LM3404/04HV
1.0A Constant Current Buck Regulator for Driving High Power LEDs

General Description
The LM3404/04HV are monolithic switching regulators designed to deliver constant currents to high power LEDs. Ideal for automotive, industrial, and general lighting applications, they contain a high-side N-channel MOSFET switch with a current limit of 1.5A (typical) for step-down (Buck) regulators. Hysteretic controlled on-time and an external resistor allow the converter output voltage to adjust as needed to deliver a constant current to series and series-parallel connected LED arrays of varying number and type. LED dimming via pulse width modulation (PWM), broken/open LED protection, low-power shutdown and thermal shutdown complete the feature set.

Features
- Integrated 1.0A MOSFET
- $V_{IN}$ Range 6V to 42V (LM3404)
- $V_{IN}$ Range 6V to 75V (LM3404HV)
- 1.2A Output Current Over Temperature
- Cycle-by-Cycle Current Limit
- No Control Loop Compensation Required
- Separate PWM Dimming and Low Power Shutdown
- Supports all-ceramic output capacitors and capacitor-less outputs
- Thermal shutdown protection
- SO-8 Package, PSOP-8 Package

Applications
- LED Driver
- Constant Current Source
- Automotive Lighting
- General Illumination
- Industrial Lighting

Typical Application
Connection Diagrams

8-Lead Plastic SO-8 Package
NS Package Number M08A

8-Lead Plastic PSOP-8 Package
NS Package Number MRA08B

Ordering Information

<table>
<thead>
<tr>
<th>Order Number</th>
<th>Package Type</th>
<th>NSC Package Drawing</th>
<th>Supplied As</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM3404MA</td>
<td>SO-8</td>
<td>M08A</td>
<td>95 units in anti-static rails</td>
</tr>
<tr>
<td>LM3404MAX</td>
<td>SO-8</td>
<td></td>
<td>2500 units on tape and reel</td>
</tr>
<tr>
<td>LM3404HVMA</td>
<td>SO-8</td>
<td></td>
<td>95 units in anti-static rails</td>
</tr>
<tr>
<td>LM3404HVMAX</td>
<td>PSOP-8</td>
<td>MRA08B</td>
<td>2500 units on tape and reel</td>
</tr>
<tr>
<td>LM3404MR</td>
<td>PSOP-8</td>
<td></td>
<td>95 units in anti-static rails</td>
</tr>
<tr>
<td>LM3404MRX</td>
<td></td>
<td></td>
<td>2500 units on tape and reel</td>
</tr>
<tr>
<td>LM3404HVMR</td>
<td></td>
<td></td>
<td>95 units in anti-static rails</td>
</tr>
<tr>
<td>LM3404HVMRX</td>
<td></td>
<td></td>
<td>2500 units on tape and reel</td>
</tr>
</tbody>
</table>

Pin Descriptions

<table>
<thead>
<tr>
<th>Pin(s)</th>
<th>Name</th>
<th>Description</th>
<th>Application Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SW</td>
<td>Switch pin</td>
<td>Connect this pin to the output inductor and Schottky diode.</td>
</tr>
<tr>
<td>2</td>
<td>BOOT</td>
<td>MOSFET drive bootstrap pin</td>
<td>Connect a 10 nF ceramic capacitor from this pin to SW.</td>
</tr>
<tr>
<td>3</td>
<td>DIM</td>
<td>Input for PWM dimming</td>
<td>Connect a logic-level PWM signal to this pin to enable/disable the power MOSFET and reduce the average light output of the LED array.</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
<td>Ground pin</td>
<td>Connect this pin to system ground.</td>
</tr>
<tr>
<td>5</td>
<td>CS</td>
<td>Current sense feedback pin</td>
<td>Set the current through the LED array by connecting a resistor from this pin to ground.</td>
</tr>
<tr>
<td>6</td>
<td>RON</td>
<td>On-time control pin</td>
<td>A resistor connected from this pin to VIN sets the regulator controlled on-time.</td>
</tr>
<tr>
<td>7</td>
<td>VCC</td>
<td>Output of the internal 7V linear regulator</td>
<td>Bypass this pin to ground with a minimum 0.1 μF ceramic capacitor with X5R or X7R dielectric.</td>
</tr>
<tr>
<td>8</td>
<td>VIN</td>
<td>Input voltage pin</td>
<td>Nominal operating input range for this pin is 6V to 42V (LM3404) or 6V to 75V (LM3404HV).</td>
</tr>
<tr>
<td></td>
<td>DAP</td>
<td>Thermal Pad</td>
<td>Connect to ground. Place 4-6 vias from DAP to bottom layer ground plane.</td>
</tr>
</tbody>
</table>
## Absolute Maximum Ratings

**LM3404** (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

- **VIN to GND**: -0.3V to 45V
- **BOOT to GND**: -0.3V to 59V
- **SW to GND**: -1.5V to 45V
- **BOOT to VCC**: -0.3V to 45V
- **BOOT to SW**: -0.3V to 14V
- **VCC to GND**: -0.3V to 14V
- **DIM to GND**: -0.3V to 7V
- **CS to GND**: -0.3V to 7V
- **RON to GND**: -0.3V to 7V
- **Junction Temperature**: 150°C

### Storage Temp. Range
- -65°C to 125°C

### ESD Rating (Note 2)
- 2kV

### Soldering Information
- **Lead Temperature (Soldering, 10sec)**: 260°C
- **Infrared/Convection Reflow (15sec)**: 235°C

### Operating Ratings (LM3404)

**Note 1**

- **$V_{IN}$**: 6V to 42V
- **Junction Temperature Range**: −40°C to +125°C
- **Thermal Resistance $\theta_{JA}$** (SO-8 Package)
  - 155°C/W
- **Thermal Resistance $\theta_{JA}$** (PSOP-8 Package) (Note 5)
  - 50°C/W
Absolute Maximum Ratings
(LM3404HV) (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. to Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIN to GND</td>
<td>-0.3V to 76V</td>
</tr>
<tr>
<td>BOOT to GND</td>
<td>-0.3V to 90V</td>
</tr>
<tr>
<td>SW to GND</td>
<td>-1.5V to 76V</td>
</tr>
<tr>
<td>BOOT to VCC</td>
<td>-0.3V to 76V</td>
</tr>
<tr>
<td>BOOT to SW</td>
<td>-0.3V to 14V</td>
</tr>
<tr>
<td>VCC to GND</td>
<td>-0.3V to 14V</td>
</tr>
<tr>
<td>DIM to GND</td>
<td>-0.3V to 7V</td>
</tr>
<tr>
<td>CS to GND</td>
<td>-0.3V to 7V</td>
</tr>
<tr>
<td>RON to GND</td>
<td>-0.3V to 7V</td>
</tr>
<tr>
<td>Junction Temperature</td>
<td>150°C</td>
</tr>
</tbody>
</table>

VCC to GND: -0.3V to 14V

Boot to VCC: -0.3V to 76V

Boot to SW: -0.3V to 14V

Boot to GND: -0.3V to 90V

SW to GND: -1.5V to 76V

Junction Temperature: 150°C

Storage Temp. Range: -65°C to 125°C

ESD Rating (Note 2): 2kV

Soldering Information

Lead Temperature (Soldering, 10sec): 260°C

Infrared/Convection Reflow (15sec): 235°C

Operating Ratings (LM3404HV)
(Note 1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. to Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_IN</td>
<td>6V to 75V</td>
</tr>
<tr>
<td>Junction Temperature Range</td>
<td>-40°C to +125°C</td>
</tr>
<tr>
<td>Thermal Resistance $\theta_{JA}$ (SO-8 Package)</td>
<td>155°C/W</td>
</tr>
<tr>
<td>Thermal Resistance $\theta_{JA}$ (PSOP-8 Package) (Note 5)</td>
<td>50°C/W</td>
</tr>
</tbody>
</table>

www.national.com
### Electrical Characteristics

$V_{IN} = 24\text{V}$ unless otherwise indicated. Typicals and limits appearing in plain type apply for $T_A = T_J = +25^\circ\text{C}$. (Note 4) Limits appearing in **boldface type** apply over full Operating Temperature Range. Datasheet min/max specification limits are guaranteed by design, test, or statistical analysis.

#### LM3404

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{ON-1}$</td>
<td>On-time 1</td>
<td>$V_{IN} = 10\text{V}, R_{ON} = 200\text{ k}\Omega$</td>
<td>2.1</td>
<td>2.75</td>
<td>3.4</td>
<td>$\mu\text{s}$</td>
</tr>
<tr>
<td>$t_{ON-2}$</td>
<td>On-time 2</td>
<td>$V_{IN} = 40\text{V}, R_{ON} = 200\text{ k}\Omega$</td>
<td>515</td>
<td>675</td>
<td>835</td>
<td>$\text{ns}$</td>
</tr>
</tbody>
</table>

#### LM3404HV

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{ON-1}$</td>
<td>On-time 1</td>
<td>$V_{IN} = 10\text{V}, R_{ON} = 200\text{ k}\Omega$</td>
<td>2.1</td>
<td>2.75</td>
<td>3.4</td>
<td>$\mu\text{s}$</td>
</tr>
<tr>
<td>$t_{ON-2}$</td>
<td>On-time 2</td>
<td>$V_{IN} = 70\text{V}, R_{ON} = 200\text{ k}\Omega$</td>
<td>325</td>
<td>415</td>
<td>505</td>
<td>$\text{ns}$</td>
</tr>
</tbody>
</table>

#### LM3404/LM3404HV

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{REF-REG}$</td>
<td>CS Regulation Threshold</td>
<td>CS Decreasing, SW turns on</td>
<td>194</td>
<td>200</td>
<td>206</td>
<td>mV</td>
</tr>
<tr>
<td>$V_{REF-0V}$</td>
<td>CS Over-voltage Threshold</td>
<td>CS Increasing, SW turns off</td>
<td>300</td>
<td></td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>$I_{CS}$</td>
<td>CS Bias Current</td>
<td>CS = 0V</td>
<td>0.1</td>
<td></td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>$V_{SD-TH}$</td>
<td>Shutdown Threshold</td>
<td>$R_{ON} / SD$ Increasing</td>
<td>0.3</td>
<td>0.7</td>
<td>1.05</td>
<td>V</td>
</tr>
<tr>
<td>$V_{SD-HYS}$</td>
<td>Shutdown Hysteresis</td>
<td>$R_{ON} / SD$ Decreasing</td>
<td>40</td>
<td></td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>$I_{OFF-MIN}$</td>
<td>Minimum Off-time</td>
<td>CS = 0V</td>
<td>270</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>$V_{CC-REG}$</td>
<td>$V_{CC}$ Regulated Output</td>
<td></td>
<td>6.4</td>
<td>7</td>
<td>7.4</td>
<td>V</td>
</tr>
<tr>
<td>$V_{IN-DO}$</td>
<td>$V_{IN} \cdot V_{CC}$</td>
<td>$I_{CC} = 5\text{ mA}, 6.0\text{V} &lt; V_{IN} &lt; 8.0\text{V}$</td>
<td>300</td>
<td></td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>$V_{CC-BP-TH}$</td>
<td>$V_{CC}$ Bypass Threshold</td>
<td>$V_{IN}$ Increasing</td>
<td>8.8</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>$V_{CC-BP-HYS}$</td>
<td>$V_{CC}$ Bypass Hysteresis</td>
<td>$V_{IN}$ Decreasing</td>
<td>230</td>
<td></td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>$V_{CC-Z-6}$</td>
<td>$V_{CC}$ Output Impedance (0 mA &lt; $I_{CC}$ &lt; 5 mA)</td>
<td>$V_{IN} = 6\text{V}$</td>
<td>55</td>
<td></td>
<td></td>
<td>Ω</td>
</tr>
<tr>
<td>$V_{CC-Z-8}$</td>
<td>$V_{CC}$ Output Impedance (0 mA &lt; $I_{CC}$ &lt; 5 mA)</td>
<td>$V_{IN} = 8\text{V}$</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{CC-Z-24}$</td>
<td>$V_{CC} = 24\text{V}$</td>
<td>$V_{IN} = 24\text{V}$</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{CC-LIM}$</td>
<td>$V_{CC}$ Current Limit (Note 3)</td>
<td>$V_{IN} = 24\text{V}, V_{CC} = 0\text{V}$</td>
<td>16</td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>$V_{CC-UV-TH}$</td>
<td>$V_{CC}$ Under-voltage Lock-out Threshold</td>
<td>$V_{CC}$ Increasing</td>
<td>5.3</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>$V_{CC-UV-HYS}$</td>
<td>$V_{CC}$ Under-voltage Lock-out Hysteresis</td>
<td>$V_{CC}$ Decreasing</td>
<td>150</td>
<td></td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>$V_{CC-UV-DLY}$</td>
<td>$V_{CC}$ Under-voltage Lock-out Filter Delay</td>
<td>100 mV Overdrive</td>
<td>3</td>
<td></td>
<td></td>
<td>µs</td>
</tr>
<tr>
<td>$I_{IN-QP}$</td>
<td>$I_{IN}$ Operating Current</td>
<td>Non-switching, CS = 0.5V</td>
<td>625</td>
<td>900</td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>$I_{IN-SD}$</td>
<td>$I_{IN}$ Shutdown Current</td>
<td>$R_{ON} / SD = 0\text{V}$</td>
<td>95</td>
<td>180</td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>$I_{LIM}$</td>
<td>Current Limit Threshold</td>
<td></td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>A</td>
</tr>
<tr>
<td>Symbol</td>
<td>Parameter</td>
<td>Conditions</td>
<td>Min</td>
<td>Typ</td>
<td>Max</td>
<td>Units</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------</td>
<td>-----------------------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-------</td>
</tr>
<tr>
<td>DIM COMPARATOR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{IH}$</td>
<td>Logic High</td>
<td>DIM Increasing</td>
<td>2.2</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>$V_{IL}$</td>
<td>Logic Low</td>
<td>DIM Decreasing</td>
<td></td>
<td>0.8</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>$I_{DIM-PU}$</td>
<td>DIM Pull-up Current</td>
<td>DIM = 1.5V</td>
<td>80</td>
<td></td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>MOSFET AND DRIVER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{DS-ON}$</td>
<td>Buck Switch On Resistance</td>
<td>$I_{SW} = 200mA$, BST-SW = 6.3V</td>
<td>0.37</td>
<td>0.75</td>
<td></td>
<td>Ω</td>
</tr>
<tr>
<td>$V_{DR-UVLO}$</td>
<td>BST Under-voltage Lock-out</td>
<td>BST–SW Increasing</td>
<td>1.7</td>
<td>3</td>
<td>4</td>
<td>V</td>
</tr>
<tr>
<td>$V_{DR-HYS}$</td>
<td>BST Under-voltage Lock-out</td>
<td>BST–SW Decreasing</td>
<td></td>
<td></td>
<td>400</td>
<td>mV</td>
</tr>
<tr>
<td>THERMAL SHUTDOWN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{SD}$</td>
<td>Thermal Shutdown Threshold</td>
<td></td>
<td>165</td>
<td></td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>$T_{SD-HYS}$</td>
<td>Thermal Shutdown Hysteresis</td>
<td></td>
<td>25</td>
<td></td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>THERMAL RESISTANCE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{JA}$</td>
<td>Junction to Ambient</td>
<td>SOIC-8 Package</td>
<td>155</td>
<td></td>
<td></td>
<td>°C/W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PSOP-8 Package (Note 5)</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not guaranteed. For guaranteed specifications and the test conditions, see Electrical Characteristics.

Note 2: The human body model is a 100 pF capacitor discharged through a 1.5 kΩ resistor into each pin.

Note 3: VCC provides self bias for the internal gate drive and control circuits. Device thermal limitations limit external loading.

Note 4: Typical specifications represent the most likely parametric norm at 25°C operation.

Note 5: $\theta_{JA}$ of 50°C/W with DAP soldered to a minimum of 2 square inches of 1oz. copper on the top or bottom PCB layer.
Typical Performance Characteristics

$V_{\text{REF}}$ vs Temperature ($V_{\text{IN}} = 24V$)

$V_{\text{REF}}$ vs $V_{\text{IN}}$, LM3404 ($T_A = 25^\circ C$)

Current Limit vs Temperature ($V_{\text{IN}} = 24V$)

Current Limit vs $V_{\text{IN}}$, LM3404 ($T_A = 25^\circ C$)

Current Limit vs $V_{\text{IN}}$, LM3404HV ($T_A = 25^\circ C$)
$T_{\text{ON}}$ vs $V_{\text{IN}}$
$R_{\text{ON}} = 100 \, \text{k}\Omega$ ($T_A = 25\, ^\circ\text{C}$)

$T_{\text{ON}}$ vs $V_{\text{IN}}$
$R_{\text{ON}} = 300 \, \text{k}\Omega$

$R_{\text{ON}} = 200 \, \text{k}\Omega$

$T_{\text{ON}}$ vs $R_{\text{ON}}$, LM3404
$T_A = 25\, ^\circ\text{C}$

$T_{\text{ON}}$ vs $R_{\text{ON}}$, LM3404HV
$T_A = 25\, ^\circ\text{C}$

$V_{\text{CC}}$ vs $V_{\text{IN}}$
$T_A = 25\, ^\circ\text{C}$
Application Information

THEORY OF OPERATION

The LM3404 and LM3404HV are buck regulators with a wide input voltage range, low voltage reference, and a fast output enable/disable function. These features combine to make them ideal for use as a constant current source for LEDs with forward currents as high as 1.2A. The controlled on-time (COT) architecture is a combination of hysteretic mode control and a one-shot on-timer that varies inversely with input voltage. Hysteretic operation eliminates the need for small-signal control loop compensation. When the converter runs in continuous conduction mode (CCM) the controlled on-time maintains a constant switching frequency over the range of input voltage. Fast transient response, PWM dimming, a low power shutdown mode, and simple output overvoltage protection round out the functions of the LM3404/04HV.

CONTROLLED ON-TIME OVERVIEW

*Figure 1* shows the feedback system used to control the current through an array of LEDs. A voltage signal, \( V_{\text{SNS}} \), is created as the LED current flows through the current setting resistor, \( R_{\text{SNS}} \), to ground. \( V_{\text{SNS}} \) is fed back to the CS pin, where it is compared against a 200 mV reference, \( V_{\text{REF}} \). The on-comparator turns on the power MOSFET when \( V_{\text{SNS}} \) falls below \( V_{\text{REF}} \). The power MOSFET conducts for a controlled on-time, \( t_{\text{ON}} \), set by an external resistor, \( R_{\text{ON}} \), and by the input voltage, \( V_{\text{IN}} \). On-time is governed by the following equation:

\[
t_{\text{ON}} = 1.34 \times 10^{-10} \times \frac{R_{\text{ON}}}{V_{\text{IN}}}
\]

At the conclusion of \( t_{\text{ON}} \) the power MOSFET turns off for a minimum off-time, \( t_{\text{OFF-MIN}} \), of 300 ns. Once \( t_{\text{OFF-MIN}} \) is complete the CS comparator compares \( V_{\text{SNS}} \) and \( V_{\text{REF}} \) again, waiting to begin the next cycle.

The LM3404/04HV regulators should be operated in continuous conduction mode (CCM), where inductor current stays positive throughout the switching cycle. During steady-state
CCM operation, the converter maintains a constant switching frequency that can be selected using the following equation:

\[ f_{SW} = \frac{V_O}{1.34 \times 10^{-10} \times R_{ON}} \]

\[ V_O = n \times V_F + 200 \text{ mV} \]

\[ V_F = \text{forward voltage of each LED, } n = \text{number of LEDs in series} \]

**AVERAGE LED CURRENT ACCURACY**

The COT architecture regulates the valley of the forward voltage of the LEDs used, \( V_{F\text{, out}} \), using the typical performance characteristics section:

\[ f_{MAX} = \text{maximum forward voltage of the LEDs used, } V_{F\text{, out}} \times 200 \text{ mV} \]

**MINIMUM OUTPUT VOLTAGE**

The minimum recommended on-time for the LM3404/04HV is 300 ns. This lower limit for \( t_{ON} \) determines the minimum duty cycle and output voltage that can be regulated based on input voltage and switching frequency. The relationship is determined by the following equation, shown on the same graphs as maximum output voltage in the Typical Performance Characteristics section:

\[ V_{O\text{MIN}} = V_{IN} \times \frac{300 \text{ ns}}{T_{SW}} \]

**HIGH VOLTAGE BIAS REGULATOR**

The LM3404/04HV contains an internal linear regulator with a 7V output, connected between the VIN and the VCC pins. The VCC pin should be bypassed to the GND pin with a 0.1 \( \mu\text{F} \) ceramic capacitor connected as close as possible to the pins of the IC. VCC tracks VIN until VIN reaches 8.8V and then regulates at 7V as VIN increases. Operation begins when VCC crosses 5.25V.

**INTERNAL MOSFET AND DRIVER**

The LM3404/04HV features an internal power MOSFET as well as a floating driver connected to the SW pin to the BOOT pin. Both rise time and fall time are 20 ns each (typical) and the approximate gate charge is 6 nC. The high-side rail for the driver circuit uses a bootstrap circuit consisting of an internal high-voltage diode and an external 10 nF capacitor, \( C_{B} \). The VCC charges \( C_{B} \) through the internal diode while the power MOSFET is off. When the MOSFET turns on, the internal diode reverse biases. This creates a floating supply equal to the VCC voltage minus the diode drop to drive the MOSFET when its source voltage is equal to \( V_{IN}^* \).

**FAST SHUTDOWN FOR PWM DIMMING**

The DIM pin of the LM3404/04HV is a TTL compatible input for low frequency PWM dimming of the LED. A logic low (below 0.8V) at DIM will disable the internal MOSFET and shut off the current flow to the LED array. While the DIM pin is in a logic low state the support circuitry (driver, bandgap, VCC) remains active in order to minimize the time needed to turn the LED array back on when the DIM pin sees a logic high (above 2.2V). A 75 \( \mu\text{A} \) pull-up current ensures that the LM3404/04HV is on when DIM is open circuit, eliminating the need for a pull-up resistor. Dimming frequency, \( f_{DIM} \), and duty cycle, \( D_{DIM} \), are limited by the LED current rise time and fall time and the delay from activation of the DIM pin to the response of the internal power MOSFET. In general, \( f_{DIM} \) should be at least one order of magnitude lower than the steady state switching frequency in order to prevent aliasing.

**PEAK CURRENT LIMIT**

The current limit comparator of the LM3404/04HV will engage whenever the power MOSFET current (equal to the inductor current while the MOSFET is on) exceeds 1.5A (typical). The power MOSFET is disabled for a cool-down time that is approximately 75x the steady-state on-time. At the conclusion of this cool-down time the system re-starts. If the current limit condition persists the cycle of cool-down time and restarting will continue, creating a low-power hiccup mode, minimizing thermal stress on the LM3404/04HV and the external circuit components.

**OVER-VOLTAGE/OVER-CURRENT COMPARATOR**

The CS pin includes an output over-voltage/over-current comparator that will disable the power MOSFET whenever...
$V_{\text{SN}}$ exceeds 300 mV. This threshold provides a hard limit for the output current. Output current overshoot is limited to 300 mV / $R_{\text{SN}}$ by this comparator during transients.

The OVP/OCP comparator can also be used to prevent the output voltage from rising to $V_{\text{O(\text{MAX})}}$ in the event of an output open-circuit. This is the most common failure mode for LEDs, due to breaking of the bond wires. In a current regulator an output open circuit causes $V_{\text{SN}}$ to fall to zero, commanding maximum duty cycle. Figure 2 shows a method using a zener diode, Z1, and zener limiting resistor, $R_Z$, to limit output voltage to the reverse breakdown voltage of Z1 plus 200 mV. The zener diode reverse breakdown voltage, $V_Z$, must be greater than the maximum combined $V_f$ of all LEDs in the array. The maximum recommended value for $R_Z$ is 1 k$\Omega$.

As discussed in the Maximum Output Voltage section, there is a limit to how high $V_O$ can rise during an output open-circuit that is always less than $V_{\text{IN}}$. If no output capacitor is used, the output stage of the LM3404/04HV is capable of withstanding $V_{\text{O(\text{MAX})}}$ indefinitely, however the voltage at the output end of the inductor will oscillate and can go above $V_{\text{IN}}$ or below 0V. A small (typically 10 nF) capacitor across the LED array dampens this oscillation. For circuits that use an output capacitor, the system can still withstand $V_{\text{O(\text{MAX})}}$ indefinitely as long as C_O is rated to handle $V_{\text{IN}}$. The high current paths are blocked in output open-circuit and the risk of thermal stress is minimal, hence the user may opt to allow the output voltage to rise in the case of an open-circuit LED failure.

**LOW POWER SHUTDOWN**

The LM3404/04HV can be placed into a low power state ($I_{\text{IN-SD}} = 90$ $\mu$A) by grounding the RON pin with a signal-level MOSFET as shown in Figure 3. Low power MOSFETs like the 2N7000, 2N3904, or equivalent are recommended devices for putting the LM3404/04HV into low power shutdown. Logic gates can also be used to shut down the LM3404/04HV as long as the logic low voltage is below the over temperature minimum threshold of 0.3V. Noise filter circuitry on the RON pin can cause a few pulses with longer on-times than normal after RON is grounded or released. In these cases the OVP/OCP comparator will ensure that the peak inductor or LED current does not exceed 300 mV / $R_{\text{SN}}$. **FIGURE 3. Low Power Shutdown**
THERMAL SHUTDOWN

Internal thermal shutdown circuitry is provided to protect the IC in the event that the maximum junction temperature is exceeded. The threshold for thermal shutdown is 165°C with a 25°C hysteresis (both values typical). During thermal shutdown the MOSFET and driver are disabled.

Design Considerations

SWITCHING FREQUENCY

Switching frequency is selected based on the trade-offs between efficiency (better at low frequency), solution size/cost (smaller at high frequency), and the range of output voltage that can be regulated (wider at lower frequency.) Many applications place limits on switching frequency due to EMI sensitivity. The on-time of the LM3404/04HV can be programmed for switching frequencies ranging from the 10’s of kHz to over 1 MHz. The maximum switching frequency is limited only by the minimum on-time and minimum off-time requirements.

LED RIPPLE CURRENT

Selection of the ripple current, $\Delta I_F$, through the LED array is analogous to the selection of output ripple voltage in a standard voltage regulator. Where the output ripple in a voltage regulator is commonly $\pm 1\%$ to $\pm 5\%$ of the DC output voltage, LED manufacturers generally recommend values for $\Delta I_F$ ranging from $\pm 5\%$ to $\pm 20\%$ of $I_F$. Higher LED ripple current allows the use of smaller inductors, smaller output capacitors, or no output capacitors at all. The advantages of higher ripple current are reduction in the solution size and cost. Lower ripple current requires more output inductance, higher switching frequency, or additional output capacitance. The advantages of lower ripple current are a reduction in heating in the LED itself and greater tolerance in the average LED current before the current limit of the LED or the driving circuitry is reached.

BUCK CONVERTERS WITHOUT OUTPUT CAPACITORS

The buck converter is unique among non-isolated topologies because of the direct connection of the inductor to the load during the entire switching cycle. By definition an inductor will control the rate of change of current that flows through it, and this control over current ripple forms the basis for component selection in both voltage regulators and current regulators. A current regulator such as the LED driver for which the LM3404/04HV was designed focuses on the control of the current through the load, not the voltage across it. A constant current regulator is free of load current transients, and has no need of output capacitance to supply the load and maintain output voltage. Referring to the Typical Application circuit on the front page of this datasheet, the inductor and LED can form a single series chain, sharing the same current. When no output capacitor is used, the same equations that govern inductor ripple current, $\Delta I_L$, also apply to the LED ripple current, $\Delta I_F$. For a controlled on-time converter such as LM3404/04HV the ripple current is described by the following expression:

$$\Delta I_L = \Delta I_F = \frac{V_{IN} - V_O}{L} \cdot I_{ON}$$

A minimum ripple voltage of 25 mV is recommended at the CS pin to provide good signal to noise ratio (SNR). The CS pin ripple voltage, $\Delta V_{SNS}$, is described by the following:

$$\Delta V_{SNS} = \Delta I_F \times R_{SNS}$$

BUCK CONVERTERS WITH OUTPUT CAPACITORS

A capacitor placed in parallel with the LED or array of LEDs can be used to reduce the LED current ripple while keeping the same average current through both the inductor and the LED array. This technique is demonstrated in Design Examples 1 and 2. With this topology the output inductance can be lowered, making the inductors smaller and less expensive. Alternatively, the circuit could be run at lower frequency but keep the same inductor value, improving the efficiency and expanding the range of output voltage that can be regulated. Both the peak current limit and the OVP/OCP comparator still monitor peak inductor current, placing a limit on how large $\Delta I_L$ can be even if $\Delta I_F$ is made very small. A parallel output capacitor is also useful in applications where the inductor or input voltage tolerance is poor. Adding a capacitor that reduces $\Delta I_F$ to well below the target provides headroom for changes in inductance or $V_{IN}$ that might otherwise push the peak LED ripple current too high.

Figure 4 shows the equivalent impedances presented to the inductor current ripple when an output capacitor, $C_O$, and its equivalent series resistance (ESR) are placed in parallel with the LED array. The entire inductor ripple current flows through $R_{SNS}$ to provide the required 25 mV of ripple voltage for proper operation of the CS comparator.

To calculate the respective ripple currents the LED array is represented as a dynamic resistance, $r_D$. LED dynamic resistance is not always specified on the manufacturer’s datasheet, but it can be calculated as the inverse slope of the LED’s $V_F$ vs. $I_F$ curve. Note that dividing $V_F$ by $I_F$ will give an incorrect value that is 5x to 10x too high. Total dynamic resistance for a string of n LEDs connected in series can be calculated as the $r_D$ of one device multiplied by n. Inductor ripple current is still calculated with the expression from Buck Regulators without Output Capacitors. The following equations can then be used to estimate $\Delta I_F$ when using a parallel capacitor:

$$\Delta I_F = \frac{\Delta I_L}{1 + \frac{r_D}{Z_C}}$$

$$Z_C = ESR + \frac{1}{2\pi \times f_{SW} \times C_O}$$

The calculation for $Z_C$ assumes that the shape of the inductor ripple current is approximately sinusoidal.
Small values of \( C_{O} \) that do not significantly reduce \( \Delta i_{F} \) can also be used to control EMI generated by the switching action of the LM3404/04HV. EMI reduction becomes more important as the length of the connections between the LED and the rest of the circuit increase.

**INPUT CAPACITORS**

Input capacitors at the VIN pin of the LM3404/04HV are selected using requirements for minimum capacitance and rms ripple current. The input capacitors supply pulses of current approximately equal to \( I_{F} \) while the power MOSFET is on, and are charged up by the input voltage while the power MOSFET is off. Switching converters such as the LM3404/04HV have a negative input impedance due to the decrease in input current as input voltage increases. This inverse proportionality of input current to input voltage can cause oscillations (sometimes called ‘power supply interaction’) if the magnitude of the negative input impedance is greater than the input filter impedance. Minimum capacitance can be selected by comparing the input impedance to the converter’s negative resistance; however, this requires accurate calculation of the input voltage source inductance and resistance, quantities which can be difficult to determine. An alternative method to select the minimum input capacitance, \( C_{IN(MIN)} \), is to select the maximum input voltage ripple which can be tolerated. This value, \( \Delta V_{IN(MAX)} \), is equal to the change in voltage across \( C_{IN} \) during the converter on-time, when \( C_{IN} \) supplies the load current. \( C_{IN(MIN)} \) can be selected with the following:

\[
C_{IN(MIN)} = \frac{I_{F} \times t_{ON}}{\Delta V_{IN(MAX)}}
\]

A good starting point for selection of \( C_{IN} \) is to use an input voltage ripple of 5% to 10% of \( V_{IN} \). A minimum input capacitance of 2x the \( C_{IN(MIN)} \) value is recommended for all LM3404/04HV circuits. To determine the rms current rating, the following formula can be used:

\[
I_{IN(rms)} = I_{F} \times \sqrt{D(1 - D)}
\]

Ceramic capacitors are the best choice for the input to the LM3404/04HV due to their high ripple current rating, low ESR, low cost, and small size compared to other types. When selecting a ceramic capacitor, special attention must be paid to the operating conditions of the application. Ceramic capacitors can lose one-half or more of their capacitance at their rated DC voltage bias and also lose capacitance with extremes in temperature. A DC voltage rating equal to twice the expected maximum input voltage is recommended. In addition, the minimum quality dielectric which is suitable for switching power supply inputs is X5R, while X7R or better is preferred.

**RECRYCLATING DIODE**

The LM3404/04HV is a non-synchronous buck regulator that requires a recirculating diode \( D_{1} \) (see the Typical Application circuit) to carrying the inductor current during the MOSFET off-time. The most efficient choice for \( D_{1} \) is a Schottky diode due to low forward drop and near-zero reverse recovery time. \( D_{1} \) must be rated to handle the maximum input voltage plus any switching node ringing when the MOSFET is on. In practice all switching converters have some ringing at the switching node due to the diode parasitic capacitance and the lead inductance. \( D_{1} \) must also be rated to handle the average current, \( I_{D} \), calculated as:

\[
I_{D} = (1 - D) \times I_{F}
\]

This calculation should be done at the maximum expected input voltage. The overall converter efficiency becomes more dependent on the selection of \( D_{1} \) at low duty cycles, where the recirculating diode carries the load current for an increasing percentage of the time. This power dissipation can be calculated by checking the typical diode forward voltage, \( V_{F} \), from the I-V curve on the product datasheet and then multiplying it by \( I_{D} \). Diode datasheets will also provide a typical junction-to-ambient thermal resistance, \( \theta_{JA} \), which can be used to estimate the operating die temperature of the device. Multiplying the power dissipation \( P_{D} = I_{D} \times V_{F} \) by \( \theta_{JA} \) gives the temperature rise. The diode case size can then be selected to maintain the Schottky diode temperature below the operational maximum.

**Design Example 1: LM3404**

The first example circuit will guide the user through component selection for an architectural accent lighting application. A regulated DC voltage input of 24V ±10% will power a 5.4W "warm white" LED module that consists of four LEDs in a 2 x 2 series-parallel configuration. The module will be treated as a two-terminal element and driven with a forward current of 700 mA ±5%. The typical forward voltage of the LED module in thermal steady state is 6.9V, hence the average output voltage will be 7.1V. The objective of this application is to place the complete current regulator and LED module in a compact space formerly occupied by a halogen light source. (The LED will be on a separate metal-core PCB and heatsink.) Switching frequency will be 400 kHz to keep switching loss low, as the confined space with no air-flow requires a maximum temperature rise of 50°C in each circuit component. A small solution size is also important, as the regulator must fit on a circular PCB with a 1.5" diameter. A complete bill of materials can be found in Table 1 at the end of this datasheet.
A moderate switching frequency is needed in this application to balance the requirements of magnetics size and efficiency. \( R_{\text{ON}} \) is selected from the equation for switching frequency as follows:

\[
R_{\text{ON}} = \frac{V_{O}}{1.34 \times 10^{-10} \times f_{\text{SW}}}
\]

\( R_{\text{ON}} = 7.1 / (1.34 \times 10^{-10} \times 4 \times 10^5) = 132.5 \, \text{k}\Omega \)

The closest 1% tolerance resistor is 133 k\( \Omega \). The switching frequency and on-time of the circuit can then be found using the equations relating \( R_{\text{ON}} \) and \( t_{\text{ON}} \) to \( f_{\text{SW}} \):

\[
f_{\text{SW}} = \frac{7.1}{(1.34 \times 10^5 \times 1.34 \times 10^{-10})} = 398 \, \text{kHz}
\]

\[
t_{\text{ON}} = (1.34 \times 10^{-10} \times 1.33 \times 10^5) / 24 = 743 \, \text{ns}
\]

**OUTPUT INDUCTOR**

Since an output capacitor will be used to filter some of the AC ripple current, the inductor ripple current can be set higher than the LED ripple current. A value of 40% \( \Delta I \) is typical in many buck converters:

\[
\Delta I_L = 0.4 \times 0.7 = 0.28 \, \text{A}
\]

With the target ripple current determined the inductance can be chosen:

\[
L_{\text{MIN}} = \frac{V_{IN} - V_{O}}{\Delta I_L} \times t_{\text{ON}}
\]

\[
L_{\text{MIN}} = [(24 - 7.1) \times 7.43 \times 10^{-7}] / (0.28) = 44.8 \, \mu\text{H}
\]

The closest standard inductor value is 47 \( \mu\text{H} \). The average current rating should be greater than 700 mA to prevent overheating in the inductor. Separation between the LM3404 drivers and the LED arrays means that heat from the inductor will not threaten the lifetime of the LEDs, but an overheated inductor could still cause the LM3404 to enter thermal shutdown.

The inductance of the standard part chosen is ±20%. With this tolerance the typical, minimum, and maximum inductor current ripples can be calculated:

\[
\Delta I_{L(TYP)} = [(24 - 7.1) \times 7.43 \times 10^{-7}] / 47 \times 10^{-6} = 266 \, \text{mA}_{p-p}
\]

\[
\Delta I_{L(MIN)} = [(24 - 7.1) \times 7.43 \times 10^{-7}] / 56 \times 10^{-6} = 223 \, \text{mA}_{p-p}
\]

\[
\Delta I_{L(MAX)} = [(24 - 7.1) \times 7.43 \times 10^{-7}] / 38 \times 10^{-6} = 330 \, \text{mA}_{p-p}
\]

The peak LED/inductor current is then estimated:

\[
I_{L(PEAK)} = I_L + 0.5 \times \Delta I_{L(MAX)}
\]

\[
I_{L(PEAK)} = 0.7 + 0.5 \times 0.330 = 866 \, \text{mA}
\]

In the case of a short circuit across the LED array, the LM3404 will continue to deliver rated current through the short but will reduce the output voltage to equal the CS pin voltage of 200 mV. The inductor ripple current and peak current in this condition would be equal to:

\[
\Delta I_{L(LED-SHORT)} = [(24 - 0.2) \times 7.43 \times 10^{-7}] / 38 \times 10^{-6} = 465 \, \text{mA}_{p-p}
\]

\[
I_{L(PEAK)} = 0.7 + 0.5 \times 0.465 = 933 \, \text{mA}
\]

In the case of a short at the switch node, the output, or from the CS pin to ground the short circuit current limit will engage...
at a typical peak current of 1.5A. In order to prevent inductor saturation during these fault conditions the inductor’s peak current rating must be above 1.5A. A 47 µH off-the-shelf inductor rated to 1.4A (peak) and 1.5A (average) with a DCR of 0.1Ω will be used.

USING AN OUTPUT CAPACITOR
This application does not require high frequency PWM dimming, allowing the use of an output capacitor to reduce the size and cost of the output inductor. To select the proper output capacitor the equation from Buck Regulators with Output Capacitors is re-arranged to yield the following:

\[ Z_C = \frac{\Delta I_F}{\Delta I_L} \times R_D \]

The target tolerance for LED ripple current is 100 mAP, and a typical value for \( R_D \) of 1.8Ω at 700 mA can be read from the LED datasheet. The required capacitor impedance to reduce the worst-case inductor ripple current of 333 mAAP, is therefore:

\[ Z_C = \frac{0.1}{0.333 - 0.1} \times 1.8 = 0.77\Omega \]

A ceramic capacitor will be used and the required capacitance is selected based on the impedance at 400 kHz:

\[ C_O = \frac{1}{(2 \pi \times 0.77 \times 4 \times 10^9)} = 0.51 \mu F \]

This calculation assumes that impedance due to the equivalent series resistance (ESR) and equivalent series inductance (ESL) of \( C_O \) is negligible. The closest 10% tolerance capacitor value is 1.0 µF. The capacitor used should be rated to 25V or more and have an X7R dielectric. Several manufacturers provide ceramic capacitors with these specifications in the 0805 case size. A typical value for ESL of 3 mΩ can be read from the curve of impedance vs. frequency in the product datasheet.

\[ R_{SNS} = \frac{0.2 \times L}{I_F \times L + V_O \times t_{SNS} \times \frac{V_{IN} - V_O}{2} \times t_{ON}} \]

\[ t_{SNS} = 220 \text{ ns}, R_{SNS} = 0.33\Omega \]

Sub-1Ω resistors are available in both 1% and 5% tolerance. A 1%, 0.33Ω device is the closest value, and a 0.33Ω, 1206 size device will handle the power dissipation of 162 mW. With the resistance selected, the average value of LED current is re-calculated to ensure that current is within the ±5% tolerance requirement. From the expression for average LED current:

\[ I_F = \frac{0.2 \times 0.33 \times (7.1 \times 2.2 \times 10^{-7})}{47 \times 10^6 + 0.266 / 2} \]

\[ I_F = 0.706 \text{ mA}, 1\% \text{ above 700 mA} \]

INPUT CAPACITOR
Following the calculations from the Input Capacitor section, \( \Delta V_{IN(MAX)} \) will be 24V x 2% AP = 480 mV. The minimum required capacitance is:

\[ C_{IN(MIN)} = \left( \frac{0.7 \times 7.4 \times 10^{-7}}{0.48} \right) = 1.1 \mu F \]

To provide additional safety margin a higher value of 3.3 µF ceramic capacitor rated to 50V with X7R dielectric in an 1210 case size will be used. From the Design Considerations section, input rms current is:

\[ I_{IN-RMS} = 0.7 \times \text{sqrt}(0.28 \times 0.72) = 314 \text{ mA} \]

Ripple current ratings for 1210 size ceramic capacitors are typically higher than 2A, more than enough for this design.

RECYCLING DIODE
The input voltage of 24V ±5% requires Schottky diodes with a reverse voltage rating greater than 30V. The next highest standard voltage rating is 40V. Selecting a 40V rated diode provides a large safety margin for the ringing of the switch node and also makes cross-referencing of diodes from different vendors easier.

The next parameters to be determined are the forward current rating and case size. In this example the low duty cycle (D = 71 / 24 = 28%) places a greater thermal stress on D1 than on the internal power MOSFET of the LM3404. The estimated average diode current is:

\[ I_D = 0.706 \times 0.72 = 509 \text{ mA} \]

A Schottky with a forward current rating of 1A would be adequate, however reducing the power dissipation is critical in this example. Higher current diodes have lower forward voltages, hence a 2A-rated diode will be used. To determine the proper case size, the dissipation and temperature rise in D1 can be calculated as shown in the Design Considerations section. \( V_D \) for a case size such as SMB in a 40V, 2A Schottky diode at 700 mA is approximately 0.3V and the \( \theta_{JA} \) is 75°C/W. Power dissipation and temperature rise can be calculated as:

\[ P_D = 0.509 \times 0.3 = 153 \text{ mW} \]

\[ T_{RISE} = 0.153 \times 75 = 11.5^\circ C \]

\( C_B \) AND \( C_F \)
The bootstrap capacitor \( C_B \) should always be a 10 nF ceramic capacitor with X7R dielectric. A 25V rating is appropriate for all application circuits. The linear regulator filter capacitor \( C_F \) should always be a 100 nF ceramic capacitor, also with X7R dielectric and a 25V rating.

EFFICIENCY
To estimate the electrical efficiency of this example the power dissipation in each current carrying element can be calculated and summed. Electrical efficiency, \( \eta \), should not be confused
with the optical efficacy of the circuit, which depends upon the LEDs themselves.

Total output power, \( P_O \), is calculated as:
\[
P_O = I_F \times V_O = 0.706 \times 7.1 = 5W
\]

Conduction loss, \( P_C \), in the internal MOSFET:
\[
P_C = (I_F^2 \times R_{DSON}) \times D = (0.706^2 \times 0.8) \times 0.28 = 112 \text{ mW}
\]

Gate charging and VCC loss, \( P_G \), in the gate drive and linear regulator:
\[
P_G = (I_{IN-OP} + f_{SW} \times Q_G) \times V_{IN}
\]
\[
P_G = (600 \times 10^{-6} + 4 \times 10^5 \times 6 \times 10^{-9}) \times 24 = 72 \text{ mW}
\]

Switching loss, \( P_S \), in the internal MOSFET:
\[
P_S = 0.5 \times V_{IN} \times I_F \times (t_R + t_F) \times f_{SW}
\]
\[
P_S = 0.5 \times 24 \times 0.706 \times 40 \times 10^{-9} \times 4 \times 10^5 = 136 \text{ mW}
\]

AC rms current loss, \( P_{CIN} \), in the input capacitor:
\[
P_{CIN} = I_{IN(m)}^2 \times ESR = 0.317^2 \times 0.003 = 0.3 \text{ mW (negligible)}
\]

DCR loss, \( P_L \), in the inductor
\[
P_L = I_F^2 \times DCR = 0.706^2 \times 0.1 = 50 \text{ mW}
\]

Recirculating diode loss, \( P_D \) = 153 mW

Current Sense Resistor Loss, \( P_{SNS} \) = 164 mW

Electrical efficiency, \( \eta = P_O / (P_O + \text{Sum of all loss terms}) = 5 / (5 + 0.687) = 88\%

Temperature Rise in the LM3404 IC is calculated as:
\[
T_{LM3404} = (P_C + P_G + P_S) \times \theta_{JA} = (0.112 + 0.072 + 0.136) \times 155 = 49.2^\circ C
\]

**Design Example 2: LM3404HV**

The second example circuit will guide the user through component selection for an outdoor general lighting application. A regulated DC voltage input of 48V ±10% will power ten series-connected LEDs at 500 mA ±10% with a ripple current of 50 mA\text{P-P} or less. The typical forward voltage of the LED module in thermal steady state is 35V, hence the average output voltage will be 35.2V. A complete bill of materials can be found in Table 2 at the end of this datasheet.

\[
R_{ON} = \frac{V_O}{1.34 \times 10^{-10} \times f_{SW}}
\]
\[
R_{ON} = 35.2 / (1.34 \times 10^{-10} \times 2.25 \times 10^9) = 1.16 \text{ M\Omega}
\]

The next highest 1% tolerance resistor is 1.18 M\Omega. The switching frequency and on-time of the circuit can then be found using the equations relating \( R_{ON} \) and \( t_{ON} \) to \( f_{SW} \):

\[
f_{SW} = \frac{35.2}{(1.18 \times 10^6 \times 1.34 \times 10^{-10})} = 223 \text{ kHz}
\]
\[
t_{ON} = (1.34 \times 10^{-10} \times 1.18 \times 10^9) / 48 = 3.3 \mu s
\]

**OUTPUT INDUCTOR**

Since an output capacitor will be used to filter some of the AC ripple current, the inductor ripple current can be set higher than the LED ripple current. A value of 30\%\text{P-P} makes a good trade-off between the current ripple and the size of the inductor:

\[
\Delta I_L = 0.3 \times 0.5 = 0.15A
\]
With the target ripple current determined the inductance can be chosen:

\[
L_{\text{MIN}} = \frac{V_{\text{IN}} - V_{\text{O}}}{\Delta i_L} \times t_{\text{ON}}
\]

\[
L_{\text{MIN}} = \left(\frac{(48 - 35.2) \times 3.3 \times 10^{-6}}{0.15}\right) = 281 \mu\text{H}
\]

The closest standard inductor value above 281 is 330 µH. The average current rating should be greater than 0.5A to prevent overheating in the inductor. In this example the LM3404HV driver and the LED array share the same metal-core PCB, meaning that heat from the inductor could threaten the lifetime of the LEDs. For this reason the average current rating of the inductor used should have a de-rating of about 50%, or 1A.

The inductance of the standard part chosen is ±20%. With this tolerance the typical, minimum, and maximum inductor current ripples can be calculated:

\[
\Delta i_{L,\text{TYP}} = \left(\frac{(48 - 35.2) \times 3.3 \times 10^{-6}}{330 \times 10^{-6}}\right) = 128 \text{ mA}_{\text{P-P}}
\]

\[
\Delta i_{L,\text{MIN}} = \left(\frac{(48 - 35.2) \times 3.3 \times 10^{-6}}{396 \times 10^{-6}}\right) = 107 \text{ mA}_{\text{P-P}}
\]

\[
\Delta i_{L,\text{MAX}} = \left(\frac{(48 - 35.2) \times 3.3 \times 10^{-6}}{264 \times 10^{-6}}\right) = 160 \text{ mA}_{\text{P-P}}
\]

The peak inductor current is then estimated:

\[
i_{L,\text{PEAK}} = I_{\text{L}} + 0.5 \times \Delta i_{L,\text{MAX}}
\]

\[
i_{L,\text{PEAK}} = 0.5 + 0.5 \times 0.16 = 0.58 \text{A}
\]

In the case of a short circuit across the LED array, the LM3404HV will continue to deliver rated current through the short but will reduce the output voltage to equal the CS pin voltage of 200 mV. The inductor ripple current and peak current in this condition would be equal to:

\[
\Delta i_{L,\text{LED-SHORT}} = \left(\frac{(48 - 0.2) \times 3.3 \times 10^{-6}}{264 \times 10^{-6}}\right) = 0.598\text{mA}_{\text{P-P}}
\]

\[
i_{L,\text{PEAK}} = 0.5 + 0.5 \times 0.598 = 0.8 \text{A}
\]

In the case of a short at the switch node, the output, or from the CS pin to ground the short circuit current limit will engage at a typical peak current of 1.5A. In order to prevent inductor saturation during these fault conditions the inductor’s peak current rating must be above 1.5A. A 330 µH off-the-shelf inductor rated to 1.9A (peak) and 1.0A (average) with a DCR of 0.56Ω will be used.

**USING AN OUTPUT CAPACITOR**

This application uses sub-1 kHz frequency PWM dimming, allowing the use of a small output capacitor to reduce the size and cost of the output inductor. To select the proper output capacitor the equation from Buck Regulators with Output Capacitors is re-arranged to yield the following:

\[
Z_C = \frac{\Delta i_{F}}{\Delta i_L - \Delta i_{F}} \times r_D
\]

The target tolerance for LED ripple current is 50 mA_{P-P}, and the typical value for r_D is 10Ω with ten LEDs in series. The required capacitor impedance to reduce the worst-case steady-state inductor ripple current of 160 mA_{P-P} is therefore:

\[
Z_C = \left[0.05 / (0.16 - 0.05)\right] \times 10 = 4.5\Omega
\]

A ceramic capacitor will be used and the required capacitance is selected based on the impedance at 223 kHz:

\[
C_O = \frac{1}{(2 \times \pi \times 4.5 \times 2.23 \times 10^5)} = 0.16 \mu\text{F}
\]

This calculation assumes that impedance due to the equivalent series resistance (ESR) and equivalent series inductance (ESL) of C_O is negligible. The closest 10% tolerance capacitor value is 0.15 µF. The capacitor used should be rated to 50V or more and have an X7R dielectric. Several manufacturers produce ceramic capacitors with these specifications in the 0805 case size. ESR values are not typically provided for such low value capacitors, however is can be assumed to be under 100 mΩ, leaving plenty of margin to meet to LED ripple current requirement. The low capacitance required allows the use of a 100V rated, 1206-size capacitor. The rating of 100V ensures that the capacitance will not decrease significantly when the DC output voltage is applied across the capacitor.

**R_{SNS}**

A preliminary value for R_{SNS} was determined in selecting \(\Delta i_L\). This value should be re-evaluated based on the calculations for \(\Delta i_{F}\):

\[
R_{SNS} = \frac{0.2 \times L}{I_F \times L + V_O \times t_{SNS} - \frac{V_{\text{IN}} - V_O}{2} \times t_{\text{ON}}}
\]

\[
t_{\text{SNS}} = 220 \text{ ns}, R_{\text{SNS}} = 0.43\Omega
\]

Sub-1Ω resistors are available in both 1% and 5% tolerance. A 1%, 0.43Ω device is the closest value, and a 0.25W, 0805 size device will handle the power dissipation of 110 mW. With the resistance selected, the average value of LED current is re-calculated to ensure that current is within the ±10% tolerance requirement. From the expression for average LED current:

\[
I_F = \frac{0.2 / 0.43 - (35.2 \times 2.2 \times 10^{-7}) / 330 \times 10^{-6} + 0.128 / 2}{2} = 505 \text{ mA}
\]
INPUT CAPACITOR

Following the calculations from the Input Capacitor section, \(\Delta V_{\text{IN(MAX)}}\) will be 48V x 2% = 960 mV. The minimum required capacitance is:

\[
C_{\text{IN(MIN)}} = \frac{(0.5 \times 3.3 \times 10^{-6})}{0.96} = 1.7 \mu F
\]

To provide additional safety margin a 2.2 \(\mu F\) ceramic capacitor rated to 100V with X7R dielectric in an 1812 case size will be used. From the Design Considerations section, input rms current is:

\[
I_{\text{IN-RMS}} = 0.5 \times \text{Sqrt}(0.73 \times 0.27) = 222 \text{ mA}
\]

Ripple current ratings for 1812 size ceramic capacitors are typically higher than 2A, more than enough for this design, and the ESR is approximately 3 m\(\Omega\).

RECYCLING DIODE

The input voltage of 48V requires Schottky diodes with a reverse voltage rating greater than 50V. The next highest standard voltage rating is 60V. Selecting a 60V rated diode provides a large safety margin for the ringing of the switch node and also makes cross-referencing of diodes from different vendors easier.

The next parameters to be determined are the forward current rating and case size. In this example the high duty cycle (\(D = 35.2 / 48 = 73\%\)) places a greater thermal stress on the internal MOSFET than on D1. The estimated average diode current is:

\[
I_D = 0.5 \times 0.27 = 135 \text{ mA}
\]

A Schottky with a forward current rating of 0.5A would be adequate, however reducing the power dissipation is critical in this example. Higher current diodes have lower forward voltages, hence a 1A-rated diode will be used. To determine the proper case size, the dissipation and temperature rise in D1 can be calculated as shown in the Design Considerations section. \(V_F\) for a case size such as SMA in a 60V, 1A Schottky diode at 0.5A is approximately 0.35V and the \(\theta_{JA}\) is 75°C/W. Power dissipation and temperature rise can be calculated as:

\[
P_D = 0.135 \times 0.35 = 47 \text{ mW}
\]

\[
T_{\text{RISE}} = 0.047 \times 75 = 3.5^\circ C
\]

**C\(\text{B}\) AND C\(\text{F}\)**

The bootstrap capacitor \(C_B\) should always be a 10 n\(\Omega\) ceramic capacitor with X7R dielectric. A 25V rating is appropriate for all application circuits. The linear regulator filter capacitor \(C_F\) should always be a 100 n\(\Omega\) ceramic capacitor, also with X7R dielectric and a 25V rating.

**EFFICIENCY**

To estimate the electrical efficiency of this example the power dissipation in each current carrying element can be calculated and summed. Electrical efficiency, \(\eta\), should not be confused with the optical efficacy of the circuit, which depends upon the LEDs themselves.

Total output power, \(P_O\), is calculated as:

\[
P_O = I_F \times V_O = 0.5 \times 35.2 = 17.6W
\]

Conduction loss, \(P_C\), in the internal MOSFET:

\[
P_C = (I_D^2 \times R_{\text{DSON}}) \times D = (0.5^2 \times 0.8) \times 0.73 = 146 \text{ mW}
\]

Gate charging and VCC loss, \(P_G\), in the gate drive and linear regulator:

\[
P_G = (I_{\text{IN-MOP}} + f_{\text{SW}} \times Q_{\text{G}}) \times V_{\text{IN}}
\]

\[
P_G = (600 \times 10^{-6} + 2.23 \times 10^5 \times 6 \times 10^{-9}) \times 48 = 94 \text{ mW}
\]

Switching loss, \(P_S\), in the internal MOSFET:

\[
P_S = 0.5 \times V_{\text{IN}} \times I_F \times (t_q + t_e) \times f_{\text{SW}}
\]

\[
P_S = 0.5 \times 48 \times 0.5 \times 40 \times 10^{-6} \times 2.23 \times 10^5 = 107 \text{ mW}
\]

AC rms current loss, \(P_{\text{CIN}}\), in the input capacitor:

\[
P_{\text{CIN}} = I_{\text{IN RMS}}^2 \times ESR = 0.222^2 \times 0.003 = 0.1 \text{ mW (negligible)}
\]

DCR loss, \(P_L\), in the inductor:

\[
P_L = I_F^2 \times DCR = 0.5^2 \times 0.56 = 140 \text{ mW}
\]

Recirculating diode loss, \(P_D\), is 47 mW

Current Sense Resistor Loss, \(P_{\text{SNS}}\) is 110 mW

Electrical efficiency, \(\eta\), should not be confused:

\[
\eta = P_O / (P_O + \text{Sum of all loss terms}) = 17.6 / (17.6 + 0.644) = 96\%
\]

Temperature Rise in the LM3404HV IC is calculated as:

\[
T_{\text{LM3404}} = (P_C + P_G + P_S) \times \theta_{JA} = (0.146 + 0.094 + 0.107) \times 155 = 54^\circ C
\]

**Layout Considerations**

The performance of any switching converter depends as much upon the layout of the PCB as the component selection. The following guidelines will help the user design a circuit with maximum rejection of outside EMI and minimum generation of unwanted EMI.

**COMPACT LAYOUT**

Parasitic inductance can be reduced by keeping the power path components close together and keeping the area of the loops that high currents travel small. Short, thick traces or copper pours (shapes) are best. In particular, the switch node (where L1, D1, and the SW pin connect) should be just large enough to connect all three components without excessive heating from the current it carries. The LM3404/04HV operates in two distinct cycles whose high current paths are shown in Figure 7.
The dark grey, inner loop represents the high current path during the MOSFET on-time. The light grey, outer loop represents the high current path during the off-time.

**GROUND PLANE AND SHAPE ROUTING**

The diagram of Figure 7 is also useful for analyzing the flow of continuous current vs. the flow of pulsating currents. The circuit paths with current flow during both the on-time and off-time are considered to be continuous current, while those that carry current during the on-time or off-time only are pulsating currents. Preference in routing should be given to the pulsating current paths, as these are the portions of the circuit most likely to emit EMI. The ground plane of a PCB is a conductor and return path, and it is susceptible to noise injection just as any other circuit path. The continuous current paths on the ground net can be routed on the system ground plane with less risk of injecting noise into other circuits. The path between the input source and the input capacitor and the path between the recirculating diode and the LEDs/current sense resistor are examples of continuous current paths. In contrast, the path between the recirculating diode and the input capacitor carries a large pulsating current. This path should be routed with a short, thick shape, preferably on the component side of the PCB. Multiple vias in parallel should be used right at the pad of the input capacitor to connect the component side shapes to the ground plane. A second pulsating current loop that is often ignored is the gate drive loop formed by the SW and BOOT pins and capacitor C_G. To minimize this loop at the EMI it generates, keep C_G close to the SW and BOOT pins.

**CURRENT SENSING**

The CS pin is a high-impedance input, and the loop created by R_SNS, R_Z (if used), the CS pin and ground should be made as small as possible to maximize noise rejection. R_SNS should therefore be placed as close as possible to the CS and GND pins of the IC.

**REMOTE LED ARRAYS**

In some applications the LED or LED array can be far away (several inches or more) from the LM3404/04HV, or on a separate PCB connected by a wiring harness. When an output capacitor is used and the LED array is large or separated from the rest of the converter, the output capacitor should be placed close to the LEDs to reduce the effects of parasitic inductance on the AC impedance of the capacitor. The current sense resistor should remain on the same PCB, close to the LM3404/04HV.
### TABLE 1. BOM for Design Example 1

<table>
<thead>
<tr>
<th>ID</th>
<th>Part Number</th>
<th>Type</th>
<th>Size</th>
<th>Parameters</th>
<th>Qty</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>LM3404</td>
<td>LED Driver</td>
<td>SO-8</td>
<td>42V, 1.2A</td>
<td>1</td>
<td>NSC</td>
</tr>
<tr>
<td>L1</td>
<td>SLF10145T-470M1R4</td>
<td>Inductor</td>
<td>10 x 10 x 4.5mm</td>
<td>47 µH, 1.4A, 120 mΩ</td>
<td>1</td>
<td>TDK</td>
</tr>
<tr>
<td>D1</td>
<td>CMSH2-40</td>
<td>Schottky Diode</td>
<td>SMB</td>
<td>40V, 2A</td>
<td>1</td>
<td>Central Semi</td>
</tr>
<tr>
<td>Cf</td>
<td>VJ0805Y104KXXAT</td>
<td>Capacitor</td>
<td>0805</td>
<td>10 nF 10%</td>
<td>1</td>
<td>Vishay</td>
</tr>
<tr>
<td>Cb</td>
<td>VJ0805Y103KXXAT</td>
<td>Capacitor</td>
<td>0805</td>
<td>10 nF 10%</td>
<td>1</td>
<td>Vishay</td>
</tr>
<tr>
<td>Cin</td>
<td>C3225X7R1H335M</td>
<td>Capacitor</td>
<td>1210</td>
<td>3.3 µF, 50V</td>
<td>1</td>
<td>TDK</td>
</tr>
<tr>
<td>Co</td>
<td>C2012X7R1E105M</td>
<td>Capacitor</td>
<td>0805</td>
<td>1.0 µF, 25V</td>
<td>1</td>
<td>TDK</td>
</tr>
<tr>
<td>Rsns</td>
<td>ERJ8BQFR33V</td>
<td>Resistor</td>
<td>1206</td>
<td>0.33Ω 1%</td>
<td>1</td>
<td>Panasonic</td>
</tr>
<tr>
<td>Ron</td>
<td>CRCW08051333F</td>
<td>Resistor</td>
<td>0805</td>
<td>133 kΩ 1%</td>
<td>1</td>
<td>Vishay</td>
</tr>
</tbody>
</table>

### TABLE 2. BOM for Design Example 2

<table>
<thead>
<tr>
<th>ID</th>
<th>Part Number</th>
<th>Type</th>
<th>Size</th>
<th>Parameters</th>
<th>Qty</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>LM3404HV</td>
<td>LED Driver</td>
<td>SO-8</td>
<td>75V, 1.2A</td>
<td>1</td>
<td>NSC</td>
</tr>
<tr>
<td>L1</td>
<td>DO5022P-334</td>
<td>Inductor</td>
<td>18.5 x 15.4 x 7.1mm</td>
<td>330 µH, 1.9A, 0.56Ω</td>
<td>1</td>
<td>Coilcraft</td>
</tr>
<tr>
<td>D1</td>
<td>CMSH1-60M</td>
<td>Schottky Diode</td>
<td>SMA</td>
<td>60V, 1A</td>
<td>1</td>
<td>Central Semi</td>
</tr>
<tr>
<td>Cf</td>
<td>VJ0805Y104KXXAT</td>
<td>Capacitor</td>
<td>0805</td>
<td>100 nF 10%</td>
<td>1</td>
<td>Vishay</td>
</tr>
<tr>
<td>Cb</td>
<td>VJ0805Y103KXXAT</td>
<td>Capacitor</td>
<td>0805</td>
<td>10 nF 10%</td>
<td>1</td>
<td>Vishay</td>
</tr>
<tr>
<td>Cin</td>
<td>C4532X7R2A225M</td>
<td>Capacitor</td>
<td>1812</td>
<td>2.2 µF, 100V</td>
<td>1</td>
<td>TDK</td>
</tr>
<tr>
<td>Co</td>
<td>C3216X7R2A154M</td>
<td>Capacitor</td>
<td>1206</td>
<td>0.15 µF, 100V</td>
<td>1</td>
<td>TDK</td>
</tr>
<tr>
<td>Rsns</td>
<td>ERJ6BQFR43V</td>
<td>Resistor</td>
<td>0805</td>
<td>0.43Ω 1%</td>
<td>1</td>
<td>Panasonic</td>
</tr>
<tr>
<td>Ron</td>
<td>CRCW08051184F</td>
<td>Resistor</td>
<td>0805</td>
<td>1.18 MΩ 1%</td>
<td>1</td>
<td>Vishay</td>
</tr>
</tbody>
</table>
Physical Dimensions inches (millimeters) unless otherwise noted

SO-8 Package
NS Package Number M08A

PSOP-8 Package
NS Package Number MRA08B