ABSTRACT
Sensing the inductor DCR voltage can be an accurate and lossless technique of obtaining current information in DC/DC regulators. The absence of a series current sense resistor permits high current and high efficiency designs at a lower cost and higher density. Inductor DCR sensing also allows continuous monitoring of the inductor current as opposed to MOSFET $R_{DS(ON)}$ sensing that usually samples the voltage information across a FET during a small interval of time. Unlike MOSFETs, inductors can be purchased with low tolerance DCR specifications thus increasing the overall current sense accuracy.

Contents

1 Introduction .................................................................................................................. 2
2 DCR Current Sense Topology .................................................................................... 2
3 LM27402 DCR Current Sense Design ........................................................................ 3
4 CS- Current Source Compliance Voltage ................................................................... 4
5 Example Application .................................................................................................. 4
6 Layout ........................................................................................................................ 5
7 $C_{SBY}$ Placement ........................................................................................................ 5
8 CS+ and CS- Traces .................................................................................................... 5

List of Figures

1 DCR Current Sense Topology ......................................................................................... 2
2 DCR Sense Equivalent Circuit ...................................................................................... 2
3 LM27402 Typical Current Limit Circuit ...................................................................... 3
4 Added Resistor for Noise Rejection ............................................................................ 3
5 Resistor Divider Network .......................................................................................... 4
1 Introduction

The LM27402 is equipped with a low offset current sense comparator to handle inductor DCR current sense applications. A +10 µA current in series with a resistor provides a voltage offset compared to the DCR voltage to set the current limit level. This application report walks through the process of choosing the DCR current sense circuit components to optimize the current limit performance of the LM27402 DC/DC buck regulator controller.

2 DCR Current Sense Topology

Figure 1 shows a typical topology for sensing the DCR voltage in a buck regulator.

![Figure 1. DCR Current Sense Topology](image)

Components $R_S$ and $C_S$ create an RC filter. The time constant of the RC filter should match the time constant related to the inductor and its DCR to accurately reproduce the DCR voltage across $C_S$. Given the following circuit:

![Figure 2. DCR Sense Equivalent Circuit](image)

The derivation for matching time constants is as follows:

$$V_{DCR}(s) = V_L \frac{R_{DCR}}{sL + R_{DCR}} = \frac{1}{C_S} R_S \left( \frac{1}{R_S C_S + 1} \right)$$

$$\frac{1}{sL} + 1 = \frac{1}{R_S C_S + 1}$$

$$R_S C_S + 1 = \frac{sL}{R_{DCR}} + 1$$

$$R_S C_S = \frac{L}{R_{DCR}}$$

$$T_{RC} = T_L$$

(1)

If the time constants do not match, the voltage $V_S$ will either lead or lag $V_{DCR}$. Particularly:

- If $T_{RC} > T_L$, $V_S$ will lag $V_{DCR}$ by a factor of $T_{RC}/T_L$ at any point in time $<< T_{RC}$.
- If $T_{RC} < T_L$, $V_S$ will lead $V_{DCR}$ by factor of $T_{RC}/T_L$ at any point in time $<< T_{RC}$.
Time constant mismatching can be useful in some situations where tight or loose limiting of current limit must be applied. For example, if a buck regulator responds readily to fast dI/dt load transients, the inductor current must supply the output current in addition to the output capacitor current. This can cause the inductor current to temporarily overshoot, thereby, exceeding the current limit setpoint. The \( V_S \) signal can filter this event if \( \tau_{RC} \) is designed moderately larger than \( \tau_L \) in anticipation of inductor overshoot. However, time constant mismatching must be used carefully. If \( \tau_{RC} \) is much greater than \( \tau_L \), the inductor current may reach dangerous levels before the current limit condition is detected.

### 3 LM27402 DCR Current Sense Design

The LM27402 is designed to detect the voltage across the DCR of an inductor through the use of a sensitive current limit comparator. Five current limit events within 32 switching cycles must occur to mitigate the effects of noise and transitory over current events before hiccup mode activates. This allows the current limit level to be set close to the peak inductor ripple current during maximum output current where the voltage across the comparator may only be several millivolts. Figure 3 shows the typical circuit used to set the current limit level:

\[ R_{SET} = \frac{I_{LIMIT} R_{DCR}}{I_{CS}} \]  

\( I_{LIMIT} \) (A) is the desired current limit level, \( R_{DCR} \) (\( \Omega \)) is the rated DC resistance of the inductor (DCR), and \( I_{CS} \) (A) is the +10 \( \mu \)A current source flowing out of the CS- pin. \( I_{LIMIT} \) should be set sufficiently higher than the peak inductor current at maximum output current to minimize false current limit signals. Components \( R_S \) and \( C_S \) should be chosen to match the inductor \( L/R_{DCR} \) time constant. A typical range of capacitance used in the \( R_S C_S \) network is 100 nF to 1 \( \mu \)F. After choosing a \( C_S \) capacitor, \( R_S \) can be calculated by:

\[ R_S = L \cdot R_{DCR} / C_S \]  

Capacitor \( C_{SBY} \) is used to filter any noise that may exist across the CS+ and CS- pins. A working range for the \( C_{SBY} \) capacitance is 47 pF to 100 pF. A second resistor can be placed between CS+ and the \( R_S C_S \) network to match the impedance into the inputs of the current sense comparator for extra noise rejection shown here as \( R_{CS+} \):

---

[Figure 3. LM27402 Typical Current Limit Circuit]

[Figure 4. Added Resistor for Noise Rejection]
The value of $R_{CS}$ should be equal to $R_{SET}$.

4 CS- Current Source Compliance Voltage

The CS- current source requires at least 1.0V of headroom to ensure a current of $+10 \mu A$. If the voltage across the current source ($V_{IN} - V_{CS}$) decreases below 1.0V, the current will decrease as with the voltage across $R_{SET}$ effectively lowering the current limit setpoint. If $V_{IN} - V_{OUT}$ is less than 1.0V, the current source will lose compliance because $V_{CS}$ closely follows $V_{OUT}$. This can be avoided by enabling the LM27402 at an input voltage 1V higher than $V_{OUT}$ or by lowering the common mode voltage of the current limit comparator with a resistor divider network shown in Figure 5.

![Figure 5. Resistor Divider Network](image)

The voltage divider network in Figure 5 reduces the common mode voltage of the comparator and will effectively sense the inductor current. $R_{SET}$ is calculated in the same way as discussed previously. $R_{S3}$ should be sized to avoid a condition where $V_{IN} - V_{CS}$ is less than 1.0V. $R_{S1}$, $R_{S2}$, and $R_{S3}$ should be sized to match the ratio set by $R_{SET}$ and $R_{S3}$.

5 Example Application

In this example, the application is as follows:

$V_{IN} = 3.3V$, $V_{OUT} = 2.5V$, $I_{OUT} = 20A$, $I_{LIMIT} = 25.7A$, $L = 0.6 \mu H$, $R_{DCR} = 1.89 \Omega$, $f_{SW} = 300 kHz$. An $I_{LIMIT}$ of 25.7A will produce a maximum DC output current of 24.5A at 25°C.

The value of $R_{SET}$ should be:

$$R_{SET} = \frac{(25.7A)(1.89 \Omega)}{10 \mu A} = 4.87 \Omega$$

(4)

The lowest input voltage for this application ($V_{INMIN}$) is 2.7V. $R_{S3}$ should be sized to force $V_{CS}$ to be less than 1.7V when $V_{IN} = 2.7V$ to maintain at least 1V of headroom. The equation solving for $R_{S3}$ is shown in Equation 5:

$$R_{S3} = R_{SET} \frac{V_{CS}}{V_{INMIN} - V_{CS}}$$

(5)

Substituting $V_{INMIN} - V_{CS} = 1V$ and $V_{CS} = V_{INMIN} - 1V$ results in:

$$R_{S3} = R_{SET}(V_{INMIN} - 1) = 4.87 \Omega(2.7 - 1) \approx 8.25 \Omega$$

(6)

Resistors $R_{S1}$, $R_{S2}$, and $R_{S3}$ must be designed to maintain the following ratio:

$$\frac{R_{SET}}{R_{S3}} = \frac{R_{S3} + R_{S1}}{R_{S2}}$$

(7)

It is recommended to design the CS+ branch of resistors to be higher impedance than the CS- branch of resistors to yield a $C_S$ value in the nanofarad range. In this example, the CS+ branch impedance will be set eight times larger than the CS- impedance. $R_{S2}$ is calculated as follows:

$$R_{S2} = 8R_{S3} = 66.5 \Omega$$

(8)
Unfortunately, the ratio of $R_{S1}/R_{S2}$ is not equal to $R_{SET}/R_{S3}$ thus allowing transient differential signals to feed through the $C_S$ capacitor causing an error voltage between the CS+ and CS- pins. $R_S$ and $R_{S1}$ should be sized appropriately to minimize this error. Specifically, $R_S$ should be sized 5% of $8R_{SET}$ and $R_{S1}$ should be sized 95% of $8R_{SET}$ as shown here:

$$R_S = (0.05)(8)R_{SET} \approx 1.96 \text{ k\Omega} \quad R_{S1} = (0.95)(8)R_{SET} = 37.4 \text{ k\Omega} \quad (9)$$

$C_S$ is calculated using the parallel combination of $R_{S1}||R_{S2}$ to match the inductor time constant shown here:

$$C_S = \frac{L}{R_{DCR}(R_{S1}||R_{S2})} = 165 \text{ nF} \quad (10)$$

6 Layout

The circuitry to sense the DCR voltage is sensitive to noise and demands careful layout practices. Following these general guidelines will help ensure a robust design.

7 $C_{SBY}$ Placement

The $C_{SBY}$ capacitor should be placed as close to the CS+ and CS- pins as possible. $C_{SBY}$ serves as the last line of defense between board noise and the current limit comparator. $C_{SBY}$ should be a small 0603 or 0402 surface mount capacitor to facilitate close placement to the LM27402.

8 CS+ and CS- Traces

Certain applications will call for long CS+ and CS- traces. For example, the LM27402 evaluation board incorporates a temperature compensated current limit circuit with a PTC resistor in series with CS-. This requires the CS- trace to be routed from the LM27402 to the inductor. It is essential to route the CS+ and CS- traces away from noise emitting nodes, particularly the switch-node and gate drives nodes on the PCB. Routing the CS+ and CS- traces side by side for close coupling and in between ground planes is a sufficient way to mitigate differential noise.
Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

### Products

<table>
<thead>
<tr>
<th>Audio</th>
<th><a href="http://www.ti.com/audio">www.ti.com/audio</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
</tr>
<tr>
<td>Data Converters</td>
<td>dataconverter.ti.com</td>
</tr>
<tr>
<td>DLP® Products</td>
<td><a href="http://www.dlp.com">www.dlp.com</a></td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td><a href="http://www.ti.com/clocks">www.ti.com/clocks</a></td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
</tr>
</tbody>
</table>

### Applications

| Automotive and Transportation | www.ti.com/automotive    |
| Communications and Telecom    | www.ti.com/communications |
| Computers and Peripherals     | www.ti.com/computers     |
| Consumer Electronics          | www.ti.com/consumer-apps |
| Energy and Lighting           | www.ti.com/energy        |
| Industrial                   | www.ti.com/industrial    |
| Medical                      | www.ti.com/medical       |
| Security                     | www.ti.com/security      |
| Space, Avionics and Defense   | www.ti.com/space-avionics-defense |
| Video and Imaging             | www.ti.com/video         |

**IMPORTANT NOTICE**

Copyright © 2013, Texas Instruments Incorporated