AC 2008-1812: TECHNICAL KNOWLEDGE TRANSFER FOR LOW-COST BUCK-BOOST CONVERTERS

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Technical Knowledge Transfer For Low-Cost Buck-Boost Converters

Abstract:

Today's DC-to-DC converters efficiently step-up (Boost), step-down (Buck) or invert DC voltages without the need for a transformer. Typically switching capacitors are utilized and this reduces physical size requirements. They open up product size reduction, especially in portable electronic devices, where they increase efficiency and reduce input power for optional micro-power requirements. This further reduces heat, which can be a factor in numerous applications and even drives battery size reductions. Opportunities in battery charging and conditioning benefit greatly from this new technology. Good examples include the fast mobile phone and NiCAD battery chargers. Boost converters enable miniature fluorescent lights and high-intensity LED products powered by low voltages and occasionally only one 1.5 Volt dry-cell battery. Liquid Crystal Display (LCD) backlighting applications benefit from high frequency and multiple-output converters that drastically increase voltages. This paper discusses several DC-DC converter applications, capabilities, designs, technical specifications, limitations and some concentrated experimental findings with the boost converters. The focus will not be on the traditional 3-terminal converters or regulators, but on the favorable new technologies. Converter pros, cons and limitations and datasheets will be available as a reference. Primary and secondary side controllers such as fly back and forward converters are also available technologies. They can replace DC-to-DC converters in the proper applications while reducing cost. Supporting electronic component selection, mounting locations and connection distance importance are addressed and experimental data will be referenced. The buck-boost converters are sensitive, electrical noise generating and unstable if not properly designed in conjunction with supporting components and physical layout. Manufacturer application notes and Spice models narrow in on component specifications. Debugging and experimental key learning's focus will be on the low-cost efficient boost converters. A suggested development path example for folks new to this area will follow Spice modeling, converter selection, prototype board selection, component purchasing, circuit building, debugging and power output improvement. This paper could provide a quick introduction into the buck-boost converter world.

Introduction

This paper introduces modern DC-DC converter options, technical specifications, capabilities and limitations. Note the DC-DC will be assumed throughout paper. Internal converter circuitry and theory of operation will not be mentioned since details are provided in component specifications. The traditional 3-terminal converters or regulators will not be discussed in this paper. Applications and designs summary will be discussed before looking at by some concentrated boost converter experimental data. The reader should think about the wide use of converters in portable electronics such as pagers, cell phones, cameras and LED-based lighting. A Linear Technology boost converter implementation was tested and discussed. Boost converters were chosen because it is much more complicated to increase DC voltage levels than decrease them through such options as simple resistors. A Linear Technology boost converter was chosen since experiments were performed using their products, they provide a wide variety of DC-Dc converters and their technical support was extremely helpful. This paper should be used as a guideline to start learning the latest technology and introduce the readers to some critical design guidelines and key points.

A suggested development path for DC-DC converter design is discussed. The development path will target engineers and students new to the DC-DC converter topic. The suggested development path will follow Spice modeling, converter selection, prototype board selection, component purchasing, circuit building, debugging and power output improvement. The suggested development path and detailed experimental data are a result of an Intel Corporation project. Results from a graduate course at Purdue University in the Dept. of Electrical & Computer Engineering Technology are also inlcuded. This paper could provide a quick introduction into the buck-boost converter world.

Converter Features, Capabilities and Usages

The converters come in Buck (step-down) and Boost (step-up) combinations. Some are well aligned for 12 V automotive applications by having a 4 – 18 V input range for outputs ranging from 3 - 20 V. This is important since automotive voltages sag during starting and heavy loading. They also surge at higher engine RPMs and heavy electrical load shutoff. For example, 5 V or 12 V portable electronics can be supplied with stable power by leveraging the converter Buck-Boost capability. Converters eliminate the need for transformers. The elimination of transformers and the inherent small converter size enable smaller electronic components that weigh less. Several micro-power converters ensure longer battery life and often include “Sleep” mode. Sleep mode allows the converter oscillator to turn off and draw zero current. A sense low micro-Amp pin monitors a trigger signal. The trigger could be a motion sensor, touch switch, light sensor and temperature controller. Lithium batteries combined with micro-power converters provide long-life and miniature portable electronic capability.

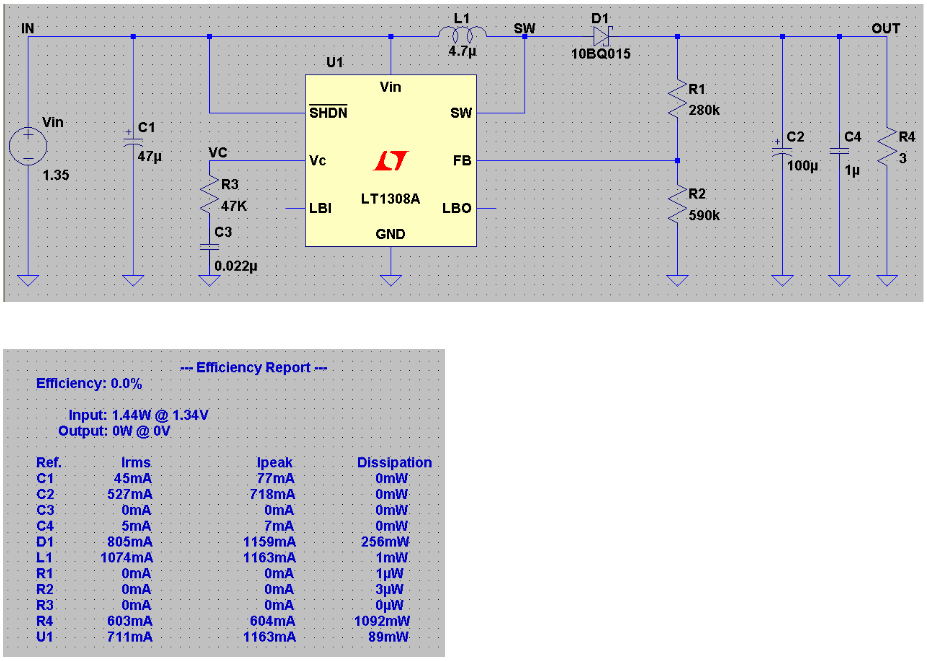
A large number of special converter options are available. Some provide high frequency and multiple-outputs to drastically increase voltages. One example is the popular Cold Cathode Florescent Lamp (CCFL) Driver capability. CCFL technology provides bright, long life white florescent lighting. Miniature form factors are available down below the 0.25” range. Very bright high-intensity LED products operate on a single 1.5 V cell battery voltage stepped up via a converter. The solution is simple, low-cost, small and usable. Certain converters are equipped with a LED driver. The LED and Liquid Crystal Display (LCD) backlighting application worlds have expanded many times with converter capabilities. Micro-power capability further reduces heat, which can be a factor in numerous applications and even drives battery size reductions. Opportunities in battery charging and conditioning benefit greatly from this new technology. Good examples include the fast mobile phone and NiCAD battery chargers.

Phase Lock Loop (PLL) converters such as the Linear Technologies LTM4603[1] are available to provide higher currents. It provides 6 A with 8 A peak capability. It also includes precision regulation through remote sensing. It has fold back capability enabling it to scale back power delivery when required without shutting down. Soft start capability is included to slowly ramp up load during power on. Over-voltage protection, up to 93% efficiency and small footprint are other key features. The Linear Technology LTM4606[2] provides 12 A with 14 A peak capability.

Primary and secondary side controllers such as fly back and forward converters are also available technologies. They can replace converters in the proper applications while reducing cost. Specific designs such as Fly back or SEPIC (Single-Ended Primary Inductance Converter)[1] can be implemented without using expensive custom transformers. These types may use two small inductors and a SEPIC coupling capacitor. Linear regulators and charge pumps are more available alternatives. Size, cost, power consumption, package mounting, environment and stability all have to be considered when determining best solution. Refer to converter data sheets for product specifications for these and other key information.

Boost Converter Experimental Design Notes

This section reviews test results from the Linear Technology LT1308A[2]. High Current Micro-power Single Cell, 600 kHz DC/DC Converter. A SPICE modeling approach was used to narrow in on component values prior to building circuits. Linear Technology provides their own free version called LSPICE to simplify efforts. A LSPICE snapshot is shown in Figure 1. The LSPICE output is an efficiency report output parameters based on selected component values. This allows a simplistic method to see converter operation with varied components prior to purchasing components.



```
                    --- Efficiency Report ---
Efficiency: 0.0%

      Input: 1.44W @ 1.34V
    Output: 0W @ 0V

Ref.         Irms              Ipeak        Dissipation
C1           45mA               77mA           0mW
C2          527mA              718mA           0mW
C3            0mA                0mA           0mW
C4            5mA                7mA           0mW
D1          805mA             1159mA         256mW
L1         1074mA             1163mA           1mW
R1            0mA                0mA           1µW
R2            0mA                0mA           3µW
R3            0mA                0mA           0µW
R4          603mA              604mA        1092mW
U1          711mA             1163mA          89mW
```

Figure 1: LSPICE Snapshot [2].

One converter circuit schematic option is located in Figure 2. Note L1 operates at higher currents and D1 limits current. The output current for one tested circuit was approximately 500 mA at 1.8 V. The test set up consisted of a demo Board sometimes referred to as "Surf Board". The demo boards are standard off-the-shelf items. The Demo Printed Circuit Board (PCB) allowed the converter Integrated Circuit (IC) to be soldered on to pads with connectivity traces to pads for supporting components. The demo board was designed for similar converters, but was supplied from another manufacturer. The Bill of Materials (BoM) is provided in Table 1.

The experiment was complicated by "Ganging" two converters to increase the current supply capability at the identical set voltage levels. Ganging is a term used when multiple power sources are connected in parallel. The selected converter supports ganging by not allowing another circuit to either be over powered by current back feeding from others or providing a majority of demanded current. In the case mentioned above it was approximately 500 mA x 2 at 1.8 V. For this experiment, two identical demo boards were built with Feedback (FB) section exception. The R1 and R2 voltage divider connected to the FB pin was included on one demo board. Jumper connections were made between the FB pins, converter amplifier error compensation (VC) pins, Voltage input (Vin) pins and output (VOUT) pins to provide more stable power. Circuit voltage monitoring was performed with high impedance voltage meters and oscilloscopes.

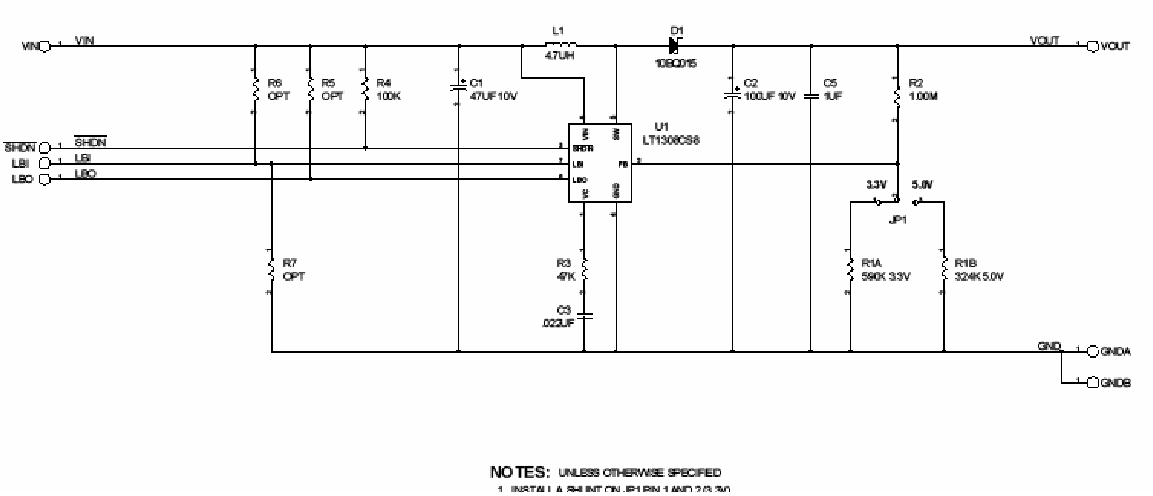


Figure 2: One Converter Experiment Schematic [2].

Table 1: Demo Board Part Bill of Materials

Item	*Qty*	*Ref. Des.*	*Part Description*	*Manufacture / Part #*
1	1	C1	CAP, 47UF, 10V, 6032	AVX, TPSC476M010R0300
2	1	C2	CAP, 100UF,10V, 7343	AVX, TPSD107M010R0100
3	1	C3,C4	CAP, TBD, 0805	TBD
4	1	C5	CAP, Y5V, 1UF, 16V, 0805	AVX, 0805YG105ZATMA
5	1	D1	RECT DIODE, 10BQ015	INT. RECT. INC., 10BQ015

6	6	LB0,LB1,VOUT,VIN,SHDN,GND	TP, TERMINAL, 1 PIN	MILL-MAX 2501-2
7	1	L1	IND, 4.7UH	TOKO, 636CY-4R7M
8	1	R1A	RES, 590K, 1%, 0805	TAD, CR10-5902FM
9	1	R1B	RES, 324K, 1%, 0805	TAD, CR10-3243FM
10	1	R2	RES, 1.00M, 1%, 0805	TAD, CR10-1004FM
11	1	R3	RES, TBD, 0805	TBD
12	1	R4	RES, 100K, 5%, 1206	TAD, CR18-104JM
13	3	R5,R6,R7 **(OPT)**	RES, TBD, 5%, 1206	TAD, CR18-XXXJM
14	1	U1 VERSION **A (150 BDS)**	IC, LT1308CS8, SO8	LINEAR TECH., LT1308CS8
		OR VERSION **B (100 BDS)**	IC, LT1308BCS8, SO8	LINEAR TECH., LT1308BCS8

The various pin descriptions could be found in the appendix [2].

Experiment Results and Key Learnings

The first and possibly most important learning was the demo board itself! As mentioned, the demo board was manufactured from a different supplier than was the converter. The demo board is compatible and supports the chosen converter. However, trace and jumper wire lengths became an experimental roadblock. Extensive debugging and component swapping revealed reduced voltage outputs, including lower than input voltage in boost mode and instability. This was corrected by shortening connections. A demo system from Linear Technology would have eliminated this problem by placing component pads closer. The second biggest concern was high noise levels. Circuit loading impacted noise by a large magnitude. Measured values were in the MHz range when sourcing low resistance loads. Refer to experimental data shown in Figures 3-8 to see noise peak variances from loading changes, ganging and signal connectivity. One noise reduction technique was connecting the feedback (FB) pins together as recommended earlier. The noise was then seen to match the converter's internal oscillator frequency. Start up power quality is another key variable to monitor. The converter amplifier compensation (VC) pins were then connected to reduce the noise to one half oscillator frequency. Further noise reduction techniques such as signal conditioning and decoupling capacitors were discussed, but not implemented during experiments. Another approach to providing two amps was to only use one converter with modified component values.

Experiment #1 Results

- Input: 1.35 VDC
- Output: 1.8 VDC
- Load: 3 Ohms (Resistive)
- O-Scope: Connected to Output
- O-Scope → AC Coupling Mode
    - ~ 260 mV P-P w/ occasional +/-550 mV Peaks
    - ~ 1 MHz
    - Spikes likely due to high impedance in FB loop (demo board had a switch in this loop)

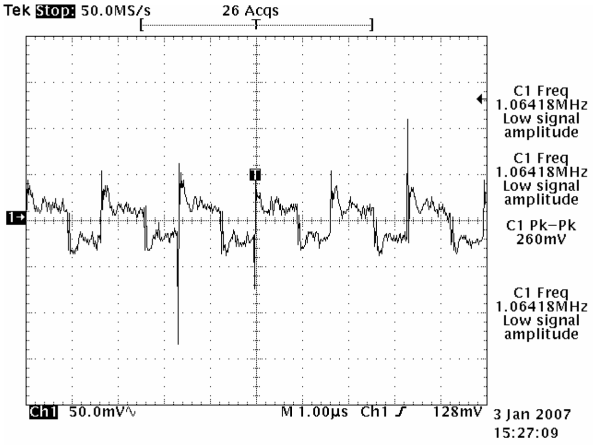


Figure 3: Experiment # 1 Results showing noise peak variances from loading changes, ganging and signal connectivity.

Experiment #2 Results

- Input: 1.35 VDC
- Output: 1.8 VDC
- Board #1: 3 Ohms (Resistive)
- Board #2: 0 Ohms
- Feedback (FB) signals: Separated
- Voltage Control (VC): Separated
- O-Scope: Connected to Board #1 Output
  - O-Scope → AC Coupling Mode
  - ~ 260 mV P-P w/ occasional +/-550 mV Peaks
  - ~ 1 MHz

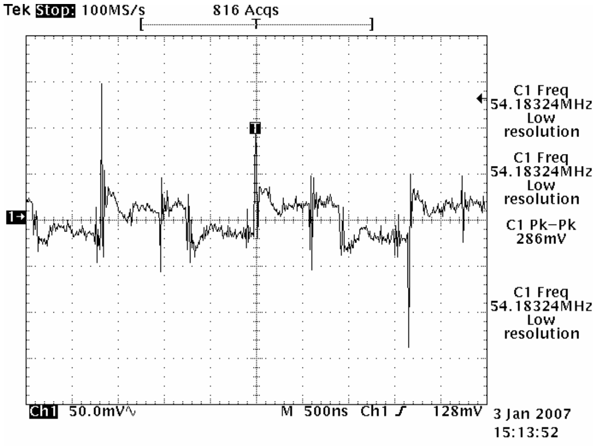


Figure 4: Experiment # 2 Results showing noise peak variances from loading changes, ganging and signal connectivity.

Experiment #3 Results

- Input: 1.35 VDC
- Output: 1.8 VDC
- Board #1: 3 Ohms (Resistive)
- Board #2: 3 Ohms (Resistive)

- Feedback (FB) signals: Separated
- Voltage Control (VC): Separated
- O-Scope: Connected to Board #1 Output
    - O-Scope → AC Coupling Mode
    - ~ 280 mV P-P w/ occasional +/-700 mV Peaks

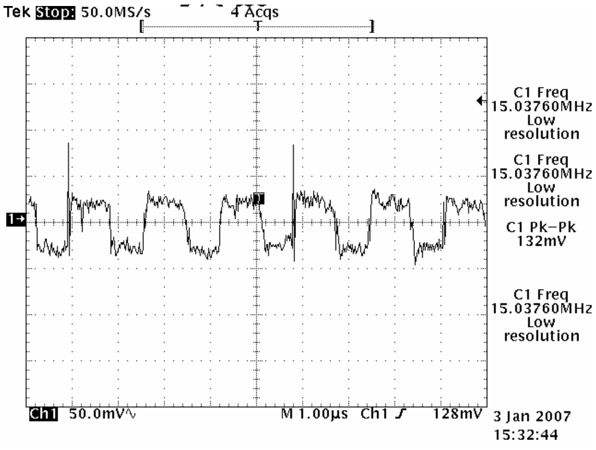


Figure 5: Experiment # 3 Results showing noise peak variances from loading changes, ganging and signal connectivity.

Experiment #4 Results

- Input: 1.35 VDC
- Output: 1.8 VDC
- Board #1: 1.5 Ohms shared (Resistive)
- Board #2: 1.5 Ohms shared (Resistive)
- Feedback (FB) signals: Separated
- Voltage Control (VC): Separated
- O-Scope: Connected to Board #1 Output
    - O-Scope → AC Coupling Mode
    - ~ 132 mV P-P w/ occasional +400 mV Peaks
    - ~ 15 MHz

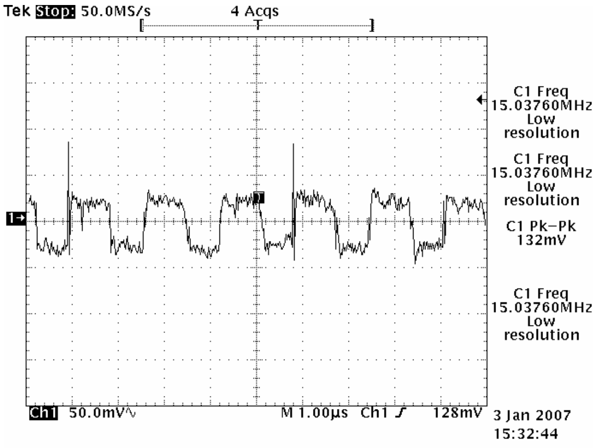


Figure 6: **Experiment # 4 Results showing noise peak variances from loading changes, ganging and signal connectivity.**

Experiment #5 Results

- Input: 1.35 VDC
- Output: 1.8 VDC
- Board #1: 1.5 Ohms shared (Resistive)
- Board #2: 1.5 Ohms shared (Resistive)
- Feedback (FB) signals: Ganged
- Voltage Control (VC): Separated
- O-Scope: Connected to Board #1 Output
  - O-Scope → AC Coupling Mode
  - ~ 172 mV P-P w/ occasional +550 mV Peaks
  - ~ 600 kHz – Note this is the IC's oscillator frequency.
- Note Startup Graph: 2 stage ramp w/o over

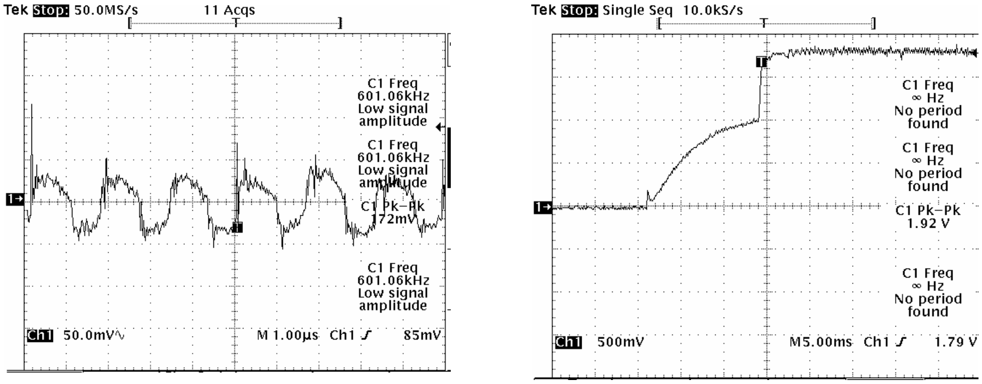


Figure 7: Experiment # 5 Results showing noise peak variances from loading changes, ganging and signal connectivity.

Experiment #6 Results

- Input: 1.35 VDC
- Output: 1.8 VDC
- Board #1: 1.5 Ohms shared (Resistive)
- Board #2: 1.5 Ohms shared (Resistive)
- Feedback (FB) signals: Ganged
- Voltage Control (VC): **Ganged**
- O-Scope: Connected to Board #1 Output
  - O-Scope → AC Coupling Mode
  - ~ 238 mV P-P w/ occasional +800 mV Peaks
  -
  - ~ 308 kHz – Note this is the IC's oscillator frequency.
- Note Startup Graph: 2 stage ramp w/o

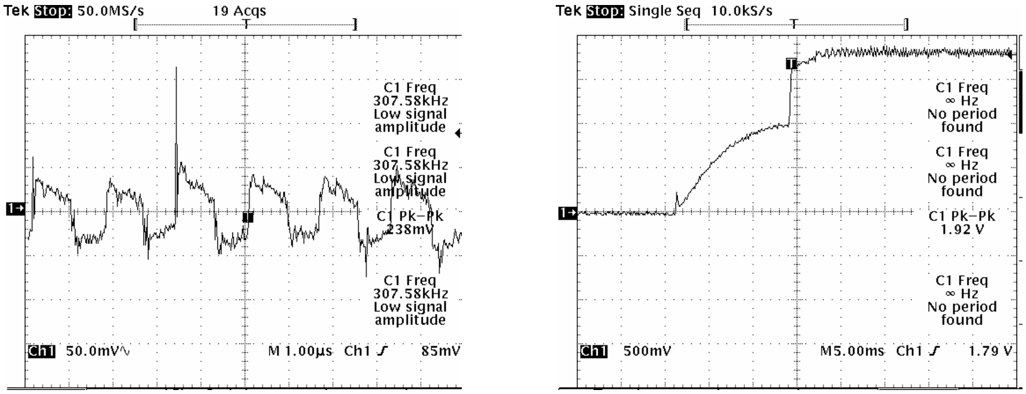


Figure 8: Experiment # 6 Results showing noise peak variances from loading changes, ganging and signal connectivity.

Experiment #7 Results

A LT1308 boost circuit was also built and tested independently at the Purdue University as a part of a graduate course on advanced Analaog Systems. Figure 9 shows the circuit schematic and Figure 10 shows the circuit built. The input was 3.6V and the output was 5V, switching frequency 600kHz. Table 2 and Figures 11 show sample results obtained. This was repeated using LT's Evaluation board. Table 3 and Figures 12 and 13 show sample results using the evaluation board. Figure 14 illustrates the efficiency of the converter at two different input voltages of 3.6V and 4.2V.

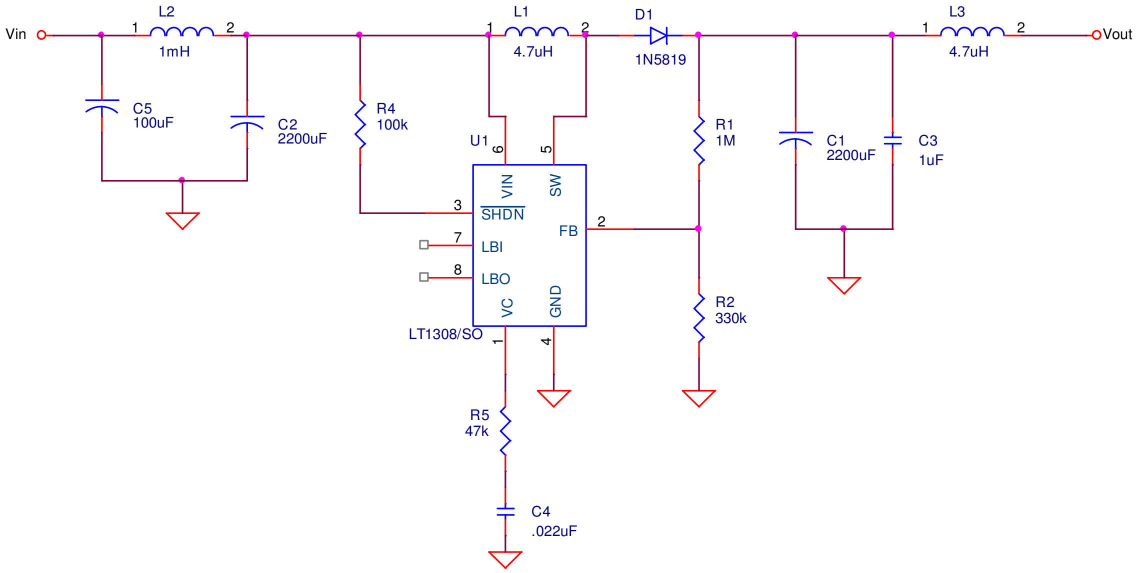


Figure 9: 5V LT1308 Boost Converter.

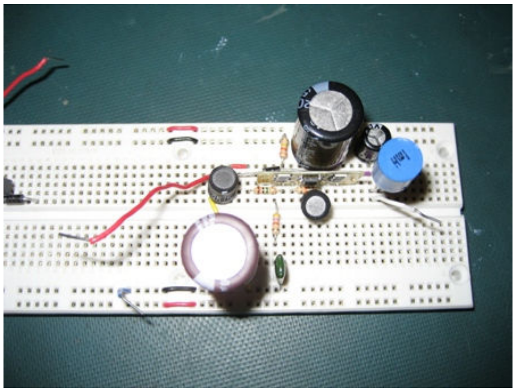
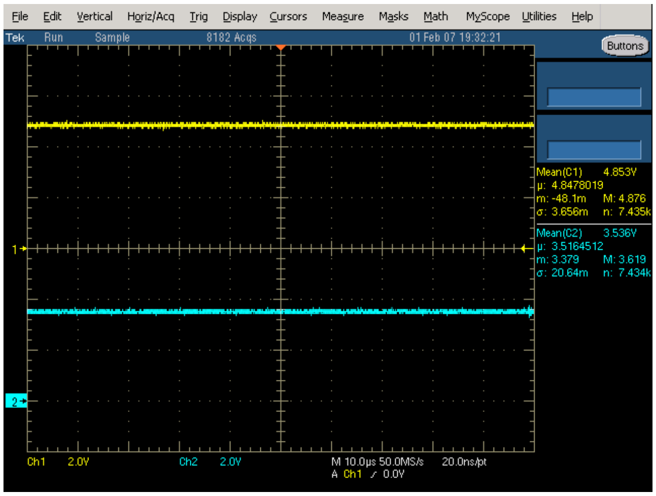


Figure 10: 5v Output Booster Circuit Built and Tested.

Table 2: Output Voltages and currents from Boost Chopper

V_{IN} (V_{DC})	V_{OUT} (V_{DC})	R_{LOAD} (Ω)	I_{IN} (A)	I_{OUT} (mA)
3.6	4.851	1000	0.01	4.82
3.6	4.845	900	0.01	5.309
3.6	4.856	800	0.01	5.991
3.6	4.81	700	0.02	6.821
3.6	4.84	600	0.02	7.933
3.6	4.833	500	0.02	9.418
3.6	4.813	400	0.03	11.62
3.6	4.8	300	0.04	15.16
3.6	4.74	200	0.05	21.83
3.6	4.506	100	0.1	39.56
3.6	3.994	50	0.2	88
3.6	3.212	25	0.26	139
3.6	2.941	20	0.31	161
3.6	2.605	15	0.38	195
3.6	2.016	10	0.47	224



```
Mean(C1)    4.853V
µ: 4.8478019
m: -48.1m   M: 4.876
σ: 3.656m   n: 7.435k
Mean(C2)    3.536V
µ: 3.5164512
m: 3.379    M: 3.619
σ: 20.64m   n: 7.434k
```

Figure 11 – Screen capture Output Voltage (Yellow) and Input Voltage (Blue) with 1kΩ load and input and output inductor filtering.

Table 3 – Input and Output Voltages and Currents from Evaluation Board at 3.6V_{DC}.

V_{in}	V_{out}	R_{load}	I_{in} (mA)	I_{out} (mA)	P_{in} (mW)	P_{out} (mW)	Efficiency (%)
3.608	4.983	1000	10.43	4.94	37.64	24.61	65.37
3.607	4.983	900	11.35	5.48	40.94	27.28	66.63
3.607	4.983	800	12.51	6.15	45.13	30.65	67.91
3.607	4.983	700	14.00	7.02	50.51	34.96	69.20
3.607	4.983	600	16.00	8.16	57.70	40.68	70.50
3.606	4.983	500	18.81	9.76	67.84	48.61	71.66
3.605	4.983	400	23.19	12.13	83.60	60.44	72.30
3.604	4.983	300	30.58	16.61	110.22	82.77	75.09
3.602	4.982	200	40.41	23.60	145.56	117.58	80.78
3.599	4.979	100	73.00	44.79	262.73	223.01	84.88
3.59	4.974	50	130.00	81.32	466.70	404.49	86.67
3.564	4.958	25	314.00	198.00	1119.10	981.68	87.72
3.552	4.952	20	393.00	246.00	1395.94	1218.19	87.27
3.533	4.94	15	528.00	326.00	1865.42	1610.44	86.33
3.493	4.917	10	813.00	484.00	2839.81	2379.83	83.80
3.351	4.833	5	1802.00	923.00	6038.50	4460.86	73.87

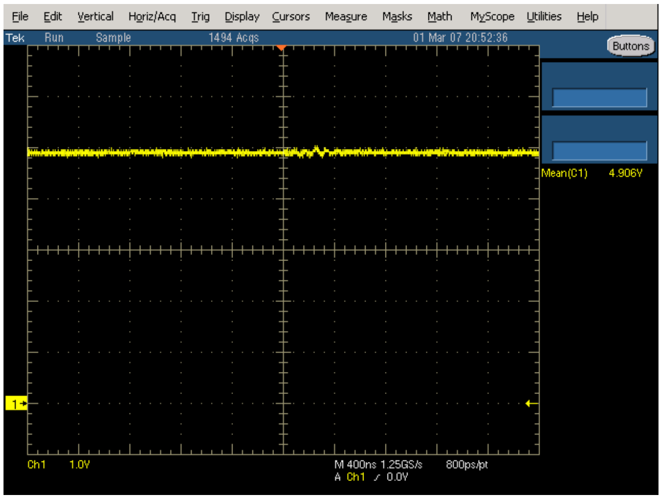
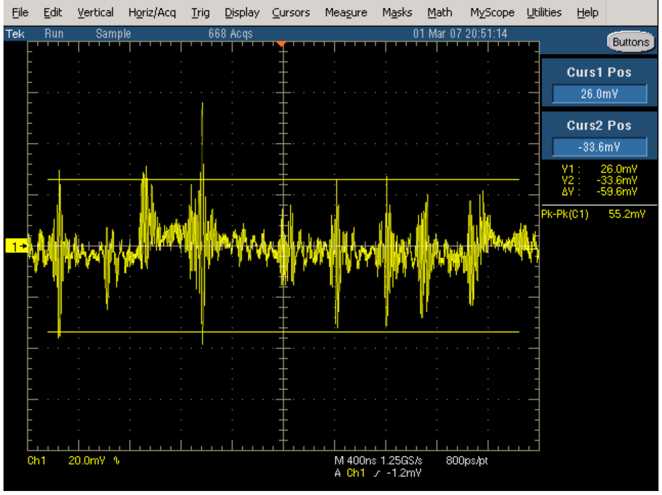


Figure 12: Screen capture of Output Voltage with 4.2V_{DC} Input Voltage and 100Ω load.



Tek Run Sample 668 Acqs 01 Mar 07 20:51:14

Curs1 Pos 26.0mV

Curs2 Pos -33.6mV

V1: 26.0mV
V2: -33.6mV
ΔV: -59.6mV

Pk-Pk(C1) 55.2mV

Ch1 20.0mV

M 400ns 1.25GS/s 800ps/pt
A Ch1 ⁄ -1.2mV

Figure 13 - Screen capture of Output Ripple Voltage with 4.2V$_{DC}$ Input Voltage and 100Ω load.

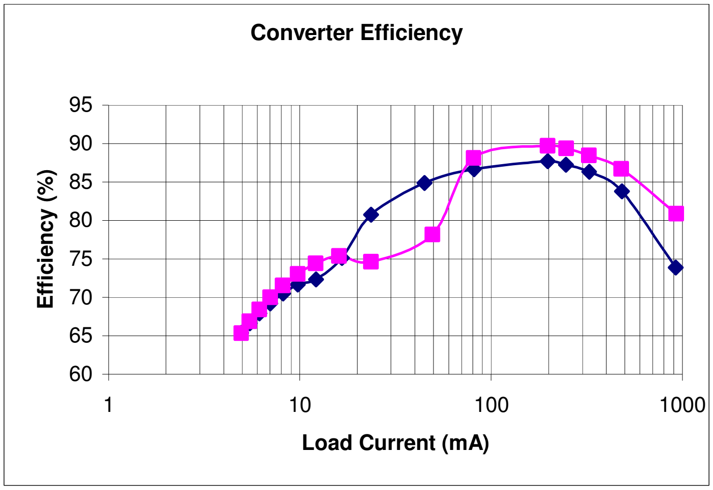


Figure 14 – LT1308 Efficiency for both Input Voltages (3.6V$_{DC}$ Blue and 4.2V$_{DC}$ Pink)

Summary

Buck-Boost converters are extremely effective and widely used. They are taught in every power electronics course in US, Canada, Japan and Inida at the senior and/or graduate level. Readers should leverage this small, low power and inexpensive technology to provide required power. Power saving and sleep modes further enhance their importance. Follow a planned development path and utilize existing tools such as modeling, sample applications and demo boards.

The buck-boost converters are sensitive, electrical noise generating and can quickly become unstable if not properly designed in conjunction with supporting components and proper physical layout. Manufacturer application notes and SPICE models narrow in on component specifications. Always procure demo boards from converter manufacturer if at all possible. Ensure converter signal and power interconnects are short to reduce instability. Fully test proposed converter applications and provide robust solutions for required loads. Diligent work may be required to get noise levels and frequencies in the desired range. Consult technical information and factory support when connecting key signals such as voltage compensation, error correction and similar critical signals. Also, ensure power start up ramps meet requirements. Power on switching circuits can be added to allow converter to fully reach needed power before switching them to loads.

The evaluated Linear Technology LT1308A[2] Buck-Boost Voltage Regulators and compatible demo boards operate with a wide voltage range as low as approximately 1.2 V or higher and output a voltage of 34 V as desired (settable with a voltage divider). The Oscilloscope measurements showed the various configuration responses including noise.

Acknowledgements

Wade Ackerman from Intel must be recognized for his converter project's support efforts. Very special thanks are due to Tim Shriner at Linear Technology, IN for the LT evaluation board.

References

[1] Linear Technology Buck-Boost Converter Guide
http://www.linear.com/ad/buckboost.jsp

[2] Linear Technology LT1308 buck-boost converter application guide.
http://www.linear.com/pc/productDetail.do?navId=H0,C1,C1003,C1042,C1031,C1060,P2321
- http://www.linear.com/pc/productDetail.do?navId=H0,C1,C1003,C1042,C1035,P1627

Appendix

VC (Pin 1): Compensation Pin for Error Amplifier. Connect a series RC from this pin to ground. Typical values are 47kW and 100pF. Minimize trace area at VC.

FB (Pin 2): Feedback Pin. Reference voltage is 1.22V. Connect resistive divider tap here. Minimize trace area at FB. Set VOUT according to: VOUT = 1.22V(1 + R1/R2).

SHDN (Pin 3): Shutdown. Ground this pin to turn off switcher. To enable, tie to 1V or more. SHDN does not need to be at VIN to enable the device.

GND (Pin 4): Ground. Connect directly to local ground plane. Ground plane should enclose all components associated with the LT1308. PCB copper connected to Pin 4 also functions as a heat sink. Maximize this area to keep chip heating to a minimum.

SW (Pin 5): Switch Pin. Connect inductor/diode here. Minimize trace area at this pin to keep EMI down.

VIN (Pin 6): Supply Pin. Must have local bypass capacitor right at the pin, connected directly to ground.

LBI (Pin 7): Low-Battery Detector Input. 200mV reference. Voltage on LBI must stay between –100mV and 1V. Low-battery detector does not function with SHDN pin grounded. Float LBI pin if not used.

LBO (Pin 8): Low-Battery Detector Output. Open collector, can sink 50mA. A 220kW pull-up is recommended. LBO is high impedance when SHDN is grounded.

VC (Pin 1): Compensation Pin for Error Amplifier. Connect a series RC from this pin to ground. Typical values are 47kW and 100pF. Minimize trace area at VC.

FB (Pin 2): Feedback Pin. Reference voltage is 1.22V. Connect resistive divider tap here. Minimize trace area at FB. Set VOUT according to: VOUT = 1.22V(1 + R1/R2).

SHDN (Pin 3): Shutdown. Ground this pin to turn off switcher. To enable, tie to 1V or more. SHDN does not need to be at VIN to enable the device.
GND (Pins 4, 5, 6, 7): Ground. Connect directly to local ground plane. Ground plane should enclose all components associated with the LT1308. PCB copper connected to these pins also functions as a heat sink.
Connect all pins to ground copper to get the best heat transfer. This keeps chip heating to a minimum.

SW (Pins 8, 9, 10): Switch Pins. Connect inductor/diode here. Minimize trace area at these pins to keep EMI down. Connect all SW pins together at the package.

VIN (Pins 11, 12): Supply Pins. Must have local bypass capacitor right at the pins, connected directly to ground. Connect both VIN pins together at the package.

LBI (Pin 13): Low-Battery Detector Input. 200mV reference. Voltage on LBI must stay between –100mV and 1V. Low-battery detector does not function with SHDN pin grounded. Float LBI pin if not used.

LBO (Pin 14): Low-Battery Detector Output. Open collector, can sink 50mA. A 220kW pull-up is recommended. LBO is high impedance when SHDN is grounded.