Application Report
SNVA736–May 2016

Know Your Limits

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ABSTRACT

This paper describes some of the more important features of current limit operation and how it effects the user application. The need for both overload and short circuit protection is highlighted along with some of the typical methods for providing this protection in DC/DC converters.

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1 Introduction

All voltage regulators require some form of current limitation to protect the converter components and/or the input supply. Although the basic idea of providing a current limit appears simple, when applied to DC/DC converters confusion can sometimes arise. This paper will help to explain what the different types of current limit strategies are and how they are used in the basic DC/DC converter topologies.

2 Why Current Limit?

A voltage regulator is designed to regulate an output voltage against variations in input voltage, temperature, and load current. Since the regulator is composed of "real life" components, as is every source of input power, some limit on the amount of current that can be supplied by the regulator must be imposed. All voltage regulators specify the rated maximum load current in their data sheets; usually on the front page. As an example, the LM43603 can supply a maximum of 3A of load current, under most conditions. Once the load exceeds this value, the output voltage will drop.

There are several reasons why every practical voltage regulator requires some kind of current limit. The most important is that circuit components and wiring all have an inherent maximum current capability. When this limit is exceeded the component will overheat and possibly be destroyed. For a DC/DC converter the inductor also imposes another limit on the current. Since these power inductors invariably use a metallic core, the maximum allowable current is limited by the saturation characteristics of the core material. If the core saturates, the inductance will drop drastically causing very high di/dt with probable damage to the regulator.

2.1 Simple Current Limit

The graph in Figure 1 shows a typical current limit profile with three load characteristics superimposed. The solid black line represents the regulator output profile, while the dotted lines represent three different load resistance. The characteristic in this figure is somewhat ideal, especially in the current limiting region, but it serves to illustrate the basic concept of what is sometimes called a "brick-wall" type of current limit. A perfect constant voltage / constant current regulator would display horizontal and vertical lines in the two regions, respectively. In order to ensure that the regulator will provide its rated output current, the current limit must be set greater than this value by some margin. A 5V linear regulator, rated for 1A maximum load current and a current limit of 1.5A is shown in the figure. The intersection of the regulator characteristic and the load resistance shown by the dashed blue line (5Ω), represents the full load operating point; providing a regulated 5V at 1A to the load. The 2Ω load resistance represents an "overload". The regulator can only source 1.5A into the 2Ω load, giving an output voltage of only 3V rather than the specified 5V. The 0Ω load is termed a "short circuit"; here the output current is 1.5A while the output voltage is 0V. Note that for both an overload and a short circuit, the output current delivered to the load is 1.5A. The output current in this region is necessarily greater than the maximum load current rating of the device. For a linear regulator the output current in the limiting region will be equal to the specified current limit for the device; this is not true for a switching regulator.

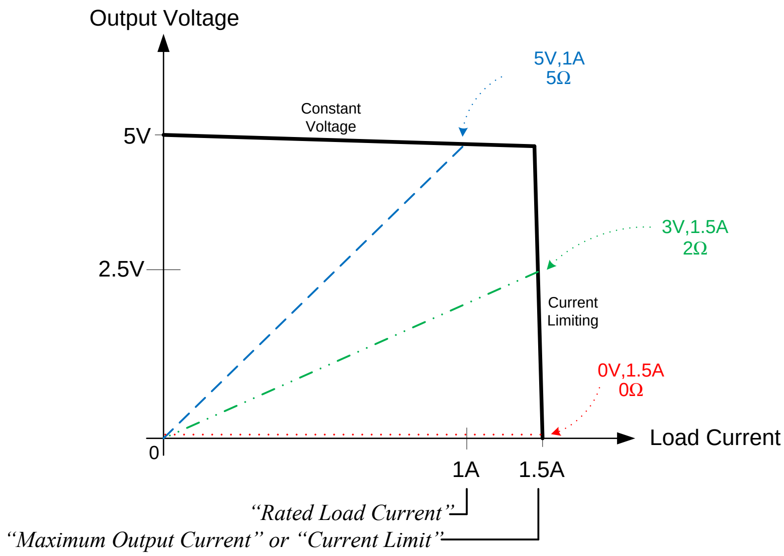

Figure 1. Brick-wall Current Limit Profile

2.2 Fold-Back Current Limit

Although it may seem trivial, the distinction between an overload and a short circuit is very important for both linear and switching power converters. The characteristic shown in Figure 2 is much more commonly found in voltage regulators and is know as "current fold-back" limiting. The distinction between an overload and a short circuit is much clearer in this figure. For an overload of 2.7Ω, the output current is 1.1A at 3V. For a short circuit of 0Ω, the output current is 0.5A at 0V. Note that the short circuit current is much lower than the maximum output current. The most obvious reason to employ this type of profile is to limit the power dissipation in the regulator. Figure 3 illustrates this point with two different linear regulators. The device at the top of the figure uses the profile shown in Figure 1, while that at the bottom uses the profile shown in Figure 2. The difference in power dissipation between the two regulators is very apparent. Note that both regulators can supply a maximum of 1A to the load. This method is also used to protect the pass transistor in the regulator from moving outside of its safe-operating-area (SOA). Finally, using a fold-back type profile will limit the short circuit current to a small value while still allowing the regulator to provide its full rated output current. This can be very important if continuos short circuit faults need to be accommodated.

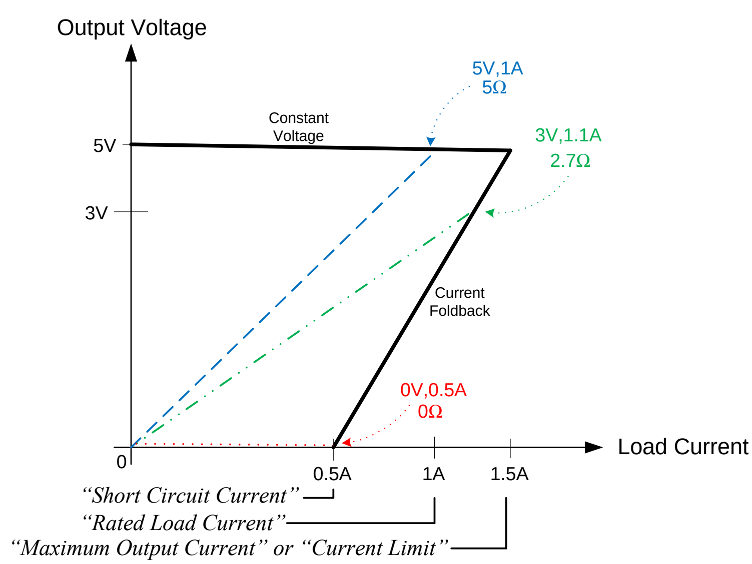

Figure 2. Fold-back Current Limit

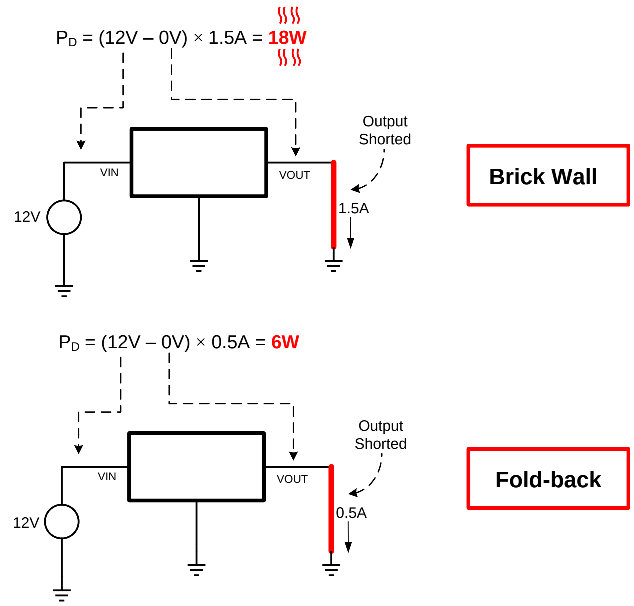

Figure 3. Short-circuited Regulator

There are some pitfalls with fold-back type current limiting. If the short-circuit current is set too low, the regulator may not start up with certain loads. This is illustrated in Figure 4. Some active loads, such as a bench-top electronic load, will have a characteristic as shown by the dashed blue line in the figure. This characteristic starts at 0A at 0V and increases "resistively" up to the knee voltage. At that point the load current becomes constant. This is typical of many real loads, as well. In the top figure, the load profile is within the current limit profile of the regulator. In this case the regulator will start up correctly, since the current provided by the regulator is always greater than required by the load for all voltages. The bottom figure shows a case where the regulator can not start up the load. As the voltage ramps up from 0V, a point is reached where the load profile intersects with the current limit profile. At that point the regulator can not supply more current, at that voltage, and the regulator gets stuck at that intersection. In the example, the output voltage reaches 1.1V and stays at that level. Note that the load profile, in both parts of the figure, becomes constant current at 1A; well within the steady state capabilities of the regulator. To start this particular load characteristic would require a larger short circuit current or the use of a "brick-wall" type current limit.

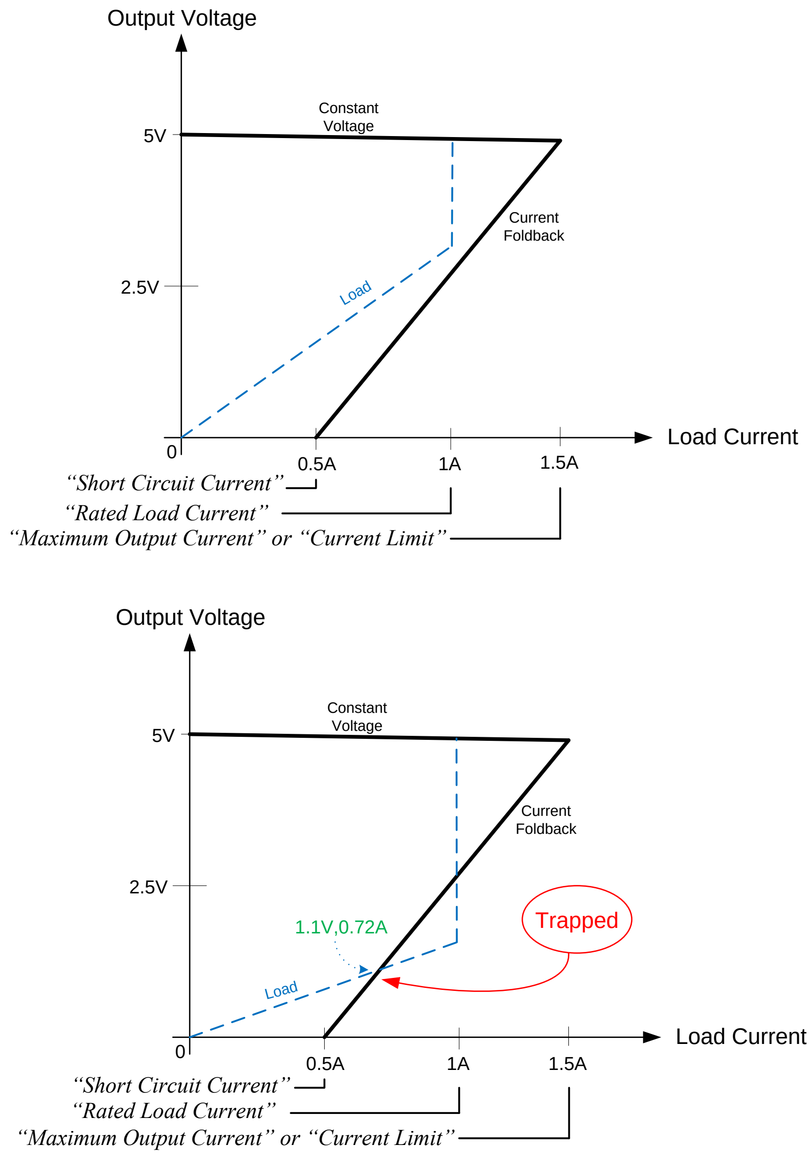

Figure 4. Active Load Profile

2.3 *Bench-Top Active Loads*

Bench-top active loads are very common in the laboratory for testing power supplies. These can be programmed to produce either a constant current or constant resistance profile. Great care must be exercised when using these types of load. First, the constant current profile will often look like those shown in Figure 4. For a supply with low short circuit current, the regulator may not start up. Furthermore, some of these units will try to pull the output voltage below ground when in constant current mode. Most regulators will not function correctly under this condition. One way to avoid these problems is to start the regulator with no load and then switch in the desired steady state current. Using the constant resistance mode of the active load may help in some cases, however this mode can also cause trouble under some conditions. The second problem is that the electronic load uses a feedback loop to control the current. This loop can interact with the regulator's control loop and cause instability and/or oscillations. This is true for both constant current and constant resistance mode. If any of these issues are encountered when testing a voltage regulator, the best way to resolve them is to use an actual resistive load. Although a power rheostat is not as convenient as a bench-top electronic load, it is the only way to be sure that there are no adverse interactions between the load and the regulator. For start-up testing a power rheostat must always be used.

2.4 Testing Current Limit Behavior

When testing the current limit behavior of a linear or switching voltage regulator it is best to use a power rheostat rather than an electronic load. The constant current mode of the bench-top load will interact with the current limiting of the power supply and probably cause trouble. This is easy to understand since the two "current sources" are fighting each other. Using the constant resistance mode, of the electronic load, is usually not a good option, either. The complex control loop that maintains the load resistance constant will interact with the regulator and may cause misbehavior and/or oscillations.

The setup should resemble that shown in Figure 5. The oscilloscope is used to check if the output is oscillating. To determine the current limit value (or maximum output current), start with the load resistance high enough to give sightly less than full load. Then reduce the resistance until the output voltage drops out of regulation by some predetermined value, such as 10%; this current will be the maximum output current. The percentage drop in output voltage, at current limit, will depend on what the user considers tolerable and on the load regulation for the converter. Some regulators will enter fold-back limiting very sharply when the load resistance is reduced, causing the output voltage and current to fall to a very small value. The load current just preceding this drop should be considered the maximum output current. The short circuit current is found by either shorting the output, or bringing the load resistance to zero. The intermediate points can be tricky to obtain, especially for the fold-back type profile. This is due to the inherent hysteresis of fold-back current limit, and is explained more fully in SNVA558. The current limit profile will depend on the input voltage, the output voltage and temperature. Typical examples are shown in SNVA558.

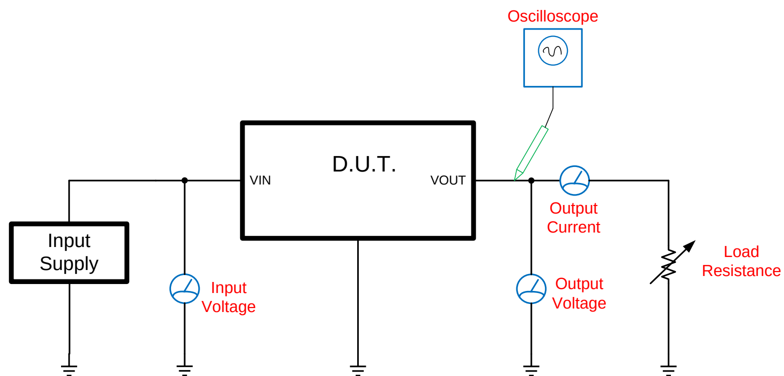

Figure 5. Current Limit Test Setup

3 Step-Down (Buck) DC/DC Converters

3.1 Current Limit

A step-down or buck DC/DC converter provides the same function as a linear regulator, with higher efficiency. A switching converter uses the MOSFET as a switch to store energy in an inductor. This allows a very high efficiency conversion. A very rudimentary buck converter is shown in Figure 6.

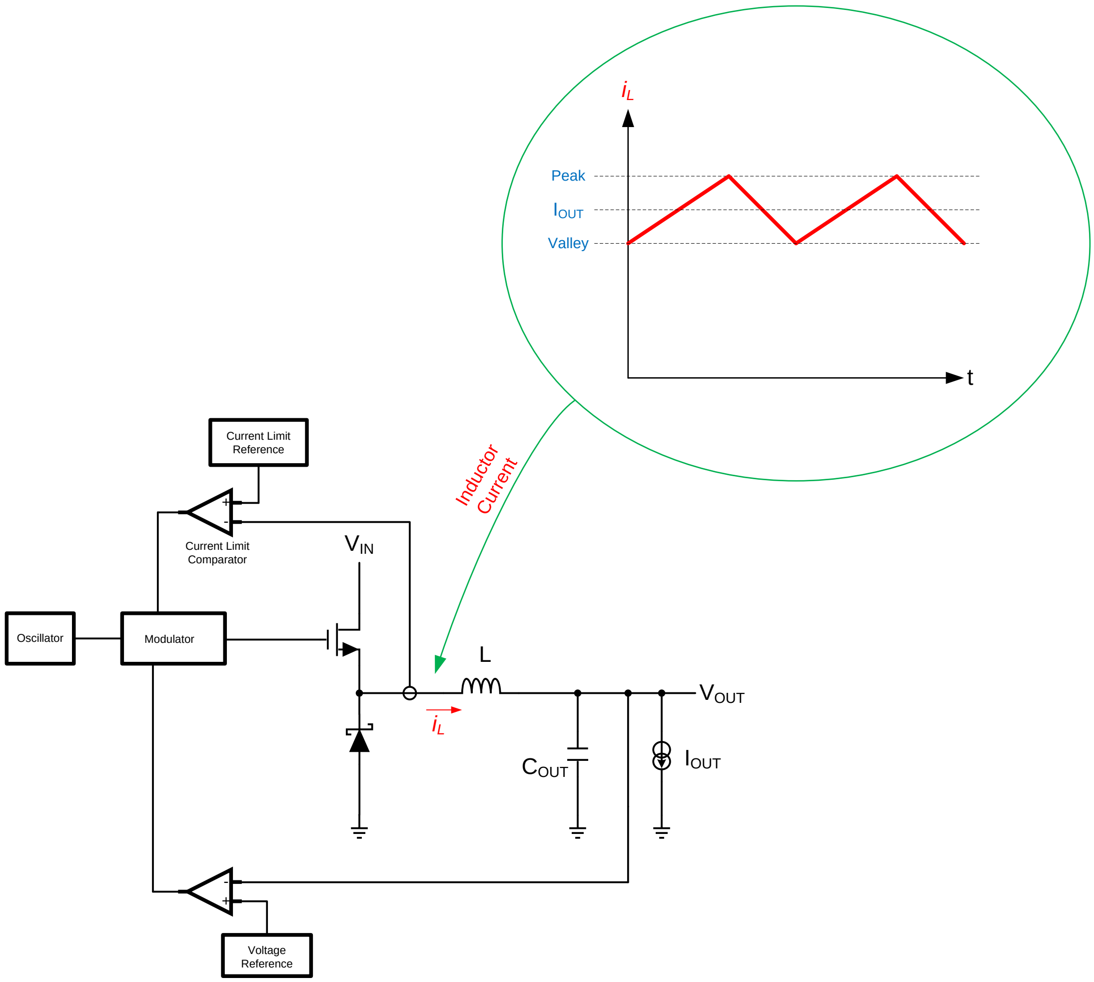

Figure 6. Simple Buck Converter

The diagram depicts a regulator with a peak current limit control. When the peak of the inductor current reaches the current limit reference, the comparator shuts off the MOSFET until the next clock cycle. In this way the peak of the inductor current is limited when the regulator is in current limit mode. Note that the average inductor current is equal to the load, or output, current and that it is not the same as the peak current limit set be the regulator. The two currents are related by Equation 1. In this equation, I_{PEAK} is the current limit set by the device (from the data sheet), F_S is the switching frequency and L is the value of the power inductor. Therefore, by limiting the peak inductor current, the maximum output current is also limited. Clearly the maximum output current is not the same as the device current limit, as it is for the linear regulator. However, the second term in Equation 1 is relatively small, so the difference in the two currents is not large. The plot in Figure 7 shows the maximum output current using the LM22670 as an example. The specific parameters are found in Table 1.

$$I_{OUT}\big|_{MAX} = I_{PEAK} - \frac{1}{2} \cdot \left(\frac{V_{IN} - V_{OUT}}{F_S \cdot L} \right) \cdot \frac{V_{OUT}}{V_{IN}} \tag{1}$$

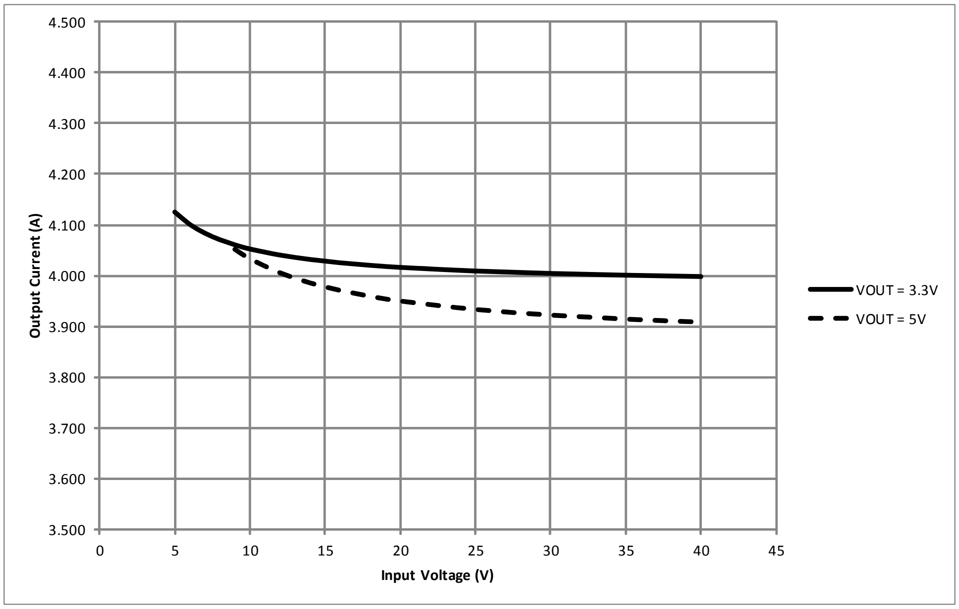

Figure 7. Maximum Output Current

Table 1. Parameters for Maximum Current Limit Example

Parameters	Symbol	Value
Switching Frequency	F_S	500 kHz
Inductor	L	15µH
Current Limit	I_{CL}	4.2A

Therefore, in the case of the LM22670 , we have a regulator that is rated for 3A of output current, with a peak current limit of 4.2A (typ), that can supply a little more than 3.9A of load under the above conditions.

The valley of the inductor current can also be used to control the current limit of the converter. In this method, if the valley of the inductor current does not fall below the current limit value, before the next clock cycle, the MOSFET is not turned on. In this way the cycle is extended until the inductor current discharges below the valley current limit. Synchronous converters, such as the LM43603 family of devices, can use this method since they incorporate a second power MOSFET in place of the diode as shown in Figure 8. This additional device is termed the "low-side" FET; it improves the efficiency of the regulator and allows the valley of the inductor current to be sensed by the control circuits. From the LM43603 data sheet we find that the valley current limit, termed $I_{LS\text{-}LIMIT}$, is 3A (typ). This value is used in Equation 2 to determine the maximum output current.

$$I_{OUT}\big|_{MAX} = I_{VALLEY} + \frac{1}{2} \cdot \left(\frac{V_{IN} - V_{OUT}}{F_S \cdot L} \right) \cdot \frac{V_{OUT}}{V_{IN}} \tag{2}$$

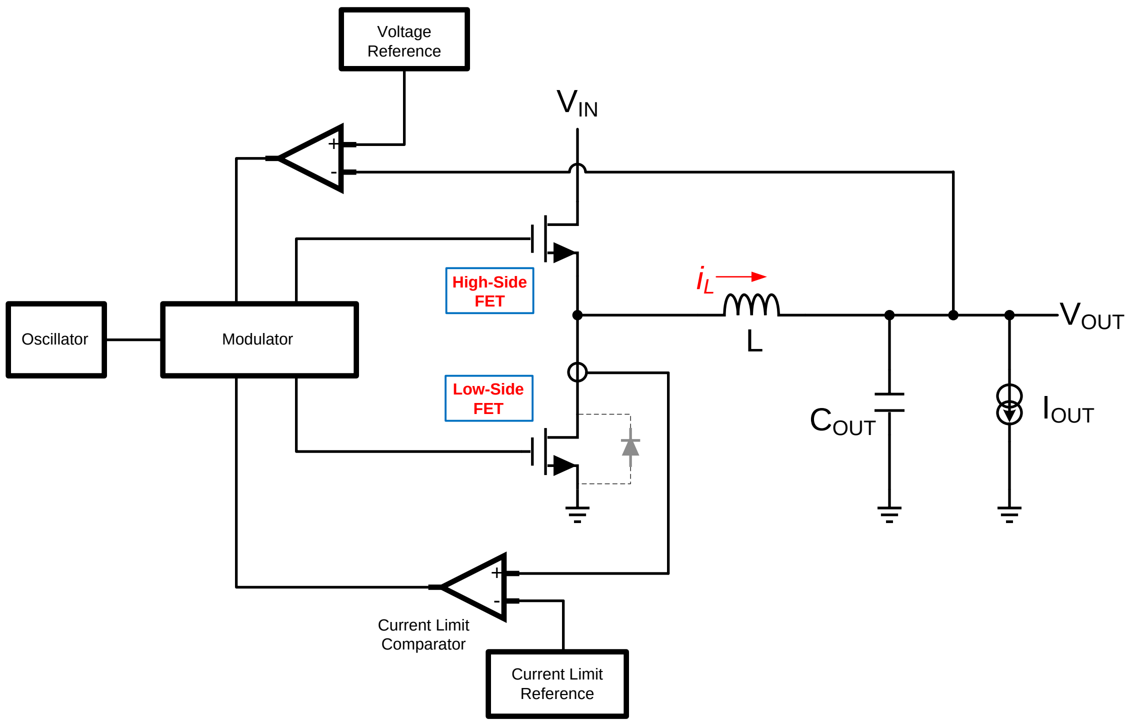

Figure 8. Synchronous Buck Converter with Valley Current Limit

This device also uses a peak type current limit on the high-side FET to protect it from inadvertent over-current events. Also, under some operating conditions the inductor current may reverse direction through the low-side FET; necessitating a "negative" current limit to prevent excessive reverse current.

3.2 Short Circuit Protection

Protection against short circuits is even more important for a DC/DC converter than for a linear regulator. In order for any switching regulator to function in steady-state, the inductor volt-second balance must be maintained in each cycle. Another way of saying this is that the average voltage across the inductor (ignoring resistance) must be zero for each cycle. If this condition is not obtained, the inductor current will not be controlled and may "run-away". Looking at the circuits in Figure 6 and Figure 8 , we see that, with the output shorted, only the diode voltage, or low-side FET voltage drop, is available to discharge the inductor. This places a maximum input voltage limit on the converter when the output is shorted. Beyond this maximum input voltage, the converter and/or the power stage components will be damaged. Because of the inherent delays in the control circuits, a simple peak current limit can not protect against a hard short circuit. An analysis of this condition results in Equation 3.

$$V_{IN} \le \frac{V_D}{T_{ON} \cdot F_S} \tag{3}$$

In the equation, V_D is the diode voltage (≈ 0.5V), T_{ON} is the minimum on-time of the MOSFET and F_S is the switching frequency. Every DC/DC converter has a particular minimum controllable on-time; the shortest time that the top side MOSFET can be turned on. This arises from the unavoidable delays in the control circuits, and from the necessity of obtaining a clean sample of the inductor current. This delay represents the fastest time that the current limit can respond to an over-current event. Equation 3 is an approximation that is valid for V_{OUT} = 0V (short circuit). As an example, the specified minimum on-time for the LM22670 is 100ns (typ). Using this value, with the 500 kHz switching frequency, in Equation 3, gives a maximum input voltage of only 10V to prevent damage. This is obviously too restrictive for a device rated at 42V. The most common way to get around this restriction is to reduce the switching frequency when a short circuit is detected. The LM22670 reduces the switching frequency to about 1/5 of normal under a short circuit condition. Using 100 kHz in Equation 3, we calculate a maximum input voltage of about 50V. Since this is greater than the maximum rated input voltage, for the LM22670, we can conclude that the device will survive a shorted output when switching at 500kHz under normal conditions. The data sheets for this family of devices gives additional information regarding the safe operating area for various switching frequencies with a shorted output. Note that the output current will also be reduced when the converter is in short circuit; providing a basic fold-back type of operation.

The valley current limit method also protects against short circuits. Since the converter waits for the valley of the inductor current to fall below the current limit, the next cycle will always start with the inductor current less than the peak. This ensures that the current can not run away with the output shorted, providing short circuit protection as well as a current fold-back characteristic. The LM43603 uses this type of current limit, for both overload and short circuit protection, along with a "hiccup" mode. In this mode, if the current limit is tripped for more than 32 clock cycles the device stops switching for 5.5ms (typ). Once the 5.5ms has timed-out, the device goes through a soft-start cycle. This feature helps to keep the die, and PCB, temperature low when a fault occurs.

In summary, every DC/DC converter requires protection against shorts on the output. Typically this is done be reducing either the actual or effective switching frequency or using a valley type inductor current limit topology. This provides a basic type of fold-back characteristic, similar to that shown in Figure 2.

3.3 Negative Output Voltage

The output voltage of a DC/DC converter must not be allowed to fall below ground during normal operation, nor during start-up. Referring to Figure 9 and assuming that the output voltage is negative and equal to the diode voltage, then the net voltage across the inductor will be zero, for the portion of the cycle that the MOSFET is off. Under these conditions the inductor current will flow through the diode, turning it on. With the output voltage equal to the diode voltage, there will be no voltage across the inductor to "discharge" the current. During the next portion of the cycle, when the MOSFET is on, the current will increase, as usual. However, since the current did not decrease in the previous cycle, it will continue to grow with each successive switching cycle. Eventually the current will reach the current limit threshold of the device. This situation is even worse than that discussed in Section 3.2; as a result neither the current limit nor short circuit protection will help. If the condition persists for only a few cycles, this may lead to the inductor current spiking to high values. If it persists for many cycles, the current may run-away with possible destruction of the power stage. If the output voltage falls more negative than the diode voltage, the inductor current will increase for both portions of the switching cycle; this increases the danger of damage.

As mentioned previously, some electronic loads can pull the output of a regulator below ground when the converter is turned off. If the regulator is turned on in this state, we have the conditions described above. Another scenario involves driving a large inductive load, such as the coil of a relay which may represent 10's to 100's of mH. If the regulator is shut down, with current in the relay coil, the output will be pulled below ground and likely ring until the energy is dissipated. During this time the load is discharged through the converter diode and inductor (Figure 6 and Figure 8). Should the regulator be inadvertently enabled, while the output is still negative, then the conditions for inductor current run-away exist. A Schottky clamp diode across the output will only help if the clamp voltage is more positive than the converter diode voltage. Needless to say these situations should be avoided whenever possible.

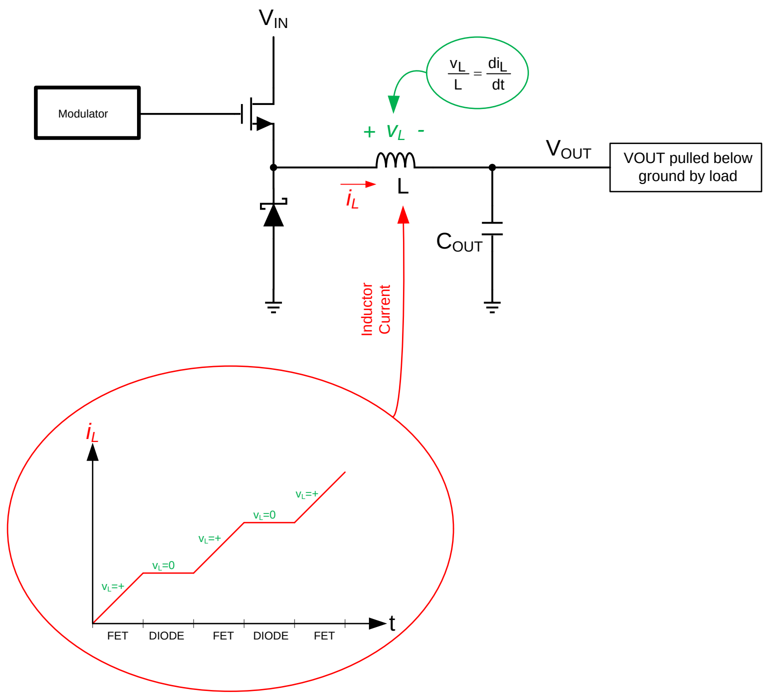

Figure 9. Negative Output Voltage Conditions

3.4 Starting With Large Output Capacitors

Another concern with fold-back type current limit is the ability to charge-up large output capacitors during the start-up phase of the regulator. As described previously, many DC/DC converters use a fold-back type current limit that limits the amount of load current available during start-up. With large values of output capacitance and heavy loads, the device may enter current limit. This can cause the output voltage to "hang-up" and not reach its nominal value as shown in Figure 4. One way around this issue is to use a device with adjustable soft-start time. In this case the soft-start time can be increased to prevent the current limit from activating during start up. Since there are many variations of current limit and start-up methods, the data sheet should be consulted whenever large output capacitance and/or heavy loads need to be accommodated.

4 Step-Up (Boost) DC/DC Converters

The boost converter is used to step-up an input voltage to some higher level required by the load. This unique capability is achieved by storing energy in the inductor and releasing it to the load at a higher voltage. Figure 10 shows a simple boost regulator employing peak current limit protection. Since most boost converters use a diode, rather than synchronous rectification, peak current limit is almost always used.

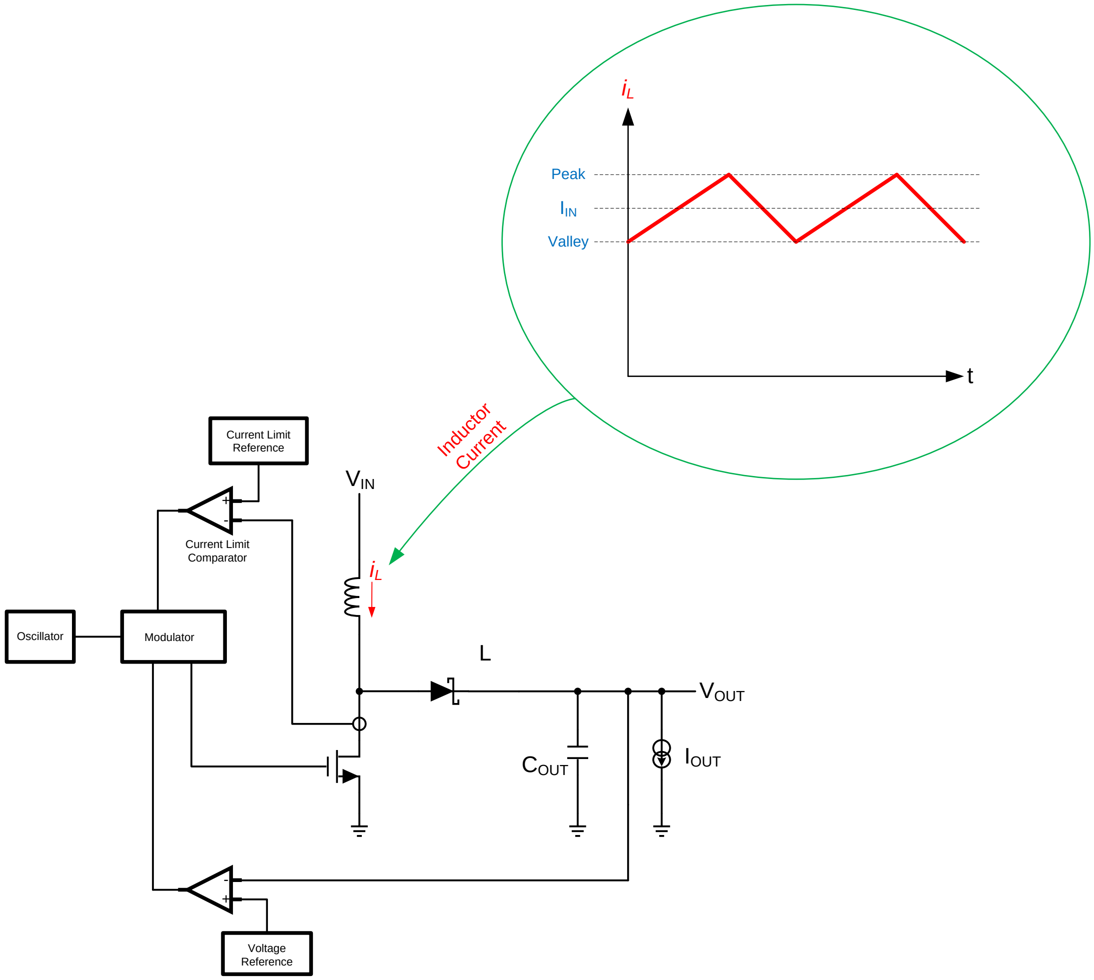

Figure 10. Simple Boost Converter

The operation of the current limit is the same as for the buck regulator. Although the average inductor current in the boost is equal to the average input current, limiting the peak current will also limit the output or load current. Straightforward analysis of the maximum output current results in Equation 4. The meaning of the parameters of this equation are the same as that for the buck; where η is the converter efficiency.

$$I_{OUT}\big|_{MAX} = \left[I_{PEAK} - \frac{1}{2} \cdot \Delta I\right] \cdot \left(\frac{V_{IN} \cdot \eta}{V_{OUT}}\right)$$

$$\Delta I = \frac{V_{IN}}{F_S \cdot L} \cdot \left(\frac{V_{OUT} - V_{IN}}{V_{OUT}}\right) \qquad (4)$$

From Figure 10 we see that there is a direct path between the input supply and the load for an ordinary non-synchronous boost converter. This has several implications. First, if the output is shorted, a potentially large current will flow from the input supply to the output short. Without going into the detailed circuit analysis, if the output of a boost regulator is pulled down to the level of the input voltage or below, the inductor current will try to increase without limit. The regulator cannot prevent this, regardless of the state of the MOSFET. Wether the MOSFET is on or off, large uncontrolled currents will flow through the inductor. If the application requires that the converter survive a hard short on the output, then either some form of disconnect switch must be used or a more advanced boost architecture is required. The LM3017 and the TPS61230 are examples of boost converters that can be used to avoid this issue. For overloads that pull the output voltage out of regulation, while still above the input voltage, the current limit of the converter will protect the input supply and the power stage components, just like for the buck. For more information about boost regulators, please refer to application note SNVA731.

5 Inverting Buck-Boost (Flyback) DC/DC Converters

The inverting buck-boost converter is used to generate a negative output voltage from a positive input voltage. Another feature of this type of converter is that the regulated output can be either higher or lower than the input voltage. Figure 11 is a diagram for a simple inverting converter. Both the current limit and short circuit behavior are the same for this converter as for the buck. The maximum output current, while in current limit, is given by Equation 5.

$$I_{OUT}\big|_{MAX} = \left[\frac{V_{IN} \cdot \eta}{V_{IN} \cdot \eta + |V_{OUT}|}\right] \cdot \left(I_{PEAK} - \frac{1}{2} \cdot \Delta I\right)$$

$$\Delta I = \frac{V_{IN}}{F_S \cdot L} \cdot \frac{|V_{OUT}|}{\left(V_{IN} \cdot \eta + |V_{OUT}|\right)} \tag{5}$$

As with the boost converter, the inductor current in this topology is not the output current. However, by controlling the peak inductor current the maximum output current is indirectly limited.

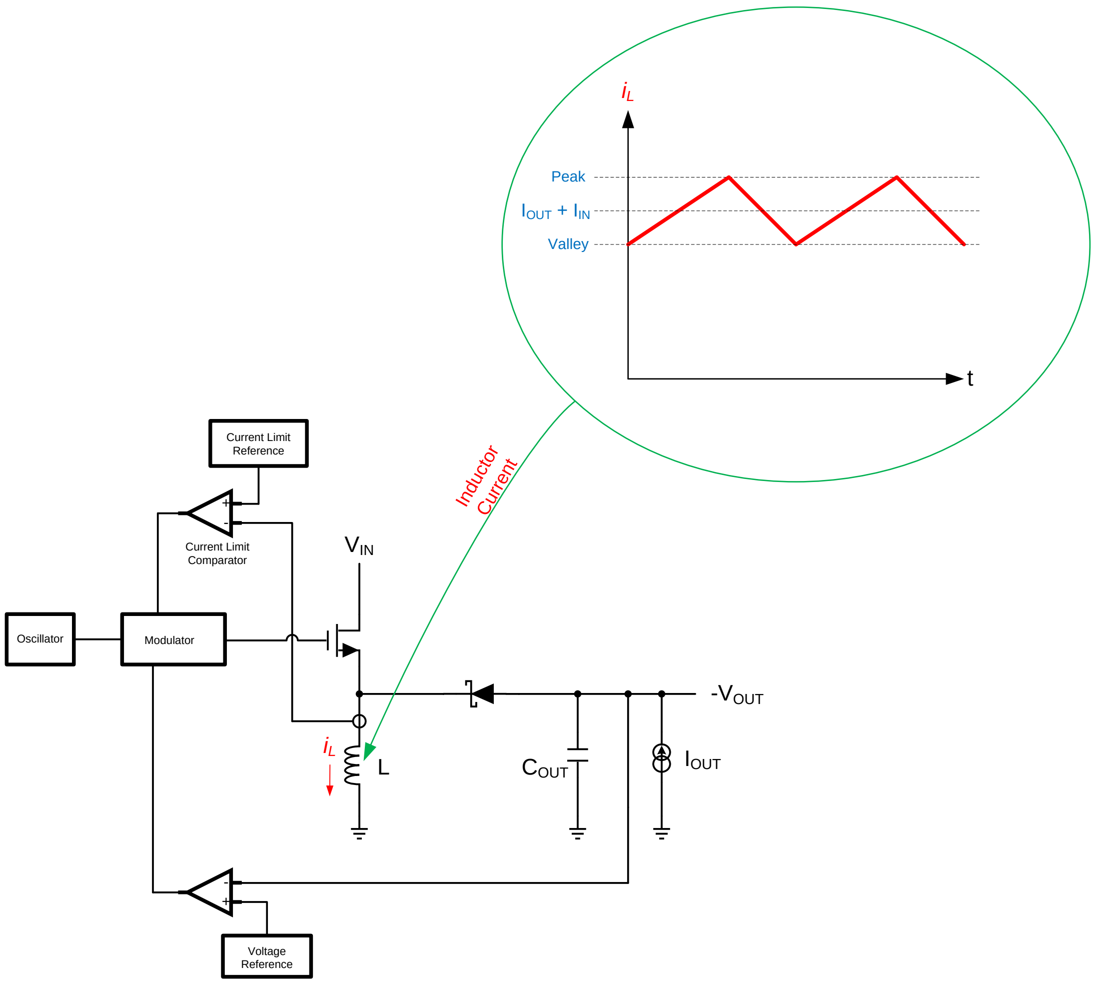

Figure 11. Simple Inverting Regulator

6 Conclusion

The preceding discussion makes clear that all regulators require both overload and short-circuit protection. The details of this protection will vary from one regulator to the next and the user must choose the converter that best suits the application. The regulator data sheet is the best resource that the engineer can use to help select the most suitable device for a given application. For those questions not answered in the data sheet, the applications engineers at Texas Instruments are always ready to help. The most direct way to get your questions answered is to post them on Texas Instruments E2E forum.

7 References

Table 2. Further Reading

TITLE	LINK
SLVA372 *Basic Calculation of a Boost Converter's Power Stage*	SLVA372
SNVA731*Working with Boost Converters*	SNVA731
SLVA059 *Understanding Buck-Boost Power Stages in Switch Mode Power Supplies*	SLVA059
SLVA477 *Basic Calculation of a Buck Converter's Power Stage*	SLVA477

Table 3. A Sample of DC/DC Converters

Device Name	Link
LM22670	LM22670
LM43603	LM43603
LM2587	LM2587
LM3017	LM3017
TPS61230	TPS61230

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