Application Report
SNOA425C–September 2002–Revised April 2013

AN-1246 Stresses in Wide Input DC-DC Converters

ABSTRACT

This application note discusses stresses in wide input DC-DC converters.

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1 Introduction

Experienced power supply designers previously working with one topology who turn their attention to another, know they must shift mental gears quite dramatically. The “rules of the game” change and therefore major design issues will arise if this fact is not recognized at the very outset.

“Equations for all topologies are available, and one just needs to use them”—correct? No, in fact though one of the things this application note also provides is such a set of design equations, that is not enough.

Equations are by nature “single-point” computations. So if for example we input a given operating condition: say V_{IN} = 15V, V_{OUT} = 5V, Io = 1A, we can use the appropriate Buck converter equation to calculate the input capacitor RMS current—valid for this specific condition. But under a more practical scenario suppose V_{IN} could vary between 8V and 22V, with 15V just representing a vague “nominal” value? What is then the most appropriate input voltage to use to calculate the worst-case input capacitor current? We will find that no set of equations, however complete, guides us to that information directly. So if Designer A “picks” the lowest input voltage 8V, Designer B picks the highest input voltage 22V, and Designer C picks the nominal value of 15V, all of them are actually wrong. For the correct answer here is V_{IN} = 10V.

Take another example: should the inductor be designed at the highest input or the lowest input voltage of the range? For a Buck it didn't seem to matter too much at what input voltage we design the inductor, but if one applies the same nonchalance to a Boost or a Buck-Boost, there may be no power supply to put through any further testing.

The important point is even while delivering this constant maximum load, the internal currents of the power supply do change their shape, peak values, RMS and average values considerably in response to changes in input voltage. The purpose of this Note is to figure out how these values vary for each topology and to thereby fix a “worst case” design or test condition for each of them. A logical design procedure finally emerges based on the topology on hand.

As mentioned, a comprehensive table of design information (Table 2) is provided for all the three main topologies: the Buck, the Buck-Boost and the Boost. Unlike most other references in literature, this table is cast in terms of 'r'. This actually makes the table very designer-friendly because it recognizes that the only real degree of design freedom available is the inductor current ripple ratio 'r'. The criterion for selection of 'r' (in fact its actual value too) happens to be the same for any topology, at any application condition, and for any switching frequency. Once 'r' is fixed (usually between 0.3-0.5), eveyrthing else is more or less pre-determined. We only have to pay heed to the appropriate input voltage end at which to set 'r, as this can change from one topology to another. It will also be noticed that the design table includes the drops across the switch and diode for all the topologies, something that is not commonly available in related literature. We must realize that because of the ever-shrinking output voltages, these 'negligible' forward “drops” have actually become increasingly important today.

The design procedure based on the design table considers a power supply operating at a constant (maximum) load with a fixed output voltage, whose input voltage is varied. We can predict its response to the resulting variation in duty cycle, and thereby figure out the worst case input test or design condition. Conclusions are summarized in Table 1. The equations are essentially cast in terms of the output voltage (V_O), max load (“I_O”) and Duty Cycle (“D”), and inductor current ripple ratio (“r”). The input voltage “V_{IN}” is not included directly in the stress formulae, as “D” is intended to reflect the input voltage variation. *The most important fact to keep in mind in this article when relating D to V_{IN} is that for all topologies, low D corresponds to high V_{IN} and a high D to low V_{IN}* (since output voltage is considered fixed).

2 Inductor Current Waveforms

An inductor current waveform consists of an AC/ramp component “ΔI”, and a DC/average component “I_{DC}”, the latter being the geometric center of the ramp. Note that in literature the 'AC' value is usually taken to be half the ramp, but here we are just equating them for convenience. The essential difference between the topologies is that for the Buck, the average inductor current equals the load current at all times, but for the Boost and the Buck-Boost, it is the average diode current that equals the load current. So as from Table 2, it can be shown that

$$I_{DC} = I_O = \text{constant} \quad \text{BUCK} \tag{1}$$

$$I_{DC} = \frac{I_O}{1 - D} \propto \frac{1}{1 - D} \quad \text{BOOST/BUCK-BOOST} \tag{2}$$

It is clear that the average inductor current for the Boost and the Buck-Boost becomes very high if D approaches 1. Remember that this corresponds to decreasing input voltage "V_{IN_MIN}". Therefore the inductor design must be conducted at the lowest input voltage for these topologies. For the Buck there is hardly any dependency of the inductor current to input voltage since the average current depends only on the load (which is considered fixed in our analysis). So for a Buck regulator, as a first pass selection, we often simply pick an inductor with a current rating equal to the load, irrespective of input voltage. These variations are included in the plots shown in Figure 1. Read these in consultation with the listing provided in Table 1

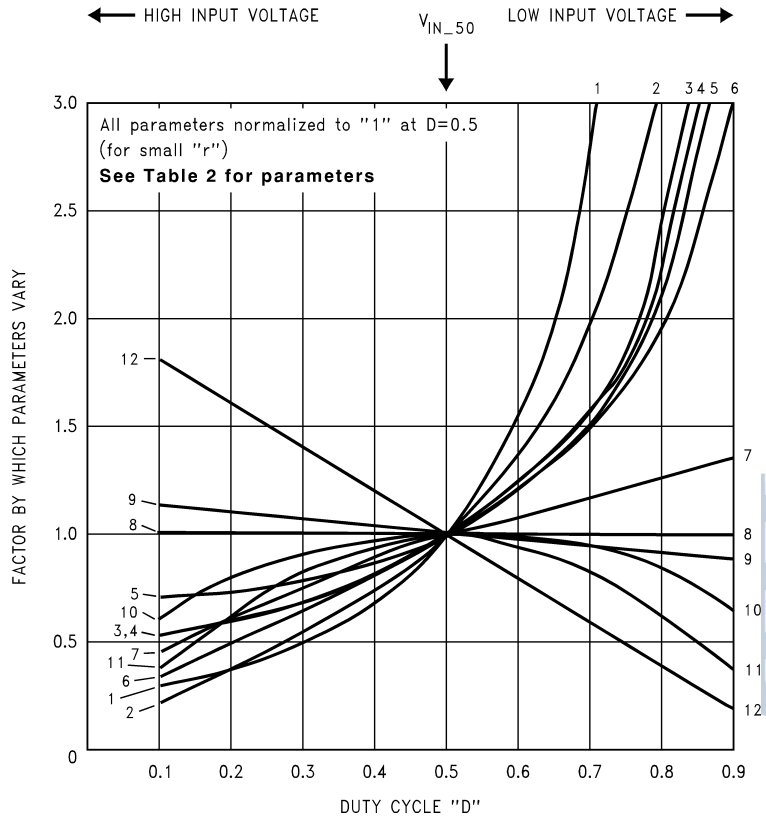

Figure 1. Inductor Design - Plot Variations

Table 1. The Worst Input Voltage Condition for Design/Test of a Given Parameter[(1)]

Parameter	Buck	Boost	Buck-Boost
ΔI (I_{AC} in Inductor)	V_{IN_MAX} 12	V_{IN_50} 11	V_{IN_MAX} 12
Core Loss	V_{IN_MAX}	V_{IN_50}	V_{IN_MAX}
Inductor Energy/Core Saturation	V_{IN_MAX}/V_{IN} 8	V_{IN_MIN} 1	V_{IN_MIN} 1
Average Current in Inductor	V_{IN} 8	V_{IN_MIN} 3	V_{IN_MIN} 3
RMS Current in Inductor	V_{IN_MAX}/V_{IN} 8	V_{IN_MIN} 3	V_{IN_MIN} 3
Copper Loss/Temperature of Inductor	V_{IN_MAX}/V_{IN}	V_{IN_MIN}	V_{IN_MIN}
RMS Current in Input Capacitor	V_{IN_50} 10	V_{IN_50} 11	V_{IN_MIN} 6
Input Voltage Ripple	V_{IN_MAX}/V_{IN} 8	V_{IN_MAX} 12	V_{IN_MIN} 3

(1) Numbers in the columns refer to corresponding numbered curves in Figure 1.
V_{IN} means any input voltage is appropriate
V_{IN_50} is input voltage at which D=0.5

Table 1. The Worst Input Voltage Condition for Design/Test of a Given Parameter[(1)] (continued)

Parameter	Buck	Boost	Buck-Boost
RMS Current in Output Capacitor	V_{IN_MAX} 12	V_{IN_MIN} 6	V_{IN_MIN} 6
Output Voltage Ripple	V_{IN_MAX} 12	V_{IN_MIN} 3	V_{IN_MIN} 3
RMS Current in Switch	V_{IN_MIN} 7	V_{IN_MIN} 2	V_{IN_MIN} 2
Average Current in Switch	V_{IN_MIN}	V_{IN_MIN}	V_{IN_MIN}
Peak Current in Switch/Diode/Inductor	V_{IN_MAX} 9	V_{IN_MIN} 4	V_{IN_MIN} 5
Average Current in Diode	V_{IN_MAX} 12	V_{IN} 8	V_{IN} 8
Temperature of Diode	V_{IN_MAX} 12	V_{IN} 8	V_{IN} 8
Worst Case Efficiency	V_{IN_MAX}	V_{IN_MIN}	V_{IN_MIN}

The AC component of the inductor current, "I_{AC}", or "ΔI" cannot be fully ignored even for a Buck. This parameter is important, firstly, because along with I_{DC}, it determines the peak value of the inductor current. This peak value needs to be known so as to accurately evaluate the energy handling requirement of the inductor (defined as ½*L*I^2_{PEAK}). If we do not size the inductor accordingly, the core may saturate. But more importantly, for all topologies, this AC component is completely responsible for the core loss. Core loss does not depend on I_{DC}, so long as the inductor is not saturating).

Now, for all the topologies, there is an applied voltage "V_{ON}" across the inductor when the switch is ON. This causes a certain resulting AC ramp component "ΔI" across the inductor based on the fundamental equation V_{ON} = L*ΔI/(D/f) or ΔI = V_{ON}*D/(L*f), where f is the frequency. As the input voltage falls, V_{ON}decreases helping to lower the ramp component, but at the same time D increases and this helps to promote the ramp. So the interesting question can be asked: what eventually happens to ΔI as input voltage falls?

The equation for ΔI are provided in Table 2. We see that

$\Delta I \propto (1 - D)$ BUCK/BUCK-BOOST

$\Delta I \propto D \bullet (1 - D)$

So plotting these out in Figure 1, we see that

ΔI →— maximum at highest input voltage for Buck/Buck-Boost

ΔI →— maximum at V_{IN_50} (or closest voltage) for Boost

where V_{IN_50} is defined here as the input voltage at which D=50% for the topology under consideration. This value is also provided in Table 2. If the input voltage range does not include V_{IN_50}, we must choose either V_{IN_MIN} or V_{IN_MAX}, *whichever happens to be closer to* V_{IN_50}.

We also define a useful parameter called the current ripple ratio "r" which is the ratio of the AC to the DC value of the inductor current, with the converter delivering maximum load. So

$$r = \frac{\Delta I}{I_{DC}} = \frac{\Delta I}{I_O} \quad \text{BUCK} \tag{3}$$

$$r = \frac{\Delta I}{I_{DC}} = \frac{\Delta I}{I_O} \bullet (1 - D) \quad \text{BOOST/BUCK-BOOST} \tag{4}$$

This parameter "r" is important as it determines among other things, the inductance "L", and the physical size of most of the power components. It can be shown that the size of the inductor is reduced by increasing "r". However an "r" of 0.3–0.4 represents the most optimum choice for any topology. The reader can refer to AN-1197 for a deeper understanding of how the current ripple ratio relates to the optimization. That particular Application Note is based on the Buck converter, but the same principles apply to all the topologies. In any case, allowing for a greater current ripple than the optimum of 0.3-0.5 (by reducing inductance) does not appreciably reduce the size of the inductor, but does increase the size/requirements of either or both the input/output capacitors. Now, having designed the inductor for a given value of "r" at

the appropriate input voltage end, as discussed earlier, as we vary the input voltage over the expected range, “r” changes accordingly. The equations in Table 2 are cast essentially in terms of “r” and D, as these are the two main parameters that vary with input voltage. The variation of “r” with D is also provided, thus making D the only actual variable in our analysis. The value of the required inductance (based on a chosen “r”) can be found in Table 2, and the physical size of this inductor can be also calculated from the required energy handling capability as listed. More on inductor design later.

3 Input Capacitor Currents

A key parameter is the RMS current, “I_{IN}”, through the input electrolytic capacitor. It determines the basic/minimum selection criterion since the capacitor must be rated at least for the worst case RMS current that may pass through it. A capacitor operated with an RMS current higher than its rated value, is not guaranteed to have any specific life by most manufacturers. Life expectancy vs. temperature curves/equations as provided, are then not considered to be valid.

From Table 2, for small “r”, we can see that this goes as

$$I_{IN} \propto \sqrt{D \cdot (1 - D)} \quad \text{BUCK} \tag{5}$$

$$I_{IN} \propto \frac{r}{1 - D} \propto \frac{D \cdot (1 - D)^2}{1 - D} = D \cdot (1 - D) \quad \text{BOOST} \tag{6}$$

$$I_{IN} \propto \frac{1}{(1 - D)} \cdot \sqrt{D \cdot (1 - D)} = \sqrt{\frac{D}{1 - D}} \quad \text{BUCK-BOOST} \tag{7}$$

Plotting these out in Figure 1, we can see that

I_{IN} →— maximum at V_{IN_50} (or closest voltage) for Buck/Boost

I_{IN} →— maximum at lowest input voltage for Buck-Boost

So the temperature of the output capacitor must also be evaluated at the above input voltages. If the input voltage range does not include V_{IN_50}, we must choose either V_{IN_MIN} or V_{IN_MAX}, *whichever happens to be closer to* V_{IN_50}.

We are also concerned with the peak to peak current, I_{PP_IN} through the input capacitor as this determines the input voltage ripple $\Delta V_{IN} = I_{PP\_IN} * ESR_{IN}$, where ESR_{IN} is the Equivalent Series Resistance of the input capacitor. This input ripple is a major component of the EMI spectrum at the input of the power supply.

From Table 2, for small “r”, we can see that this goes as

$$I_{PP\_IN} \propto \text{constant} \quad \text{BUCK} \tag{8}$$

$$I_{PP\_IN} \propto \frac{r}{1 - D} \propto \frac{(1 - D)^2}{1 - D} = (1 - D) \quad \text{BOOST} \tag{9}$$

$$I_{PP\_IN} \propto \frac{1}{1 - D} \quad \text{BUCK-BOOST} \tag{10}$$

Plotting these out in Figure 1, we can see that

I_{PP_IN} →— constant/maximum at highest input voltage for Buck

I_{PP_IN} →— maximum at highest input voltage for Boost

I_{PP_IN} →— maximum at lowest input voltage for Buck-Boost

For a Buck stage, the input voltage ripple is almost a constant with respect to input voltage variations, provided “r” is very small. However since “r” does increase somewhat at high input voltages, it is preferable to evaluate this parameter at the highest input voltage.

4 Output Capacitor Currents

The Output Capacitor also needs to be at least big enough to handle the worst case RMS current through it, "I_{OUT}".

From Table 2, for small "r", we can see that this goes as

$$I_{OUT} \propto r \propto (1 - D) \quad \text{BUCK} \tag{11}$$

$$I_{OUT} \propto \sqrt{\frac{D}{1 - D}} \quad \text{BOOST/BUCK-BOOST} \tag{12}$$

Plotting these out in Figure 1, we can see that

I_{OUT} →— maximum at highest input voltage for Buck

I_{OUT} →— maximum at lowest input voltage for Boost/Buck-Boost

So the temperature of the output capacitor must also be evaluated at the above input voltages.

We are also concerned with the peak to peak current, I_{PP_OUT} through the output capacitor as this determines the output voltage ripple $\Delta V_{OUT} = I_{PP\_OUT} * ESR_{OUT}$, where ESR_{OUT} is the Equivalent Series Resistance of the output capacitor. This output ripple is a major component of the noise spectrum at the output of the power supply.

From Table 2, for small "r", we can see that this goes as

$$I_{PP\_OUT} \propto r \propto (1 - D) \quad \text{BUCK} \tag{13}$$

$$I_{PP\_OUT} \propto \frac{1}{1 - D} \quad \text{BOOST/BUCK-BOOST} \tag{14}$$

Plotting these out in Figure 1, we can see that

I_{PP_OUT} →— maximum at highest input voltage for Buck

I_{PP_OUT} →— maximum at lowest input voltage for Boost/Buck-Boost

5 Switch RMS/Avg Current

For a MOSFET Switch we need to calculate the conduction loss as given by $I^2_{RMS} * rds$. The crossover losses are lowest at the minimum input voltage. But since they are usually a small fraction of the conduction losses, and are thus ignored here. The I_{RMS} of the switch varies in the following manner.

From Table 2, for small "r", we can see that this goes as

$$I_{RMS} \propto \sqrt{D} \quad \text{BUCK} \tag{15}$$

$$I_{RMS} \propto \frac{\sqrt{D}}{1 - D} \quad \text{BOOST/BUCK-BOOST} \tag{16}$$

Plotting these out in Figure 1, we can see that

I_{RMS} →— maximum at lowest input voltage for Buck/Boost/Buck-Boost

It should however be noted that for a Buck, the dissipation in the Switch at low input voltages goes up only slightly, but for the remaining topologies, this dissipation is expected to go up steeply at low input voltages, leading to a large drop in efficiency. In Table 2, the average switch current is also provided, for calculation of dissipation in bipolar switches. It can be shown that the above conclusions for RMS are also valid for the average value of the switch current (which is required to calculate the conduction loss for a bipolar switch).

Talking about efficiency leads to the other main component of loss in a power supply, the diode loss. We will now see how this varies, and what it implies for the effect of input variations on the efficiency of the power supply.

6 Average Diode Current/Efficiency

For a diode we need to calculate the forward loss as given by I_{AVG}*V_D, where "V_D" is the drop across the diode when it conducts. For the Boost and the Buck-Boost, the average diode current is the load current, so it is not going to change with duty cycle. But for the Buck it does vary.

From Table 2, we can see that this goes as

$I_{AVG} \propto (1 - D)$ BUCK

$I_{AVG} \propto$ constant BOOST/BUCK-BOOST

Plotting these out in Figure 1, we can see that

I_{AVG} →— maximum at highest input voltage for Buck

I_{AVG} →— constant for Boost/Buck-Boost

We saw that the dissipation in the switch of a Buck remains almost constant as input voltage increases, and now we see that the diode dissipation however increases as we do so. So we expect the efficiency of a Buck regulator to *fall at high input voltages on account of increased diode dissipation.* For the Boost and Buck-Boost, the diode dissipation does not change as input voltage falls, but the switch dissipation increases dramatically. So we expect the efficiency of a Boost or a Buck-Boost to *fall at low input voltages on account of increased switch dissipation* (unless crossover losses are very large, in which case the reverse is occasionally found to be true).

For diode temperatures, we need to test a Buck regulator at the highest input voltage. For the other topologies, it does not matter. This is shown as "V_{IN}" in Table 1, implying any input voltage.

This also tells us at what input voltage we need to check efficiency check of a power supply. It clearly varies from topology to topology. See Table 1.

7 Inductor Energy

The "Energy Handling Capability" is e=½*L*I^2_{PEAK}. This parameter literally "sizes" up the inductor for a given application. Note that the size is not determined just by inductance, since almost any inductance can be theoretically achieved on any core, simply by winding the appropriate number of turns on it. The complete equations for "e" are provided in Table 2. For our analysis here, we first make an approximation for the rather complicated term involving "r". Assuming "r" to be small this term becomes

$$r \cdot \left[\frac{2}{r} + 1\right]^2 \approx r \cdot \left[\frac{2}{r}\right]^2 \propto \frac{1}{r} \tag{17}$$

From Table 2, for small "r", we can see that the Energy handling Capability goes as

$$e \propto \frac{Et}{r} \propto \frac{(1 - D)}{(1 - D)} = 1 \quad \text{BUCK} \tag{18}$$

$$e \propto \frac{Et}{(1 - D) \cdot r} \propto \frac{D \cdot (1 - D)}{D \cdot (1 - D)^3} \propto \frac{1}{(1 - D)^2} \quad \text{BOOST} \tag{19}$$

$$e \propto \frac{Et}{(1 - D) \cdot r} \propto \frac{(1 - D)}{(1 - D)^3} \propto \frac{1}{(1 - D)^2} \quad \text{BUCK-BOOST} \tag{20}$$

Plotting these out in Figure 1, we can see that

e →— constant/maximum at highest input voltage for Buck

e →— maximum at lowest input voltage for Boost/Buck-Boost

Note that for both the Boost and the Buck-Boost, the required energy handling capability increases dramatically as duty cycle approaches 0.6. This is known to designers of front-end PFC stages. Such stages are typically of Boost topology, providing an internal 400VDC rail from a worldwide AC input. It is seen that the size of the required inductor goes up sharply as the minimum input voltage falls, and so the inductor design should be carried out at the minimum input voltage. As for the Buck, some designers use the maximum input voltage, some the minimum, and some simply use the nominal input voltage. It really does not matter too much, provided "r" is, and remains, small as we assumed. In reality, "r" does increase as input voltage increases (thereby causing a slight increase in peak value), so it is preferable to design the inductor of a buck regulator for the highest input voltage.

8 Inductor Avg/RMS Currents

If “r” is small, the average and RMS values of the inductor current are the same, “I_L”. The copper loss in the inductor is I_L^2*R, where “R” is the winding resistance. The copper loss is usually very large compared to the core loss (which depends on ΔI, as discussed earlier), and largely determines the temperature rise of the inductor.

From Table 2, for small “r”, we can see that the RMS/Avg current goes as

$$I_L \propto \text{constant} \quad \text{BUCK} \tag{21}$$

$$I_L \propto \frac{1}{(1 - D)} \quad \text{BOOST/BUCK-BOOST} \tag{22}$$

We can see that for the Boost and Buck-Boost, if D is large, I_L increases. Therefore when evaluating copper loss or temperature rise of the inductor for these, we need to use the minimum input voltage. For the Buck, since “r” does increase with increasing input voltage, the RMS value of the inductor current is also higher, and so we should use the maximum input voltage.

I_L →— constant/maximum at highest input voltage for Buck

I_L →— maximum at lowest input voltage for Boost/Buck-Boost

9 Peak Switch Current

This parameter is important because every controller has a current limit for the switch, and if the calculated peak exceeds the lowest value possible of the switch current limit, *anywhere in the input voltage range*, the required output power cannot be delivered. The peak current in a Buck is just a little higher than the load current, and so for example, the LM2593HV “Step Down (Buck) regulator” IC from National Semiconductor, which is designed for “2A load”, has a minimum set value of 2.3A for the switch current limit. Yet, as seen in Figure 2, and from the datasheet of this device, this Buck IC can be operated as a “positive to negative” regulator, which is actually a standard Buck-Boost topology. In this mode, the peak current values are much higher, as can be seen from Table 2, and in fact depend not only on load, but on the duty cycle/input voltage too. We now try to see how the peak current values vary for all the topologies, with changes in input voltage.

From Table 2, for small “r”, we can see that the peak current goes as

$$I_{PEAK} \propto \left[1 + \frac{r}{2}\right] \propto \left[2 + (1 - D)\right] = (3 - D) \quad \text{BUCK} \tag{23}$$

$$I_{PEAK} \propto \frac{\left[1 + \frac{r}{2}\right]}{1 - D} \propto \frac{\left[2 + (D \cdot (1 - D)^2)\right]}{1 - D} \quad \text{BOOST} \tag{24}$$

$$I_{PEAK} \propto \frac{\left[1 + \frac{r}{2}\right]}{1 - D} \propto \frac{\left[2 + (1 - D)^2\right]}{1 - D} \quad \text{BUCK-BOOST} \tag{25}$$

Plotting these in Figure 1 we see that for the Boost and the Buck-Boost the peak value of switch current occurs at maximum duty cycle (minimum input voltage), whereas for the Buck this occurs at lowest duty cycle (highest input voltage). Therefore Current Limit must be tested at minimum input voltage for the Boost and the Buck-Boost, but for the Buck we must go to the highest input voltage. We conclude

I_{PEAK} →— maximum at highest input voltage for Buck

I_{PEAK} →— maximum at lowest input voltage for Boost/Buck-Boost

Therefore the designer can use Table 2 to calculate the peak current, but must do so at the lowest input voltage for the Boost and Buck-Boost, to ensure that it is less than the current limit. For a Buck, the peak current must be calculated and compared to the current limit at the highest input voltage.

10 Example

The LM2593HV (5V fixed output version) is to be used to generate a −5V output from an input voltage ranging from 4.5V to 20V. This is a 150 kHz Buck Regulator IC with a switch current limit of 2.3A (min). What is the maximum load it can deliver in this positive to negative configuration. (Assume V_D = 0.5V and V_{SW} = 1.5V).

The inductor design must be done at the minimum input i.e. 4.5V for a Buck-Boost topology according to the guidelines in Table 1. We fix an "r" of 0.3 as this always represents an optimum size for the inductor. The worst-case peak current in the switch for a buck-boost (which this is) corresponds to the curve #5 from Table 1. Looking for this curve in Figure 1 shows that this reaches its maximum at high duty cycle (low input voltage). Therefore we can proceed with this peak switch current calculation at the minimum input voltage, at which we will also perform the inductor design.

The duty cycle is calculated from Table 2

$$D = \frac{V_O + V_D}{V_{IN} + V_O - V_{SW} + V_D} = \frac{5 + 0.5}{4.5 + 5 - 1.5 + 0.5}$$

- D = 0.65 (26)

The peak current in the switch is

$$I_{PEAK} = \frac{I_O}{1 - D} \cdot \left[1 + \frac{r}{2}\right] \quad (27)$$

So setting I_{PEAK} = 2.3A, we can solve for I_O

$$I_O = \frac{I_{PEAK} \cdot (1 - D)}{\left(1 + \frac{r}{2}\right)} = \frac{2.3 \cdot (1 - 0.65)}{\left(1 + \frac{0.3}{2}\right)}$$

- I_O = 0.7A (28)

So we can assure ourselves of only a maximum load of 0.7A in this configuration. The required L can be evaluated from Table 2

$$L = \frac{V_O + V_D}{I_O \cdot r \cdot f} \cdot (1 - D)^2 \cdot 10^6 \ \mu H \quad (29)$$

$$L = \frac{5 + 0.5}{0.7 \cdot 0.3 \cdot 150000} \cdot (1 - 0.65)^2 \cdot 10^6 \ \mu H$$

- L = 21.4 µH (30)

This is the minimum inductance for the application. If the inductance is higher than this, the calculated peak current may exceed the current limit of the device, causing foldback. Remaining parameters/ratings can be calculated in a similar way, by looking at Table 2, but using the guidelines from Table 1.

Note that if we want to estimate core losses in the inductor, which depends on the AC swing ΔI, this has a maximum at highest input voltage, not at minimum input voltage. So we would need to first set r = 0.3 at the lowest input voltage, then calculate the required inductance, and then finally to use the equations for ΔI, to calculate it at the highest input voltage. Basically "L" forms the required "bridge" to go from one voltage end to another, because once we fix its value, it remains so. Everything else can change.

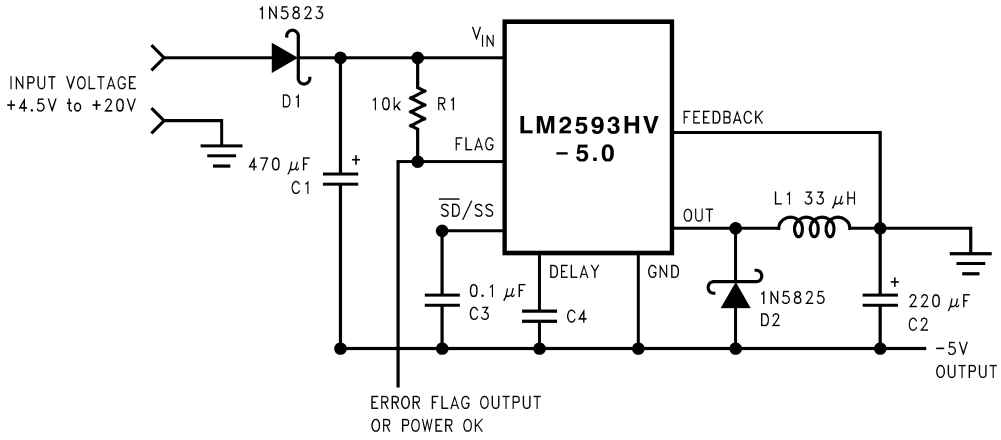

Figure 2. Buck Regulator IC Used in a Buck-Boost Application

Table 2. Design Table: r = ΔI/I_{DC}, Et in Vμsecs, L in μH, f in Hz, All voltages and currents are magnitudes.

Parameter	Buck	Boost	Buck-Boost
Duty Cycle	$\frac{V_O + V_D}{V_{IN} - V_{SW} + V_D}$	$\frac{V_O - V_{IN} + V_D}{V_O - V_{SW} + V_D}$	$\frac{V_O + V_D}{V_{IN} + V_O - V_{SW} + V_D}$
V_{IN_50} *(V)*	$(2 \cdot V_O) + V_{SW} + V_D \approx 2 \cdot V_O$	$\frac{1}{2} \cdot \left[V_O + V_{SW} + V_D\right] \approx \frac{V_O}{2}$	$V_O + V_{SW} + V_D \approx V_O$
Output Voltage, V_O *(V)*	$V_{IN} \cdot D - V_{SW} \cdot D - V_D \cdot (1 - D)$	$\frac{V_{IN} - V_{SW} \cdot D - V_D \cdot (1 - D)}{1 - D}$	$\frac{V_{IN} \cdot D - V_{SW} \cdot D - V_D \cdot (1 - D)}{1 - D}$
Et *(Vμsec)*	$\frac{V_O + V_D}{f} \cdot (1 - D) \cdot 10^6$	$\frac{V_O - V_{SW} + V_D}{f} \cdot D \cdot (1 - D) \cdot 10^6$	$\frac{V_O + V_D}{f} \cdot (1 - D) \cdot 10^6$
L *(μH)*	$\frac{V_O + V_D}{I_O \cdot r \cdot f} \cdot (1 - D) \cdot 10^6$	$\frac{V_O - V_{SW} + V_D}{I_O \cdot r \cdot f} \cdot D \cdot (1 - D)^2 \cdot 10^6$	$\frac{V_O + V_D}{I_O \cdot r \cdot f} \cdot (1 - D)^2 \cdot 10^6$
"r"	$\frac{V_O + V_D}{I_O \cdot L \cdot f} \cdot (1 - D) \cdot 10^6$	$\frac{V_O - V_{SW} + V_D}{I_O \cdot L \cdot f} \cdot D \cdot (1 - D)^2 \cdot 10^6$	$\frac{V_O + V_D}{I_O \cdot L \cdot f} \cdot (1 - D)^2 \cdot 10^6$
ΔI *(A)*	$\frac{V_O + V_D}{L \cdot f} \cdot (1 - D) \cdot 10^6$	$\frac{V_O - V_{SW} + V_D}{L \cdot f} \cdot D \cdot (1 - D) \cdot 10^6$	$\frac{V_O + V_D}{L \cdot f} \cdot (1 - D) \cdot 10^6$
RMS Current in Input Cap *(A)*	$I_O \cdot \sqrt{D \cdot \left[1 - D + \frac{r^2}{12}\right]}$	$\frac{I_O}{1 - D} \cdot \frac{r}{\sqrt{12}}$	$\frac{I_O}{1 - D} \cdot \sqrt{D \cdot \left[1 - D + \frac{r^2}{12}\right]}$
I_{PP} in Input Capacitor *(A)*	$I_O \cdot \left[1 + \frac{r}{2}\right]$	$\frac{I_O \cdot r}{1 - D}$	$\frac{I_O}{1 - D} \cdot \left[1 + \frac{r}{2}\right]$
RMS Current in Output Cap *(A)*	$I_O \cdot \frac{r}{\sqrt{12}}$	$I_O \cdot \sqrt{\frac{D + \frac{r^2}{12}}{1 - D}}$	$I_O \cdot \sqrt{\frac{D + \frac{r^2}{12}}{1 - D}}$
I_{PP} in Output Capacitor *(A)*	$I_O \cdot r$	$\frac{I_O}{1 - D} \cdot \left[1 + \frac{r}{2}\right]$	$\frac{I_O}{1 - D} \cdot \left[1 + \frac{r}{2}\right]$
Energy Handling Capability *(μJoules)*	$\frac{I_O \cdot Et}{8} \cdot \left[r \cdot \left(\frac{2}{r} + 1\right)^2\right]$	$\frac{I_O \cdot Et}{8 \cdot (1 - D)} \cdot \left[r \cdot \left(\frac{2}{r} + 1\right)^2\right]$	$\frac{I_O \cdot Et}{8 \cdot (1 - D)} \cdot \left[r \cdot \left(\frac{2}{r} + 1\right)^2\right]$
RMS Current in Inductor *(A)*	$I_O \cdot \sqrt{1 + \frac{r^2}{12}}$	$\frac{I_O}{1 - D} \cdot \sqrt{1 + \frac{r^2}{12}}$	$\frac{I_O}{1 - D} \cdot \sqrt{1 + \frac{r^2}{12}}$
Average Current in Inductor *(A)*	I_O	$\frac{I_O}{1 - D}$	$\frac{I_O}{1 - D}$
RMS Current in Switch *(A)*	$I_O \cdot \sqrt{D \cdot \left[1 + \frac{r^2}{12}\right]}$	$\frac{I_O}{1 - D} \cdot \sqrt{D \cdot \left[1 + \frac{r^2}{12}\right]}$	$\frac{I_O}{1 - D} \cdot \sqrt{D \cdot \left[1 + \frac{r^2}{12}\right]}$
Peak Current Switch/Diode/ Inductor *(A)*	$I_O \cdot \left[1 + \frac{r}{2}\right]$	$\frac{I_O}{1 - D} \cdot \left[1 + \frac{r}{2}\right]$	$\frac{I_O}{1 - D} \cdot \left[1 + \frac{r}{2}\right]$
Average Current in Switch *(A)*	$I_O \cdot D$	$I_O \cdot \frac{D}{1 - D}$	$I_O \cdot \frac{D}{1 - D}$
Average Current in Diode *(A)*	$I_O \cdot (1 - D)$	I_O	I_O

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