the diode was changed. Note that SwitcherPro had selected a more efficient component.



The Switcher Pro Bill of Materials tab displays the purchasing data for the components in the design. Notice that these are all real (not ideal) components. The various parasitic parameters (capacitor ESR, FET Rdson, Inductor resistance) are all included in the model used for the design analysis.

The BOM table can be exported to either Excel or Word documents by selecting the appropriate icon in the upper left.

Switcher Pro™ - Layout Tab



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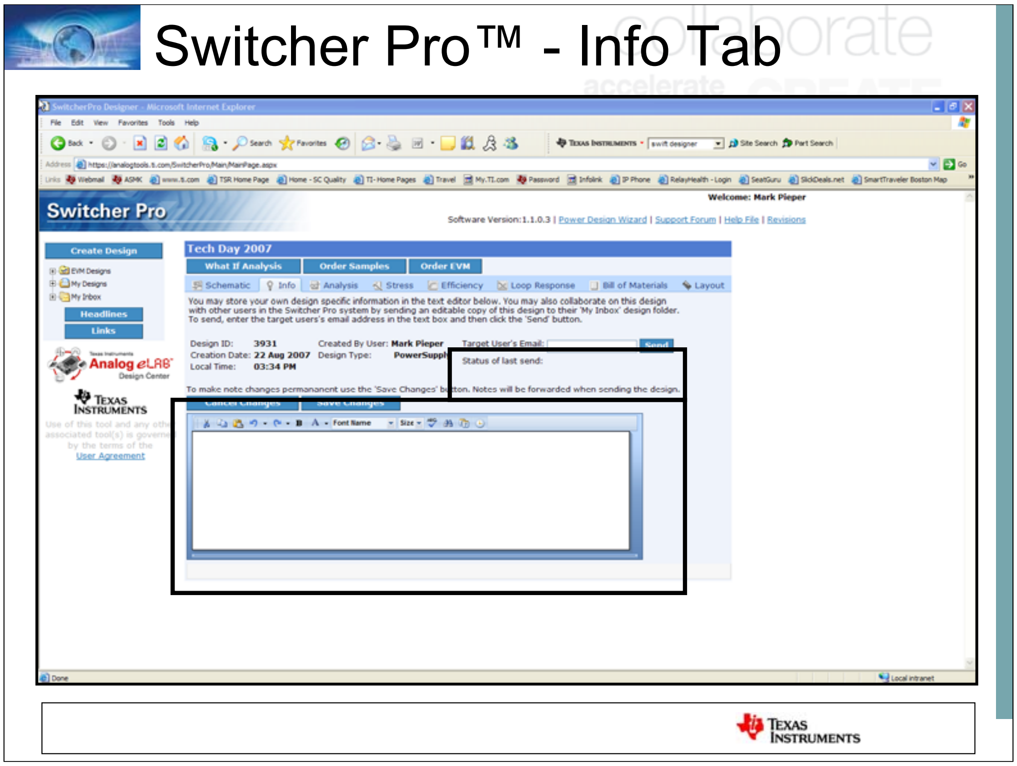
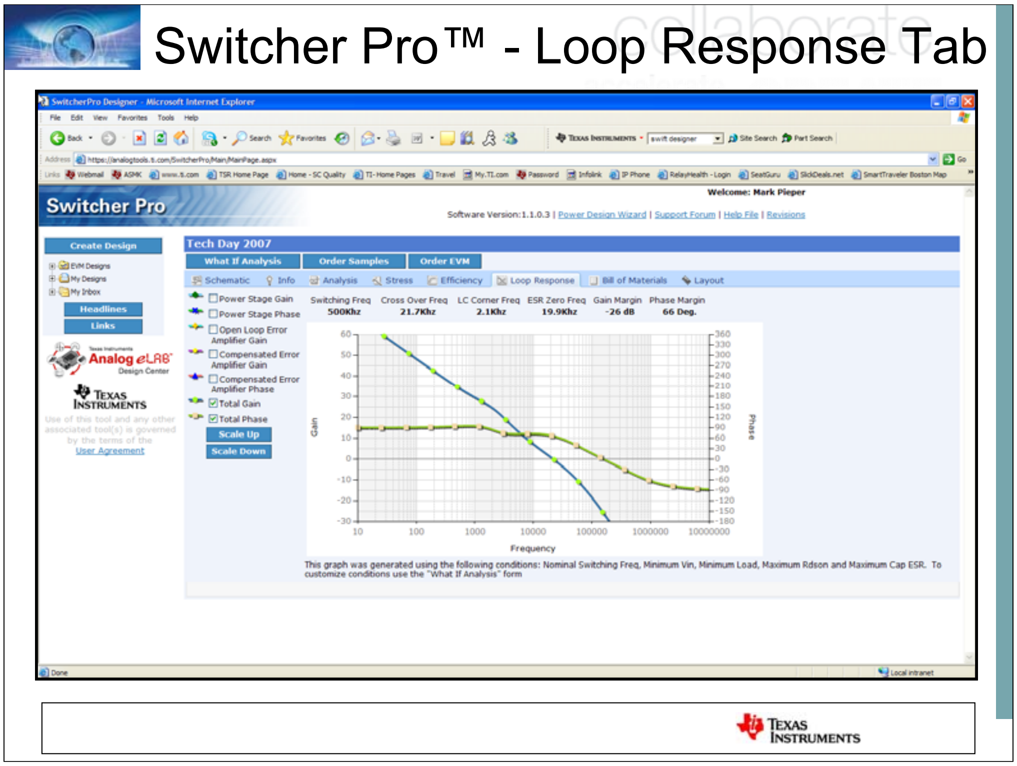
The Layout tab presents an example PCB layout for the specific controller selected

Additionally, layout guidelines are included that explain the specific issues that need to be considered during the PCB design.



The Switcher Pro Info tab is a place to store notes, design analysis, or any other information related to the design that is needed <click>.

This tab also enables you to send the design to a co-worker for collaboration and/or review <click>.



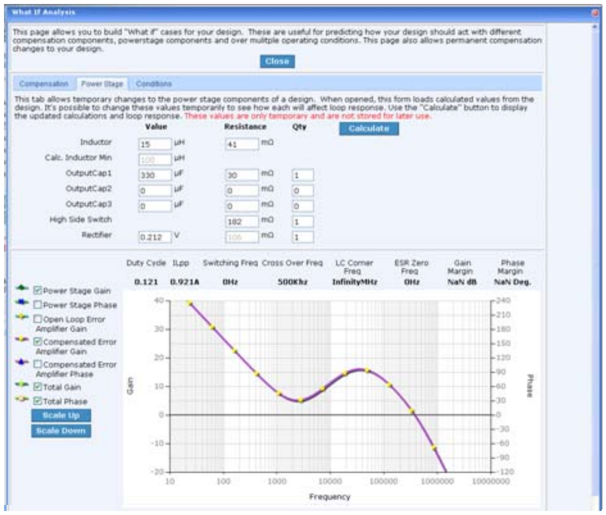
The Loop Response tab enables the designer to examine the bode plot of the Power Stage, compensation <click> (feedback including the error amplifier), and the total closed loop bode plot <click>.

The bode plot is a means of assessing the relative stability of the power supply design.

Phase Margin is the phase above 360° when the gain = 0dB. The phase margin should be above 45 degrees, and 60 degrees is a good goal.

Gain margin is the gain below 0dB when the phase crosses over 360 degrees. Gain margin of 10dB or greater is a good design goal.

What If Analysis Tool



Working with the tool

- 3 Examples to try on your own

Questions?

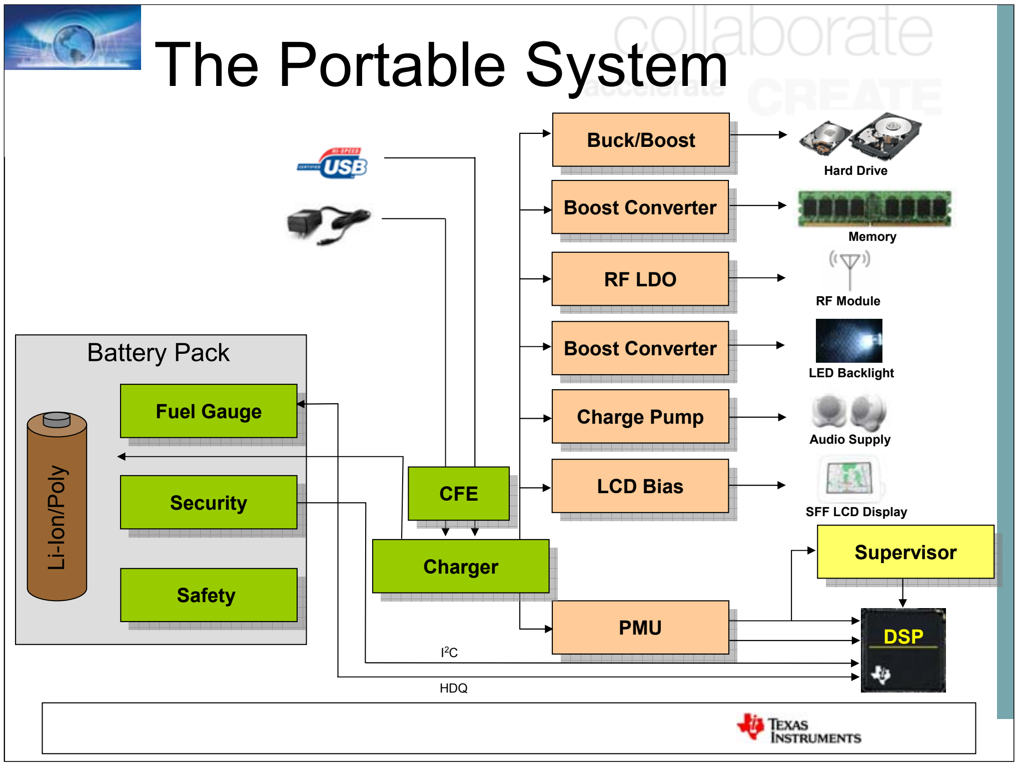
Batteries for Portable Systems

Rich DelRossi

TEXAS INSTRUMENTS

Agenda

- The Portable System
- Common Battery Technologies
- Li-Ion Technology
- Battery Management Overview
  - Fuel Gauging
  - Safety
  - Authentication
  - Charge Management

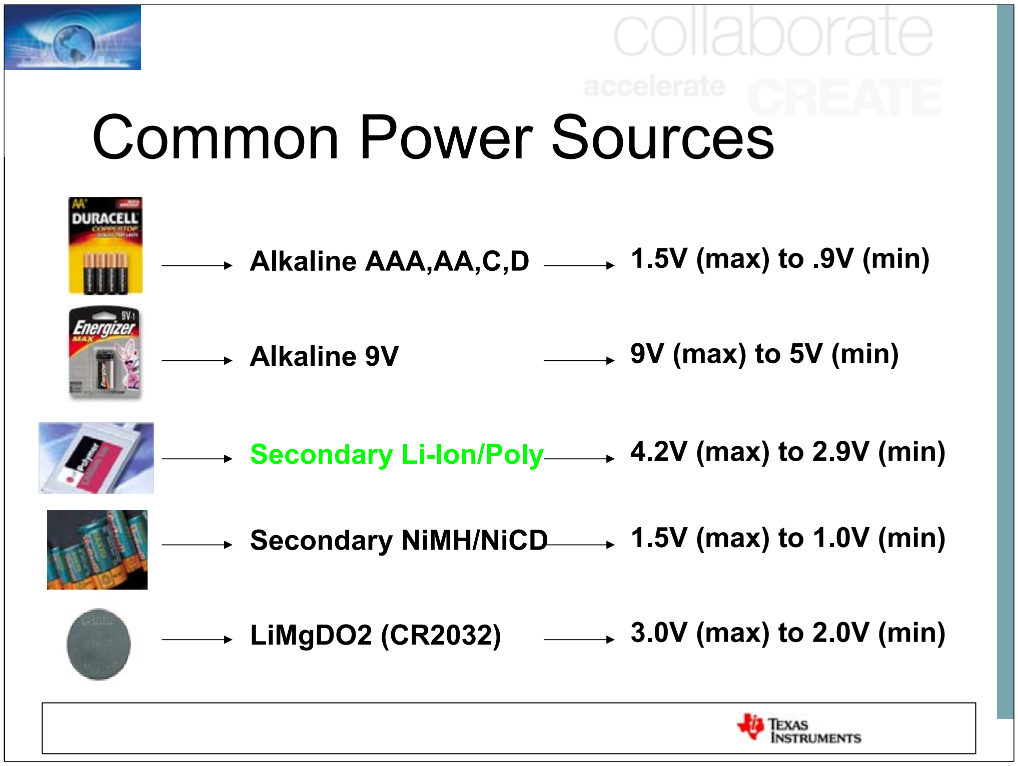

The Portable System
collaborate
accelerate
CREATE
Buck/Boost
Hard Drive
Boost Converter
Memory
RF LDO
RF Module
Boost Converter
LED Backlight
Charge Pump
Audio Supply
LCD Bias
SFF LCD Display
Supervisor
Battery Pack
Fuel Gauge
Li-Ion/Poly
Security
Safety
CFE
Charger
PMU
DSP
I2C
HDQ
USB
Texas Instruments

Portable Development Focus

- What makes power management products for portable end equipment different?

Needs

– Low quiescent current
– Higher Efficiency
– Small Solution Size / Packaging
– Lower Cost
– More Voltage Levels



There are several different battery chemistries that one can choose from in designing their power source. They range from Alkaline, to Li-Ion, Ni based chemistries. The voltage output on these batteries ranges from a minimum of 1.5V to a maximum of 9V. These batteries drop from fully charged to discharged through the battery life.

You could also have a regulated bus which provides you with a voltage of 5V or 12V and that stays constant.

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Chemistry Comparison

	Ni-Cd	Ni-MH	Li-Ion	Li-Polymer	Alkaline
Operating Voltage	1V - 1.4V	1V - 1.4V	2.5V - 4.2V	2.5V - 4.2V	0.9V-1.5V
Cell Cap. (Ah)	0.3 -10	0.1 –12.5	0.13 –5.6	0.15 –4.4	D-12; C-6 AA-2; AAA-1
Cost	$	$$	$$$	$$$$	$
Advantage	Low Cost & Medium Self Discharge Rate; Rechargeable	Low Cost & Lower Self Discharge Rate; Rechargeable	Good Energy Density; Doesn't suffer from memory loss; Rechargeable	Good Energy Density and flexible form factor; Doesn't suffer from memory loss; Rechargeable	Low Cost & Virtually no self discharge rate
End Equipment	Portable hand tools. Remote controlled toys -anything requiring a fast discharge	Digital cameras and other common electronic devices	Consumer electronics: cellular phones, digital cameras, and notebook computers	Consumer electronics: cellular phones, digital cameras, and notebook computers	low-drain electronics like smoke detectors

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1)The first thing to look at is operating voltage. Know the range of voltage that your unit can handle and where your cutoff voltages should be.

Cutoff voltages are extremely important

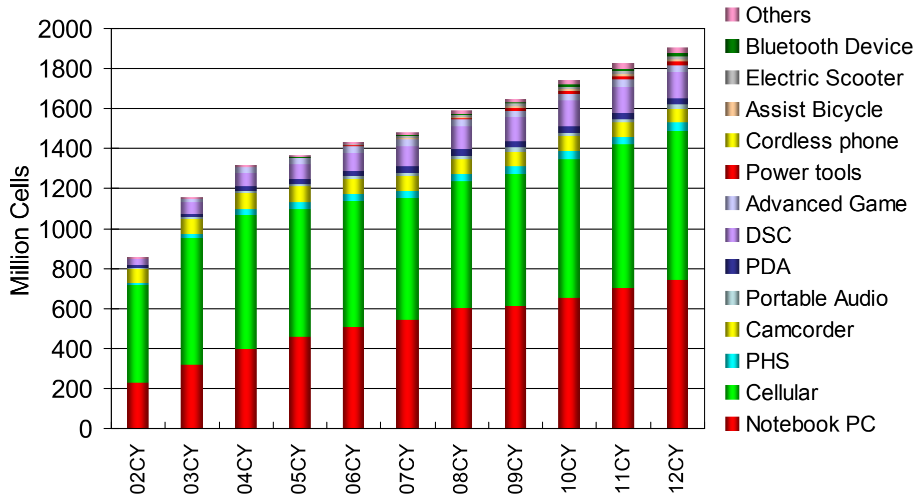
A small variation in cutoff voltage will affect cycle life

2)Note the advantages of each chemistry. This can help you understand the designers' goals.

3)What is different about Alkaline batteries? They are non-rechargeable. Whatever you do – don't try to sell TI chargers to an engineer that is using Alkaline batteries.

Li-Ion Battery Growth

WW LIB/LIP Cell Demand For Portable Devices (HEV not included)



Driving forces of Li-Ion Development

- **Cost reduction (Co elimination/reduction)**
- **Higher energy (capacity/voltage increase)**
- **Higher discharge rate capability**
- **Increased safety**

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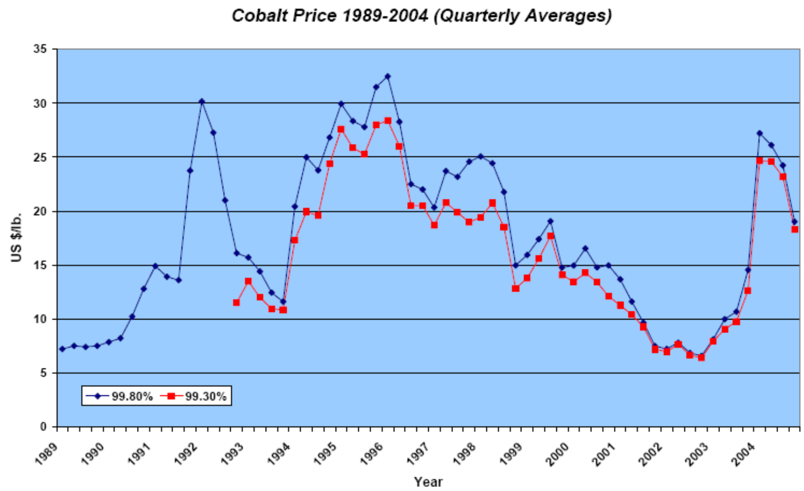
Cost reduction need



Cobalt News, April 2005, http://www.thecdi.com/cdi/images/news_pdf/Cobalt_News_April_2005.pdf

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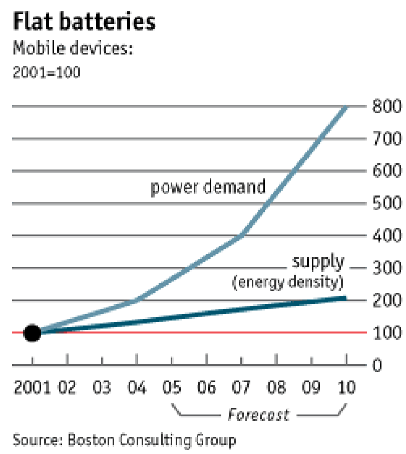
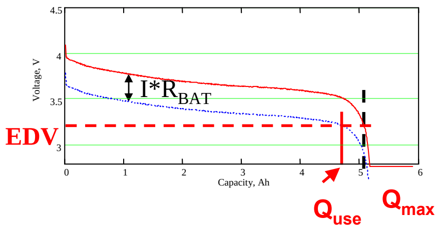
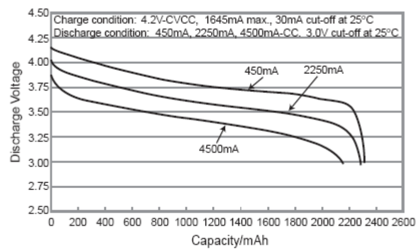
Need for higher energy



Higher discharge rates problem





*Panasonic CGR18650D datasheet

- High internal resistance of traditional Li-ion battery causes large I*R drop at discharge rates above 2C rate
- Minimal system voltage is reached too early, reducing useable capacity
- Some markets that Li-ion makers try to penetrate require full discharge in 5-20 min (15C-3C rate)

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Need for improved safety

- **Lithium-ion battery is known to undergo thermal run-away on overcharge or overheating**
- **Large battery support is needed for moving into new markets such as power tools and hybrid vehicles**
- **Explosion of mobile battery is a dangerous accident, but explosion of a larger hybrid car battery is likely to be a disaster**

Screen shot from Valence Techology video of large battery overcharge

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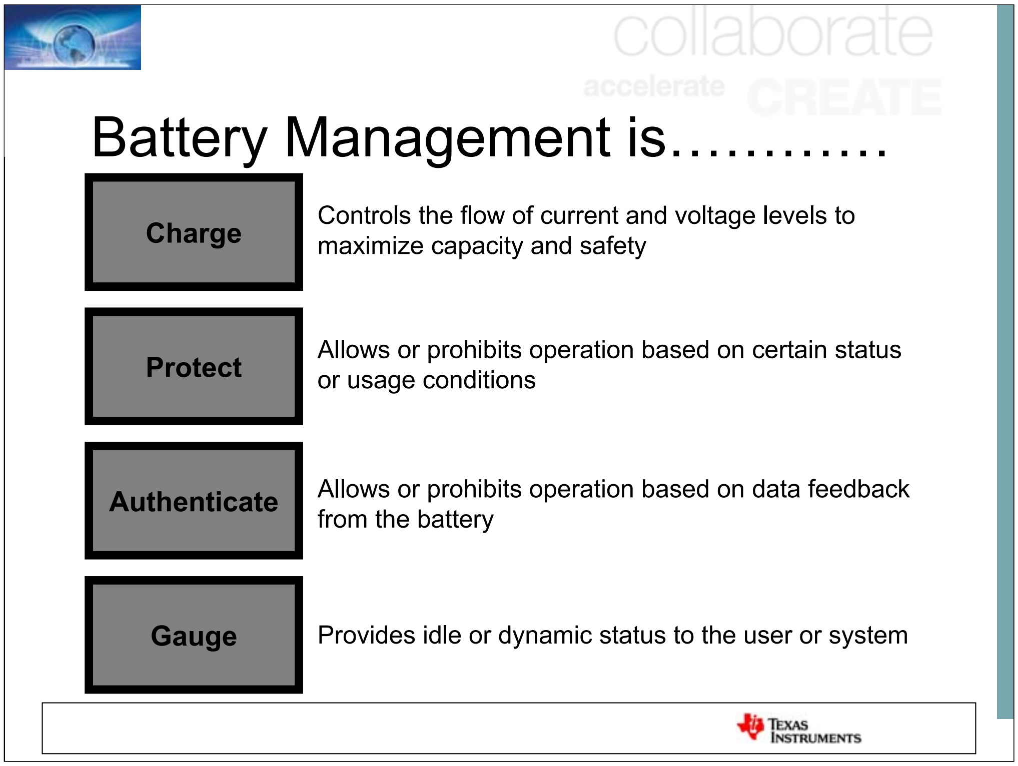

Systems require battery management to:

- Extend run times
- Maximize safety
- Maximize battery life

Components of Battery Management:

- **Battery Fuel Gauging**: Continuous battery monitoring & communication
- **Charge Management**: Battery charge control
- **Battery Protection**: Primary battery protection from abuse conditions
- **Battery Authentication:** Identifies peripherals

Note on Protection:

A second set of design challenges results from the basic properties of rechargeable lithium cells. First, there are certain safety issues when designing with the most common lithium batteries: LiIon and LiPolymer. A LiIon pack contains multiple levels of protection, including mechanical and electrical protection-circuit modules, which prevent charging above 4.3 V, discharging below 2.3 V, and short circuits.

Customer Demands for Battery Management

- Number of mobile users increasing
- Functionality increasing
- More power applications
- Power demand increasing 2x faster than battery improvements
- Efficiency increasing
- Cost
- Portable consumers demand more out of their battery

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Fuel Gauging

- Predicts battery capacity **under all system active and inactive conditions**
- Battery capacity **can be reported in terms of accurate percentage, time to empty/full, milliamp-hours or watt-hours, talk time, idle time, # of pictures, etc.**
- Other data **can be obtained for battery health and safety diagnostics.**
  - # of charge/discharge cycles
  - Maximum operating temperature
  - Current I, V & T conditions
  - Fully charged, empty conditions
  - Near empty warnings
  - Over- / under-charge conditions

73%

Run Time 6:23

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Fuel Gauging – Ease of Use

Standard Gauging (Today):

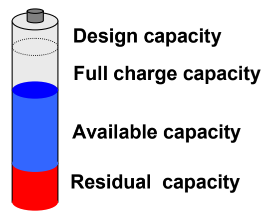
- Measures current, voltage, and temperature, and integrate current over time (*coulomb counting*).
- Models the battery cells reaction to discharge rate, temperature, age.
- Models self-discharge and non-measurable currents.
- ***Re-learns*** the full charge capacity over time
- Calculates and accumulates prediction error (could increase significantly over six months).
- Remaining Capacity = full charge capacity - ∑i∆t – self discharge – module current – residual capacity - error.

Impedance Track™

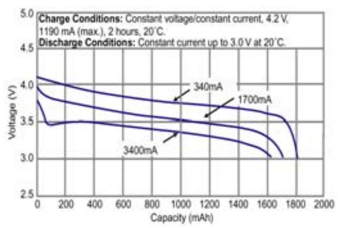
Directly measures effect of discharge rate, temp, age and other factors on cell impedance

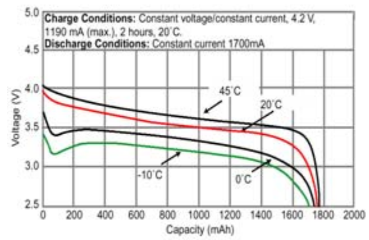
Calculates effect on remaining capacity and full charge capacity

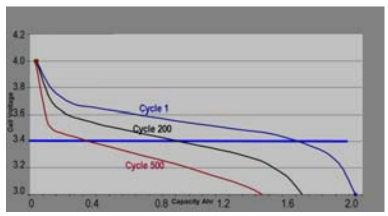
No models/learning needed



Li-Ion Current Load Discharge Profile







Usable Capacity and Shutdown Voltage vary with Discharge Rate, temperature, and cycle count

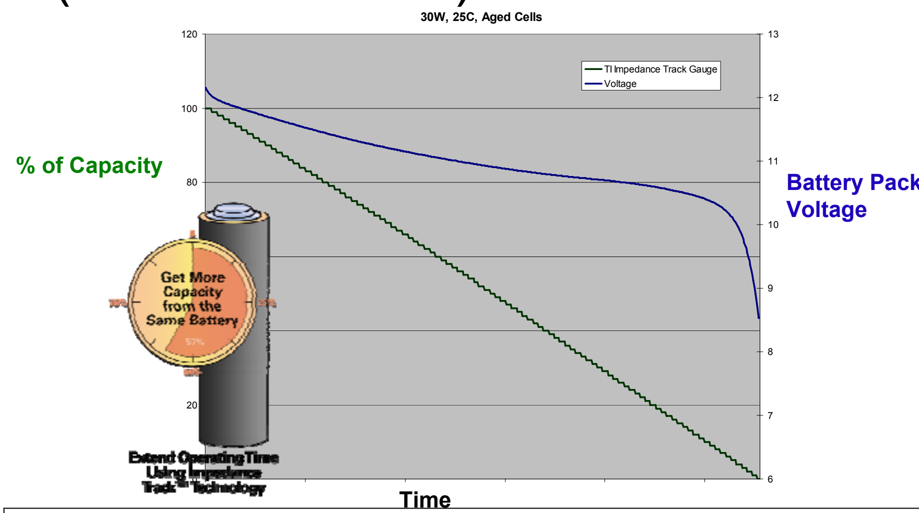
Li-ion battery rate capability can be tailored in wide range by using thicker or thinner layers of active materials. Thinner layers mean higher rate capability but less energy density. Typical 18650 cylindrical cells used in notebooks are designed for maximal C rate discharge. However, there are cells rated for 10C discharge used in portable power-tools, and even cells capable to 60C rate discharge used for power backup/regenerative breaking in hybrid gas-electric vehicles.

Rate capability is severely degraded at low temperatures below 0C because of low conductivity of organic electrolytes. Some electrolytes are better than other, therefore referring to manufacturers data on low-temperature discharge is important.

Fuel Gauging Benefits

- Accurate report of remaining run time
- Better Power Management
- Orderly shutdown
  - Automatically save data to flash with reserve energy when battery dies
- Longer Run Time
  - Power management
  - Accuracy: less guard band needed for shutdown
  - Variable shutdown voltage with temperature, discharge rate, and age based on impedance

Results! Reported Capacity (3 cells in series)



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Why the need for Battery Authentication?

Front page news on EETimes 09/20/2004:

"Fake batteries blow up in the Industry's face"

Also:

- HELSINKI (Reuters Oct 2003) - Nokia pointed the finger at counterfeit batteries after another of its phones exploded and burned its user, the third such case in two months, and said original batteries sold with its phones were safe…… ……Following the latest Dutch incident, which left a 15-year-old boy in the town of Hengelo with leg burns, the country's consumer watchdog said it would probe the case.

- June 2004: 50,000 Verizon phones recalled with fake LG batteries – 18 reports of injuries or property damage due to exploding batteries.

- October 2004: Kyocera recalls 1,000,000 cell phones due to fraudulent batteries in its KE/KX 400 series of phones

Why the need for Battery Authentication?

- Safety
  - System compatibility (charger, battery, system)
- Brand Protection
  - People say “The *Nokia Phone* caught fire…”, not “The *aftermarket battery* caught fire…”
- Protect Business Model
  - Maintain and control after market battery sales
- IP Protection
  - Protect IP embedded in battery management system

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Protection

- ALL Li-Ion battery packs MUST have protection circuits
- Over & Under Voltage, Over Current and some have Over Temp
- Primary IC Controls CHG and DCHG FET
- Common solutions include 1-4 cell in series
  - Series = Add Voltage
  - Parallel = Add Capacity
- Additional system side protection is also available

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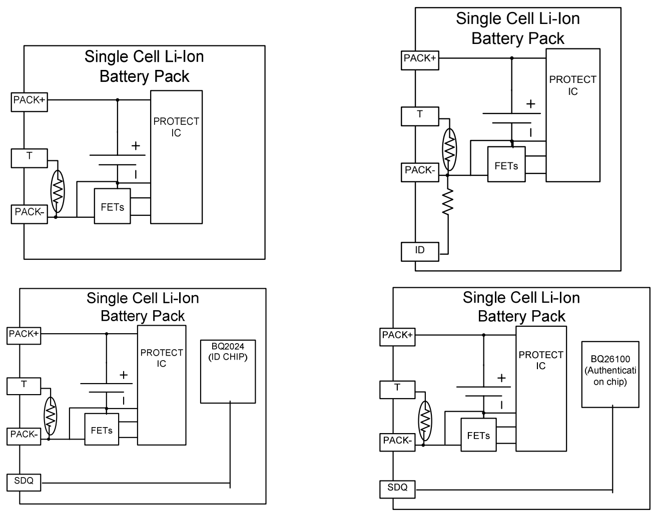
Protection + Authentication in 1S Battery Packs



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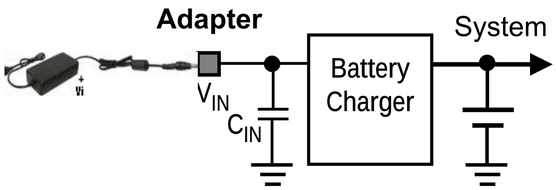
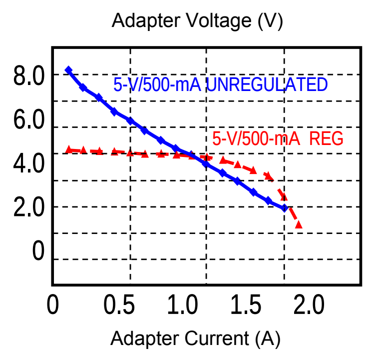
System Side Protection



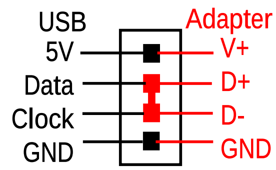


Input Over-Voltage is caused by…

- **Wrong adapter or after-market adapter**
- **Transformer–rectifier adapters (un-regulated)**
- **Hot-plug event**

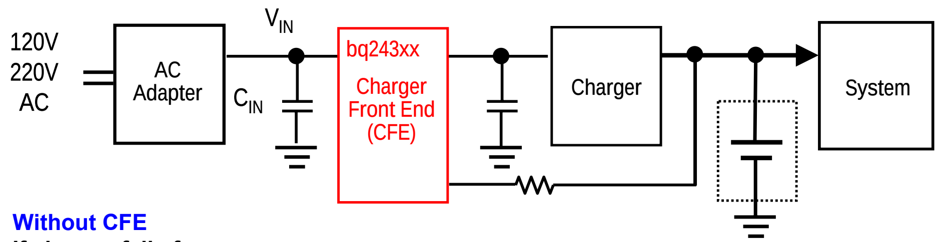
New USB Standard driven by China

AC 100-240 V 50/60 Hz
DC 5 V, 0.31 A



- **USB type A connector for cell phone charger**
- **Purpose is to share adapter and cable among different cell phones to save cost and save environment**
- **New standard to drive "after-market" accessory makers to develop phone adapters that may or may not need safety standards**
  - This drives the need for redundant safety features

CFE Improves Safety



Without CFE

If charger fails for any reason...

- **System will be in over-voltage condition and fail**
- **Battery will be over-charged**

CFE Provide System Level Protections

- **Input transient over-voltage up to 30V**
- **Steady state over-voltage**
- **Up to 1.5A Over-current protection**
- **Optional adapter reverse polarity**
- **Battery over-voltage**

Charge Management

Linear Charger

Features

- ✓ Simple low-cost design
- ✓ Uses few external components
- ✓ No switching noise
- ✓ Fast transient response
- ✓ Low quiescent current

Limitations

- ✓ *Potential* Poor Efficiency: V_{OUT}/V_{IN}
- ✓ Power dissipation may be a concern

Best Used When

- ✓ V_{IN} to V_{OUT} is small
- ✓ Low output noise is important
- ✓ Space and cost are important
- ✓ Low output current

1S Segment

Switchmode Charger

Features

- ✓ Wide range of V_{IN} and I_{OUT}
- ✓ Very Efficient
- ✓ Limited Power Dissipation

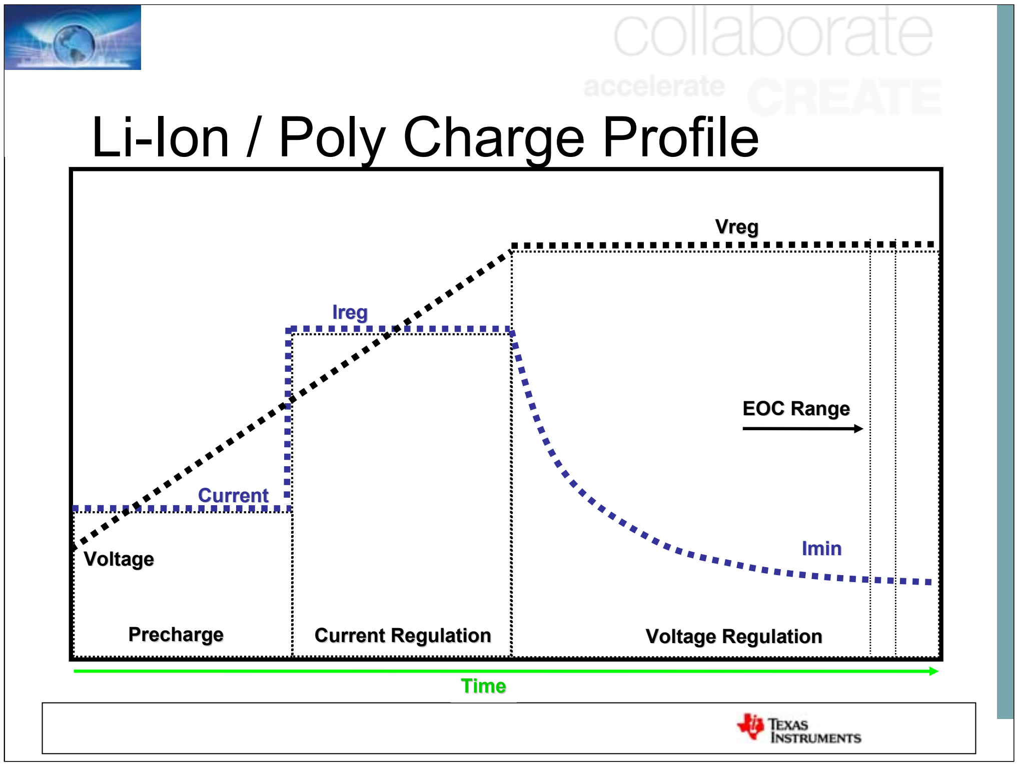
Limitations

- ✓ Larger solution size
- ✓ More expensive to implement
- ✓ Noise

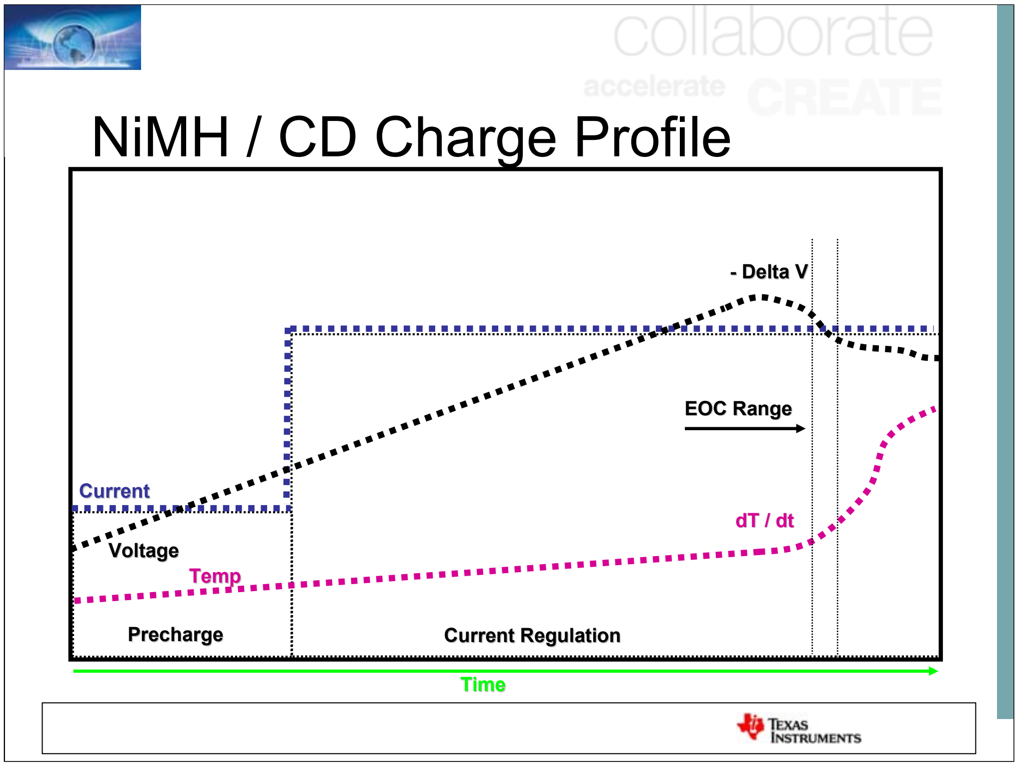
Best Used When

- ✓ Need best efficiency for battery life
- ✓ Higher currents are needed
- ✓ V_{IN} and V_{OUT} are wide

2,3,4S Segment



This is a lithium-ion charge profile → It is a constant current/constant voltage configuration. During the linear voltage increase in the pre-charge phase the current stays the same. Once it hits the current Regulation phase the current jumps up to Ireg or the maximum current output. Once the voltage hits 4.15-4.2 Volts its at its' Vreg- max voltage in the safe zone for lithium ion batteries. It will stay charging at the Vreg while the current slopes down. Once the current is detected at a minimum the charger will stop discharging.



The NiMH Charge Profile is a little different. This profile is known as a constant current profile. In the pre-charge phase the current is stable and then it hits a certain voltage and jumps to the max where the current stays constant. The voltage will continue to increase until it reaches a threshold where it begins to fall off. This is known as –delta V and is one indicator that the battery is charged. The other indicator is that the DT/dt gets higher and higher as the voltage keeps increasing and the current stays the same – the IC gets Hotter. When the dT/dt reaches a certain point the charger will enter the end of charge range and stop charging the battery.

Do I need?

- Thermal Regulation
  - The ability to lower charge current when high temp conditions exist
- Powerpath Management
  - The ability to run the system at full power while charging the battery
  - System has priority power
- Over Voltage Protection
  - An extra level of voltage transient protection on the input
- Single or Dual Input
  - USB and Supply

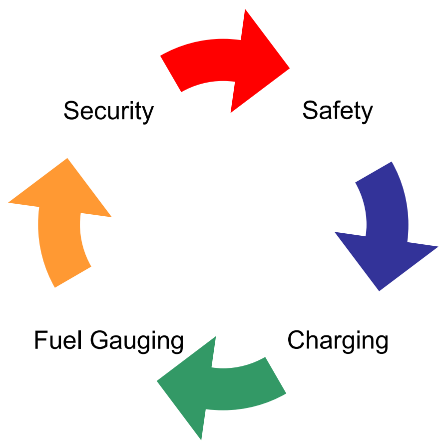
Single Cell Charger trend

- Linear dominate the 1S segment but some customers are moving to Switchmode for better charge times plus less heat

Dec 2007

- **Highly efficient charging from USB or AC/DC**
- **Reduces charge time vs. linear charger approach**
- **Ultra-small solution for USB On-the-Go (3-MHz, WCSP, integrated reverse-boost function)**
- **Compatible with new battery chemistries (adjustable regulation voltage)**

Battery Management is a System level approach



Final Question:

What battery management products do you think are in these products?

Example #1

Example #2

Example #3

Conclusion

- The Li-Ion battery is evolving into different “Versions” generating new voltage levels and power characteristics
- The solutions that manage Li-Ion need to work together to provide the maximum performance and safety
- TI is the leader in power & battery management and continues to deliver innovative products that meet the changing environment

Questions?

Thank You!