DC/DC Power Supply Module 1

Buck-Boost DC/DC Converter

Application Report

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Contents

Abstract

On July 2020 I finish the design of the module. DC-DC converters are present in many electronic devices including laptops, cellphones and industrial equipment. The reason behind its popularity started increasing as energy efficiency become more relevant in today's world, same as appliance miniaturization processes across the electronic industry.
Through this document you will find all the information needed to build a reliable buck-boost DC-DC converter that can be used in any electronic lab.

What is a Buck-Boost DC-DC Converter?

A buck-boost DC-DC converter is a type of electronic circuit that can produce a DC output voltage smaller, equal or bigger compared to its input voltage. As the name suggest, it combines the functions of a buck and boost converter for stepping up or down DC voltage. Figure 1 shows a simplified representation of the circuit.

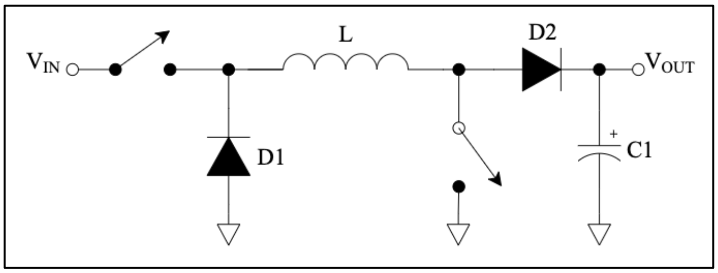

Figure 1 Simplified Buck-Boost Converter Circuit

A 4-switch buck-boost topology is used for this design. A simplified model is showed on Figure 2.

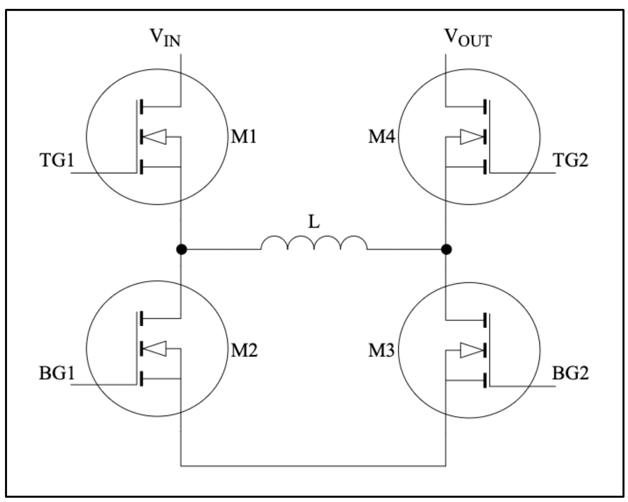

Figure 2 Simplified 4-Switch Buck-Boost Topology

This topology offers many advantages:

- Enhanced Efficiency: by using four switches, switching losses are minimized leading to a better efficiency particularly on load varying conditions.
- Dynamic Response: when load changes output conditions are adjusted instantly due to an improved dynamic response.
- Voltage Regulation: output voltage can be controlled more precisely as a result of a stable regulation.

Module Characteristics

To achieve a high-quality design, I use LTpowerCAD™ tool [1] developed by Analog Devices. This software provides an easy way when selecting the supply parameters and components, bringing confidence it will behave as expected under all scenarios. Figure 3 shows the power stage design screen of the tool.

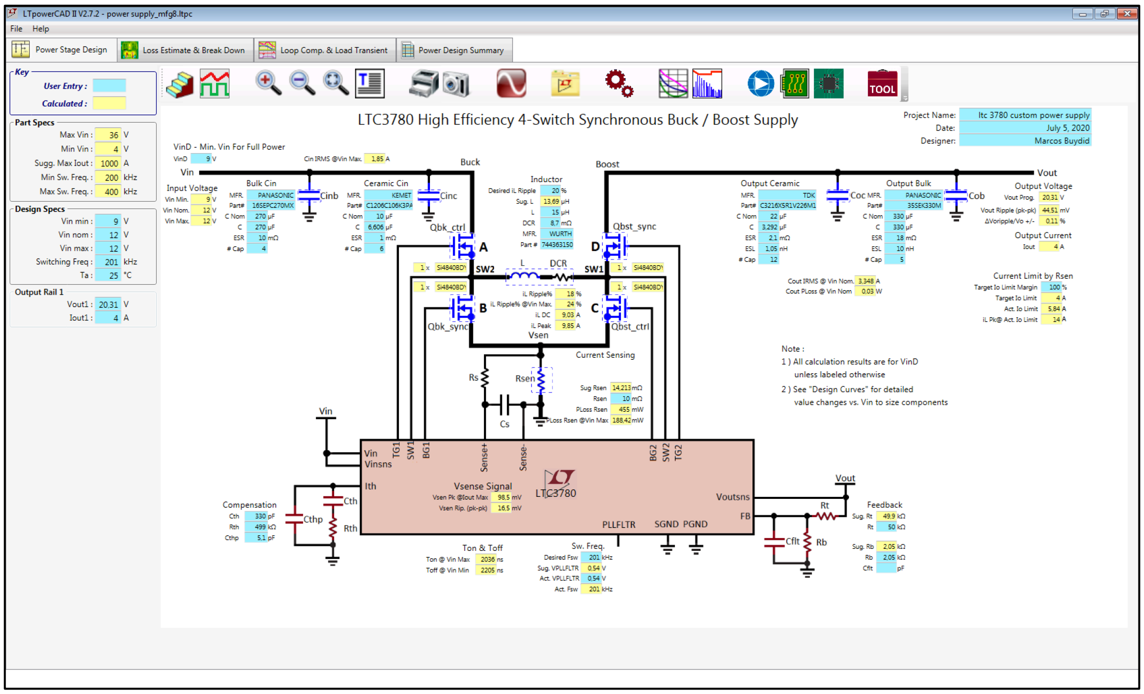

Figure 3 Power Stage Design Screen

General Parameters

As it's showed on Figure 3, voltage input (VIN) is 12V, output voltage (VOUT) is 20.31V and output current (IOUT) is 4A. Both output voltage and current refers to its maximum values but on the design, the capability of varying any of them is added (discussed later).

Input Stage

To protect the circuit from overcurrent, a fast-acting fuse (F1) [2] is used. I choose one with a 7A of current rating. Let's see the calcs associated to this value.

Module maximum power is:

P_{MAX} = VOUT x IOUT = 20.31V x 4A = 81.24W

The input current (I_{IN}) needed is:

$I_{IN} = P_{MAX}$ / VIN = 81.24W / 12V = 6.77A

Considering the efficiency of the buck-boost converter IC (η) is around 90%, the input power needed is:

$P_{IN} = P_{MAX} / \eta = 81.24W / 0.9 = 90.26W$

Adjusting the input current:

$I_{IN} = P_{IN} / VIN = 90.26W / 12V = 7.52A$

Now, you may question if the current rate of the selected fuse is accordingly to this value. Let's see the average time current curve extracted from fuse datasheet:

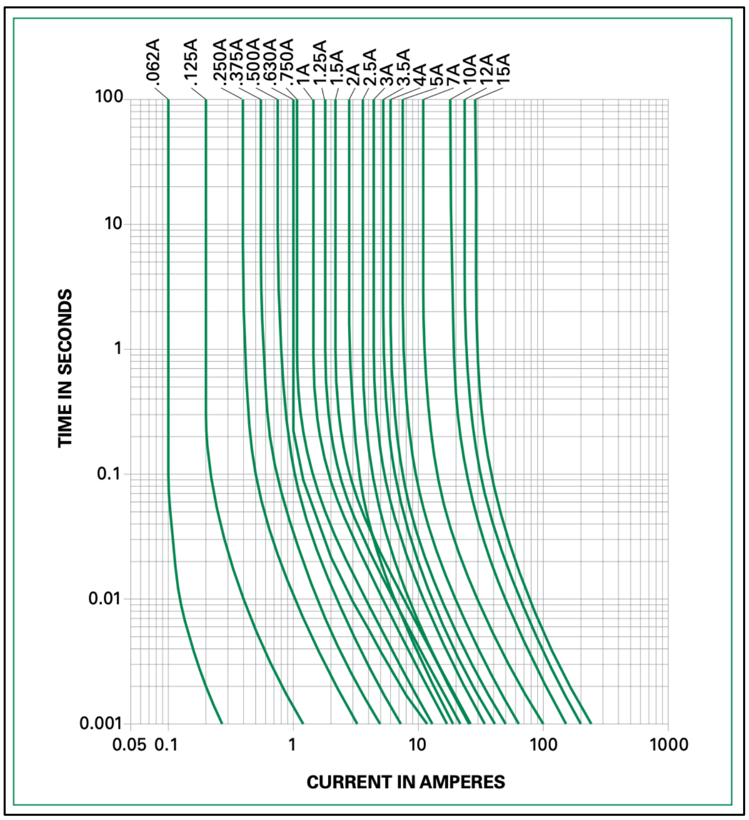

Figure 4 Average Time Current Curves

According to Figure 4 and positioning on 8A (at the bottom of the chart) because 7.52A is lower than 8A, you can see that if you try to intersect 7A green line (associated with the fuse current rate used) with 8A vertical grey line, they never cross each other, meaning that although 7.52A is 107% of the fuse amperage rate, it will tolerate it without fail.

To protect the input from reverse polarity there is a P-Mosfet (Q1) [3] connected to F1.

When input current is 7.52A, mosfet power dissipation is:

$P_{Q1} = I^2 \times R_{DS(on)} = 7.52^2A \times 0.06\Omega = 3.39W$ with $R_{DS(on)}$ the drain-to-source mosfet on-resistance.

Additionally, if input voltage gets over 20V (max V_{GS} voltage of Q1 according to datasheet) and eventually fuse does not fail, a unidirectional TVS diode (D11) [4] connected across Q1 source pin and GND protect the inbound circuit from overvoltage. A unidirectional type is selected because voltage is always positive in the circuit.

The main controller IC of the module is U1 [5], a buck-boost switching regulator. VIN pin of U1 has connected in series a 10Ω resistor (R5) and a 0.1uF capacitor (C8) in parallel. They are used to create a RC Low Pass Filter to reduce EMI.
High-frequency EMI is commonly manifested as high frequency noise or spikes. R5 limits the current through the filter while C8 provides a path for this frequencies to be shunted to ground isolating them from U1. Together they set the cut-off point at which frequencies above it will be attenuated. By using this formula $f_c = 1 / 2\pi RC = 1 / 2\pi \times 10\Omega \times 0.1uF = 159.1549KHz$, we obtain the desired point.

There are two LDO Voltage Regulators U3 [6] and U4 [7] with their inputs connected to VIN. U3 provides +3.3V to RUN pin of U1. It's important to use a stable voltage to feed this pin because as stated on U1 datasheet, exceeding it above 6V will destroy irreversibly some of its internal components.
On the other side, U4 provides +5V to a 499Ω resistor (R10) connected to U1 PGOOD pin through D6 diode. This pin is pulled to ground when the output voltage is outside of ± 7.5% regulation point. Additionally, this voltage regulator feeds U2 [8], an operational amplifier used in current control (discussed later).

Parameter Configuration and Core Component Selection

Frequency Operation

The switching frequency of U1 is determined by an internal oscillator capacitor that gets charged by a fixed current plus an additional current proportional to voltage on PLLFLTR pin. If the pin is tied to ground, frequency is set to 200KHz and if 2.4V are applied, frequency goes to approximately 400KHz.
Selecting the frequency is always a tradeoff, choosing a lower one increases switching regulator efficiency but implies bigger inductor and capacitor values. On the other side, a high frequency lowers the efficiency but allows to use small inductors and capacitor values.
In the design, PLLFLTR pin is tied to ground using a 10KΩ resistor (R20).

Inductor

Based on U1 datasheet and LTpowerCAD™ tool, a high current inductor (L1) [9] is selected. It can tolerate up to 14A of DC current and also has low DC resistance (8.7mΩ) to reduce I^2R losses. Due to its shielded type is able to reduce high frequency noise during operation.

Sense Resistor

According to the maximum current specified on LTpowerCAD™ tool, a value of 14mΩ is suggested for the sense resistor.

Despite the suggestion, a 10mΩ one is used (R1) [10] allowing to limit the current up to 5.84A. A current control circuit is added (discussed later) to limit the current to the specified value on the tool using a similar sense resistor value.

More details of the sense resistor selection can be found on U1 datasheet on applications information section.

Input And Output Capacitors

The selection is based on LTpowerCAD™ tool parameters and also taking into account C_{IN} and C_{OUT} section of U1 datasheet.

For input bulk capacitors (C1, C2, C3, C40, C41) [11] and output bulk capacitors (C14, C15, C16, C17, C42) [12] aluminum polymer type is selected because they offer many advantages including:

- Lower ESR: leading to better performance in high frequency applications including switching power supplies.
- Higher Ripple Current Capability: because of their low ESR they can handle higher currents.
- Enhanced Lifetime and Reliability: due to their solid electrolyte type they are less prone of drying out or leaking, also they have better temperature stability making them less sensitive to temperature fluctuations.

On the other side, for input ceramic capacitors (C4, C5, C6, C21, C22, C23) [13] multilayer type with X5R dielectric is selected offering good performance in decouple, bypass and filtering.

For output ceramic capacitors (C18, C24, C25, C26, C27, C28, C31, C32, C35, C37, C38,C39) [14] multilayer type TDK C series with X5R dielectric is selected because they have outstanding frequency characteristics such as low ESR, ESL and high resistance to ripple.

Mosfets

U1 requires four N-Channel power Mosfets as part of its topology. Among the important parameters, when selecting them is important to consider: breakdown voltage (V_{DS}), threshold voltage (V_{GS}), drain source on state resistance ($R_{DS(ON)}$) and maximum current (I_D).

On U1 datasheet, as a consequence of drive voltage set by 6V INTVCC supply, logic-level threshold mosfets must be used. According to datasheet, selected mosfets (Q2, Q3, Q4, Q5) [15] have a typical $R_{DS(ON)}$ of 0.0095Ω with V_{GS} = 4.5V and I_D = 10.8A, so in the context of module application their properties are suitable for the required parameters.

Voltage Control

To control the voltage output, a 10-turn potentiometer (VR1) [16] is used. This allows more precision when selecting a value while turning the knob.

U1 uses a voltage reference (V_{OSENSE}) of 0.800V. This voltage is very sensitive and exceeding its value above 2.4V will damage irreversibly internal circuits of U1.

To set the maximum voltage output this equation is used: $V_{OUT} = V_{OSENSE} \times (1 + VR1 / R9)$ with R9 the resistor used in the feedback resistor divider along with VR1.
Selecting a maximum voltage of 20V and a 50KΩ value for VR1 gives R9 = 2.08KΩ. According to component availability a 2.05KΩ resistor is used giving a maximum voltage of 20.312V.

Current Control

Figure 5 shows the associated circuit for current control that's similar to schematic but in a clearer representation. U2 is a dual operational amplifier, only one of them is showed on the figure, the other is unused.

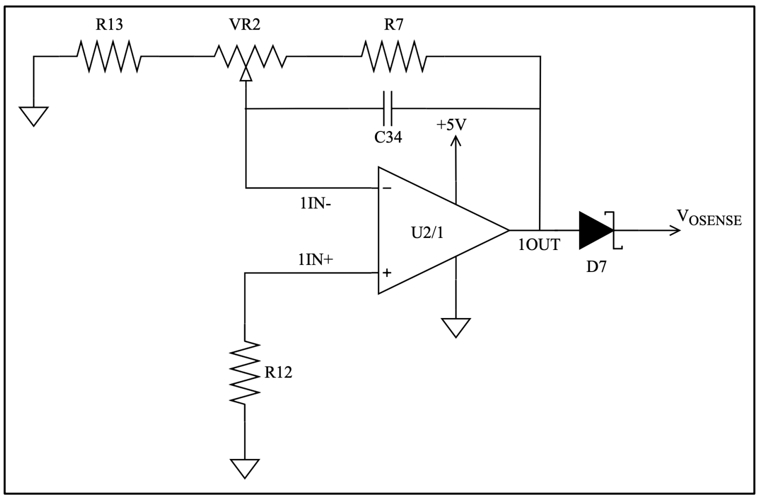

Figure 5 Current Control Circuit

First, for a non-inverting amplifier the voltage output (1OUT) is obtained using this formula:
$V_{OUT} = V_{IN} \times (1 + R_F / R_{IN})$ with V_{IN} the voltage sensed at the output (1IN+), R_F = R7 and R_{IN} the junction of R13 and VR2. In the formula $(1 + R_F / R_{IN})$ refers to the gain of the amplifier.

VR2 can vary the gain, so current can be adjusted. In an overcurrent scenario U2 pulls V_{OSENSE} above 0.8V making U1 drop the output voltage until the condition disappear.

In order to limit the current up to 4A and considering V_{OSENSE} voltage (0.8V) and D7 [17] forward voltage (0.3V), relation between R_F / R_{IN} should be around:
$R_F / R_{IN} = V_{OUT} / V_{IN} – 1$
At 4A voltage at 1IN+ input $(V_{IN}) = V_{1IN+} = I \times R12 = 4A \times 0.01Ω = 0.04V$
$R_F / R_{IN} = (0.8V + 0.3V / 0.04V) – 1 = 26.5$

According to component availability, choosing VR2 = 50KΩ, R7 = 1M2Ω and R13 = 1KΩ, gain of the amplifier (A_V) will be:
$A_V = 1 + (R7 / R13 + VR2) = 1 + 1200000Ω / 51000Ω = 24.53$
Now, at 4A $V_{OUT} = V_{IN} \times A_V = 0.04V \times 24.53 = 0.981V$

Minimum current limit will be around 100mA assuming VR2 with a value of 10ohm.
At 100mA, $A_V = 1 + (1200000\Omega / 1010\Omega) = 1189{,}11$
Voltage at 1IN+ input (V_{IN}) = V_{1IN+} = I x R12 = 0.100A x 0.01Ω = 0.001V
$V_{OUT} = V_{IN} \times A_V = 0.001V \times 1189{,}11 = 1.189V$

Output Stage

There's a schottky diode (D5) [18] across the output used as a protection from reverse polarity. If output is reversed, D5 becomes forward biased and conducts current shorting the output. This can be done due to module current control implemented.

Additional Information

Details of some components selection not available on LTpowerCAD™ tool were not discussed including, soft-start or boost capacitors, diodes connected across switching mosfets, diodes connected across INTVCC and BOOST pins (including the INTVCC bypass capacitor). Depending on your component availability and the performance to achieve, components may vary. You can choose any suggested value from U1 datasheet (inside typical application schematic figure) or from demo boards schematics [19] [20].

Conclusions

After testing the module, I consider it can offer all the basic capabilities needed in a buck-boost DC-DC converter.
Both voltage and current control works ok. It’s important to use a supply with double the current capacity of the module.

References

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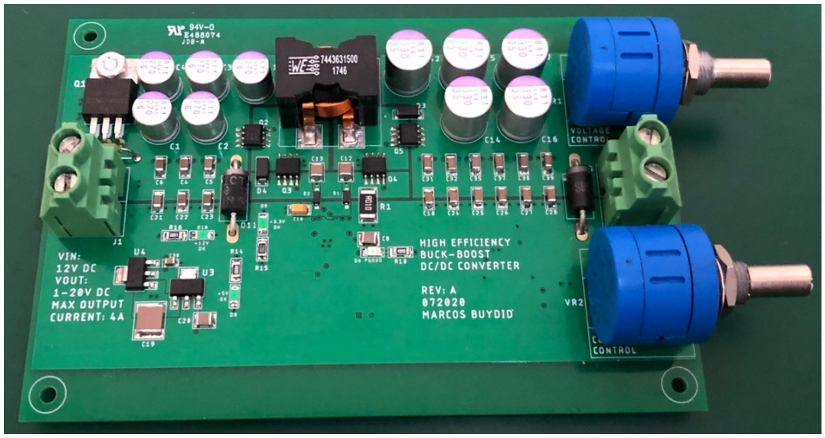
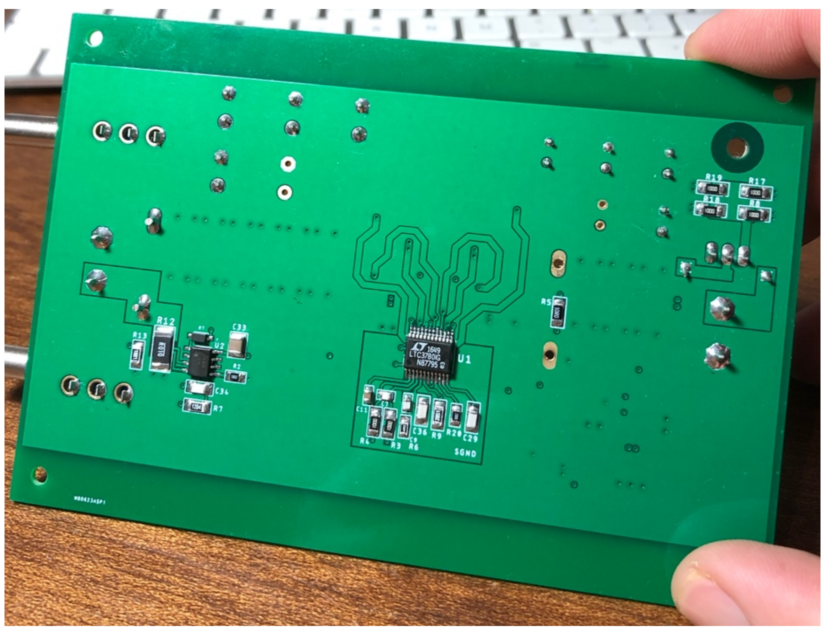
Annexes

Finish Assembly Photos



Module Upper View



Module Bottom View

Note on upper view image, VOUT label text is “1-20V DC” but was written mistakenly, instead, it should’ve been labeled as “0.8-20V DC”.

Revision History

Date	Version	Changes
Dec-2024	1	First version