Application Report

SNVA085B–May 2004–Revised April 2013

AN-1319 Analysis and Design of a Hysteretic Constant Frequency Buck Regulator Using the LM5007

ABSTRACT

This application report describes the operation of the LM5007, and provides a step-by-step procedure for selecting the external components. This procedure is also available on WEBENCH® on the TI website.

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1 Introduction

The LM5007 buck regulator differs in operation from other conventional control methods, such as fixed frequency current-mode, fixed on-time voltage mode, variable on-time, and variable off-time. The LM5007 hysteretic constant frequency control method offers better performance with smaller output capacitance and no loop compensation. The LM5007 is a high voltage IC designed to accept an input voltage of 9V - 75V (80V max). The bootstrap diode and high voltage N-Channel MOSFET buck switch are integrated in the IC, making the LM5007 attractive for applications where board space is at a premium.

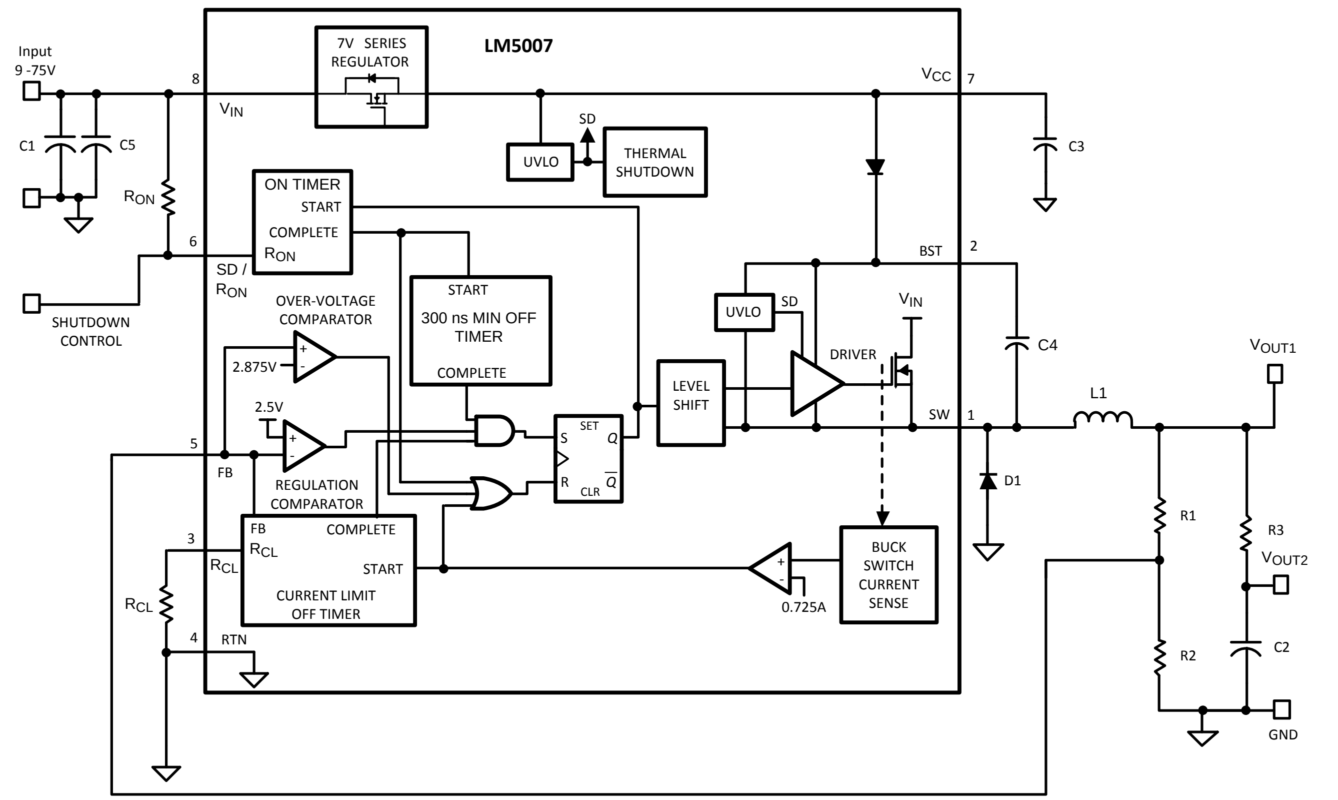

Figure 1. Block Diagram and Basic Application Circuit

2 LM5007 Functional Description

2.1 Control Loop

The control loop includes a comparator, internal reference, and a programmable timer to control the on-time. The output voltage feedback at FB (pin 5), taken from the R1/R2 junction, is compared to an internal 2.5V reference. If the voltage at FB (V_{FB}) is below the reference, the buck switch is turned on for a fixed time period (t_{ON}), determined by the R_{ON} resistor and the input voltage (V_{IN}) according to the following (see Figure 2):

$$t_{ON} = \frac{1.42 \times 10^{-10} \times R_{ON}}{V_{IN}} \quad (1)$$

If at the end of the on-time V_{FB} is still below 2.5V (circuit is not in regulation and not in current limit) the buck switch will be off for a minimum of 300ns, set by the 300ns OFF Timer. Following the off-time, the switch will turn on for another on-time period. This cycle will continue until regulation is achieved. The minimum off-time limits the switching frequency during start-up and load transients, and establishes a maximum duty cycle.

When V_{FB} reaches 2.5V (circuit is in regulation), the off-time will exceed 300 ns, as each ON period will start when the output voltage falls, taking V_{FB} below 2.5 volts. In this manner, regulation is maintained. For a buck controller in continuous conduction mode the duty cycle (DC) is equal to V_{OUT}/V_{IN}, and the off-time is determined from:

$$t_{OFF} = \frac{t_{ON} \times (1 - DC)}{DC} \quad (2)$$

Because of the inverse relationship between t_{on} and V_{IN}, the operating frequency will be nearly constant as V_{IN} is varied over its range. See Appendix A for more details. For proper current limit operation, the operating frequency should be selected such that the on-time is greater than 300ns at all values of V_{IN} in a given application.

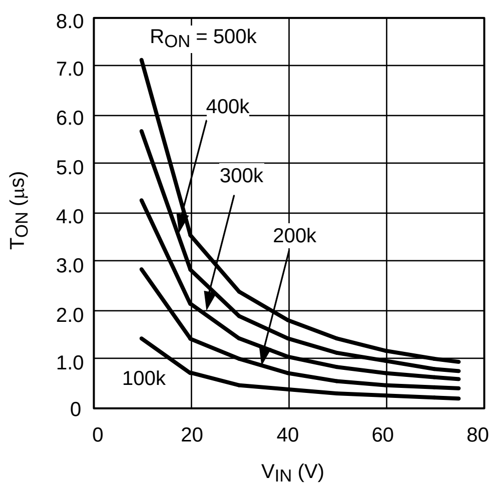

Figure 2. t_{ON} vs V_{IN} and R_{ON}

2.2 Buck Switch

The N-channel buck switch is integrated into the IC, and provides a current path to the inductor (L1) from V_{IN}. When the circuit is in regulation, and in continuous conduction mode, the peak current in this path is determined by:

$$Ip = Io + \frac{(V_{IN} - V_{OUT1}) \times t_{ON}}{2 \times L1} \quad (3)$$

where Io is the nominal load current, t_{on} is the on-time, and L1 is the inductor value (see Figure 9). At the end of the on-time, the buck switch is turned off, and the voltage at the SW pin goes to a voltage below ground determined by the forward voltage drop of the external diode D1.

C4 (bootstrap capacitor) provides the power to drive the buck switch gate. During the off-time, C4 is charged from V_{CC} to approximately 7V. When the buck switch is turned on, the SW pin goes to V_{IN}, and since the voltage across a capacitor cannot change instantaneously, pin 2 (BST) is at V_{IN} + 7 volts. Thus, C4 maintains the charge on the buck switch gate during the on-time.

If the voltage across C4 falls below 4.1 volts, the buck switch is immediately disabled. The off-time which results allows C4 to recharge, and when its voltage reaches 4.5 volts, the buck switch is enabled. This protection feature prevents excessive power dissipation in the buck switch. A low C4 voltage can occur during start-up (off-time = 300ns) at minimum V_{IN} (on-time is maximum) if the frequency is set to a low value (for example, R_{ON} = 500k). In this case C4 should be increased.

2.3 Current Limit

The current limit circuit senses the buck switch current using loss-less current sensing within the buck switch, and compares it to a reference set to (nominally) 725mA. If the threshold is exceeded, the present ON cycle is terminated, and a non-resetable OFF timer is triggered. The off-time is determined by the R_{CL} resistor (Pin 3), and V_{FB} (Pin 5), according to the following:

$$t_{OFFCL} = \frac{10^{-5}}{(0.59 + (V_{FB}/(7.22 \times 10^{-6} \times R_{CL}))} \quad (4)$$

See Figure 3. If the current overload condition is such that V_{FB} = 0V (which occurs at start-up, or with a shorted output) the off-time is 17µs. In a less severe overload condition, where V_{FB} is between ground and 2.5V, the off-time is shorter, resulting in a faster recovery and reduced current foldback. If the current overload persists, the LM5007 provides cycle-by-cycle current limiting, and the output characteristic of the converter is that of a current source.

Two requirements must be met for proper current limit operation. The first, previously mentioned, is that the minimum on-time, which occurs at maximum V_{IN}, must be greater than 300ns, so as to exceed the response time of the current limit detection circuit. This ensures that the delay caused by this detection circuit is never greater than the normal on-time, during which the current limit was reached. The second requirement is that the forced off-time set by the R_{CL} resistor (at V_{FB} = 2.5V) be greater than the maximum normal off-time, which occurs at maximum V_{IN}. See Appendix C.

In normal operation, when the buck switch is turned on, a current surge occurs while the free wheeling diode (D1) turns off. The surge amplitude can be several hundred milliamps, and the duration depends on D1's recovery time. Because of this surge, the current sense detection circuit is blanked for 50-70 ns at the buck switch turn-on.

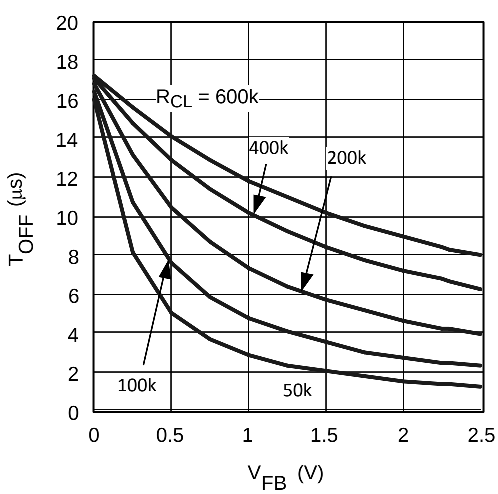

Figure 3. Current Limit Off-Time vs V_{FB} and R_{CL}

3 Start-Up Regulator

The LM5007 contains a startup regulator, which provides a nominal 7.0V at pin 7 (V_{CC}). The input pin (V_{IN}) can be connected directly to line voltages as high as 75V for normal operation, with transient capability to 80V. The regulator output is internally current limited to source (typically) 11 mA. During power up, the capacitor (C3) at V_{CC} charges up providing a time delay while internal circuits stabilize. When V_{CC} reaches the upper threshold of the under-voltage sensor (typically 6.3V), the buck switch is enabled. The output voltage (V_{OUT1}) then increases until regulation is established. In applications involving several buck regulators, where a power up sequence among the regulators is desired, C3 in each circuit can be used to set a different start-up delay for each regulator. If V_{CC} falls below the lower threshold of the undervoltage sensor (typically 6.1V), the buck switch is disabled. When V_{CC} again increases above the upper threshold the buck switch is re-enabled.

V_{CC} powers the buck switch driver via the internal diode to the BST pin. The external capacitor C4 provides power to the buck switch driver during the on-time, when the SW and BST pins are above V_{CC}.

V_{CC} can be powered from an external supply once the start-up sequence is complete, to reduce power dissipation within the LM5007. This is particularly beneficial if V_{IN} is at the high end of its range, as the internal regulator's dissipation can exceed 100 mW. An applied voltage between 8V and 14V will shut off the internal regulator. If V_{OUT1} is in that range, it can be diode connected to V_{CC} as shown in Figure 4. The required current into the V_{CC} pin is shown in Figure 5 for both the normal operating mode, and the shutdown mode (Pin 6 = 0V). D2 can be a low cost general purpose diode .

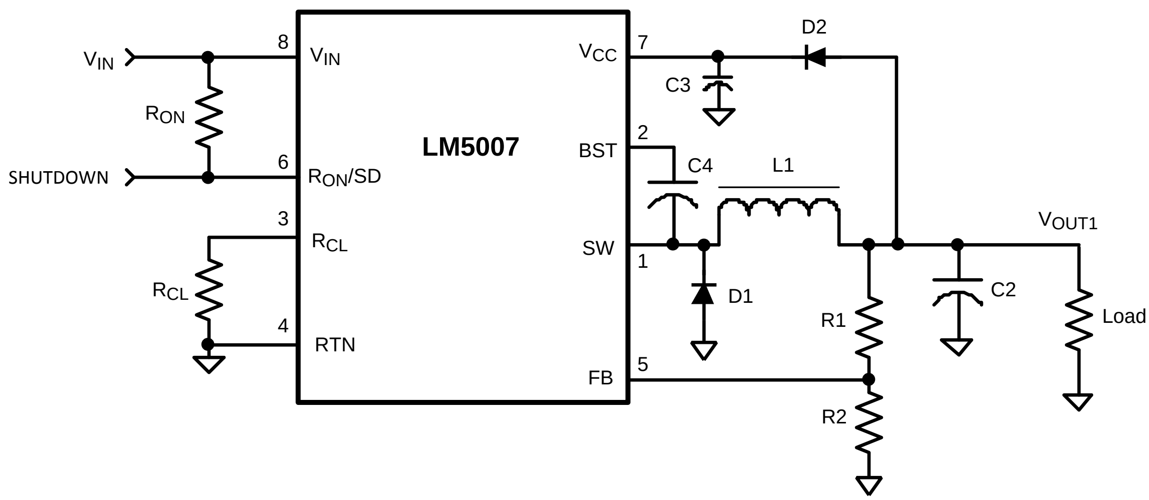

Figure 4. V_{CC} Powered by V_{OUT1}

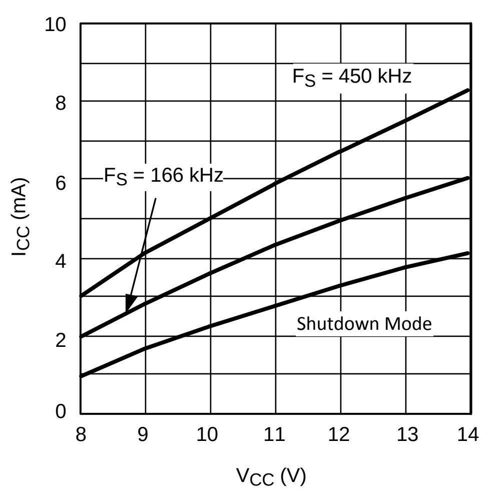

Figure 5. I_{CC} vs Externally Applied V_{CC}

4 Start-Up Sequence

When power is applied at V_{IN}, the start-up sequence is shown in Figure 6. During the initial delay (t1), V_{CC} ramps up at a rate determined by its current limit and C3, while internal circuitry stabilizes. For example, if C3 = 0.1µF, t1 is nominally 57µs. When V_{CC} reaches the upper threshold of the under-voltage sensor (UVLO, typically 6.3V), the buck switch is enabled. The inductor current then ratchets up to the current limit threshold (I_{LIM}), with each on-time determined by V_{IN} and R_{ON}, and off-times of 300ns. Once the current limit is reached, the off-time is 17µs since V_{FB} is near zero (see Equation 4 and Figure 3). As V_{OUT1} ramps up during t2, the inductor current will continue to reach I_{LIM}, but the off-times will decrease as V_{FB} increases with V_{OUT1}. The time t2 can be as much as 500µs. Once V_{OUT1} reaches its intended value (and V_{FB} = 2.5V), the average inductor current will decrease (t3) to the nominal load current (Io), and the ripple amplitude is determined by the on-time, inductor value, V_{IN} and V_{OUT1}, discussed in a later section. The off-time is determined by the on-time, V_{IN} and V_{OUT1} according to Equation 2. The time t3 is generally 30 to 100µs.

The time periods mentioned above assume V_{IN} has a fast rise time (<5µs). If V_{IN} comes up slowly, t1 will be longer, and t2 and t3 could be longer, depending on the final values for V_{IN} and Io.

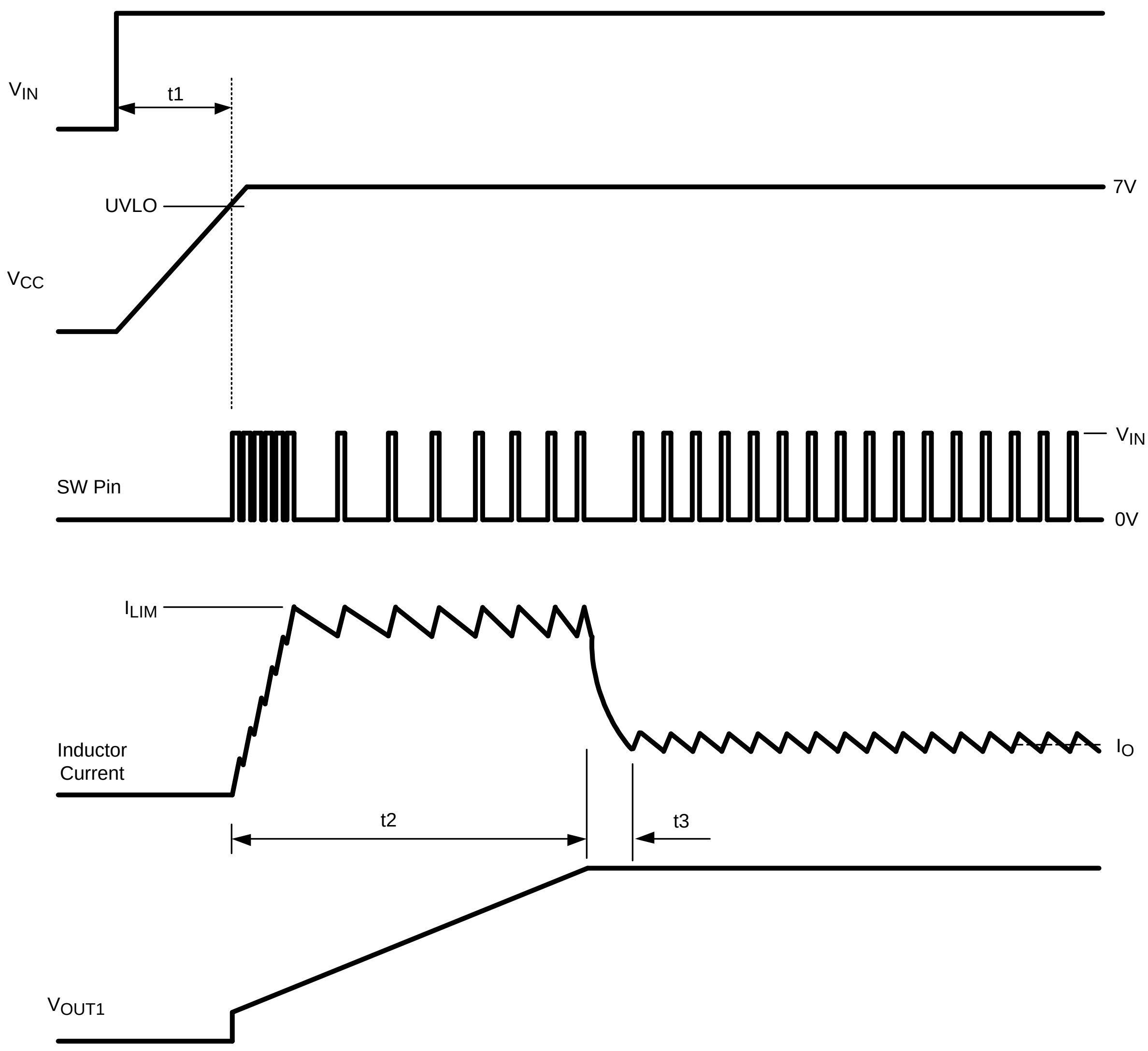

Figure 6. Start-Up Sequence

5 Start-up/Shutdown Using the R_{ON}/SD pin

By taking pin 6 (R_{ON}/SD) below 0.7V with an open collector or open drain device, the buck switch is disabled, and V_{OUT} will go to zero. The V_{CC} regulator remains operational during shutdown, but other internal circuitry is powered down. Referring to Figure 7, before R_{ON}/SD is taken low, the circuit is in regulation, the on-time is determined by R_{ON} and V_{IN}, the duty cycle at SW depends on V_{OUT1} and V_{IN}, and the average inductor current is the load current (Io). After R_{ON}/SD is taken low, the next on-time will be longer than normal since current into the R_{ON}/SD pin has been reduced (the same effect as increasing R_{ON}), and the inductor current will ramp up to a higher than normal value (I1). The time t1 depends on what point in the SW on/off cycle the R_{ON}/SD pin was taken low, and ends when either the ON pulse has timed out, or if I1 reaches the current limit value, or if the internal circuitry has powered down enough to shut off the buck switch. Typically t1 is less than 6µs. The inductor current then ramps down to zero, and time t2 depends on the inductor value, I1, and V_{OUT1}, with a range of 2 - 15µs. At the end of t2, a ringing period (t3) occurs due to the residual energy in the inductor and parasitic capacitance at the SW pin. The ringing frequency is typically 1 - 5MHz, and t3 is nominally 15µs. V_{OUT1} will decay starting at the beginning of t2, with a time constant equal to $R_L \times C2$, where R_L is the load resistance. This decay time can be several milliseconds.

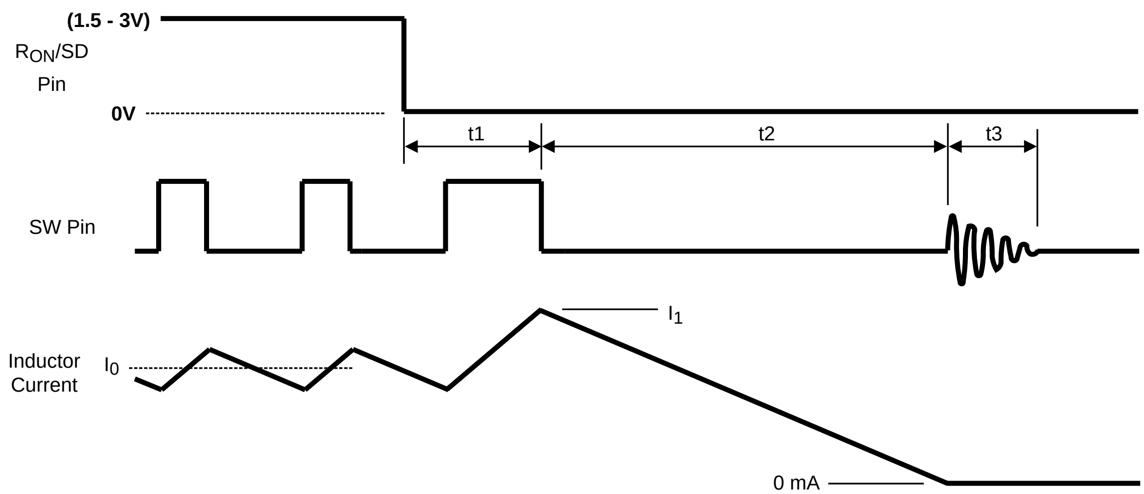

Figure 7. Shutdown Using the R_{ON}/SD Pin

Start-up using the R_{ON}/SD pin is shown in Figure 8. After releasing the R_{ON}/SD pin, there is an initial delay of approximately 3.5µs (t1) while internal circuitry powers up to enable the buck switch. During t2 several on/off cycles occur during which the inductor current ramps up to the current limit threshold (I_{LIM}, nominally 725mA). Each cycle's on-time is determined by V_{IN} and R_{ON}, and the off-time is the minimum 300ns. The time t2, and consequently the number of SW cycles, depends on the inductor value and V_{IN}, with t2 ranging from 2 - 20µs. After t2, the longer off-time (t3) is determined by R_{CL}, and V_{FB} which is near zero volts at this time. As V_{OUT1} increases, and V_{FB} with it, t3 decreases according to Equation 4. The inductor current will continue to reach I_{LIM} each cycle until regulation is achieved (V_{FB} = 2.5V). The time for V_{OUT1} to reach its final value can be as much as 500µs.

When the circuit is in regulation (right side of Figure 8), the inductor current's waveform will have an average value (Io) which is the load current, and the ripple amplitude is determined by the on-time, inductor value, V_{IN} and V_{OUT1}, discussed in a later section. The off-time (t4) is determined by the on-time, V_{IN} and V_{OUT1} according to Equation 2.

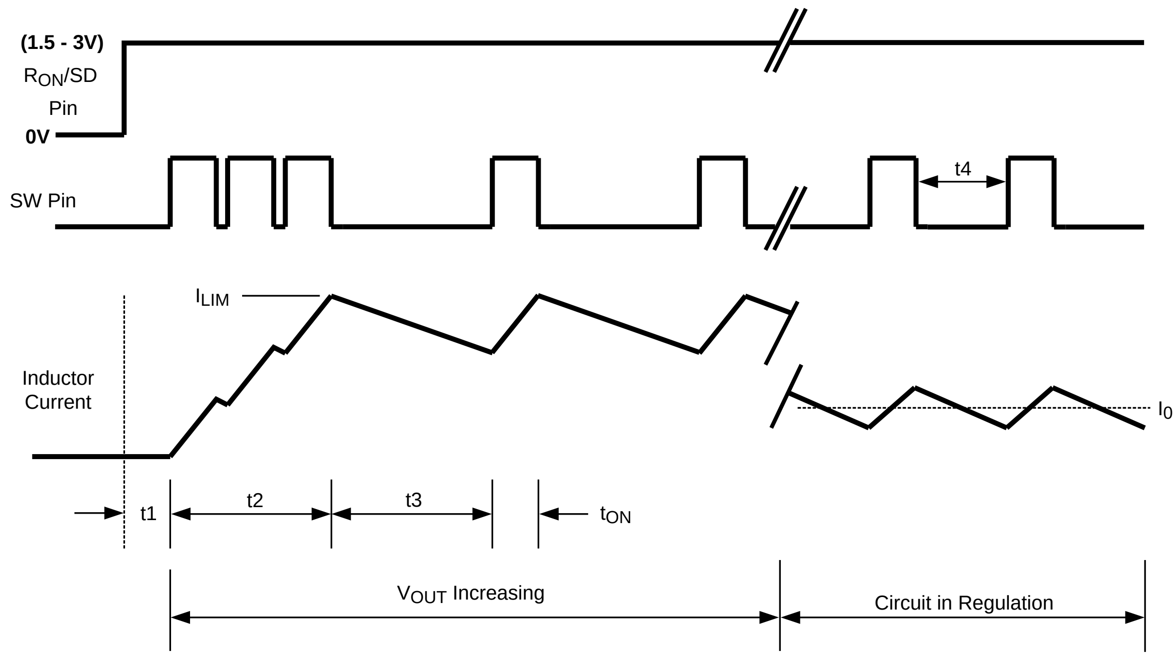

Figure 8. Start-Up Timing Using the R_{ON}/SD Pin

6 Current Conduction Modes

When in regulation the LM5007 buck regulator operates in one of two modes, depending on the load current and the ripple current. The operating frequency (Fs), and some of the waveforms differ, since the dependency on external components differs in the two modes.

6.1 Continuous Conduction Mode

In this mode, the load current is high enough, relative to the ripple current, so that current in L1 is always greater than zero, as shown in Figure 9.

The inductor current ramps up to Ip during the on-time. The SW voltage is V_{IN} , and the voltage across the inductor is V_{IN} - V_{OUT1}. During the off-time the inductor current ramps down to Im, when the SW voltage is below ground at V_{D1} (D1's forward voltage drop). The voltage across the inductor is V_{D1} + V_{OUT1}. The average value of the ripple waveform is I_O, which is the nominal load current, and is equal to (Ip + Im)/2. The output ripple current amplitude (I_{OR}) is calculated from:

$$I_{OR} = Ip - Im = \frac{(V_{IN} - V_{OUT1}) \times t_{ON}}{L1} = \frac{V_{OUT1}(V_{IN} - V_{OUT1})}{V_{IN} \times L1 \times F_S} \quad (5)$$

Equation 5 indicates that I_{OR} is not constant in a given application, but increases with V_{IN}. For example, if V_{OUT1} = 10V, and Fs = 400kHz, Figure 10 shows how I_{OR} varies for two values of L1. The operating frequency is determined by the following :

$$F_S = \frac{V_{OUT1}}{1.42 \times 10^{-10} \times R_{ON}} \quad (6)$$

It can be seen that the operating frequency in continuous conduction mode does not depend on the input voltage, or the load current, but rather is constant since it depends only on the output voltage and the R_{ON} resistor, both of which are fixed in a given application. See Appendix A for a more detailed discussion of Equation 6.

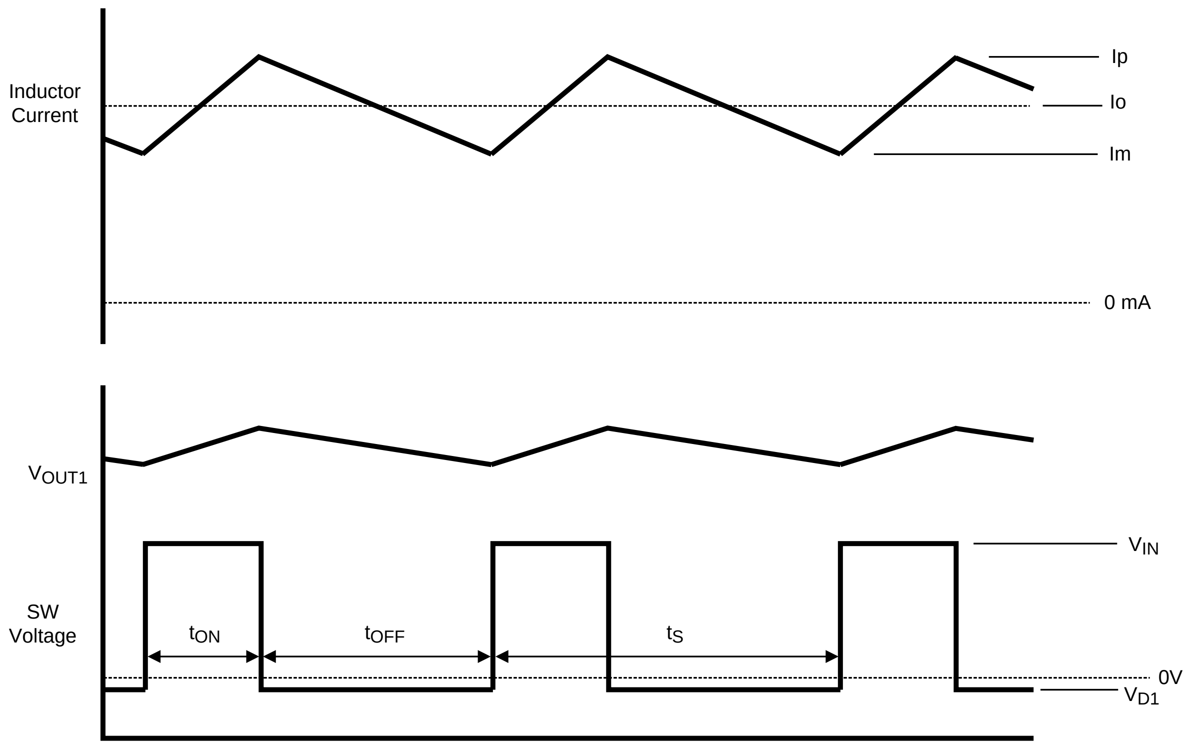

Figure 9. Continuous Conduction Mode

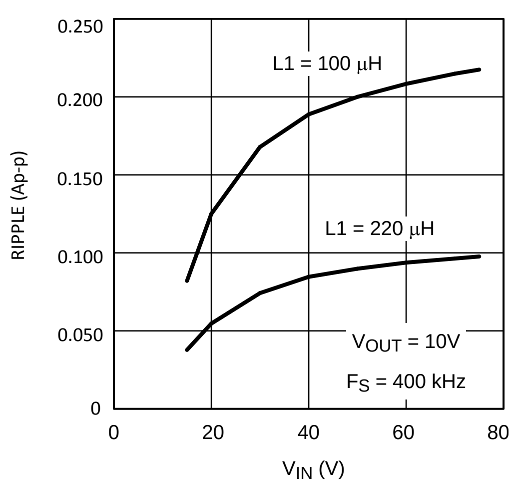

Figure 10. Inductor Ripple Current vs V_{IN} and L1

6.2 Discontinuous Conduction Mode

In this mode, the nominal load current (I_O) is low enough that the inductor current reaches zero during the down ramp portion of the waveform. The LM5007 maintains regulation in this mode by varying the off-time, and consequently the frequency. See Figure 11.

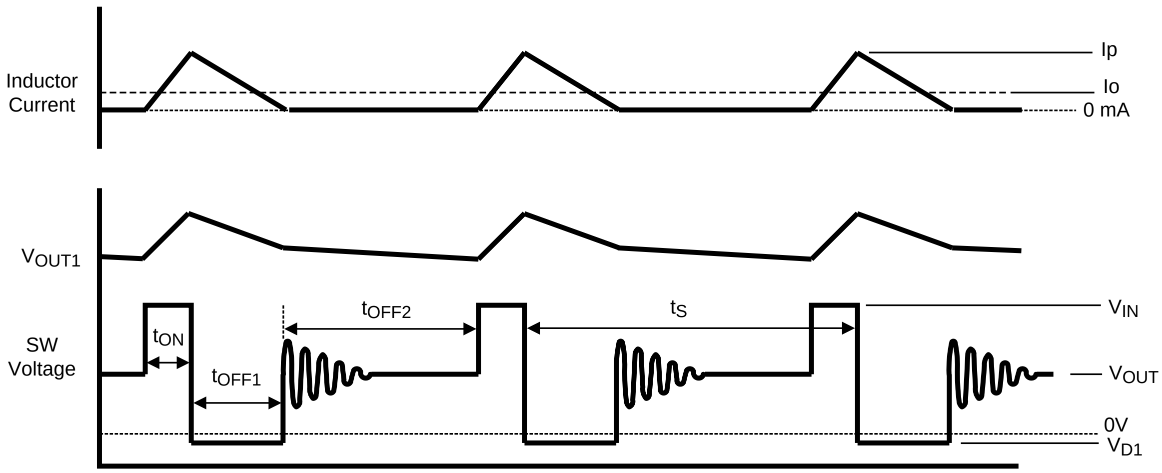

Figure 11. Discontinuous Conduction Mode

The inductor current ramps up to Ip during the on-time, when the SW voltage is at V_{IN} . The voltage across the inductor during this time is V_{IN} - V_{OUT1} . During the first part of the off-time (t_{OFF1}) the inductor current ramps down to zero, SW is below ground at V_{D1}, and the voltage across the inductor is V_{D1} + V_{OUT1}. During t_{OFF2}, the inductor current is zero, and the voltage at SW goes to Vout. The ringing which occurs at the beginning of t_{OFF2} is due to residual energy stored in the inductor and parasitic capacitance at the SW pin. Its frequency is typically 1 - 5MHz.

With the inductor current ramping up from zero each cycle, its peak value (Ip) is equal to:

$$Ip = \frac{(V_{IN} - V_{OUT1}) \times t_{ON}}{L1} \quad (7)$$

which is the same as the ripple amplitude (I_{OR}) in the continuous conduction mode (Equation 5). The inductor current's average value is I_O, and is less than half of the peak current since the inductor current is zero for a portion of the cycle. The voltage ripple amplitude at V_{OUT1} during t_{ON} and t_{OFF1} is the same as that in the continuous conduction mode. During t_{OFF2}, V_{OUT1} falls since the load current is supplied solely by C2. When the voltage at FB falls below 2.5V, the next ON period begins. The operating frequency is calculated from:

$$F_S = \frac{V_{OUT1}^2 \times L1}{R_L \times R_{ON}^2 \times 10^{-20}} \quad (8)$$

where R_L is the load impedance. See Appendix B for the derivation of Equation 8.

7 Thermal Shutdown Protection

The system design should limit the LM5007 junction temperature to not exceed 125ºC during normal operation. However, in the event of a fault which results in the die temperature exceeding 165°C, the Thermal Shutdown activates, disabling the buck switch and reducing bias currents. This feature helps prevent catastrophic failures from accidental device overheating. When the die temperature has reduced below 140°C (typical hysteresis = 25°C), the buck switch is enabled.

8 Selection of External Components

A guide for determining the component values will be illustrated with a design example. Refer to Figure 1. The following steps will configure the LM5007 for:

1. Input voltage range (V_{IN}): 15V to 75V
2. Output voltage (V_{OUT1}): 10V
3. Load current (for continuous conduction mode): 100mA to 400mA
4. Maximum ripple at V_{OUT2}: 200mV p-p

R1 and R2: From Figure 1, $V_{OUT1} = V_{FB} \times (R1 + R2)/R2$, and since V_{FB} = 2.5V, the ratio of R1 to R2 calculates as 3:1. Standard values of 3.01kΩ (R1) and 1.00kΩ (R2) are chosen. Other values could be used as long as the 3:1 ratio is maintained. The selected values, however, provide a small amount of output loading (2.5mA) in the event the main load is disconnected. This allows the circuit to maintain regulation until the main load is reconnected.

F_S and R_{ON}: The recommended operating frequency range for the LM5007 is 50kHz to 600kHz. Unless the application requires a specific frequency, the choice of frequency is generally a compromise since it affects the size of L1 and C2 and the switching losses. A high frequency means a smaller inductor and capacitor (physically as well as their value), while a lower frequency means lower switching losses. The maximum allowed frequency in each application, based on a minimum on-time of 300ns, is calculated from:

$$F_{MAX} = \frac{V_{OUT}}{V_{INMAX} \times 300 \text{ ns}} \quad (9)$$

For this exercise, Fmax = 444kHz. From Equation 6, R_{ON} calculates to 159kΩ. A standard value 178kΩ resistor will be used to allow for tolerances in Equation 6, resulting in a nominal frequency of 396kHz.

L1: The main parameter affected by the inductor is the output current ripple amplitude. The choice of inductor value therefore depends on both the minimum and maximum load currents, keeping in mind that the maximum ripple occurs at maximum V_{IN}.

a) Minimum load current: To maintain continuous conduction at minimum Io (100mA), the ripple amplitude must be less than 200mA p-p so the lower peak of the waveform (Im in Figure 9) does not reach zero. Using Equation 5, and solving for L1 yields:

$$L1 = \frac{V_{OUT1}(V_{IN} - V_{OUT1})}{I_{OR} \times F_S \times V_{IN}} \quad (10)$$

At V_{IN} = 75V, L1 calculates to 109µH. The next larger standard value (150µH) is chosen to allow for component tolerances. With this value for L1, I_{OR} calculates to 146mA p-p at V_{IN} = 75V, and 56mA p-p at V_{IN} = 15V.

b) Maximum load current: At a load current of 400mA the peak of the waveform (Ip in Figure 9) must not reach the LM5007's current limit threshold. The minimum guaranteed value for this threshold is 535mA, requiring the ripple amplitude be less than 270mA p-p. Since the inductor value calculated above already satisfies this requirement, a new calculation for L1 is not required. At maximum V_{IN} and Io, Ip in Figure 9 is 473mA. While L1 must carry this peak current without saturating or exceeding its temperature rating, it also must be capable of carrying the maximum guaranteed value of the current limit threshold (900mA) without saturating since the current limit is reached during startup (Figure 6 and Figure 8). The DC resistance of the inductor should be as low as possible. For example, if the inductor's DCR is one ohm, the power dissipated at maximum load current (400mA) is 0.16W. While small, it is not insignificant compared to the load power of 4W. Generally it is not difficult to find an inductor for this design example with a DCR of less than 0.5Ω.

C3: The capacitor on the V_{CC} output provides not only noise filtering and stability, but its primary purpose is to prevent false triggering of the V_{CC} UVLO at the buck switch on/off transitions. For this reason, C3 should be a good quality ceramic capacitor no smaller than 0.1µF.

C2 and R3: When selecting the output filter capacitor C2, the items to consider are ripple voltage due to its ESR, ripple voltage due to its capacitance, and the ripple allowed at the load.

a) ESR and R3: A low ESR for C2 is generally desirable so as to minimize power losses and heating within the capacitor. However, a hysteretic regulator requires a minimum amount of ripple voltage at the feedback input for proper loop operation. The minimum recommended ripple required at pin 5 of the LM5007 is 25mV p-p, requiring a minimum ripple at V_{OUT1} of 100mV (due to R1 and R2). Since the minimum ripple current (at minimum V_{IN}) is 56mA p-p, the minimum ESR required at V_{OUT1} is 100mV/56mA = 1.78Ω. Since quality capacitors for SMPS applications have an ESR considerably less than this, R3 is inserted as shown in Figure 1. R3's value, along with C2's ESR, must result in at least 25mV p-p ripple at pin 5. Typically, R3 will be 1.0 - 2.0Ω.

b) Allowable Ripple: For a maximum allowed ripple voltage of 200mVp-p at V_{OUT2} (@ V_{IN} = 75V), assume an ESR of 0.5Ω for C2. At maximum V_{IN}, the ripple current is 146mAp-p, creating a ripple voltage of 73mVp-p. This leaves 127mVp-p of ripple due to the capacitance. The average current into C2 due to the ripple current is calculated using the waveform in Figure 12.

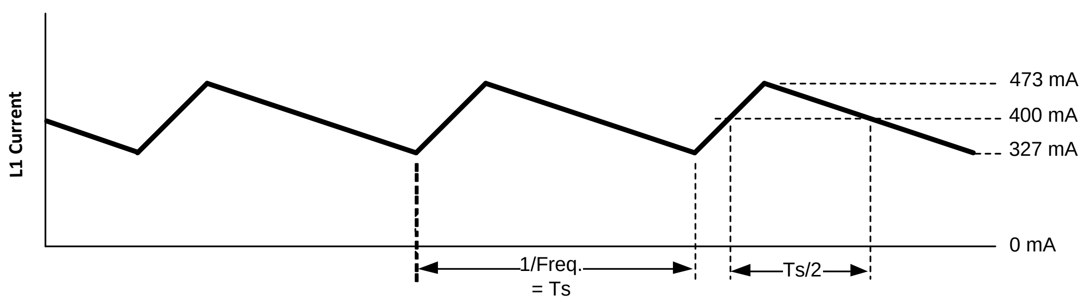

Figure 12. Inductor Current Waveform

Starting when the current reaches Io (400mA in Figure 12) halfway through the on-time, the current continues to increase to the peak (473mA), and then decreases to 400mA halfway through the off-time. The average value of this portion of the waveform is 36.5mA, and will cause half of the voltage ripple, or 63.5mV. The interval is half of the frequency cycle time, or 1.26µs. Using the capacitor's basic equation:

$$C = \frac{I \times \Delta t}{\Delta V} \tag{11}$$

the minimum value for C2 is 0.72µF. The ripple due to C2's capacitance is 90° out of phase from the ESR ripple, and the two numbers do not add directly. However, this calculation provides a practical minimum value for C2 based on its ESR, and the target spec. To allow for the capacitor's tolerance, temperature effects, and voltage effects, a 2.2µF, X7R capacitor will be used.

c) In summary: The above calculations provide a minimum value for C2, and a guideline for R3. The ESR is just as important as the capacitance. The calculated values should be considered starting points, with experimentation needed to determine the optimum values for R3 and C2. The load can be connected to V_{OUT1} or V_{OUT2}. V_{OUT1} provides good regulation, but with ripple which varies from 100 mVp-p to 260 mVp-p. V_{OUT2} has low ripple but lower load regulation due to R3. If the application requires low ripple and good regulation see Appendix D.

R_{CL}: At the onset of a current limit condition, the minimum off-time set by this resistor must be greater than the maximum normal off-time which occurs at maximum V_{IN}. Using Equation 1, the minimum on-time is 0.337µs, yielding a maximum off-time of 2.19µs. This is increased by 84ns (to 2.27µs) due to a ±25% tolerance of the on-time. This value is then increased to allow for:

- The response time of the current limit detection loop (300ns)
- The off-time determined by Equation 4 has a ±25% tolerance

$$t_{OFFCL(MIN)} = (2.27\mu s + 0.30\mu s) \times 1.25 = 3.21\mu s \tag{12}$$

Using Equation 4, R_{CL} calculates to 137kΩ (at V_{FB} = 2.5V). The closest standard value is 140kΩ. This will result in minimum current foldback for overload situations other than a short circuit (where the off-time is fixed at 17µs). A higher value R_{CL} resistor will increase the amount of foldback, reducing the stress on the power train devices.

D1: The important parameters are reverse recovery time and forward voltage. The reverse recovery time determines how long the reverse current surge lasts each time the buck switch is turned on. The shorter the better. The forward voltage drop is significant in the event the output is short-circuited as it is only this diode's voltage which forces the inductor current to reduce during the forced off-time. For this reason, a higher voltage is better, although that affects efficiency. A good choice is an ultrafast power diode, such as the MURA110T3 from ON Semiconductor. Its reverse recovery time is 30ns, and its forward voltage drop is approximately 0.74V at 400mA at 25°C. Other types of diodes may have a lower forward voltage drop, but may have longer recovery times, or greater reverse leakage. The reverse voltage rating must be at least as great as the maximum V_{IN}, and its current rating be greater than the maximum current limit threshold (900mA).

C1 and C5: C1's purpose is to supply most of the switch current during the on-time, and limit the voltage ripple at V_{IN}, on the assumption that the voltage source feeding V_{IN} has an output impedance greater than zero. If the source's dynamic impedance is high (effectively a current source), it will supply the average input current, but not the ripple current. At maximum load current, when the buck switch turns on, the current into pin 8 will suddenly increase to the value Im (Figure 9), ramp up to Ip, then decrease to zero at turn-off. The average current during the on-time is Io, the load current. For a worst case calculation, C1 must supply this average load current during the maximum on-time. To keep the input voltage ripple to less than 2V (for this exercise), C1 calculates to:

$$C1 = \frac{I \times t_{ON}}{\Delta V} = \frac{0.4A \times 1.69\ \mu s}{2.0V} = 0.34\ \mu F \tag{13}$$

Quality ceramic capacitors in this value have a low ESR which adds only a few millivolts to the ripple. It is the capacitance which is dominant in this case. To allow for the capacitor's tolerance, temperature effects, and voltage effects, a 1.0µF, 100V, X7R capacitor will be used.

C5's purpose is to help avoid supply voltage transients and ringing due to long lead inductance at V_{IN}. A low ESR, 0.1µF ceramic chip capacitor is recommended, located close to the LM5007.

C4: The recommended value for C4 is 0.01µF. A high quality ceramic capacitor, with low ESR is recommended as C4 supplies a surge current to charge the buck switch gate at turn-on. A low ESR also helps ensure a complete recharge during each off-time.

9 Final Circuit

The final circuit is shown in Figure 13. The circuit was tested, and the resulting performance is shown in Section 11.

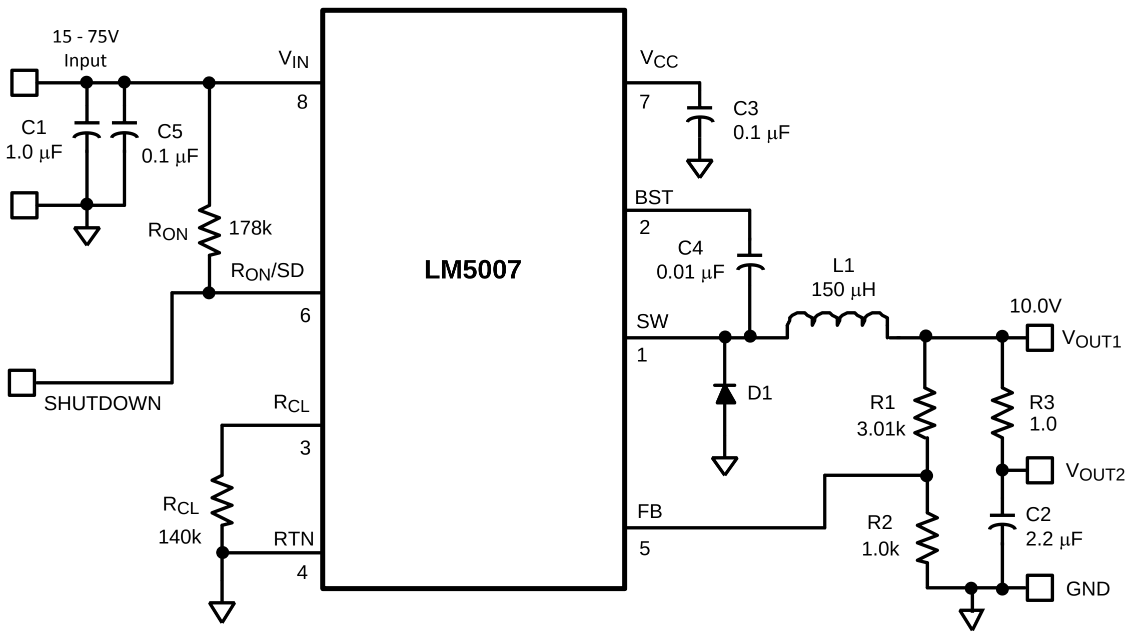

Figure 13. LM5007 Example Circuit

10 Bill of Materials (circuit of Figure 13)

Table 1. Bill of Materials

Item	Description	Part Number	Value
C1	Ceramic Capacitor	TDK C4532X7R2A105M	1µF, 100V
C2	Ceramic Capacitor	TDK C4532X7R1E225M	2.2µF, 25V
C3	Ceramic Capacitor	Kemet C1206C104K5RAC	0.1µF, 50V
C4	Ceramic Capacitor	Kemet C1206C103K5RAC	0.01µF, 50V
C5	Ceramic Capacitor	TDK C3216X7R2A104M	0.1µF, 100V
D1	UltraFast Power Diode	ON Semi MURA110T3	100V, 1A
L1	Power Inductor	Coilcraft DO3316-154 or TDK SLF10145T-151MR79	150 µH
R1	Resistor	Vishay CRCW12063011F	3.01kΩ
R2	Resistor	Vishay CRCW12061001F	1.0kΩ
R3	Resistor	Vishay CRCW12061R00F	1.0Ω
R_{ON}	Resistor	Vishay CRCW12061783F	178kΩ
R_{CL}	Resistor	Vishay CRCW12061403F	140kΩ
U1	Switching Regulator	Texas Instruments LM5007	

11 Typical Performance Waveforms

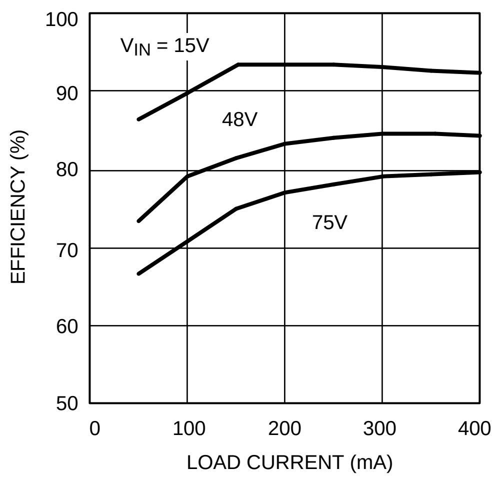

Figure 14. Efficiency vs Load Current at V_{OUT1}

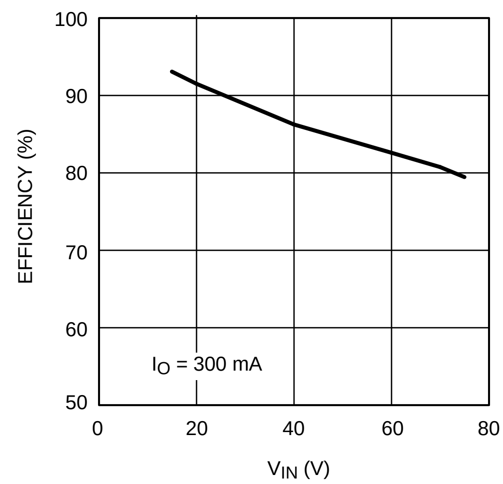

Figure 15. Efficiency at V_{OUT1} vs. V_{IN}

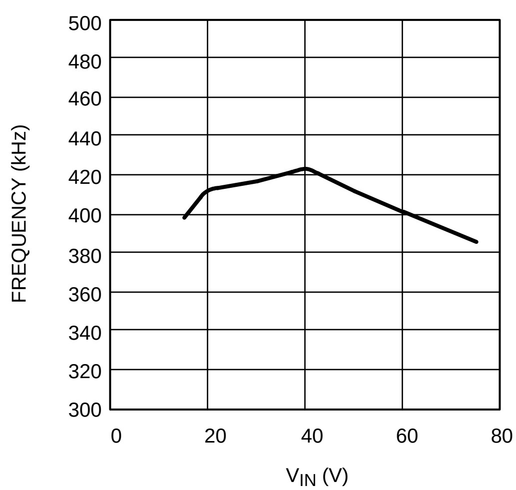

Figure 16. Frequency vs. V_{IN}

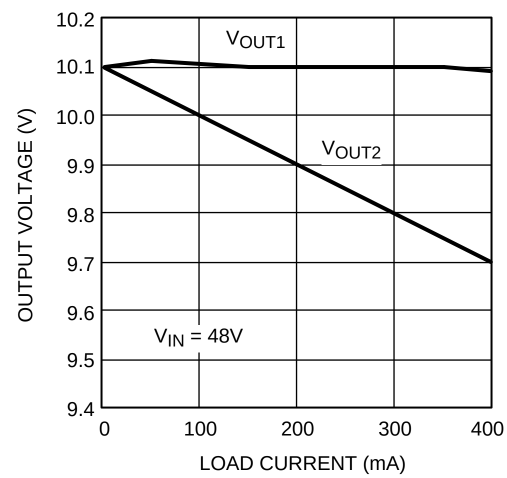

Figure 17. V_{OUT1} and V_{OUT2} vs. Load Current

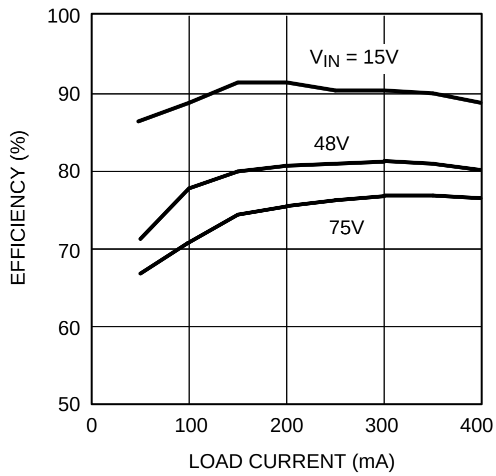

Figure 18. Efficiency vs. Load Current at V_{OUT2}

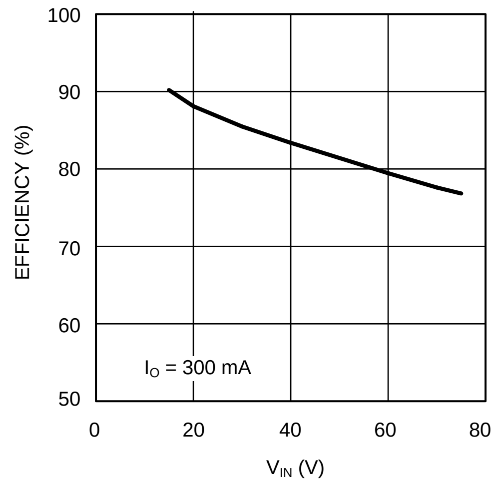

Figure 19. Efficiency vs V_{IN} at V_{OUT2}

12 PCB Layout

The LM5007 regulation and over-voltage comparators are very fast, and as such will respond to short duration noise pulses. Layout considerations are therefore critical for optimum performance. The components at pins 1, 2, 3, 5, and 6 should be as physically close as possible to the IC, thereby minimizing noise pickup in the PC tracks. The current loop formed by D1, L1, and C2 should be as small as possible. The ground connection from C2 to C1 should be as short and direct as possible. Figure 20 through Figure 22 show the layout of the LM5007 evaluation board, designed according to the above guidelines (some of the component designations differ from those in Figure 1 and Figure 13). The board measures 1.75” × 1.25”, and is available fully populated from Texas Instruments.

If the internal dissipation of the LM5007 produces excessive junction temperatures during normal operation, good use of the PC board’s ground plane can help considerably to dissipate heat. The exposed pad on the bottom of the LLP-8 package can be soldered to a ground plane on the PC board, and that plane should extend out from beneath the IC to help dissipate the heat. Additionally, the use of wide PC board traces, where possible, can also help conduct heat away from the IC. Judicious positioning of the PC board within the end product, along with use of any available air flow (forced or natural convection) can help reduce the junction temperatures.

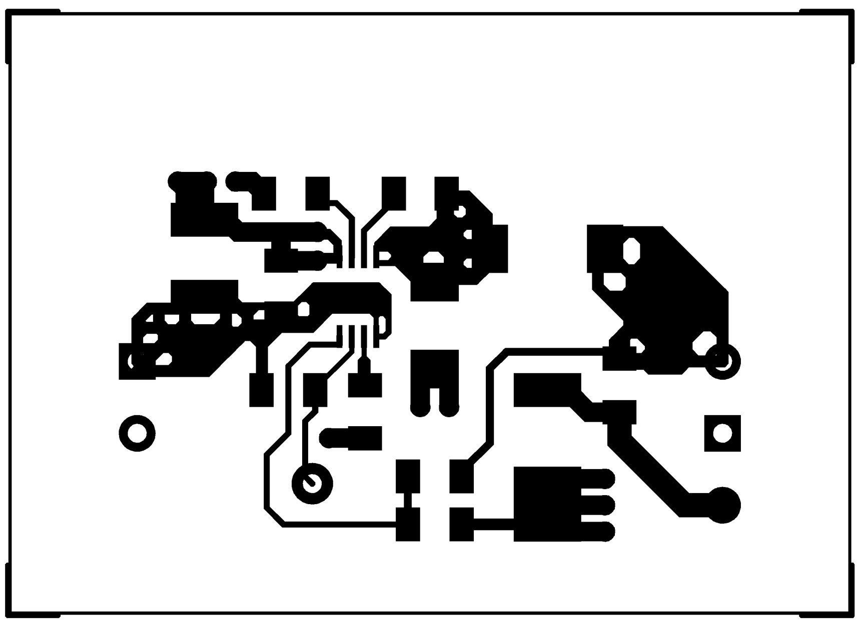

Figure 20. Top Layer

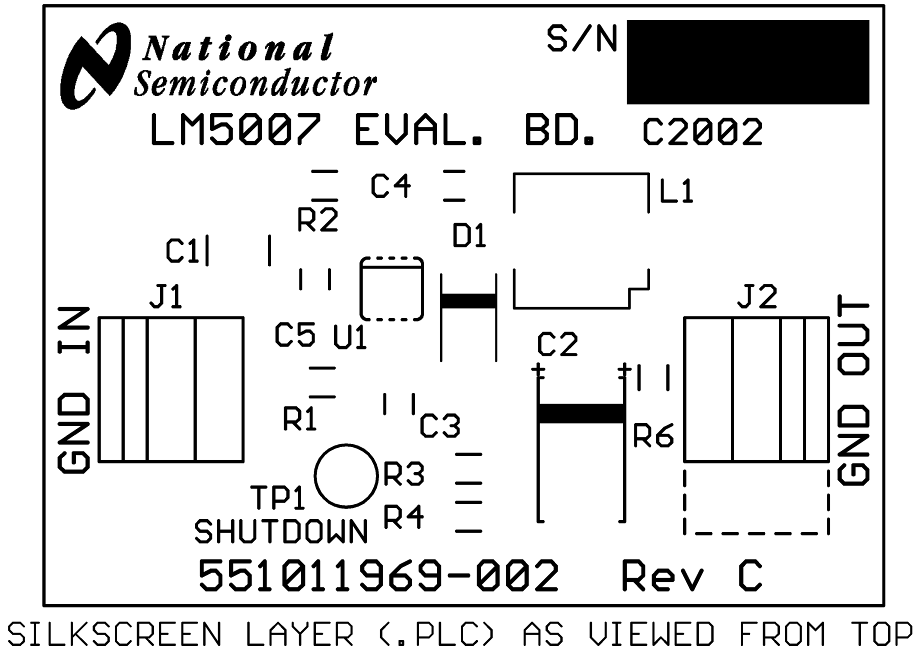

Figure 21. Silk Screen

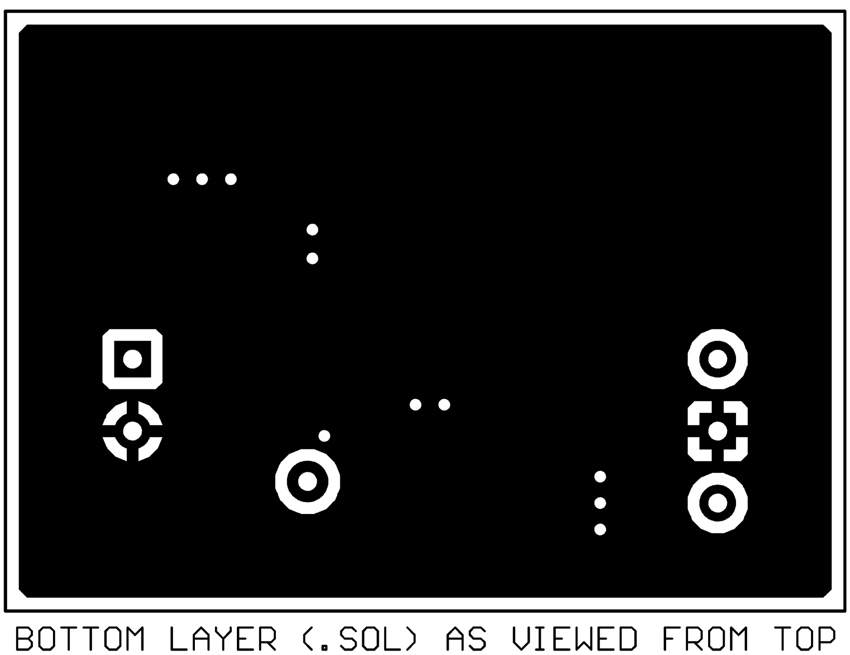

Figure 22. Bottom Layer

Appendix A Operating Frequency in Continuous Conduction Mode

The operating frequency of a Buck regulator operating in Continuous Conduction Mode (Figure 9) is determined as follows:

From the general inductor equation ($V = L \times \Delta i/\Delta t$), the change in current (ripple current) in the inductor during the on-time is

$$\Delta I = \frac{\Delta V \times t_{ON}}{L} \quad (14)$$

where ΔV is the voltage across the inductor, and is (V_{IN} - Vo) for the LM5007. V_{IN} is the input voltage at pin 8, and Vo is the output voltage at the load. The term t_{ON} is the on-time of the Buck Switch. The voltage drop across the Buck Switch is neglected as it is small compared to V_{IN} and Vo, although it may become significant if the term (V_{IN} - V_O) becomes small.

The on-time can be expressed as D/Fs, where D is the duty cycle of the on-time relative to the frequency Fs. Equation 14 can be rewritten as:

$$\Delta I = \frac{(V_{IN} - V_{OUT}) \times D}{L \times F_S} \quad (15)$$

In a buck regulator, the duty cycle (D) can also be expressed as:

$$D = \frac{V_{OUT}}{V_{IN}} \quad (16)$$

Equation 16 neglects the voltage drops across the Buck Switch and the flyback diode (D1) as they are considered small relative to Vo and V_{IN}.

Substituting Equation 16 into Equation 15, rearranging, and solving for Fs yields:

$$F_S = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{V_{IN} \times L \times \Delta I} \quad (17)$$

Using Equation 14 to substitute for ($L \times \Delta I$) yields:

$$F_S = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{V_{IN} \times (V_{IN} - V_{OUT}) \times t_{ON}} = \frac{V_{OUT}}{V_{IN} \times t_{ON}} \quad (18)$$

From Equation 18, it can be seen that if the on-time were inversely proportional to V_{IN}, then Fs would be constant with respect to V_{IN}. Equation 1 indicates the LM5007 is designed to achieve this, but a more precise version of that equation is:

$$t_{ON} = \frac{1.42 \times 10^{-10} \times R_{ON}}{V_{IN} - V_{offset}} \quad (19)$$

V_{offset} is the voltage at pin 6, and varies from 1.5 to 3V, as shown in Figure 23. For large values of V_{IN}, the offset becomes negligible, and the inverse relationship exists. R_{ON} is the resistor between pins 8 and 6. Equation 18 can be rewritten as follows:

$$F_S = \frac{V_{OUT} \times (V_{IN} - V_{offset})}{V_{IN} \times 1.42 \times 10^{-10} \times R_{ON}} \tag{20}$$

For V_{IN} greater than 20V, Equation 20 simplifies to Equation 6.

$$F_S = \frac{V_{OUT}}{1.42 \times 10^{-10} \times R_{ON}} \tag{21}$$

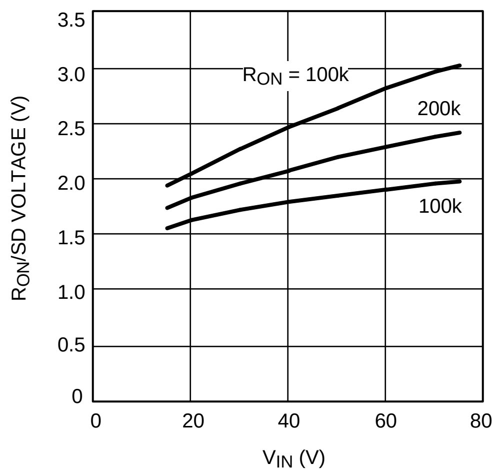

Figure 23. Voltage at Pin 6 vs V_{IN} and R_{ON}

Appendix B Operating Frequency in Discontinuous Conduction Mode

In the discontinuous conduction mode, the premise for this derivation is that all the energy supplied to the inductor (L1) in each cycle is delivered to the load. The peak energy supplied to the inductor during the on-time is:

$$E_{PK} = ½ \times L1 \times I_P^2 \tag{22}$$

Averaged over one cycle, the power is:

$$P_L = ½ \times L1 \times I_P^2 \times F_S \tag{23}$$

The load power is:

$$P_{OUT} = \frac{V_{OUT}^2}{R_L} \tag{24}$$

From Equation 1 and Equation 7, the inductor's peak current is:

$$Ip = \frac{(V_{IN} - V_{OUT}) \times t_{ON}}{L1} = \frac{(V_{IN} - V_{OUT}) \times K \times R_{ON}}{L1 \times V_{IN}} \tag{25}$$

where K is the constant specific to the LM5007 (1.42×10^{-10}). Substituting Equation 25 into Equation 23 yields:

$$P_L = \frac{[(V_{IN} - V_{OUT}) \times K \times R_{ON}]^2 \times F_S}{2 \times L1 \times V_{IN}^2} \tag{26}$$

Equating this to the load power, and solving for F_S yields:

$$F_S = \frac{2 \times L1 \times (V_{OUT} \times V_{IN})^2}{[(V_{IN} - V_{OUT}) \times K \times R_{ON}]^2 \times R_L} \tag{27}$$

Substituting the value of K into Equation 27 yields:

$$F_S = \frac{(V_{OUT} \times V_{IN})^2 \times L1 \times 10^{20}}{[(V_{IN} - V_{OUT}) \times R_{ON}]^2 \times R_L} \tag{28}$$

When V_{IN} is significantly larger than V_{OUT}, the term (V_{IN} - V_{OUT}) can be reduced to V_{IN}, simplifying Equation 28 to:

$$F_S = \frac{V_{OUT}^2 \times L1 \times 10^{20}}{R_{ON}^2 \times R_L} \tag{29}$$

This is the same as Equation 8. The frequency varies with the load current due to the R_L term in the denominator.

Appendix C Current Limit Operation

When a current limit condition is detected, the LM5007 immediately responds to turn off the buck switch, and then forces an off-time so the inductor current can reduce to a safe level. The worst case situation occurs when V_{IN} is at maximum (75V), and the output is short circuited (V_{OUT} = 0V). The necessary off-time for this condition is based on the principle that the inductor's volt-second product during the off-time must at least equal (preferably exceed) the volt-second product during the on-time. The on-time in this case is not determined by R_{ON}, but is the response time of the current limit detection circuit to shut off the buck switch (typically 225ns). Since the voltage across the inductor is V_{IN} (since V_{OUT} = 0V), the maximum volt-second product is equal to 75V × 225ns = 16.88 V-µsec. During this response time, the inductor current increases an additional 112mA (for V_{IN} = 75V and L1 = 150µH).

During the off-time the voltage across the inductor is D1's forward voltage drop plus the voltage due to the inductor's DC resistance. Assume they are 0.74V, and 0.3Ω respectively, the required off-time is:

$$t_{off} = \frac{16.88\text{V - }\mu\text{sec}}{0.74\text{V} + (0.3 \times (0.725\text{A} + 0.112\text{A}))} = 17\ \mu\text{s} \qquad (30)$$

During this off-time, the inductor's current will be reduced an amount equal to the increase which occurred during the response time (112 mA in this example).

Equation 30 indicates that the 17µs off-time provided by the LM5007 is sufficient, with the assumptions used in the above calculation. A longer off-time could have been selected, but at the expense of increased foldback, and recovery time when the overload is removed. Each application should be checked for its actual diode and inductor characteristics over temperature and at maximum input voltage. If a marginal, or potentially runaway situation is determined to exist for a particular design, this can be corrected by choosing a diode with a higher forward voltage drop, an inductor with higher DCR, and/or by reducing the maximum V_{IN}.

For a less severe overload condition, where V_{OUT} is partially reduced, less off-time is needed than in a short circuit situation. The LM5007 provides this feature with proper selection of the R_{CL} resistor. The criteria for selecting this resistor is that the minimum off-time set by R_{CL}, which occurs when V_{FB} = 2.5V, be longer than the maximum normal off-time, which occurs at maximum V_{IN}. The design example in this application report describes the calculation for determining the R_{CL} resistor.

Appendix D Low Output Ripple Configuration

The circuit of Figure 13 has two outputs:

- V_{OUT1} which provides good regulation, but with ripple which varies from 100 mVp-p to 260 mVp-p
- V_{OUT2} which has low ripple (10 mV to 26 mV) but relatively poor load regulation (see Figure 17)

If the application requires low ripple and good regulation, the circuit of Figure 24 can be used where the feedback is taken from V_{OUT2}. The addition of R4 and C6 injects ripple current from V_{OUT1} to the FB/R1/R2 node to increase the ripple voltage to that required by the LM5007 at the FB pin.

Comparing this circuit's performance (Figure 25 and Figure 26) to Figure 18 and Figure 19 shows no significant efficiency loss while V_{OUT2} load regulation is ±15 mV for a load current range of 50 mA to 400 mA. The ripple voltage at V_{OUT2} ranged from 10 to 26 mVp-p.

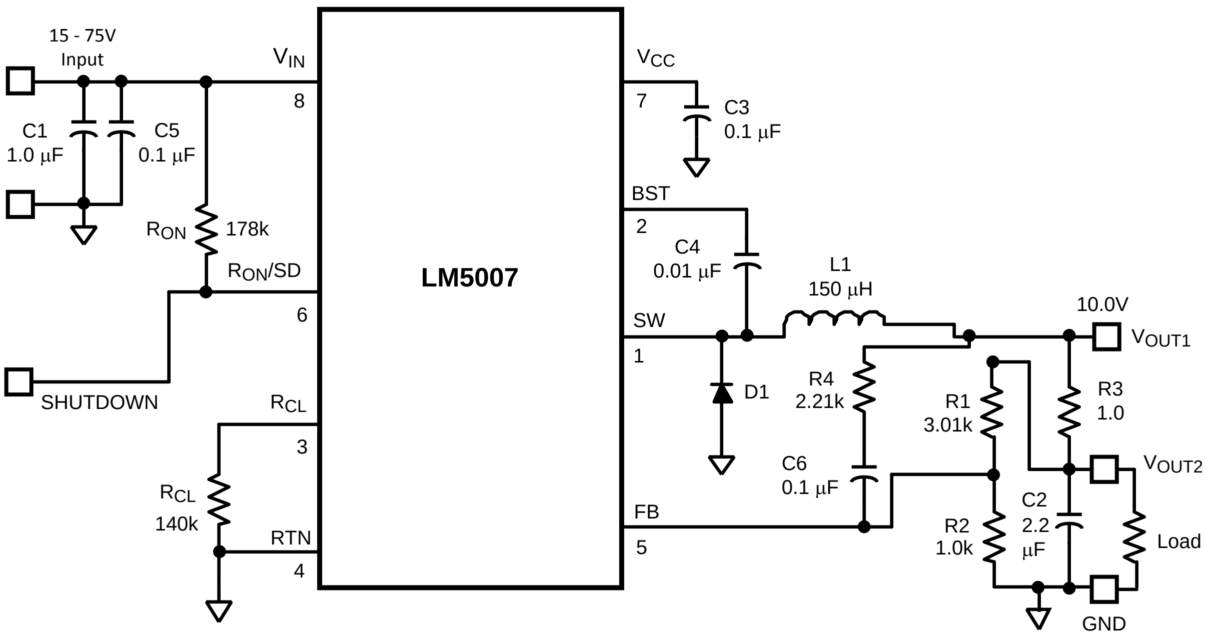

Figure 24. Low Output Ripple Configuration

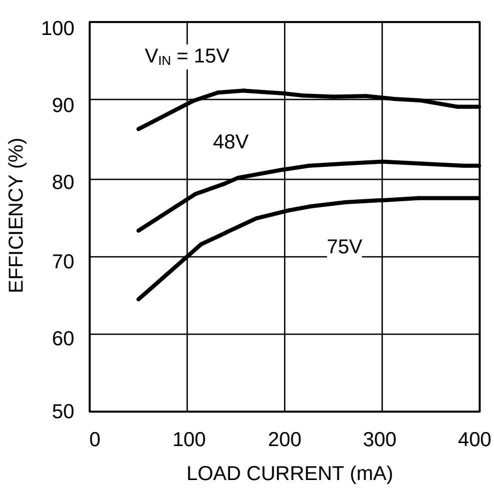

Figure 25. Efficiency vs Load Current

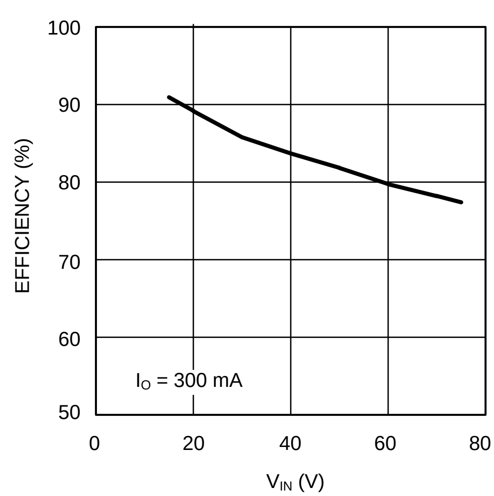

Figure 26. Efficiency vs V_{IN}

Products		**Applications**	
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Logic	logic.ti.com	Security	www.ti.com/security
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