Setting the Current Limit for the AAT1184/85/89, AAT2687/88/89 High Voltage Step-Down Family

Introduction

This application note describes the current limit network calculations for the different DC winding resistances (DCR) of inductors selected for the Skyworks family of high-voltage step-down converters. This family includes the AAT1184, AAT1185, AAT1189, AAT2687, AAT2688, and AAT2689. In order to protect the device from permanent damage during over-current stress or short circuit events, the current is sensed through the output inductor DC winding resistance. An external resistor (R1) and capacitor (C4) network adjusts the pre-set over-current threshold (I_{PRESET}) based on the DCR of the inductor.

The over-current offset voltage threshold (V_{DCP}) is internally set to 100mV. The R1-C4 network senses the voltage drop across the inductor and compares it to the over-current offset voltage threshold. As illustrated in Figure 2, in normal operation the differential voltage (V_{RS} - V_{OS}) signal is a triangle waveform and in phase with the inductor current. The over-current controller is triggered when the differential voltage signal from RS to OS exceeds 100mV (nominal). When the over-current is triggered, the switching frequency and the output voltage reduce to limit the current to a user designed value (see Figure 3). The designed current limit threshold (I_{LIMIT}) can be set by the current limit network. The operating frequency returns to the nominal setting when over-current conditions are removed.

The current limit network including components (R1, C4, R6, R7, and R8) can be calculated and configured according to the DCR of the selected inductor. With the same inductor value, a small footprint inductor has a greater DCR compared to a larger footprint inductor. The inductor DCR variation results in the variation of the pre-set over current threshold (I_{PRESET}). There are three current limit network configurations used to set the design current limit (I_{LIMIT}) for different pre-set over-current thresholds (I_{PRESET}) due to the inductor DCR selection.

Figure 1: AAT1189 Typical Application Schematic with Current Limit Network (R1, C4, R6, R7, R8).

1. R1, C4, R6, R7, R8 may have different names in AAT1184, AAT1185, AAT2687, AAT2688, and AAT2689 schematics.
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Figure 2: AAT1189 (V_{RS} – V_{OS}) Signal and Inductor Current are In Phase. CH2 (Blue): RS signal; CH3 (Pink): OS signal; CHM (Red): (RS-OS) signal; CH4: Inductor Current (1A/div).

Figure 3: AAT1189 Short Circuit Test. CH1: Output Voltage (2V/div); CH2: Switching Node (LX); CH4: Inductor Current (1A/div).
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Current Limit Network Calculation

In order to correctly sense the inductor current, the $R_1$-$C_4$ network time constant needs to be matched to the inductor time constant as shown in the following equation:

$$\text{Eq. 1: } R_1 \cdot C_4 = \frac{L_1}{\text{DCR}}$$

The pre-set over-current threshold with the matching $R_1$-$C_4$ network is the ratio of the over-current offset voltage threshold and the winding resistance (DCR) of the inductor:

$$\text{Eq. 2: } I_{\text{PRESET}} = \frac{V_{\text{OCP}}}{\text{DCR}} = \frac{100\text{mV}}{35\text{m}\Omega} = 2.86\text{A}$$

Where the over-current offset voltage threshold ($V_{\text{OCP}}$) is internally set at 100mV with 20% tolerance.

1. Setting the Current Limit close to the Pre-set Over-Current ($I_{\text{LIMIT}} = I_{\text{PRESET}}$)

For example, for the 7447789004, 4.7µH Würth inductor with a typical DCR of 35mΩ is used in the AAT1189. The pre-set over-current threshold is determined as Equation 2:

$$I_{\text{PRESET}} = \frac{V_{\text{OCP}}}{\text{DCR}} = \frac{100\text{mV}}{35\text{m}\Omega} = 2.86\text{A}$$

If the current limit threshold is set around 3A, there is no need to use the divider $R_6$ and $R_7$ (Figure 4). The sensing capacitor $C_4 = 68nF$ and the sensing resistor $R_1$ can be calculated from Equation 1:

$$R_1 = \frac{L_1}{\text{DCR} \cdot C_4} = \frac{4.7\mu\text{H}}{35\text{m}\Omega \cdot 68nF} = 1.97k\Omega; \text{ choose } R_1 = 1.91k\Omega$$

![Figure 4: Setting the Current Limit Close to the Pre-set Over-Current for the AAT1189 (R6 = 0, R7 = Open).](image)

Note: The value of $R_1$ should be adjusted from the calculation value to derive the designed current limit due to the variation of over-current offset voltage threshold ($V_{\text{OCP}}$) between parts.
2. Setting the Current Limit less than the Pre-set Over-Current \( (I_{\text{LIMIT}} < I_{\text{PRESET}}) \)

For example, the RCH108NP-4R7M, 4.7μH Sumida inductor with a typical DCR of 11.7mΩ is used with the AAT1189. The pre-set over-current threshold is determined by Equation 2:

\[
I_{\text{PRESET}} = \frac{V_{\text{DCR}}}{\text{DCR}} = \frac{100\text{mV}}{11.7\text{mΩ}} = 8.5\text{A} > I_{\text{LIMIT}} = 3\text{A}
\]

If the AAT1189 current limit is set to 3A, the divider \( (R_6 \text{ and } R_7) \) needs to be added into the network (Figure 5). If the sensing capacitor \( C_4 = 68\text{nF} \), then the sensing resistor \( R_1 \) value can be calculated using Equation 1:

\[
R_1 = \frac{L}{\text{DCR} \cdot C_4} = \frac{4.7\mu\text{H}}{11.7\text{mΩ} \cdot 68\text{nF}} = 5.9\text{kΩ}; \text{ choose } R_1 = 5.9\text{kΩ}
\]

Neglecting the current that sinks into RS and OS terminals of the comparator, the voltage drop on the inductor \( (V_{L1}) \) should be identical to the voltage drop across \( C_4 \), hence:

\[
\text{Eq. 3: } V_{L1} + V_{R6} = 100\text{mV}
\]

\[
\text{Eq. 4: } I_{\text{LIMIT}} \cdot \text{DCR} + \frac{R_6 \cdot V_{\text{OUT}}}{R_6 + R_7} = 100\text{mV}
\]

\[
\text{Eq. 5: } I_{\text{LIMIT}} \cdot \text{DCR} + \frac{R_6 \cdot R_7 \cdot V_{\text{OUT}}}{(R_6 + R_7) \cdot R_7} = 100\text{mV}
\]

To balance the impedance between the two terminals of the comparator, \( R_1 \) should be equal to the equivalent resistance of \( R_6 \) and \( R_7 \) in parallel:
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Eq. 6: \[ R_7 = \frac{R_6 \cdot R_7}{R_6 + R_7} \]

Substituting Equation 6 into Equation 5 and solving for \( R_7 \):

\[ R_7 = \frac{V_{\text{OUT}} \cdot R_1}{V_{\text{DCP}} \cdot I_{\text{LIMIT}} \cdot \text{DCR}} = \frac{5V \cdot 5.9k\Omega}{0.1V \cdot 3A \cdot 11.7m\Omega} = 454.5k\Omega; \text{ choose } R_7 = 464k\Omega \]

Substituting \( R_1 \) and \( R_7 \) into Equation 6 and solving for \( R_6 \):

Eq. 7: \[ R_6 = \frac{R_1 \cdot R_7}{R_7 - R_1} = \frac{5.9k\Omega \cdot 464k\Omega}{464k\Omega - 5.9k\Omega} = 5.9k\Omega \]

Note: The value of \( R_1, R_6 \) and \( R_7 \) should be adjusted from the calculated values to get the designed current limit due to the variation of over-current offset voltage threshold (\( V_{\text{OCPP}} \)) between parts.

3. Setting the Current Limit Greater than the Pre-set Over-Current (\( I_{\text{LIMIT}}> I_{\text{PRESET}} \))

The AAT2687 and AAT2688 can provide up to 4.5A constant output current which is equivalent to a 5.0A peak inductor current. That requires at least 5.5A or above for the designed current limit. If the IHLP-2525CZ-01, 4.7\( \mu \)H Vishay inductor with a maximum DCR of 40m\( \Omega \) is used, the pre-set over-current threshold is determined by Equation 2:

\[ I_{\text{PRESET}} = \frac{V_{\text{DCP}}}{\text{DCR}} = \frac{100mV}{40m\Omega} = 2.5A < I_{\text{LIMIT}} = 6A \]

If the current limit is set to 6A, \( R_6 \) and \( R_8 \) need to be added to the network (see Figure 6). If the sensing capacitor \( C_4 = 56nF \), then the sensing resistor \( R_1 \) can be calculated from Equation 1:

\[ R_1 = \frac{L}{\text{DCR} \cdot C_4} = \frac{4.7\mu\text{H}}{35m\Omega \cdot 56nF} = 2.098k\Omega; \text{ choose } R_1 = 2.05k\Omega \]

Figure 6: Setting the Current Limit Greater than the Pre-set Over-Current (\( R_6 = 1k, R_8 = 2.05k \)) for the AAT2687 and AAT2688.
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Neglecting the current that sinks into the RS and OS terminals of the comparator, the over-current offset voltage threshold is identical to the voltage drop across Rs:

Eq. 8: \( V_{R8} = V_{CA} = V_{OCP} = 100\text{mV} \)

Where:

Eq. 9: \( V_{R8} = \frac{R_8 \cdot V_{L1}}{R_8 + R_1} = \frac{R_8 \cdot I_{LIM} \cdot DCR}{R_8 + R_1} = V_{OCP} = 100\text{mV} \)

Solve for \( R_8 \):

Eq. 10: \( R_8 = \frac{V_{OCP} \cdot R_1}{I_{LIM} \cdot DCR - V_{OCP}} = \frac{100\text{mV} \cdot 2.05k\Omega}{6A \cdot 40\text{m}\Omega - 100\text{mV}} = 1.47k\Omega \)

To balance the impedance between two terminals of the comparator, \( R_6 \) should equal the equivalent resistance of \( R_1 \) and \( R_8 \) in parallel:

Eq. 11: \( R_6 = \frac{R_1 \cdot R_8}{R_1 + R_8} = \frac{2.05k\Omega \cdot 1.47k\Omega}{2.05k\Omega + 1.47k\Omega} = 856\Omega \)

Note: The value of \( R_1, R_6 \) and \( R_8 \) should be adjusted from the calculated values to derive the designed current limit due to the variation of over-current offset voltage threshold (\( V_{OCP} \)) between parts.

Sensing Capacitor Selection and Current Limit Network Layout Considerations

The sensing capacitor \( C_4 \) should be large enough to hold the sensing voltage from noise interference. A typical value of \( C_4 \) is not smaller than 47nF for adequate filtering.

The sensing components \( C_4 \) and \( R_1 \) should be connected as close as possible to the RS1 and OS1 pins and can be placed on the bottom side of the layout to avoid noise coupling from the inductor. The trace that connects from RS and OS to the inductor terminals should be kept as short as possible to prevent adding more DCR to the inductor.