LM5009 Wide Input, 100-V, 150-mA, Step-Down Switching Regulator

1 Features
- Integrated N-Channel MOSFET
- 150-mA Output Current Capability
- Ultra-Fast Transient Response
- No Loop Compensation Required
- $V_{IN}$ Feed-Forward Provides Constant Operating Frequency
- Switching Frequency Can Exceed 600 kHz
- Highly Efficient Operation
- 2% Accurate 2.5-V Feedback From $-40^\circ C$ to $+125^\circ C$
- Internal Startup Regulator
- Intelligent Current Limit Protection
- External Shutdown Control
- Thermal Shutdown
- 8-Pin VSSOP and Thermally-Enhanced 8-Pin WSON Packages

2 Applications
- Heat Sink Eliminator for Classic Linear Regulator Applications
- 12-V, 24-V, 36-V, and 48-V Rectified AC Systems
- 42-V Automotive
- Non-Isolated AC Mains Charge-Coupled Supplies
- LED Current Source

3 Description
The LM5009 step-down switching regulator features all of the functions needed to implement a low-cost, efficient, buck bias regulator. This device is capable of driving a 150-mA load current from a 9.5-V to 95-V input source. The switching frequency can exceed 600 kHz, depending on the input and output voltages. The output voltage can be set from 2.5 V to 85 V. This high-voltage regulator contains an N-channel buck switch and an internal startup regulator. The device is easy to implement and is provided in 8-pin VSSOP and thermally-enhanced, 8-pin WSON packages. The LM5009 is a well-suited alternative to a high-voltage monolithic or discrete linear solution where the power loss becomes unacceptable. The regulator operation is based on a control scheme using an on-time inversely proportional to $V_{IN}$. This feature allows the operating frequency to remain relatively constant over load and input voltage variations. The control scheme requires no loop compensation, resulting in an ultrafast transient response. An intelligent current limit is implemented with forced off-time that is inversely proportional to $V_{OUT}$. This scheme ensures short-circuit protection and provides minimum foldback. Other features include thermal shutdown, $V_{CC}$ undervoltage lockout, gate drive undervoltage lockout, and maximum duty cycle limiter.

Device Information (1)

<table>
<thead>
<tr>
<th>PART NUMBER</th>
<th>PACKAGE</th>
<th>BODY SIZE (NOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM5009</td>
<td>VSSOP (8)</td>
<td>3.00 mm × 3.00 mm</td>
</tr>
<tr>
<td></td>
<td>WSON (8)</td>
<td>4.00 mm × 4.00 mm</td>
</tr>
</tbody>
</table>

(1) For all available packages, see the orderable addendum at the end of the data sheet.

An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.
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## 4 Revision History

**NOTE:** Page numbers for previous revisions may differ from page numbers in the current version.

### Changes from Revision G (February 2013) to Revision H

<table>
<thead>
<tr>
<th>Section Added/Modified</th>
<th>Page</th>
</tr>
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<tbody>
<tr>
<td>ESD Ratings table, Feature Description section, Device Functional Modes, Application and Implementation section, Power Supply Recommendations section, Layout section, Device and Documentation Support section, and Mechanical, Packaging, and Orderable Information section.</td>
<td>1</td>
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### Changes from Revision F (February 2013) to Revision G

<table>
<thead>
<tr>
<th>Change</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changed layout of National Data Sheet to TI format</td>
<td>16</td>
</tr>
</tbody>
</table>
### 5 Pin Configuration and Functions

**DGK, NGU Packages**

8-Pin VSSOP, WSON

**Top View**

<table>
<thead>
<tr>
<th>PIN</th>
<th>I/O</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>BST</td>
<td>2 I</td>
<td>Boost pin. An external capacitor is required between the BST and SW pins. A 0.022-µF ceramic capacitor is recommended. An internal diode charges the capacitor from V&lt;sub&gt;CC&lt;/sub&gt;.</td>
</tr>
<tr>
<td>EP</td>
<td>—</td>
<td>Exposed pad (WSON package only). Exposed metal pad on the underside of the device. Connecting this pad to the PC board ground plane is recommended to aid in heat dissipation.</td>
</tr>
<tr>
<td>FB</td>
<td>5 I</td>
<td>Feedback input from regulated output. This pin is connected to the inverting input of the internal regulation comparator. The regulation threshold is 2.5 V.</td>
</tr>
<tr>
<td>RCL</td>
<td>3 I</td>
<td>Current limit off-time set pin. A resistor between this pin and RTN sets the off-time when current limit is detected. The off-time is preset to 35 µs if FB = 0 V.</td>
</tr>
<tr>
<td>RON/SD</td>
<td>6 I</td>
<td>On-time set pin. A resistor between this pin and VIN sets the switch on-time as a function of V&lt;sub&gt;N&lt;/sub&gt;. The minimum recommended on-time is 250 ns at the maximum input voltage. This pin can be used for remote shutdown.</td>
</tr>
<tr>
<td>RTN</td>
<td>4 —</td>
<td>Ground pin. Ground for the entire circuit.</td>
</tr>
<tr>
<td>SW</td>
<td>1 O</td>
<td>Switching output. Power switching output. Connect to the inductor, recirculating diode, and bootstrap capacitor.</td>
</tr>
<tr>
<td>VCC</td>
<td>7 O</td>
<td>Output from the internal high-voltage startup regulator. Regulated at 7.0 V. If an auxiliary voltage is available to raise the voltage on this pin above the regulation set point (7 V), the internal series pass regulator shuts down, reducing the device power dissipation. Do not exceed 14 V. This voltage provides gate drive power for the internal buck switch. An internal diode is provided between this pin and the BST pin. A local 0.1-µF decoupling capacitor is required.</td>
</tr>
<tr>
<td>VIN</td>
<td>8 I</td>
<td>Input voltage. Recommended operating range: 9.5 V to 95 V.</td>
</tr>
</tbody>
</table>
6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)\(^{(1)}\)

<table>
<thead>
<tr>
<th>MIN</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>V(_{IN}) to RTN</td>
<td>–0.3</td>
<td>100</td>
</tr>
<tr>
<td>BST to RTN</td>
<td>–0.3</td>
<td>114</td>
</tr>
<tr>
<td>SW to RTN (steady-state)</td>
<td>–1</td>
<td></td>
</tr>
<tr>
<td>BST to VCC</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>BST to SW</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>VCC to RTN</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>All other inputs to RTN</td>
<td>–0.3</td>
<td>7</td>
</tr>
<tr>
<td>Storage temperature, (T)(_{stg})</td>
<td>–65</td>
<td>150</td>
</tr>
</tbody>
</table>

(1) Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under Recommended Operating Conditions. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

6.2 ESD Ratings

<table>
<thead>
<tr>
<th>VALUE</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBM, per ANSI/ESDA/JEDEC JS-001(^{(1)})(2)</td>
<td>±2000</td>
</tr>
<tr>
<td>CDM, per JEDEC specification JESD22-C101(^{(3)})</td>
<td>±750</td>
</tr>
</tbody>
</table>

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
(2) The human body model is a 100-pF capacitor discharged through a 1.5-kΩ resistor into each pin.
(3) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)\(^{(1)}\)

<table>
<thead>
<tr>
<th>MIN</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>V(_{IN})</td>
<td>9.5</td>
<td>95</td>
</tr>
<tr>
<td>Operating junction temperature</td>
<td>–40</td>
<td>125</td>
</tr>
</tbody>
</table>

(1) Operating ratings are conditions under which operation of the device is intended to be functional. For specifications and test conditions, see the Electrical Characteristics.

6.4 Thermal Information

<table>
<thead>
<tr>
<th>THERMAL METRIC(^{(1)})</th>
<th>LM5009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DGK (VSSOP)</td>
</tr>
<tr>
<td></td>
<td>8 PINS</td>
</tr>
<tr>
<td>(R)(_{JA})</td>
<td>Junction-to-ambient thermal resistance</td>
</tr>
<tr>
<td>(R)(_{JUC(top)})</td>
<td>Junction-to-case (top) thermal resistance</td>
</tr>
<tr>
<td>(R)(_{JB})</td>
<td>Junction-to-board thermal resistance</td>
</tr>
<tr>
<td>(\psi)(_{JT})</td>
<td>Junction-to-top characterization parameter</td>
</tr>
<tr>
<td>(\psi)(_{JB})</td>
<td>Junction-to-board characterization parameter</td>
</tr>
<tr>
<td>(R)(_{JUC(bot)})</td>
<td>Junction-to-case (bottom) thermal resistance</td>
</tr>
</tbody>
</table>

(1) For more information about traditional and new thermal metrics, see the Semiconductor and IC Package Thermal Metrics application report, SPRA953.
6.5 Electrical Characteristics

Typical limits are for \( T_J = 25°C \) only, and all maximum and minimum limits apply over the junction temperature \( (T_J) \) range of –40°C to +125°C. Minimum and maximum limits are specified through test, design, or statistical correlation. Typical values represent the most likely parametric norm at \( T_J = 25°C \), and are provided for reference purposes only. Unless otherwise stated, the following conditions apply: \( V_{IN} = 48 \) V and \( R_{ON} = 200 \) kΩ. \(^{(1)}\).

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{CC} ) regulator output</td>
<td>( V_{CC} )</td>
<td>6.6</td>
<td>7</td>
<td>7.4</td>
<td>V</td>
</tr>
<tr>
<td>( V_{CC} ) current limit (^{(2)})</td>
<td>( V_{CC} )</td>
<td>9.5</td>
<td>mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_{CC} ) undervoltage lockout voltage (( V_{CC} ) increasing)</td>
<td>6.3</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_{CC} ) undervoltage hysteresis</td>
<td>200</td>
<td>mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_{CC} ) UVLO delay (filter)</td>
<td>100-mV overdrive</td>
<td>10</td>
<td>μs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( I_N ) operating current</td>
<td>Non-switching, ( FB = 3 ) V</td>
<td>485</td>
<td>675</td>
<td>μA</td>
<td></td>
</tr>
<tr>
<td>( I_N ) shutdown current</td>
<td>( R_{ON/SD} = 0 ) V</td>
<td>76</td>
<td>150</td>
<td>μA</td>
<td></td>
</tr>
</tbody>
</table>

**SWITCH CHARACTERISTICS**

- Buck switch \( R_{ds(on)} \)
  - \( I_{TEST} = 200 \) mA \(^{(3)}\)
  - 2.0 | 4.4 | Ω
- Gate drive UVLO
  - \( V_{BS} - V_{SW} \) rising
  - 3.4 | 4.5 | 5.5 | V
- Gate drive UVLO hysteresis
  - 430 | mV

**CURRENT LIMIT**

- Current limit threshold
  - 0.25 | 0.31 | 0.37 | A
- Current limit response time
  - \( I_{switch} \) overdrive = 0.1-A time to switch off
  - 400 | ns
- OFF time generator (test 1)
  - \( FB = 0 \) V, \( R_{CL} = 100 \) kΩ
  - 35 | μs
- OFF time generator (test 2)
  - \( FB = 2.3 \) V, \( R_{CL} = 100 \) kΩ
  - 2.56 | μs

**ON TIME GENERATOR**

- \( T_{ON} - 1 \)
  - \( V_{IN} = 10 \) V, \( R_{ON} = 200 \) kΩ
  - 2.15 | 2.77 | 3.5 | μs
- \( T_{ON} - 2 \)
  - \( V_{IN} = 95 \) V, \( R_{ON} = 200 \) kΩ
  - 200 | 300 | 420 | ns
- Remote shutdown threshold
  - Rising
  - 0.4 | 0.7 | 1.05 | V
- Remote shutdown hysteresis
  - 35 | mV

**MINIMUM OFF TIME**

- Minimum off timer
  - \( FB = 0 \) V
  - 300 | ns

**REGULATION AND OV COMPARATORS**

- FB reference threshold
  - Internal reference, trip point for switch on
  - 2.445 | 2.5 | 2.550 | V
- FB overvoltage threshold
  - Trip point for switch off
  - 2.875 | V
- FB bias current
  - 1 | nA

**THERMAL SHUTDOWN**

- \( T_{sd} \)
  - Thermal shutdown temperature
  - 165 | °C
- Thermal shutdown hysteresis
  - 25 | °C

\(^{(1)}\) All electrical characteristics having room temperature limits are tested during production with \( T_A = T_J = 25°C \). All hot and cold limits are specified by correlating the electrical characteristics to process and temperature variations and applying statistical process control.

\(^{(2)}\) The \( V_{CC} \) output is intended as a self bias for the internal gate drive power and control circuits. Device thermal limitations limit external loading.

\(^{(3)}\) For devices procured in the WSON-8 package, the \( R_{ds(on)} \) limits are specified by design characterization data only.
6.6 Typical Characteristics

Figure 1. On-Time vs \( V_{IN} \) and \( R_{ON} \)

Figure 2. \( V_{CC} \) vs \( V_{IN} \) and \( F_S \)

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

Figure 4. \( V_{CC} \) vs \( I_{CC} \) and \( V_{IN} \)

Figure 5. \( I_{CC} \) Current vs Applied \( V_{CC} \) Voltage
7 Detailed Description

7.1 Overview
The LM5009 step-down switching regulator features all the functions needed to implement a low-cost, efficient, buck bias power converter. This high-voltage regulator contains a 100-V N-channel buck switch, is easy to implement, and is provided in VSSOP-8 and thermally-enhanced, WSON-8 packages. The regulator is based on a control scheme using an on-time inversely proportional to \( V_{IN} \). The control scheme requires no loop compensation. Current limit is implemented with forced off-time that is inversely proportional to \( V_{OUT} \). This scheme ensures short-circuit protection and provides minimum foldback. The functional block diagram of the LM5009 is shown in the Functional Block Diagram section.

The LM5009 can be applied in numerous applications to efficiently regulate down higher voltages. This regulator is well-suited for 48-V telecom and 42-V automotive power bus ranges. Additional features include: thermal shutdown, \( V_{CC} \) undervoltage lockout, gate drive undervoltage lockout, maximum duty cycle limit timer, and the intelligent current limit off timer.

7.2 Functional Block Diagram

7.3 Feature Description

7.3.1 Control Circuit Overview
The LM5009 is a buck dc-dc regulator that uses a control scheme where the on-time varies inversely with line voltage (\( V_{IN} \)). Control is based on a comparator and the on-time one-shot, with the output voltage feedback (FB) compared to an internal reference (2.5 V). If the FB level is below the reference, then the buck switch is turned on for a fixed time determined by the line voltage and a programming resistor (\( R_{ON} \)). Following the on period, the switch remains off for at least the minimum off-timer period of 300 ns. If FB is still below the reference at that time, then the switch turns on again for another on-time period. This cycle continues until regulation is achieved, at which time the off-time increases based on the required duty cycle.
Feature Description (continued)

The LM5009 operates in discontinuous conduction mode at light load currents, and continuous conduction mode at heavy load current. In discontinuous conduction mode, current through the output inductor starts at zero and ramps up to a peak during the on-time, then ramps back to zero before the end of the off-time. The next on-time period starts when the voltage at FB falls below the internal reference—until then, the inductor current remains zero. In this mode the operating frequency is lower than in continuous conduction mode, and varies with load current. Therefore, at light loads the conversion efficiency is maintained because the switching losses reduce with the reduction in load and frequency. The discontinuous operating frequency can be calculated as by Equation 1:

\[
F = \frac{V_{OUT}^2 \times L \times 1.28 \times 10^{20}}{R_L \times (R_{ON})^2}
\]

where

- \( R_L = \) the load resistance

In continuous conduction mode, current flows continuously through the inductor and never ramps down to zero. In this mode, the operating frequency is greater than the discontinuous mode frequency and remains relatively constant with load and line variations. The approximate continuous mode operating frequency can be calculated by Equation 2:

\[
F = \frac{V_{OUT}}{1.25 \times 10^{-10} \times R_{ON}}
\]

The output voltage \( V_{OUT} \) is programmed by two external resistors; see the Functional Block Diagram section. The regulation point is calculated by Equation 3:

\[
V_{OUT} = 2.5 \times \left( \frac{R_1 + R_2}{R_2} \right)
\]

This regulator regulates the output voltage based on ripple voltage at the feedback input, requiring a minimum amount of equivalent series resistance (ESR) for the output capacitor C2. A minimum of 25 mV of ripple voltage at the feedback pin (FB) is required for the LM5009. In cases where the capacitor ESR is too small, additional series resistance may be required (see R3 in the Functional Block Diagram section).

For applications where lower output voltage ripple is required, the output can be taken directly from a low-ESR output capacitor, as shown in Figure 6. However, R3 slightly degrades the load regulation.

![Functional Block Diagram](image)

Figure 6. Low Ripple Output Configuration

7.3.2 High Voltage Startup Regulator

The LM5009 contains an internal high voltage startup regulator. The input pin (VIN) can be connected directly to line voltages up to 95 V, with transient capability to 100 V. The regulator is internally current limited at 9.5 mA. Upon power-up, the regulator sources current into the external capacitor at VCC (C3). When the voltage on the VCC pin reaches the undervoltage lockout threshold of 6.3 V, the buck switch is enabled.
Feature Description (continued)

In applications involving a high value for \( V_{IN} \), where power dissipation in the \( V_{CC} \) regulator is a concern, an auxiliary voltage can be diode connected to the VCC pin. Setting the voltage between 8 V and 14 V shuts off the internal regulator, reducing internal power dissipation, as shown in Figure 7. The current required into the VCC pin is illustrated in the Typical Characteristics section.

![Figure 7. Self-Biased Configuration](image)

7.3.3 Regulation Comparator

The feedback voltage at FB is compared to an internal 2.5-V reference. In normal operation (the output voltage is regulated), an on-time period is initiated when the voltage at FB falls below 2.5 V. The buck switch stays on for the programmed on-time, causing the FB voltage to rise above 2.5 V. After the on-time period, the buck switch stays off until the FB voltage again falls below 2.5 V. During start-up, the FB voltage is below 2.5 V at the end of each on-time, resulting in the minimum off-time. Bias current at the FB pin is less than 5 nA over temperature.

7.3.4 Overvoltage Comparator

The feedback voltage at FB is compared to an internal 2.875-V reference. If the voltage at FB rises above 2.875 V, then the on-time pulse is immediately terminated. This condition can occur if the input voltage, or the output load, changes suddenly. The buck switch does not turn on again until the voltage at FB falls below 2.5 V.

7.3.5 On-Time Generator

The on-time for the LM5009 is determined by the \( R_{ON} \) resistor, and is inversely proportional to the input voltage \( (V_{IN}) \), resulting in a nearly constant frequency because \( V_{IN} \) is varied over its range. The on-time equation is shown in Equation 4:

\[
T_{ON} = 1.25 \times 10^{-10} \times R_{ON} / V_{IN}
\]

Select \( R_{ON} \) for a minimum on-time (at maximum \( V_{IN} \)) greater than 250 ns, for proper current limit operation. This requirement limits the maximum frequency for each application, depending on \( V_{IN} \) and \( V_{OUT} \).
Feature Description (continued)

7.3.6 Current Limit

The LM5009 contains an intelligent current limit off timer. If the current in the buck switch exceeds 0.31 A, then the present cycle is immediately terminated and a non-resettable off timer is initiated. The length of off-time is controlled by an external resistor (\(R_{CL}\)) and the FB voltage. When \(FB = 0\) V, a maximum off-time is required and the time is preset to 35 \(\mu\)s. This condition occurs when the output is shorted and during the initial part of start-up. This amount of time ensures safe short-circuit operation up to the maximum input voltage of 95 V. In cases of overload where the FB voltage is above 0 V (not a short-circuit) the current limit off-time is less than 35 \(\mu\)s. Reducing the off-time during less severe overloads reduces the amount of foldback, recovery time, and start-up time. The off-time is calculated from Equation 5:

\[
T_{OFF} = \frac{10^5}{0.285 + \frac{V_{FB}}{(6.35 \times 10^{-6} \times R_{CL})}}
\]

The current limit sensing circuit is blanked for the first 50 ns to 70 ns of each on-time so it is not falsely tripped by the current surge that occurs at turn-on. The current surge is required by the recirculating diode (D1) for its turn-off recovery.

7.3.7 N-Channel Buck Switch and Driver

The LM5009 integrates an N-channel buck switch and associated floating high-voltage gate driver. The gate driver circuit works in conjunction with an external bootstrap capacitor and an internal high-voltage diode. A 0.022-\(\mu\)F ceramic capacitor (C4) connected between the BST pin and SW pin provides the voltage to the driver during the on-time.

During each off-time, the SW pin is at approximately –1 V, and the bootstrap capacitor charges from \(V_{CC}\) through the internal diode. The minimum off timer ensures a minimum time for each cycle to recharge the bootstrap capacitor.

An external re-circulating diode (D1) carries the inductor current after the internal buck switch turns off. This diode must be of the ultra-fast or Schottky type to minimize turn-on losses and current overshoot.

7.3.8 Thermal Protection

Operate the LM5009 so that the junction temperature does not exceed 125°C during normal operation. An internal thermal shutdown circuit is provided to protect the LM5009 in the event of a higher than normal junction temperature. When activated, typically at 165°C, the controller is forced into a low-power reset state, disabling the buck switch. This feature prevents catastrophic failures from accidental device overheating. When the junction temperature reduces below 140°C (typical hysteresis = 25°C), the buck switch is enabled and normal operation is resumed.

7.4 Device Functional Modes

The LM5009 can be remotely disabled by taking the RON/SD pin to ground, as shown in Figure 8. The voltage at the RON/SD pin is between 1.7 V and 5 V, depending on \(V_{IN}\) and the value of the \(R_{ON}\) resistor.

Figure 8. Shutdown Implementation
8 Application and Implementation

NOTE
Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI’s customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

8.1 Application Information
The LM5009 is a non-synchronous buck regulator designed to operate over a wide input voltage range and output current. Spreadsheet-based quick-start calculation tools and the on-line WEBENCH® software can be used to create a buck design along with the bill of materials, estimated efficiency, and the complete solution cost.

8.2 Typical Application
A typical buck application circuit with the LM5009 is shown in Figure 9. The circuit can operate over a wide input voltage range of 9.5 V to 95 V and provides a stable output of 10 V over the load current being varied from 50 mA to 200 mA. The resulting curves are shown in Figure 10 through Figure 13.

8.2.1 Design Requirements
A typical buck application circuit with the LM5009 can be summarized by the operating conditions listed in Table 1.

Table 1. Design Parameters

<table>
<thead>
<tr>
<th>DESIGN PARAMETER</th>
<th>EXAMPLE VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage range</td>
<td>9.5 V to 95 V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>10 V</td>
</tr>
<tr>
<td>Load current range</td>
<td>50 mA to 200 mA</td>
</tr>
<tr>
<td>Nominal switching frequency</td>
<td>330 kHz</td>
</tr>
</tbody>
</table>
8.2.2 Detailed Design Procedure

8.2.2.1 Output Resistor Divider Selection

R1 and R2: From the Functional Block Diagram section, V_{\text{OUT1}} can be determined to be equal to V_{\text{FB}} \times (R1 + R2) / R2, and because V_{\text{FB}} = 2.5 V, the ratio of R1 to R2 calculates as 3:1. Standard values of 3.01 k\(\Omega\) (R1) and 1.00 k\(\Omega\) (R2) are chosen. Other values can be used as long as the 3:1 ratio is maintained. The selected values, however, provide a small amount of output loading (2.5 mA) in the event that the main load is disconnected and allows the circuit to maintain regulation until the main load is reconnected.

8.2.2.2 Frequency Selection

F_s and R_{\text{ON}}: Unless the application requires a specific frequency, the choice of frequency is generally a compromise because the size of L1 and C2, and the switching losses are affected. The maximum-allowed frequency, based on a minimum on-time of 250 ns, is calculated by Equation 6:

\[
F_{\text{MAX}} = \frac{V_{\text{OUT}}}{(V_{\text{INMAX}} \times 250 \text{ ns})}
\] (6)

For this exercise, F_{\text{MAX}} = 444 kHz. From Equation 2, R_{\text{ON}} calculates to 180 k\(\Omega\). A standard-value, 237-k\(\Omega\) resistor is used to allow for tolerances in Equation 2, resulting in a nominal frequency of 337 kHz.

8.2.2.3 Inductor Selection

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 current occurs at maximum V_{\text{IN}}.

a. Minimum load current: To maintain continuous conduction at minimum I_O (100 mA), the ripple amplitude (I_{\text{OR}}) must be less than 200 mA peak-to-peak so the lower peak of the waveform does not reach zero. L1 is calculated using Equation 7:

\[
L1 = \frac{V_{\text{OUT1}} \times (V_{\text{IN}} - V_{\text{OUT1}})}{I_{\text{OR}} \times F_s \times V_{\text{IN}}}
\] (7)

At V_{\text{IN}} = 90 V, L1 (min) calculates to 132 \(\mu\)H. The next larger standard value (150 \(\mu\)H) is chosen and, with this value, I_{\text{OR}} calculates to 176 mA peak-to-peak at V_{\text{IN}} = 90 V and 33 mA peak-to-peak at V_{\text{IN}} = 12 V.

b. Maximum load current: At a load current of 150 mA, the peak of the ripple waveform must not reach the minimum value of the LM5009 current limit threshold (250 mA). Therefore, the ripple amplitude must be less than 200 mA peak-to-peak, which is already satisfied in Equation 7. With L1 = 150 \(\mu\)H, at maximum V_{\text{IN}} and I_O, the peak of the ripple is 238 mA. Although L1 must carry this peak current without saturating or exceeding its temperature rating, L1 must also be capable of carrying the maximum value of the LM5009 current limit threshold (370 mA) without saturating because the current limit is reached during startup.

8.2.2.4 VCC and Bootstrap Capacitor

C3: The capacitor on the V_{\text{CC}} output provides not only noise filtering and stability, but also prevents false triggering of the V_{\text{CC}} UVLO at the buck switch on and off transitions. For this reason, C3 must be no smaller than 0.1 \(\mu\)F.

C4: The recommended value is 0.022 \(\mu\)F for C4 because this value is appropriate in the majority of applications. A high-quality ceramic capacitor, with low ESR is recommended because C4 supplies the surge current to charge the buck switch gate at turn-on. A low ESR also ensures a quick recharge during each off-time. At minimum VIN when the on-time is at maximum, C4 can possibly not fully recharge at start-up during each 300-ns off-time. This failure to recharge results from the circuit being unable to complete the start-up and achieve output regulation. This condition can occur when the frequency is intended to be low (for example, R_{\text{ON}} = 500 k\(\Omega\)). In this case, increase C4 to maintain sufficient voltage across the buck switch driver during each on-time.
8.2.2.5 Output Capacitor Selection

C2 and R3: When selecting the output filter capacitor C2, the items to consider are ripple voltage resulting from the C2 ESR, ripple voltage resulting from the C2 capacitance, and the nature of the load.

a. ESR and R3: A low ESR for C2 is generally desirable to minimize power losses and heating within the capacitor. However, this regulator requires a minimum amount of ripple voltage at the feedback input for proper loop operation. For the LM5009, the minimum ripple required at pin 5 is 25 mV peak-to-peak, requiring a minimum ripple at \( V_{OUT1} \) of 100 mV. The minimum ESR required at \( V_{OUT1} \) is 3 \( \Omega \) because the minimum ripple current (at minimum \( V_{IN} \)) is 33 mA peak-to-peak. R3 is inserted as illustrated in the Functional Block Diagram section because quality capacitors for SMPS applications have considerably less ESR. The value of R3, along with the ESR of C2, must result in at least a 25-mV peak-to-peak ripple at pin 5. Generally, R3 is 0.5 \( \Omega \) to 5.0 \( \Omega \).

b. Nature of the load: The load can be connected to \( V_{OUT1} \) or \( V_{OUT2} \). \( V_{OUT1} \) provides good regulation, but with a ripple voltage that ranges from 100 mV (at \( V_{IN} = 12 \) V) to 580 mV (at \( V_{IN} = 90 \) V). Alternatively, \( V_{OUT2} \) provides low ripple (3 mV to 13 mV) but lower regulation resulting from R3. C2 generally must be no smaller than 3.3 \( \mu F \). Typically, the value of C2 is 10 \( \mu F \) to 20 \( \mu F \), with the optimum value determined by the load. If the load current is fairly constant, a small value suffices for C2. If the load current includes significant transients, a larger value is necessary. For each application, experimentation is needed to determine the optimum values for R3 and C2.

c. Ripple reduction: The ripple amplitude at \( V_{OUT1} \) can be reduced by reducing R3 and by adding a capacitor across R1 to transfer the ripple at \( V_{OUT1} \) directly to the FB pin without attenuation. The new value of R3 is calculated by Equation 8:

\[
R3 = \frac{25 \text{ mV}}{I_{OR(min)}}
\]

where

- \( I_{OR(min)} \) is the minimum ripple current amplitude—33 mA peak-to-peak in this example

The added capacitor value is calculated by Equation 9:

\[
C = \frac{T_{ON(max)}}{(R1 // R2)}
\]

where

- \( T_{ON(max)} \) is the maximum on-time (at minimum \( V_{IN} \))

The selected capacitor must be larger than the value calculated in Equation 9.

8.2.2.6 Current Limit Off-Timer Setting

R\(_{CL}\): When a current limit condition is detected, the minimum off-time set by this resistor must be greater than the maximum normal off-time that occurs at maximum \( V_{IN} \). Using Equation 4, the minimum on-time is 0.329 \( \mu \)s, yielding a maximum off-time of 2.63 \( \mu \)s. This value is further increased by 82 ns (to 2.72 \( \mu \)s), resulting from a \( \pm 25\% \) tolerance of the on-time. This value is then increased to allow for the response time of the current limit detection loop (400 ns).

The off-time determined by Equation 5 has a \( \pm 25\% \) tolerance, as given by Equation 10:

\[
I_{OFFCL(MIN)} = (2.72 \mu s \times 1.25) + 0.4 \mu s = 3.8 \mu s
\]

Using Equation 5, \( R_{CL} \) calculates to 167 k\( \Omega \) (at \( V_{FB} = 2.5 \) V). The closest standard value is 169 k\( \Omega \).
8.2.2.7 Rectifier Diode Selection

D1: The important parameters are reverse recovery time and forward voltage. Reverse recovery time determines how long the reverse current surge lasts each time that the buck switch is turned on. The forward voltage drop is significant in the event that the output is short-circuited because only this diode voltage forces the inductor current to reduce during the forced off-time. For this reason, a higher voltage is better, although higher voltages affect efficiency. A good choice is an ultrafast or Schottky diode with a reverse recovery time of approximately 30 ns and a forward voltage drop of approximately 0.7 V. Other types of diodes can have a lower forward voltage drop, but can also have longer recovery times or greater reverse leakage. The D1 reverse voltage rating must be at least as great as the maximum \( V_{IN} \), and the D1 current rating must be greater than the maximum current limit threshold (370 mA).

8.2.2.8 Input Capacitor Selection

C1: The purpose of this capacitor is to supply most of the switch current during the on-time and to limit the voltage ripple at \( V_{IN} \), on the assumption that the voltage source feeding \( V_{IN} \) has an output impedance greater than zero. At maximum load current, when the buck switch turns on, the current into pin 8 suddenly increases to the lower peak of the output current waveform, ramps up to the peak value, and then drops to zero at turn-off. The average input current during this on-time is the load current (150 mA). 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 2 V (for this exercise), C1 calculates to \( \frac{I \times t_{ON}}{\Delta V} \) where \( I = 0.15 \text{A} \), \( t_{ON} = 2.47 \mu s \), and \( V_{IN} = 2.0 \text{V} \), which results in an expression of 0.185 \( \mu F \) (Equation 11):

\[
C1 = \frac{I \times t_{ON}}{\Delta V} = \frac{0.15 \text{A} \times 2.47 \mu s}{2.0 \text{V}} = 0.185 \mu F
\]

Quality ceramic capacitors in this value have a low ESR that adds only a few millivolts to the ripple. The capacitance is dominant in this case. To allow for the capacitor tolerance, temperature effects, and voltage effects, a 1.0-\( \mu F \), 100-V, X7R capacitor is used.

C5: This capacitor helps avoid supply voltage transients and ringing resulting from long lead inductance at \( V_{IN} \). A low-ESR, 0.1-\( \mu F \) ceramic chip capacitor is recommended, located close to the LM5009.
8.2.2.9 Ripple Configuration

The LM5009 uses a constant-on-time (COT) control scheme where the on-time is terminated by a one-shot and the off-time is terminated by the feedback voltage ($V_{FB}$) falling below the reference voltage. Therefore, for stable operation, the feedback voltage must decrease monotonically in phase with the inductor current during the off-time. Furthermore, this change in feedback voltage ($V_{FB}$) during off-time must be large enough to dominate any noise present at the feedback node.

Table 2 presents three different methods for generating appropriate voltage ripple at the feedback node. Type 1 and type 2 ripple circuits couple the ripple from the output of the converter to the feedback node (FB). The output voltage ripple has two components:

1. Capacitive ripple caused by the inductor current ripple charging or discharging the output capacitor.
2. Resistive ripple caused by the inductor current ripple flowing through the ESR of the output capacitor and $R_3$.

Table 2. Ripple Configuration

<table>
<thead>
<tr>
<th>TYPE 1</th>
<th>TYPE 2</th>
<th>TYPE 3</th>
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</thead>
<tbody>
<tr>
<td>Lowest cost</td>
<td>Reduced ripple</td>
<td>Minimum ripple</td>
</tr>
</tbody>
</table>

$R_3 \geq \frac{25 \text{ mV} \times V_O}{V_{REF} \times \Delta I_{L1,\text{min}}}$  \hspace{1cm} (12) \\
$C_{th} \geq \frac{5}{F_{SW} \times (R_{FB2} || R_{FB1})}$  \hspace{1cm} (13) \\
$R_A C_A \geq \frac{(V_{IN,\text{min}} - V_O) \times T_{ON@V_{IN,\text{min}}}}{25 \text{ mV}}$  \hspace{1cm} (14)

The capacitive ripple is out of phase with the inductor current. As a result, the capacitive ripple does not decrease monotonically during the off-time. The resistive ripple is in phase with the inductor current and decreases monotonically during the off-time. The resistive ripple must exceed the capacitive ripple at output ($V_{OUT}$) for stable operation. If this condition is not satisfied, then unstable switching behavior is observed in COT converters with multiple on-time bursts in close succession followed by a long off-time.

The type 3 ripple method uses a ripple injection circuit with $R_A$, $C_A$, and the switch node (SW) voltage to generate a triangular ramp. This triangular ramp is then ac-coupled into the feedback node (FB) using the capacitor $C_B$. This circuit is suited for applications where low output voltage ripple is imperative because this circuit does not use the output voltage ripple. See application note AN-1481 Controlling Output Ripple and Achieving ESR Independence in Constant On-Time (COT) Regulator Designs, SNVA166 for more details on each ripple generation method.
8.2.3 Application Curves

![Efficiency vs Load Current and V_IN](image1)

![Efficiency vs V_IN and Load Current](image2)

![V_OUT vs Load Current](image3)

![Current Limit vs V_IN](image4)

8.3 Do’s and Don’ts

A minimum load current of 1 mA is required to maintain proper operation. If the load current falls below that level, the bootstrap capacitor can discharge during the long off-time and the circuit either shuts down or cycles on and off at a low frequency. If the load current is expected to drop below 1 mA in the application, choose the feedback resistors to be low enough in value to provide the minimum required current at nominal V_OUT.

9 Power Supply Recommendations

The LM5009 is designed to operate with an input power supply capable of supplying a voltage range between 9 V and 95 V. The input power supply must be well-regulated and capable of supplying sufficient current to the regulator during peak load operation. Also, like in all applications, the power-supply source impedance must be small compared to the module input impedance to maintain the stability of the converter.
10 Layout

10.1 Layout Guidelines

The LM5009 regulation and overvoltage comparators are very fast, and as such respond to short-duration noise pulses. Layout considerations are therefore critical for optimum performance. The components at pins 1, 2, 3, 5, and 6 must be as physically close as possible to the device, thereby minimizing noise pickup in the PC tracks. The two major current loops conduct currents that switch very fast and, therefore, those loops must be as small as possible to minimize conducted and radiated electromagnetic interference (EMI). The first loop is formed by $C_{IN}$, through the VIN to SW pins, $L_{IND}$, $C_{OUT}$, and back to $C_{IN}$. The second current loop is formed by D1, $L_{IND}$, and $C_{OUT}$.

If the internal dissipation of the LM5009 produces excessive junction temperatures during normal operation, good use of the PC board ground plane can help considerably to dissipate heat. The exposed pad on the bottom of the WSON-8 package can be soldered to a ground plane on the PC board, and that plane must extend out from beneath the device to help dissipate heat. Additionally, the use of wide PC board traces, where possible, can also help conduct heat away from the device. Judicious positioning of the PC board within the end product, along with the use of any available air flow (forced or natural convection) can help reduce the junction temperatures.

10.2 Layout Example

![Diagram of LM5009 Buck Layout Example with the WSON Package](image)

Figure 14. LM5009 Buck Layout Example with the WSON Package
11 Device and Documentation Support

11.1 Documentation Support

11.1.1 Related Documentation

Application note AN-1481 Controlling Output Ripple and Achieving ESR Independence in Constant On-Time (COT) Regulator Designs, SNVA166

11.2 Community Resources

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's Terms of Use.

**TI E2E™ Online Community**  *TI's Engineer-to-Engineer (E2E) Community.* Created to foster collaboration among engineers. At e2e.ti.com, you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

**Design Support**  *TI's Design Support* Quickly find helpful E2E forums along with design support tools and contact information for technical support.

11.3 Trademarks

E2E is a trademark of Texas Instruments. WEBENCH is a registered trademark of Texas Instruments. All other trademarks are the property of their respective owners.

11.4 Electrostatic Discharge Caution

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

11.5 Glossary

**SLYZ022 — Ti Glossary.**

This glossary lists and explains terms, acronyms, and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.
### PACKAGING INFORMATION

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<th>Orderable Device</th>
<th>Status</th>
<th>Package Type</th>
<th>Package Drawing</th>
<th>Pins</th>
<th>Package Qty</th>
<th>Eco Plan</th>
<th>Lead/Ball Finish</th>
<th>MSL Peak Temp</th>
<th>Op Temp (°C)</th>
<th>Device Marking</th>
<th>Samples</th>
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<td>Call TI</td>
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(1) The marketing status values are defined as follows:
- **ACTIVE**: Product device recommended for new designs.
- **LIFEBUY**: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
- **NRND**: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
- **PREVIEW**: Device has been announced but is not in production. Samples may or may not be available.
- **OBSOLETE**: TI has discontinued the production of the device.

(2) **RoHS**: TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".
- **RoHS Exempt**: TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.
- **Green**: TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(3) **MSL, Peak Temp. -** The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

(6) **Lead/Ball Finish -** Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.
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## TAPE AND REEL INFORMATION

**REEL DIMENSIONS**

**TAPE DIMENSIONS**

*A0 Dimension designed to accommodate the component width
*B0 Dimension designed to accommodate the component length
*K0 Dimension designed to accommodate the component thickness
*W Overall width of the carrier tape
*P1 Pitch between successive cavity centers

**QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE**

*All dimensions are nominal.

<table>
<thead>
<tr>
<th>Device</th>
<th>Package Type</th>
<th>Drawing</th>
<th>Pins</th>
<th>SPQ</th>
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### TAPE AND REEL BOX DIMENSIONS

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*All dimensions are nominal*
DGK (S-PDSO-G8)  PLASTIC SMALL-OUTLINE PACKAGE

NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 per end.
D. Body width does not include interlead flash. Interlead flash shall not exceed 0.50 per side.
E. Falls within JEDEC MO-187 variation AA, except interlead flash.

4073329/E 05/06
NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Publication IPC–7351 is recommended for alternate designs.
D. Laser cutting apertures with trapezoidal walls and also rounding corners will offer better paste release. Customers should contact their board assembly site for stencil design recommendations. Refer to IPC–7525 for other stencil recommendations.
E. Customers should contact their board fabrication site for solder mask tolerances between and around signal pads.
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