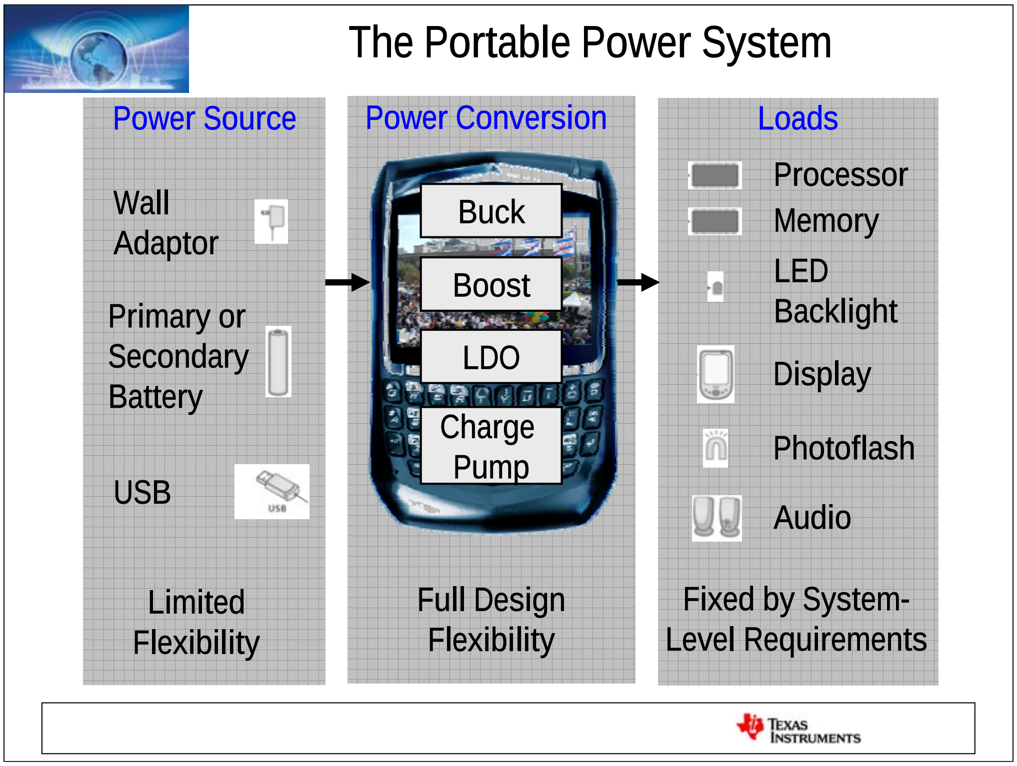
2009 Washington DC Tech Day

Buck-Boost Converters for Portable Systems

Allen Wachter
Local AFA

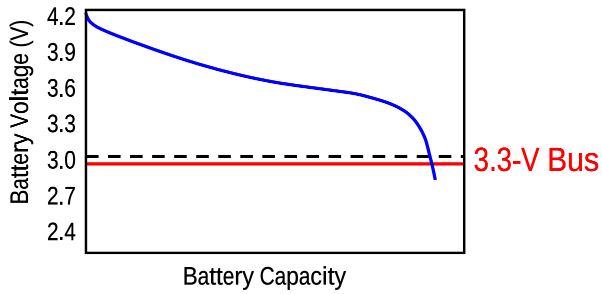
Agenda

- **Portable Power Regulation Problem (Li-Ion to 3.3 V)**
- **Li-Ion to 3.3-V solutions**
  - Cascaded Buck and Boost, Buck-Only, LDO, SEPIC, Classical Buck-Boost, TPS63000 Buck-Boost
  - Advantages/disadvantages
  - Runtime comparison
  - Compare solutions
- **Detailed look at TPS63000 buck-boost**
  - Functionality
  - Waveforms
  - Benefits vs. competition
- **Other system level considerations**
  - Battery voltage variations vs. temp, aging, load
  - Show battery voltage with load transient
- **System level solution Li-Ion to 3.3 V and 1.8 V**
  - Block diagrams
  - Overall system efficiency


The Portable Power System
Power Source
Wall
Adaptor
Primary or
Secondary
Battery
USB
Limited
Flexibility
Power Conversion
Buck
Boost
LDO
Charge
Pump
Full Design
Flexibility
Loads
Processor
Memory
LED
Backlight
Display
Photoflash
Audio
Fixed by System-
Level Requirements
Texas Instruments

The Problems

- What happens when the unregulated input voltage is above and below the regulated output voltage?
  - 3.3 V from a Li-Ion battery (4.2 V-3.0 V)
  - 2.5 V from dual series alkaline (3.0 V-1.8 V)
- Most solutions are inefficient or leave capacity in the battery.
- Source impedance coupled with pulsed loads



Texas Instruments

Potential Solutions

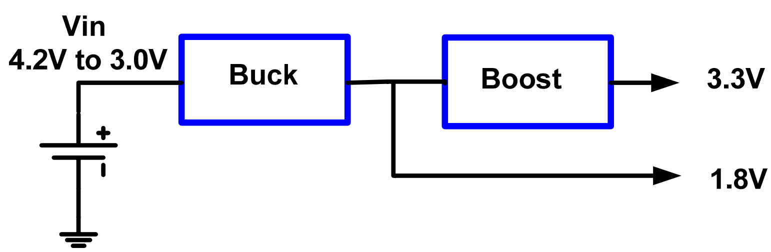
- Cascaded Buck and Boost
- Buck-Only
- LDO
- SEPIC
- Classical Buck-Boost
- TPS63000 Buck+Boost

Potential Solution #1

Cascaded Buck and Boost

Solution #1 Cascaded Buck and Boost

- Two independent converters are used
  - Buck converter ➔ 1.8 V (intermediate voltage for boost)
  - Boost converter ➔ 3.3 V



Cascade Buck and Boost

- **Advantages**
  - Provides intermediate rail required by many systems.
  - Utilizes 100% of battery capacity.
- **Disadvantages**
  - Reduced 3.3-V Efficiency
    - 3.3-V efficiency is the product of both converters efficiency
      - Typical Buck 90% (3.6 V to 1.8 V)
      - Typical Boost 90% (1.8 V to 3.3 V)
      - Effective 3.3-V efficiency = 90% • 90% = 81%
  - Large solution size (two discrete converters)
  - Cost
- **Parts and Application Note**
  - TPS62XXX buck
  - TPS61XXX boost

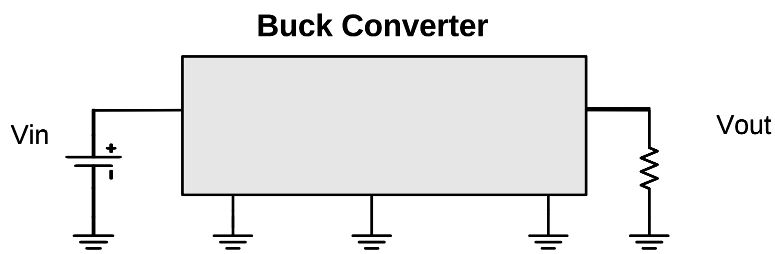
TEXAS INSTRUMENTS

Potential Solution #2

Buck Only

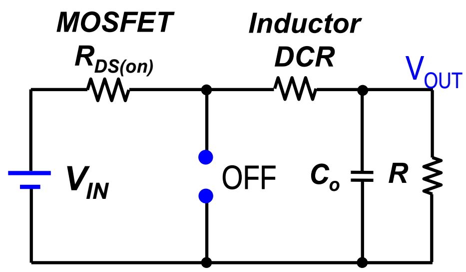
Solution #2: Buck-Only

- Standard Buck converter
- Should have 100% duty cycle capability to ensure lowest dropout.
  - $V_{OUT} = V_{IN} \cdot D$



Buck Converter 100% duty cycle

- Enters dropout when V_{IN} drops below the level required to maintain regulation.
- Function of V_{IN}, V_{OUT}, I_{OUT}, FET $R_{DS(on)}$, Inductor DCR.
- Switching stops and V_{IN} is connected directly to the output.
- Power MOSFET turns on, sync rectifier turns off.
- $V_{OUT} = V_{IN}$ less DC resistive losses



Buck Converter V_{IN-MIN}

- When does the system start 100% duty cycle mode operation?

$$D = \frac{V_{OUT} + I_O(R_{DSON\_PWR} + R_{DCR})}{V_{IN} + I_O(R_{DSON\_SYN} - R_{DSON\_PWR})}$$

- For 100% duty cycle mode equation reduces to:

$$V_{IN} = V_{OUT} + I_o(R_{DSON\_PWR} + R_{DCR})$$

- When does the 3.3V bus drop out of regulation for the TPS62040

$$V_{BAT\_MIN} = V_{OUT}\frac{100 - V_{OUT\_Tolerance}}{100} + I_o(R_{DSON\_PWR} + R_{DCR})$$

Texas Instruments

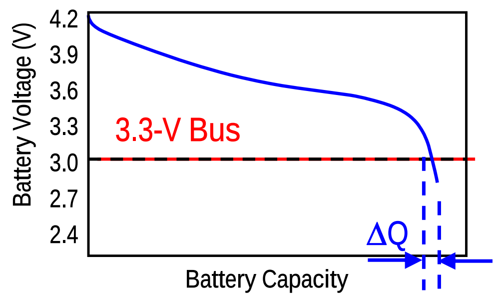
Buck Converter V_{IN-MIN}

- For a 3.3V system with a +/-3% tolerance

$$
\begin{aligned}
V_{BAT\_MIN} &= 3.3V\,\frac{100\% - 3\%}{100\%} + 500mA(0.21\Omega + 0.05\Omega) \\
&= 3.201V + 0.13V \\
&= 3.331V
\end{aligned}
$$

Solution #2 Buck-Only

- Advantages
  - High efficiency (up to 96%)
- Disadvantages
  - Can not utilize 100% of battery capacity
  - Enters 100% duty cycle mode when V_{IN} drops to V_{OUT}
- Parts and Application Note
  - TPS62300 buck converter
  - TPS62400 buck converter
  - TPS62040 buck converter



Texas Instruments

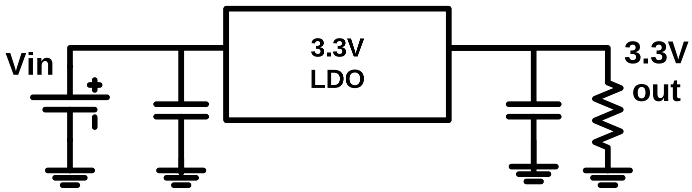
Potential Solution #3

Low Drop Out (LDO)

Linear Regulator

Solution #3   LDO

- Standard Low Drop Out (LDO) linear regulator
- Lower dropout voltage is better



LDO Efficiency

What is the Li-Ion 3.6 V to 3.3 V

Conversion efficiency?

91.7%

What about Li-Ion 3.6 V to 1.8 V

Conversion efficiency?

50%

$$\text{Efficiency} = \frac{P_{OUT}}{P_{IN}}$$
$$= \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot I_{IN}}$$
$$= \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot (I_{OUT} + I_{Quiescent})}$$
$$\approx \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot I_{OUT}}$$
$$= \frac{V_{OUT}}{V_{IN}}$$

- LDOs have significant efficiency variations as a function of V_{IN}
- LDO Efficiency is comparable to a switchers when V_{IN} to V_{OUT} ratio is small

Texas Instruments

Solution #3 LDO

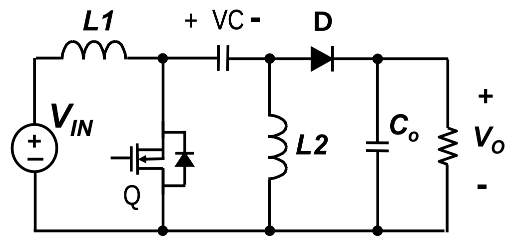
- Advantages
  - Lowest cost solution
  - Smallest solution size due to low parts count
    - Depending on power dissipation
- Disadvantages
  - Can not utilize 100% of battery capacity
  - Depending on input voltage, efficiency can be unacceptable.
- Parts and Application Note
  - TPS79901 LDO
  - TPS73601 LDO
  - TPS72501 LDO
  - Understanding LDO Dropout – SLVA207

Potential Solution #4

SEPIC

Solution #4 SEPIC

- Single Ended Primary Inductance Converter (SEPIC)
- Seldom used in smaller, portable applications.



$$V_O = \frac{D}{1-D} V_{IN}$$

$$V_C = V_{IN}$$

Texas Instruments

Solution #4 SEPIC

- Advantages
  - Fully utilizes battery capacity
  - Provides both buck and boost function
- Disadvantages
  - Higher parts count
    - Two inductors or a coupled inductor, additional flying capacitor
    - Larger solution size
  - Higher RMS currents, lower efficiency
  - Higher cost
  - Few ICs available
- Parts and Application Note
  - TPS61130 SEPIC

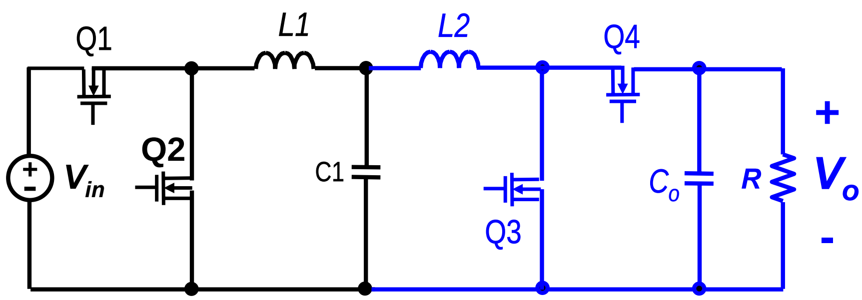
Texas Instruments

Potential Solution #5

Classical Buck-Boost

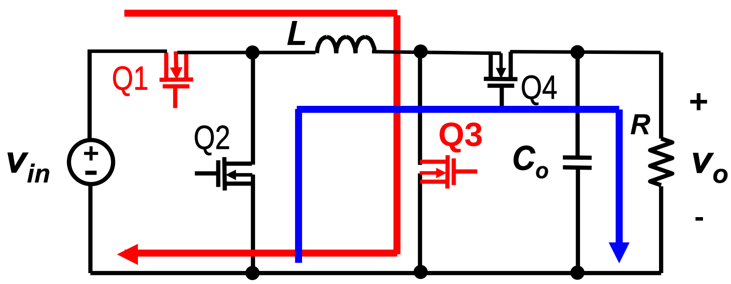
Solution #5 Classical Buck-Boost

- Combines a buck and a boost into a single topology.
- All four transistors switch during a single cycle.
- Not a popular topology for many reasons.



TEXAS INSTRUMENTS

Classical Buck - Boost DC-DC Converter



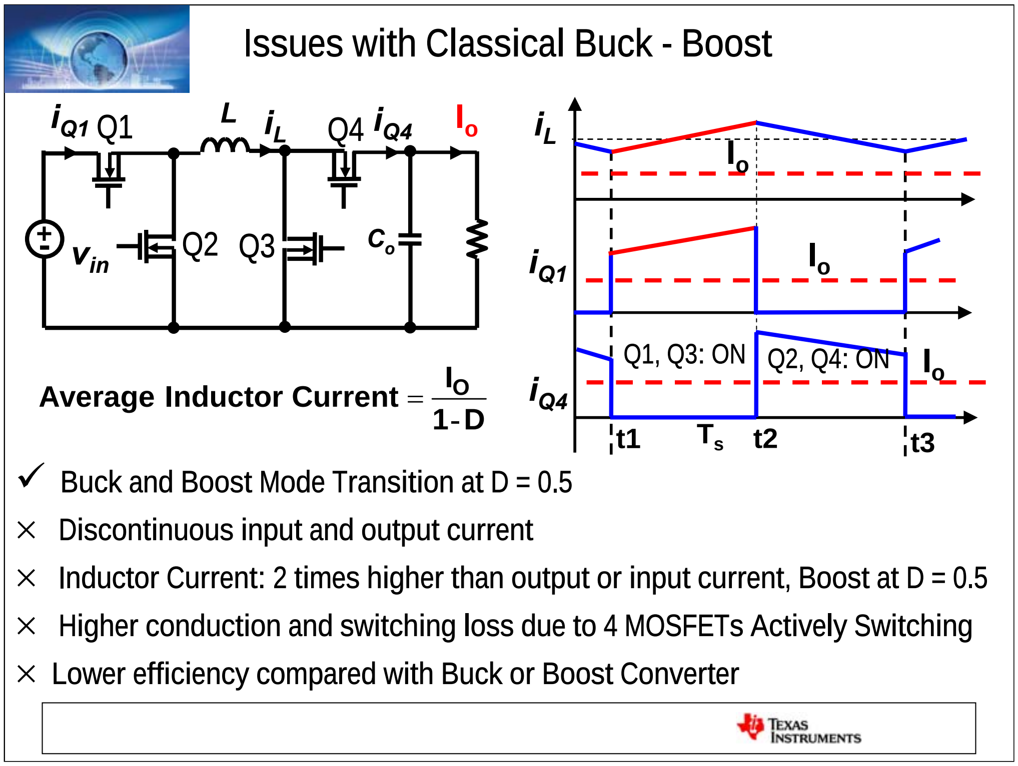
Control Method 1

	Q1 and Q3	Q2 and Q4	Voltage Gain
Buck-Boost	ON	OFF	$\frac{D}{1-D}$
	OFF	ON	

Again this is a modified buck-boost converter. These two red MOSFETs turn on and off at the same time while the other two MOSFETs Q2 and Q4 turn on and off at the same time, but complementarily with MOSFETs Q2 and Q4.

When two red MOSFETs Q1 and Q3 turns on, the inductor is applied to a input voltage and starts to store the energy. When Q1 and Q3 turns off, then Q2 and Q4 turn on, so the stored inductor energy is transferred to the output. Based on the volt-second balance across the inductor, we can derive the voltage gain. From this voltage gain equation, we can see that it can achieve buck function when the duty cycle is less than 0.5, it has boost function when the duty cycle is higher than 0.5.

Now let’s analyze what’s kind of performance that we can expect from this control architecture.



Let's review its switching waveforms. The inductor current increases when these two MOSFETs are conducting. The inductor current is then reduced and it stored energy is delivered to the output when these two MOSFETs turn on.

Simple conclusions:

Both input current and output current are discontinuous, which results in high ESR loss in the input capacitor and output capacitor.

Assuming 50% duty cycle, the average inductor current is two times of the output current and input current. Since the current through the switch is the same as inductor current, therefore, all switching has higher RMS current compared with simple buck or boost converter.

Besides, it has higher switching loss since they are turning on and off with two times load current. So, this buck-boost converter has lower efficiency compared with buck or boost converter.

Do we have better control architecture to achieve better efficiency, comparable with buck or boost converter?

Solution #5 Classical Buck-Boost

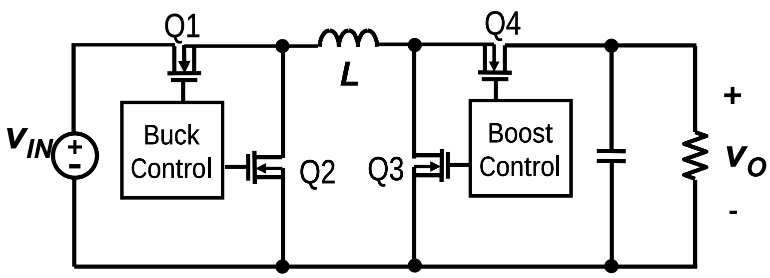
- Advantages
  - Provides both buck and boost function
  - Fully utilizes battery capacity
- Disadvantages
  - Low efficiency due to excessive power dissipation
  - Industry does not provide any supporting ICs

Potential Solution #6

TPS63000 Buck + Boost

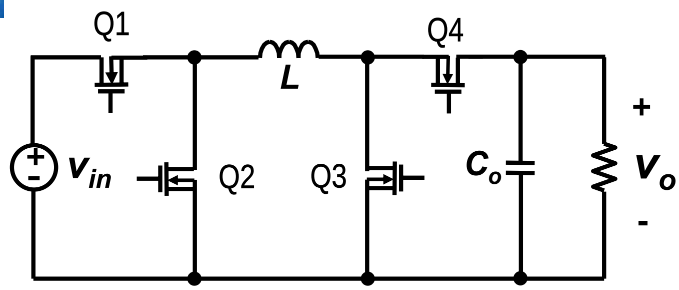
Solution #6 TPS63000 Buck-Boost

- The TPS63000 operates as Buck or Boost
- Automatically transitions between buck mode and boost mode.
- Innovative control topology uses only two switches at a time.



Texas Instruments

Buck + Boost DC/DC Converter



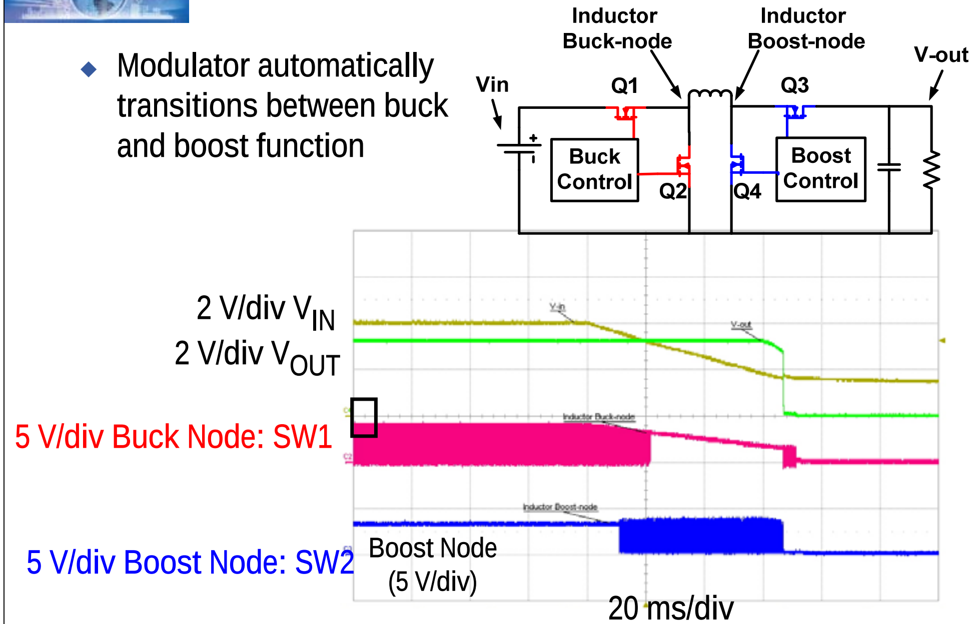
Control Method

	Q1	Q2	Q3	Q4	Voltage Gain
Buck	Switching	Switching	OFF	ON	D
Boost	ON	OFF	Switching	Switching	1 / (1-D)

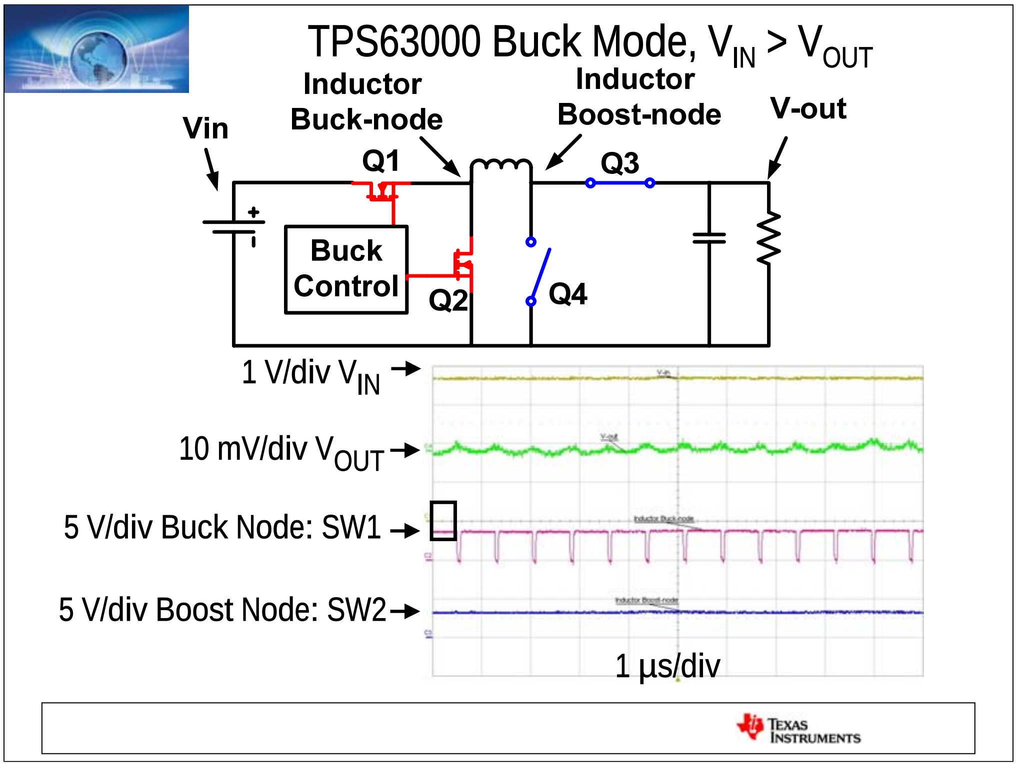
- Operate either Buck or Boost
- Traditional buck-boost: D/(1-D): higher loss, and lower efficiency

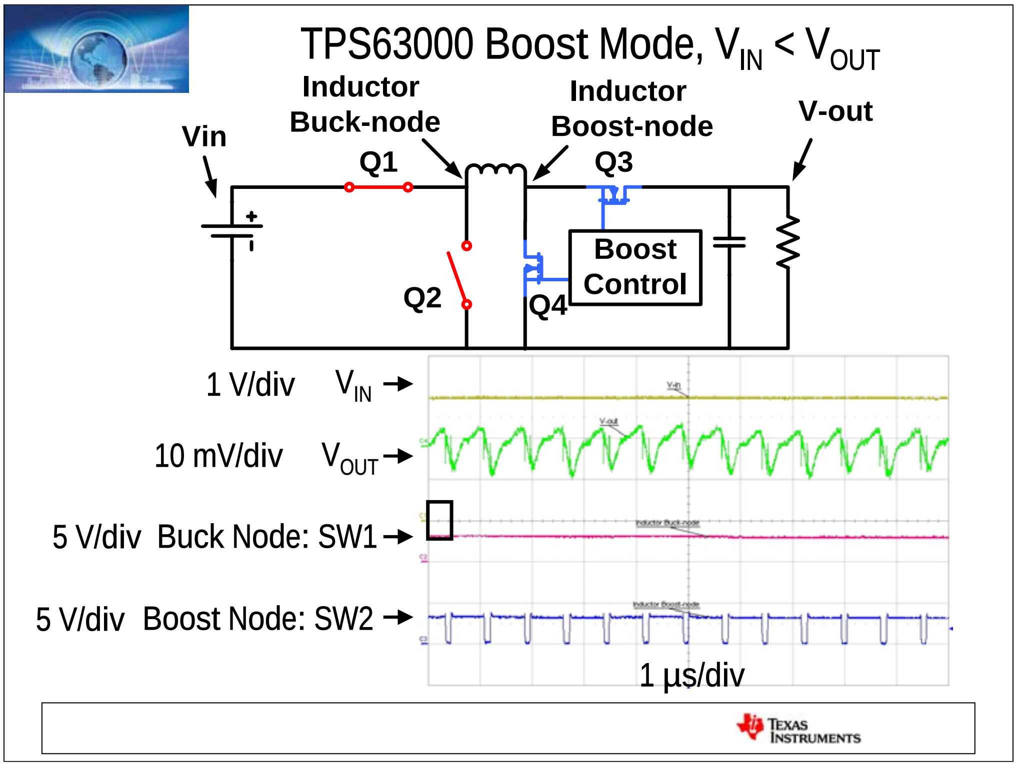
Solution #6 TPS63000 Buck + Boost

- Modulator automatically transitions between buck and boost function

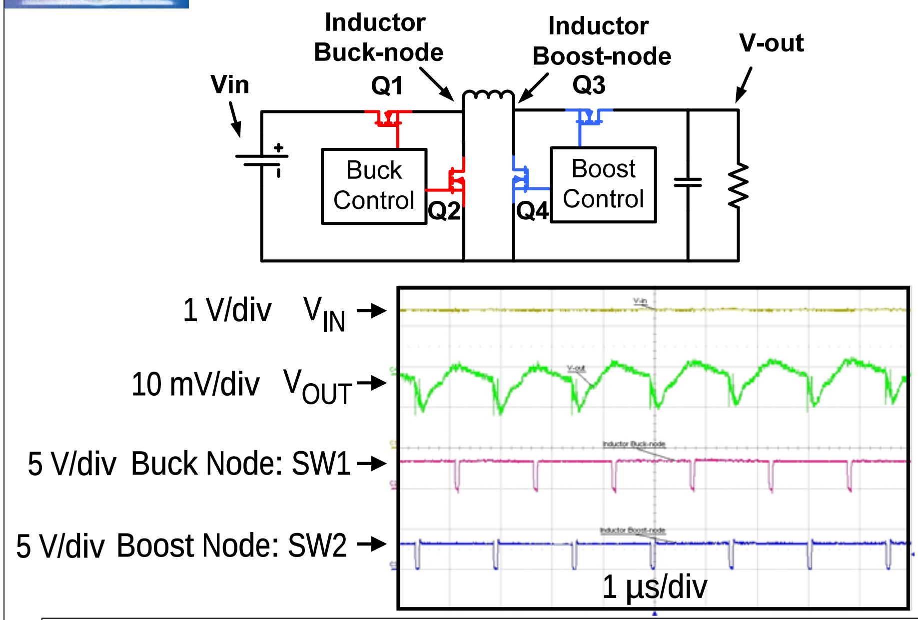


TEXAS INSTRUMENTS


TPS63000 Buck Mode, V_IN > V_OUT
Inductor Buck-node
Inductor Boost-node
Vin
V-out
Q1
Q3
Buck Control
Q2
Q4
1 V/div V_IN
10 mV/div V_OUT
5 V/div Buck Node: SW1
5 V/div Boost Node: SW2
1 µs/div
Texas Instruments


TPS63000 Boost Mode, V_IN < V_OUT
Inductor Buck-node
Inductor Boost-node
Vin
V-out
Q1
Q2
Q3
Q4
Boost Control
1 V/div V_IN
10 mV/div V_OUT
5 V/div Buck Node: SW1
5 V/div Boost Node: SW2
1 µs/div
Texas Instruments

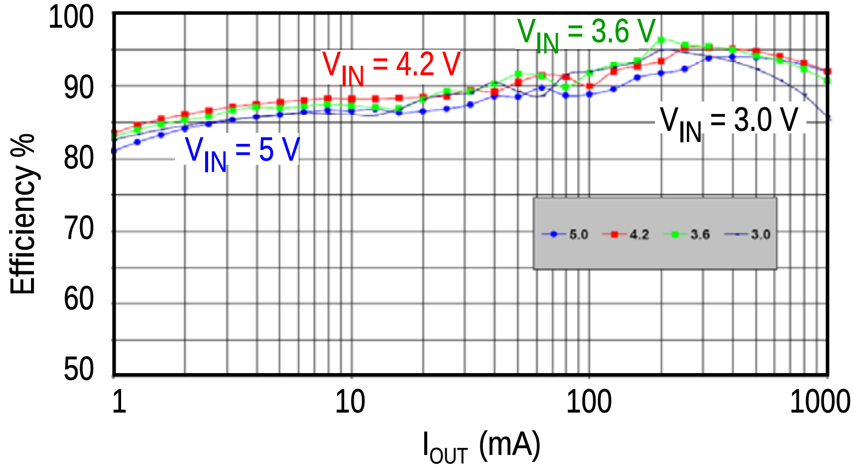
TPS63000 Transition Mode $V_{IN} \sim V_{OUT}$



Texas Instruments

TPS6300x Efficiency

V_{IN} = 5 V, 4.2 V, 3.6 V, and 3.0 V (SYN = Low); V_{OUT} = 3.3 V



- Optimized for Li-Ion Operation

TPS63000: 96% Efficient Buck + Boost Converter

Features

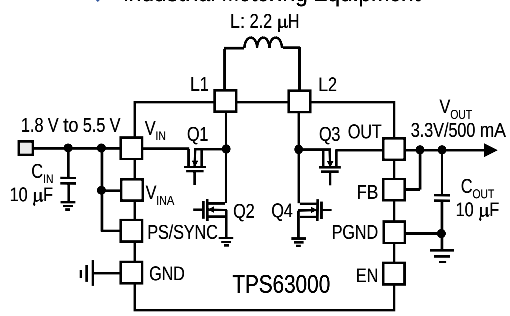
- Efficiency: 96% over wide Vin range (max)
- Input Voltage: 1.8 V to 5.5 V
- Output Voltage: 1.2 V to 5.5 V
- Output current Switch: 1.8 A
  - Iout > 1400 mA in Buck mode @ 3.3 V
  - Iout > 1200 mA in Boost mode @ 3.3 V
- N-MOSFETS for both PWM switch and Syn FET
- Package: 3x3 QFN
- 41-µA Quiescent Current
- Over-Temperature Protection

Benefits

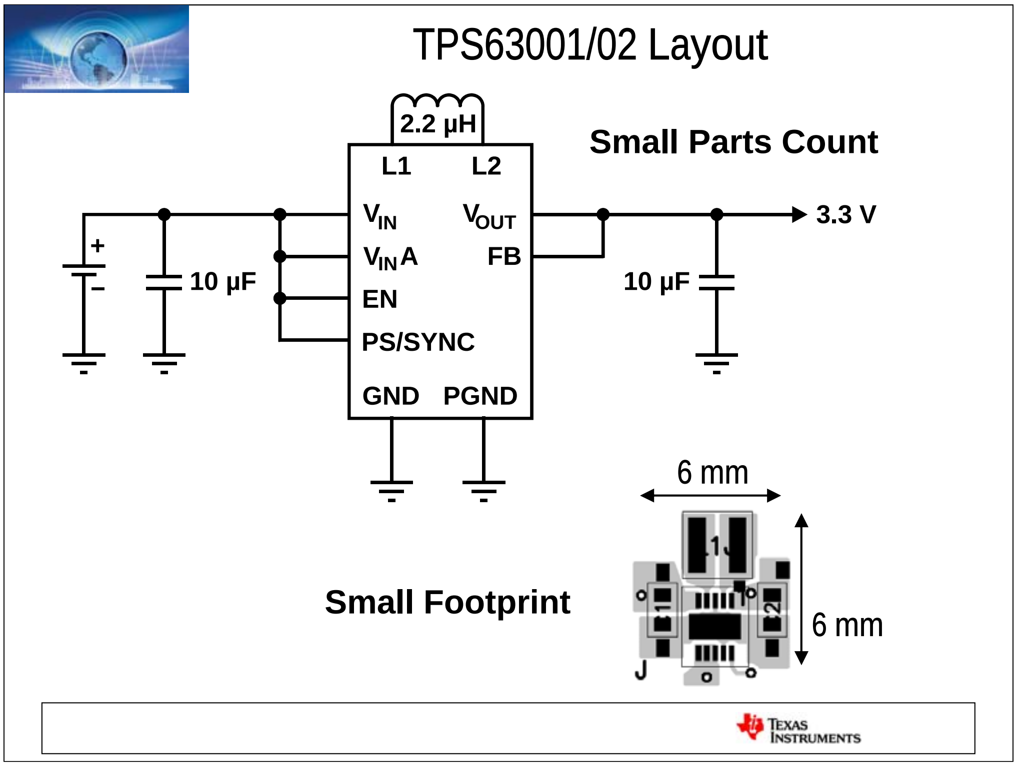
- Small size, requires only 2.2 µH
- Low input voltage 1.8 V (for 2-cell Alkaline)
- Highest efficiency over wide V_{IN}

Applications

- 2-Cell and 3-Cell Alkaline, NiCd or NiMH, or one Cell Li-Ion or Li-Poly
- Cellular Phones / Smartphones
- DSC, Camcorder
- Personal Medical Products
- Portable Audio Players
- Industrial Metering Equipment



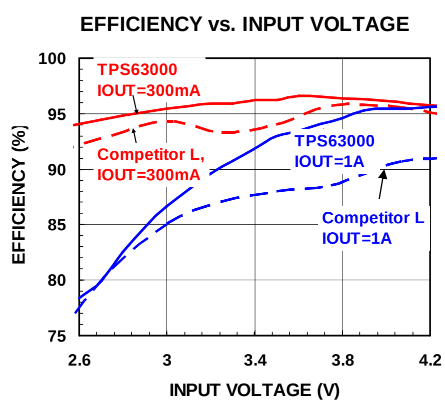
Texas Instruments


TPS63001/02 Layout
2.2 µH
L1
L2
Small Parts Count
VIN
VOUT
3.3 V
VINA
FB
10 µF
10 µF
EN
PS/SYNC
GND
PGND
6 mm
6 mm
Small Footprint
Texas Instruments

TPS63000 versus Competitor L Efficiency

Efficiency Chart

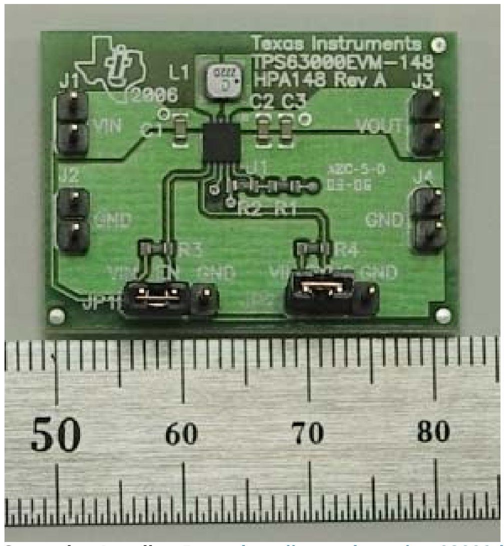
TPS63000 and Competitor L



TPS63000 vs. Competitor L

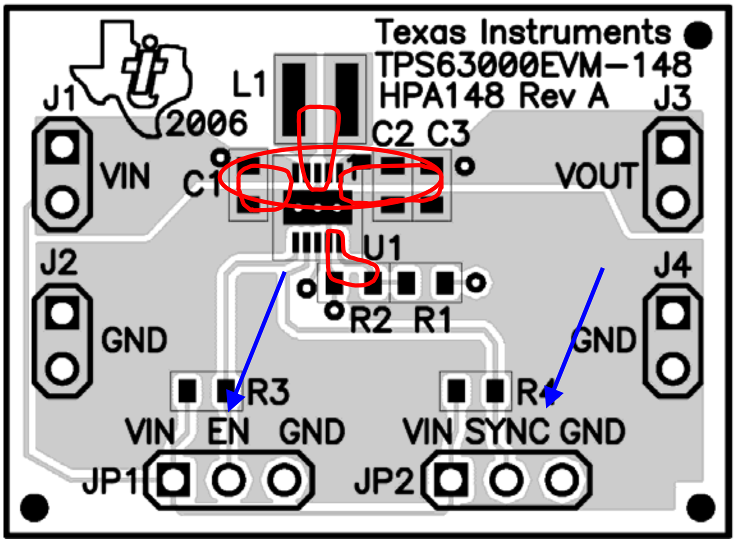
	TPS63000	Competitor L
Converter Type	PWM/PFM	-
Topology	synchronous	synchronous
Efficiency (max)	96%	95%
Input Voltage	1.8 V – 5.5 V	2.4 V – 5.5 V
Buck Current @ 3.3 V	1400 mA	1200 mA
Boost Current @ 3.3 V	1200 mA	1000 mA
Output Voltage	1.2 V – 5.5 V	2.4 V – 5.25 V
Quiescent Current (typ)	41 µA	600 µA
Switching Frequency	1.2 MHz – 1.8 MHz	300 kHz – 2 MHz
Inductor Size	2.2 µH	4.7 µH
Softstart	Yes	Yes (pg.9)
Package	3x3 QFN	4x3 DFN
Price @ 1k units	$2.75	$3.55 (web)

TPS63000EVM-148



Leadership Campaign Landing Page: http://www.ti.com/tps63000-bb
Product Folder: http://focus.ti.com/docs/prod/folders/print/tps63000.html
EVM Folder: http://focus.ti.com/docs/toolsw/folders/print/tps63000evm-148.html

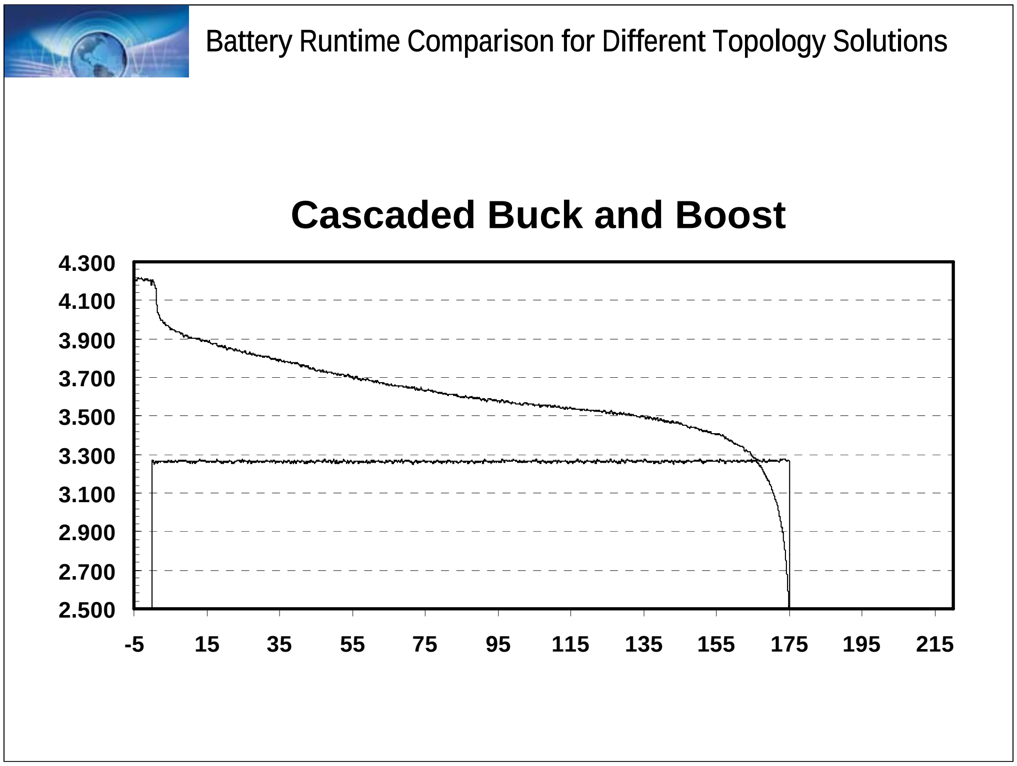
TPS63000 EVM Optimized Layout



Solution #6 TPS63000 Buck+Boost

- Advantages
  - Fully utilizes battery capacity
  - High efficiency
  - Provides both buck and boost function
  - Innovative control topology eliminates the low efficiency buck-boost mode of operation
- Disadvantages
  - ???
- Parts and Application Note
  - TPS63000 buck-boost (1.8A rated, 1.5MHz in 3mm x 3mm QFN)
  - TPS63010 buck-boost (2A rated, 2.4MHz in 2mm x 2mm chip scale)

Runtime Comparison for Different Topology Solutions



LDO is TPS72533 with rdson at dropout (vin approx 3.3V) = 150mohm. Note that this is a 1A LDO and we are only loading it at 500mA. If we used a smaller LDO, the Rdson would be higher and the run time would be shorter.

Buck is TPS62040 EVM with Pch rdson=130mohm and inductor DCR=45mohm for a total of 175mohm. Again, only 500mA through this 1.2A part. A smaller part's runtime would be shorter.

The buck then boost is a TPS62040 (86%) and a TPS61030 (90%)

Solution Comparison

INPUT: Li-Ion Battery

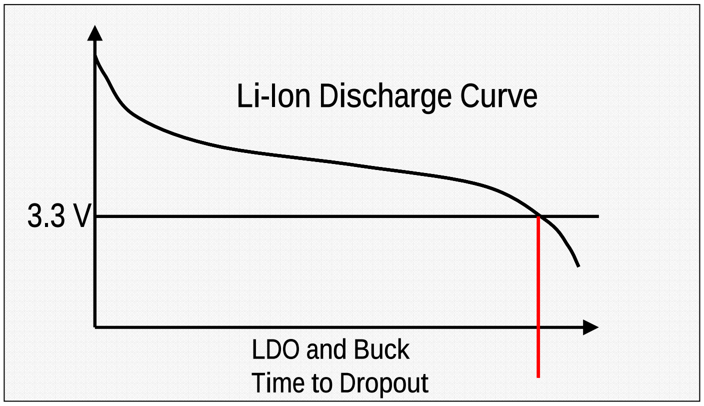
OUTPUT: 3.3 V

Topology	Size	Cost	Efficiency/Run-Time
LDO	Low	Low	Medium
Buck	Medium	Medium	Medium
Buck then Boost	High	High	Low
Buck-Boost	Medium	Medium	High

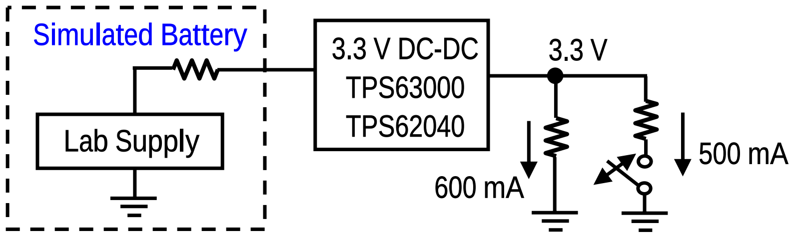
Texas Instruments

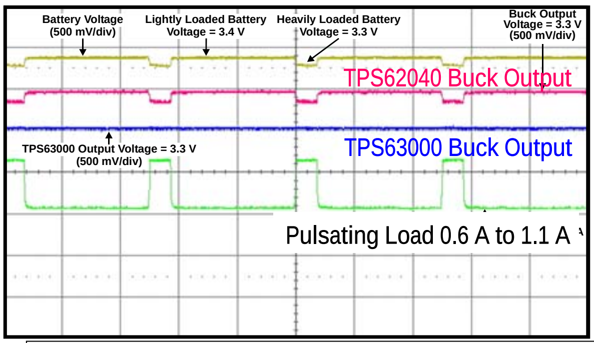
Other Considerations

- Cold
- Aging
- Pulsed Load



Pulsed Load

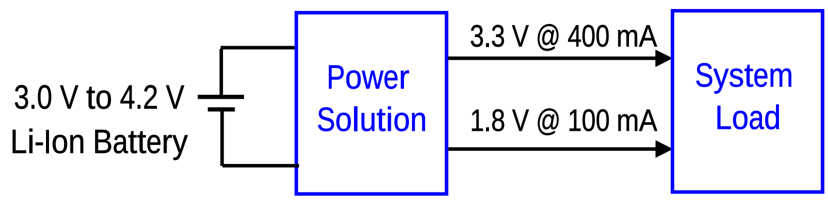




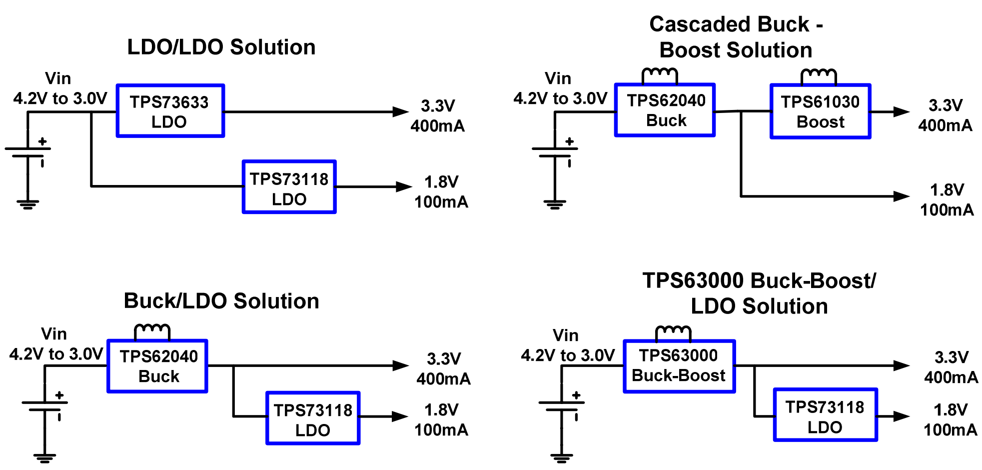
- V_{BAT} drops = I • R_{BAT}
- V_{OUT} drops for buck TPS62040
- V_{OUT} stable for TPS63000
- Time base 10ms/div

System Level Approach

- Multiple Voltages
  - Buck, boost, buck-boost (depending on voltage requirement)
- Sequencing
- System Level Tradeoffs
  - Size
  - Efficiency
  - Cost



System Level Trade Study

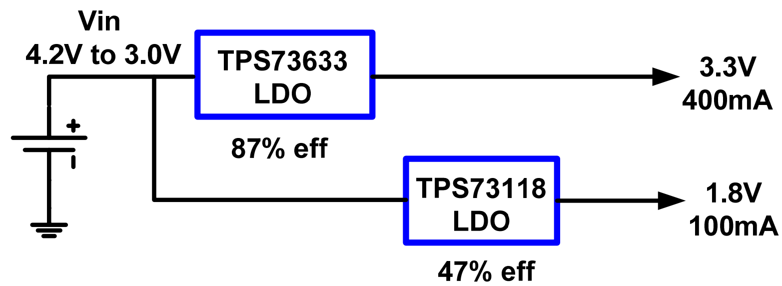


System Level Trade Study

- 3.3-V effective efficiency = 87%
- 1.8-V effective efficiency = 47%
- Overall system efficiency = 78.9%

- Flexible sequencing
- Low cost
- Low efficiency
- Doesn't use 100% battery

LDO/LDO Solution

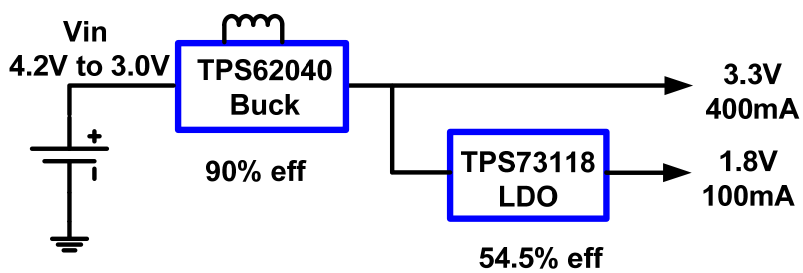


System Level Trade Study

- 3.3-V effective efficiency = 90%
- 1.8-V effective efficiency = 49.1%
- Overall system efficiency = 81.8%

- Sequencing limited
- Medium cost
- Medium efficiency
- Doesn't use 100% battery

Buck/LDO Solution

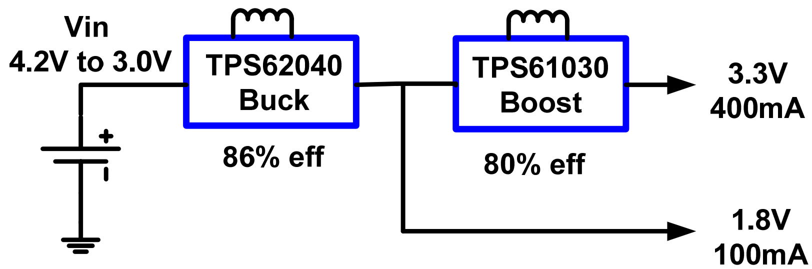


System Level Trade Study

- 3.3-V effective efficiency = 68.8%
- 1.8-V effective efficiency = 86%
- Overall system efficiency = 70.5%

- Sequencing Limited
- High cost
- Low efficiency
- Uses 100% battery

Cascaded Buck - Boost Solution

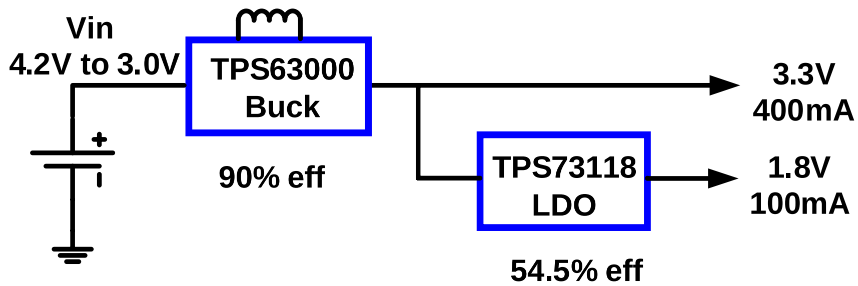


System Level Trade Study

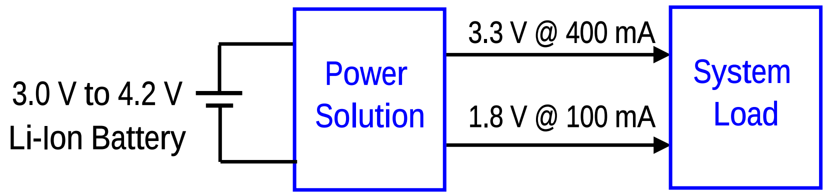
- 3.3-V effective efficiency = 90%
- 1.8-V effective efficiency = 50.1%
- Overall system efficiency = 83.6%

- Sequencing Limited
- Medium cost
- Highest efficiency
- Uses 100% battery

TPS63000Buck-Boost/LDO Solution



System Level Trade Study



Topology	Overall Efficiency	Cost	Size
LDO/LDO	78.9%	Low	Small
Buck/LDO	81.8%	Medium	Medium
Cascaded Buck and Boost	70.5%	High	Large
TPS63000 Buck-Boost/LDO	83.6%	Medium	Medium

Conclusions

- **Not all power sources are compatible with system needs**
- **Many ways to get the required regulated voltages**
- **System run time is a function of battery utilization and power conversion efficiency**
- **Optimal solution depends on system level requirements**
- **TPS63000 buck-boost provides optimal Li-Ion to 3.3-V solution**
  - Minimal parts count
  - High efficiency
  - 100% battery utilization
  - Runs through line and load transients