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Current Limits in Electronic Fuses using Direct and Kelvin R Limit Connections

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APPLICATION NOTE

Introduction

The primary function of an Electronic Fuse, or eFuse, is to limit current, the same function provided by any fuse or positive temperature coefficient device (PTC). An eFuse, however, provides this function with much more versatility than either of these devices. An eFuse, unlike a standard fuse, need not be replaced after it functions and eFuses also respond more rapidly than a either a fuse or PTC. eFuses can also limit current in situations in which a traditional fuses and PTCs will not work. This is especially true when voltage is first provided to a circuit, such as during a hot plug operation, when inrush current can be extremely high. This application note will explain the basic operation of an eFuse's current limit function and explain important eFuse concepts such as Overload and Short Circuit currents, and Kelvin versus Direct connection of the eFuse's current sense resistor. This document is valid for eFuses NIS5135, NIS5132, and NIS5232 as well as other eFuses which share their internal configuration. The basic concepts work also for eFuse designs using separate die for the SENSEFET® and control circuits but there are subtle differences in the equations.

Basic eFuse Operation

ON Semiconductor's family of Electronic Fuses use a power MOSFET known as a SENSEFET to control current in the load. All power MOSFETs are made up of thousands of parallel FETs or cells. In a SENSEFET a small percent of the FET cells have their sources separated from the sources of the remaining FET cells. The ratio of cells in the main and small section of the SENSEFET is often about 1000. All of the FET cells share common gate and drain connections. The use of a SENSEFET in an eFuse is illustrated conceptually in Figure 1, where Q_M is the main section of the SENSEFET, and Q_S is the small, or sense, section of the SENSEFET.

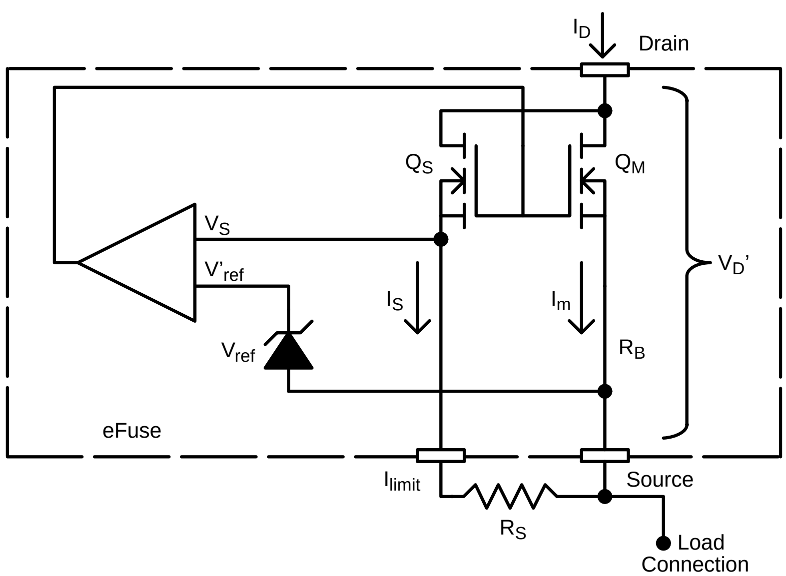

Figure 1. SENSEFET and Current Limit Circuit

In eFuse operation a sense resistor, R_S, is placed between the source of the sense section of the SENSEFET and the source of the main section of the SENSEFET as shown in Figure 1. Measuring the voltage drop across R_S provides a measure of current through the sense section of the SENSEFET. As long as R_S is much less than the resistance of Q_S the current through the full SENSEFET will be $k \cdot I_S$, where k is the ratio of cells between the main and sense sections of the SENSEFET.

Since only a small fraction of the main current flows in the sense FET, the current sensing resistor can be a more reasonable value in terms of resistance and power dissipation. For example, to sense a 100 mV signal from a 5.0 A current using a normal MOSFET would require a 20 mΩ, 1.5 W resistor, assuming a factor of 3 derating for power. If a SENSEFET with a ratio of 1000:1 is used for the same current and sense voltage, a 20 Ω (R = 0.1 V/0.005 A) resistor is needed and dissipates just 0.5 mW. This results in a significant cost savings for the current sense resistor.

To initiate current limitation through the SENSEFET a comparator circuit compares the voltage across R_S to a reference voltage, V_{ref}. (For convenience in this document the reference voltage will be represented by a Zener diode.) Current through the SENSEFET will be restricted when

$$V_S = I_S \cdot R_S = V_{ref} \quad \text{(eq. 1)}$$

Since $I_m = k \cdot I_S$

$$I_m = k\frac{V_{ref}}{R_S} \quad \text{(eq. 2)}$$

This equation appears to provide a simple way to choose a resistor value to limit current at a desired current, if the values of k and V_{ref} are known. Unfortunately, two factors complicate the situation. First of all, MOS transistors operate very differently when they are fully turned on and when they in a fully or partially turned off state. Secondly, even though SENSEFET transistors are designed to have very low resistance in their on state, parasitic resistances such as in bond wires cannot be ignored in some situations.

Analysis

Four types of analysis will be done. Overload and Short Circuit current limits will be derived for both Kelvin and Direct connection of the sense resistor. These terms will be explained below.

The analysis below provides good understanding of the functionality of an eFuse and the meanings of terms such as Overload and Short Circuit currents and Kelvin and Direct connection. Final system design should however be based on datasheet plots of the Overload and Short Circuit Currents for Kelvin and Direct connection since the equations below do not include all of the subtle effects present in the SENSEFET and other circuit elements.

Overload and Short Circuit Current Limits

When an eFuse is in normal operation the SENSEFET provides a low resistance path between a power source and the load. In this situation the SENSEFET is fully enhanced and in its linear state. In the linear state the SENSEFET behaves as a low value resistor, as shown in Figure 2. When the SENSEFET is restricting current there will be significant voltage drop between drain and source and SENSEFET will be in saturation. In saturation current through the SENSEFET is insensitive to the voltage across the device as shown in Figure 2. For this reason it is necessary to analyze the relation between the sense resistor and limiting current differently for the situation of the load resistance dropping during normal operation and the situation when the eFuse is limiting current, such as during a hot plug operation.

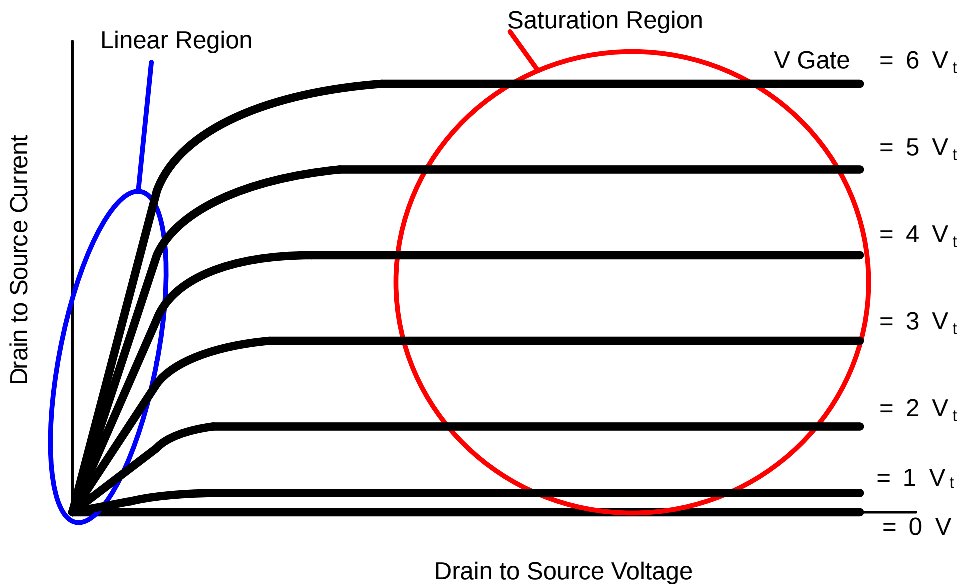

Figure 2. Basic MOS functionality

To distinguish the different limiting currents between linear and saturated operation the following terms are used.

- Overload Current: an overload condition occurs when the eFuse is in normal operation in the linear mode and a drop in load resistance creates an increase in current. When operating in the linear region an eFuse will limit current if the Overload current is exceeded.
- Short Circuit Current: When the source or output of an eFuse is shorted to ground there will be a large voltage drop between the eFuse drain and source. The eFuse is then in saturation mode and current will be limited to the Short Circuit current. The Short Circuit current limit applies anytime the eFuse in operating in saturation.

When the SENSEFET is fully enhanced a typical resistance can be just 30 or 40 mΩ. This is not much higher than bond wire resistances which can be on the order of several mΩ, even if several bond wires are used in parallel. For this reason bond wire resistance either needs to be accounted for in the analysis or accounted for in how the eFuse is configured.

Kelvin versus Direct Connection

Most eFuse packages have several pins dedicated to the source connection of the SENSEFET. This gives two options for connecting R_S, as shown in Figure 3. If one of the source pins is used to connect R_S directly to the source of the main section of the SENSEFET on the eFuse die, the voltage drop across bond wires does not affect the voltages seen by the comparator. This type of connection is known as Kelvin connection. The disadvantage of the Kelvin connection is that the resistance of bond wires in the current path for the main section of the SENSEFET is increased, resulting in a net increase in voltage drop across the eFuse. Analysis will be done for both configurations below.

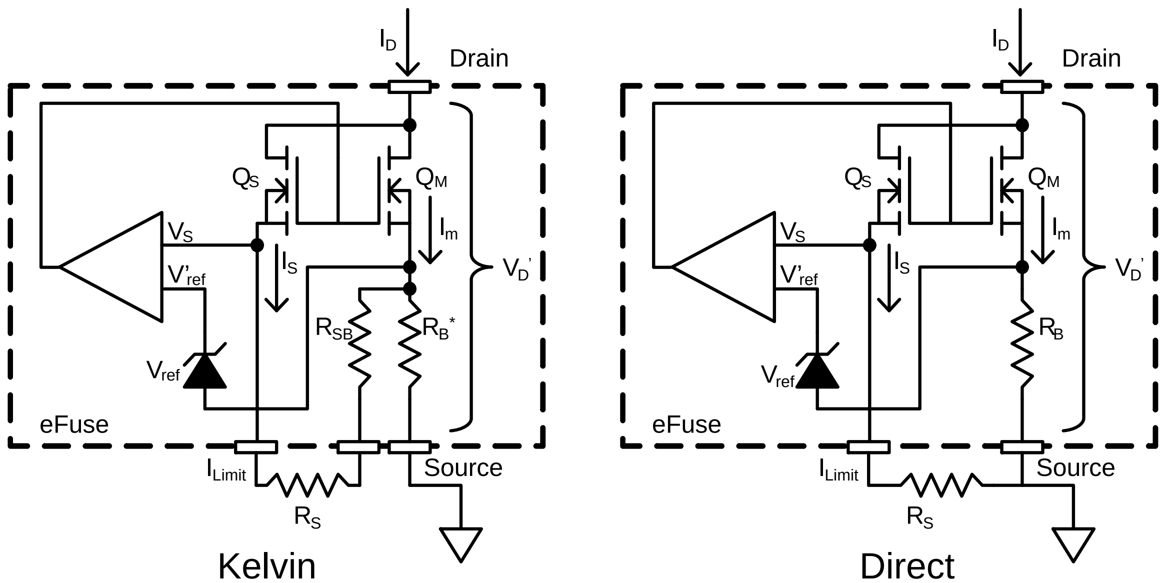

Figure 3. Comparison of Kelvin and Direct connection of the sense resistor R_S

Kelvin Connection

Analysis for Kelvin connection will be done first since the equations are simpler:

Kelvin Connection in Saturation Mode (Short Circuit)

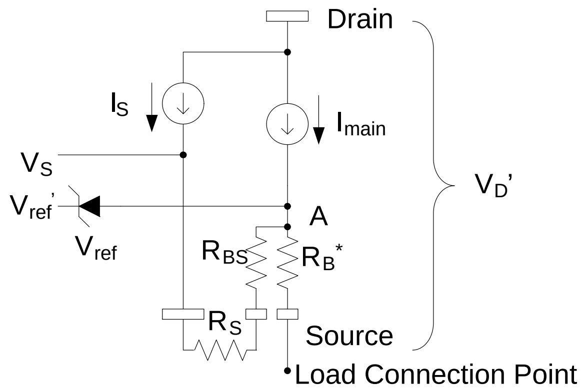

Figure 4. Circuit for Kelvin connection in saturation mode

An equivalent circuit when the SENSEFET is in saturation mode using Kelvin sensing is shown in Figure 4. In saturation mode the current through the SENSEFET is insensitive to the voltage across the device. The current through the sense and main FETs will then scale with their size, or $I_S = I_m/k$. The resistor R_{BS} is the resistance of the wire bond for the single Source pin used to connect the single Source pin to the sense resistor, while R_B is the resistance of the wire bonds of the Source pins connected to the load. In this analysis R_{BS} will be ignored since it is a small resistance in series with $R_{ds(sense)}$ and R_S.

In this analysis all voltages will be referenced to point A in Figure 4.

$$V_S = I_S \cdot R_S = \frac{I_m \cdot R_S}{k} \quad \text{(eq. 3)}$$

The condition of current limiting is $V_S = V_{ref}$ giving:

$$V_{ref} = \frac{I_m \cdot R_S}{k} \quad \text{(eq. 4)}$$

Solving for I_m

$$I_m = \frac{k \cdot V_{ref}}{R_S} \quad \text{(eq. 5)}$$

Equation (4) gives an expression for the limiting current as a function of the sense resistor value in the saturation mode for a Kelvin connected eFuse. Note that this is the same expression as Equation (2). This is the Short Circuit current for Kelvin connection.

Kelvin Connection in Linear Mode (Overload)

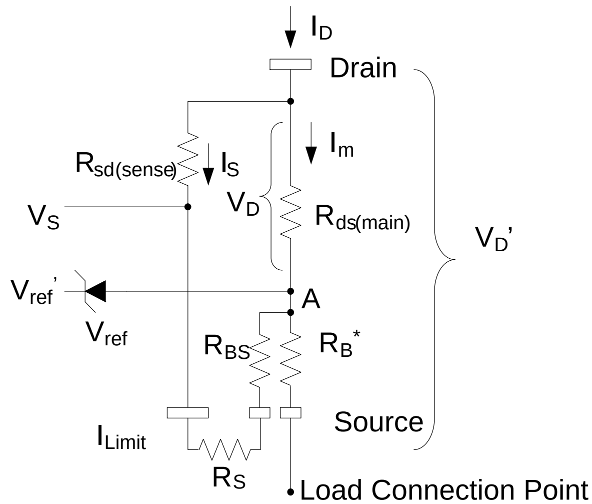

Figure 5. Circuit for Kelvin connection in linear mode

The equivalent for linear mode using Kelvin sensing is shown in Figure 5. In linear mode the SENSEFETs can be considered resistors, with $R_{ds(sense)} = kR_{ds(main)}$. As in the analysis in the saturation mode, R_{BS} can again be ignored.

In this analysis all voltages will be referenced to point A in Figure 5.

$$V_S = \frac{R_S}{R_{ds(sense)} + R_S} \cdot V_D \quad \text{(eq. 6)}$$

Since:

$$V_D = I_m \cdot R_{ds(main)} \quad \text{(eq. 7)}$$

We get:

$$V_S = \frac{R_S}{R_{ds(sense)} + R_S} \cdot I_m \cdot R_{ds(main)} \quad \text{(eq. 8)}$$

Using $R_{ds(sense)} = kR_{DS(main)}$, and $V_S = V_{ref}$

$$V_{ref} = \frac{R_S}{kR_{ds(main)} + R_S} \cdot I_m \cdot R_{ds(main)} \quad \text{(eq. 9)}$$

Solving for I_m

$$I_m = \frac{k \cdot V_{ref}}{R_S} + \frac{V_{ref}}{R_{ds(main)}} \quad \text{(eq. 10)}$$

Equation (10) gives an expression for the limiting current for the eFuse in linear mode when the eFuse is wired in Kelvin mode. Note that the expression for the limiting current in linear mode, Equation (10), is the same as that for the saturation mode, Equation (6), except for the addition of a constant term. The significance of this extra term in the Overload or linear mode is that when the voltage drop across the main portion of the the SENSEFET equals V_{ref} the eFuse will always start to limit current.

Kelvin Example

An example of calculated Overload and Short Circuit Currents is shown in Figure 6. The following parameter values are used in all examples.

$k = 1000$

$V_S = 70$ mV

Single bond wire resistance = 15 mΩ

$R_B^* = 3.75$ mΩ for 4 bond wires in parallel (Kelvin example)

$R_B = 3$ mΩ for 5 bond wire in parallel (Direct example)

$R_{ds(main)} = 38$ mΩ

Figure 6. Sample of Overload and Short circuit Currents for Kelvin connection

Direct Connection

In direct connection the sense resistor, R_S, is connected directly between the I_{Limit} pin and the source of the SENSEFET as shown in Figure 1.

Direct Connection in Saturation Mode

Figure 7 shows an equivalent circuit for an eFuse in saturation when the sense resistor is in direct connection.

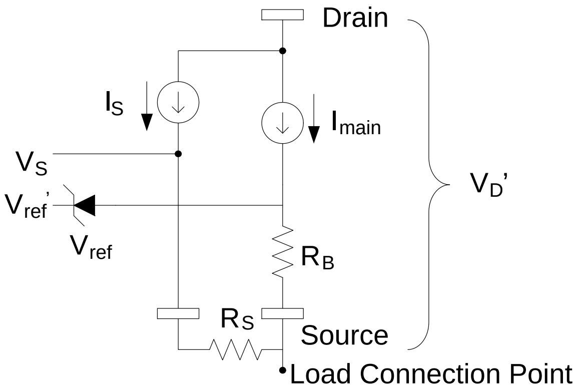

Figure 7. Saturation Mode Equivalent Circuit

As in the analysis of saturation mode for Kelvin connection the SENSEFET elements can be considered current sources. In this situation the ratio of the current through Q_M and Q_S closely match the ratio of the number of cells or:

$$I_S = \frac{I_m}{k} \quad \text{(eq. 11)}$$

In this analysis all voltages are referenced to the Load Connection Point in Figure 7.

Current is limited when the following condition is met;

$$V_S = V'_{ref} = V_{ref} + I_m \cdot R_B \quad \text{(eq. 12)}$$

Since $V_S = I_S \cdot R_S$

$$I_S \cdot R_S = V_{ref} + I_m \cdot R_B \quad \text{(eq. 13)}$$

Using Equation (11) yields

$$\frac{I_m}{k} \cdot R_S = V_{ref} + I_m \cdot R_B \quad \text{(eq. 14)}$$

Solving for I_m

$$I_m = \frac{k \cdot V_{ref}}{R_S - k \cdot R_B} \quad \text{(eq. 15)}$$

Equation (15) describes the relationship between the limiting current and sense resistor when the SENSEFET is in saturation mode. This is the Short Circuit current for an eFuse with the sense resistor in Direct connection. Note that the Direct connection expression for Short Circuit current, Equation (15), reduces to the Kelvin connection expression for Short Circuit current, Equation (5), if the bond wire resistance is set to zero.

Direct Connection in Linear Mode

An equivalent circuit for the eFuse in linear mode with Direct connection is shown in Figure 8.

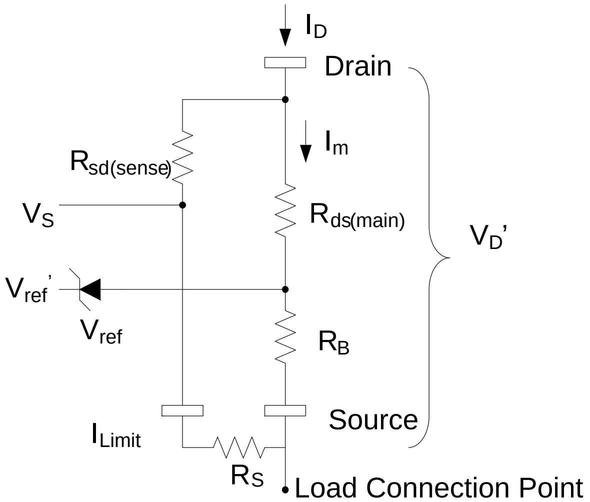

Figure 8. Linear (Overload) equivalent circuit

As in the case of linear mode with Kelvin connection the SENSEFET transistors can be considered resistors.

In this analysis voltages are referenced to the Load Connection Point in Figure 8.

The voltage drop across the eFuse drain−source terminals is:

$$V'_D = I_m \cdot \left(R_{ds(main)} + R_B\right) \qquad \text{(eq. 16)}$$

Assuming $I_m \cong I_D$ the sense voltage V_S is generated by the voltage V'_D and the voltage divider consisting of $R_{ds(sense)}$ and R_S:

$$V_S = V'_D \cdot \frac{R_S}{R_{ds(sense)} + R_S} \qquad \text{(eq. 17)}$$

Using the relation $R_{ds(sense)} = kR_{DS(main)}$ and Equation (16) we obtain:

$$V_S = \frac{I_m \cdot R_S \cdot \left(R_{ds(main)} + R_B\right)}{k \cdot R_{ds(main)} + R_S} \qquad \text{(eq. 18)}$$

Current limiting will begin when $V_S = V'_{ref}$. Since

$$V'_{ref} = V_{ref} + I_m \cdot R_B \qquad \text{(eq. 19)}$$

and, using Equation (18) we get

$$V_{ref} + I_m \cdot R_B = \frac{I_m \cdot R_S \cdot \left(R_{ds(main)} + R_B\right)}{k \cdot R_{ds(main)} + R_S} \qquad \text{(eq. 20)}$$

Solving for I_m gives

$$I_m = \frac{V_{ref}\left(k \cdot R_{ds(main)} + R_S\right)}{R_S\left(R_{ds(main)} + R_B\right) - R_B\left(k \cdot R_{ds(main)} + R_S\right)} \qquad \text{(eq. 21)}$$

Expanding the numerator and denominator allows this to be written as:

$$I_m = \frac{k \cdot V_{ref}}{R_S + k \cdot R_B} + \frac{V_{ref} \cdot R_S}{R_{ds(main)}\left(R_S - k \cdot R_B\right)} \qquad \text{(eq. 22)}$$

Equation (22) is the Overload current with Direct connection. Note that Equation (22) reduces to the Kelvin expression for the Overload current Equation (10) if the bond wire resistance is set to zero.

Direct Connection Example

Figure 9 adds curves for Direct connection to the ones for Kelvin connection from Figure 6. For high values of R_S the Direct and Kelvin curves merge, while for low R_S the Direct connection limiting currents are always larger. In Direct connection, current through the bond wires increases the value of V_{ref}', increasing the currents at which the eFuse begins to limit current.

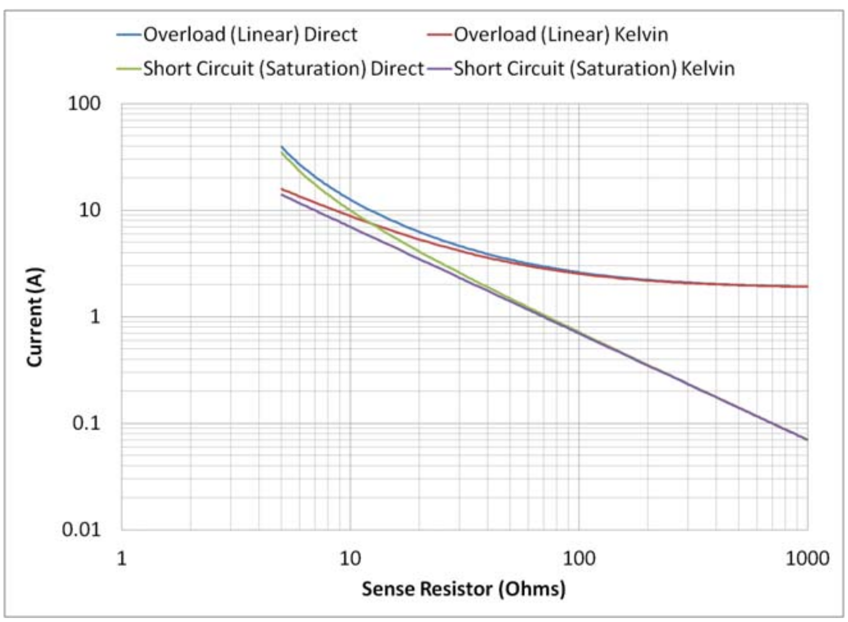

Figure 9. Samples of Overload and Short circuit Currents for both Direct and Kelvin connection using the same parameter values

Examples

Two specific cases will be used to help explain the nature of the Short Circuit and Overload curves. Both examples will be based on the calculated curves for Direct connection in Figure 10. We will first consider the following situation.

Case 1

R_S = 30 Ω

Operating voltage = 5 V

Normal load impedance = 5 Ω

Load during fault = 0.5 Ω

Well after turn on and any turn on transients this device will carry 1 A of current, point A in Figure 10.This is below both the Short Circuit and Overload curves. This means that the SENSEFET will be in linear mode with low impedance. If the load resistance drops to 0.5 Ω the current will rise, but the question is, how far? If the eFuse were not present we would expect the current to increase to 10 A (5 V/0.5 Ω), point B in Figure 10. Since the SENSEFET is in the linear mode the Short Circuit curve, which is valid for saturation, is not relevant. The current will therefore increase until it reaches the Overload curve at about 4.6 A. Once the current reaches the Over Load curve the current limit circuit will activate and begin to turn off the SENSEFET. The maximum current will therefore be 6.28 A. Once the SENSEFET begins to limit current the SENSEFET moves from linear mode to saturation mode. At this point the Short Circuit curve becomes important and the current will decrease to the Short Circuit curve, or about 2.6 A.

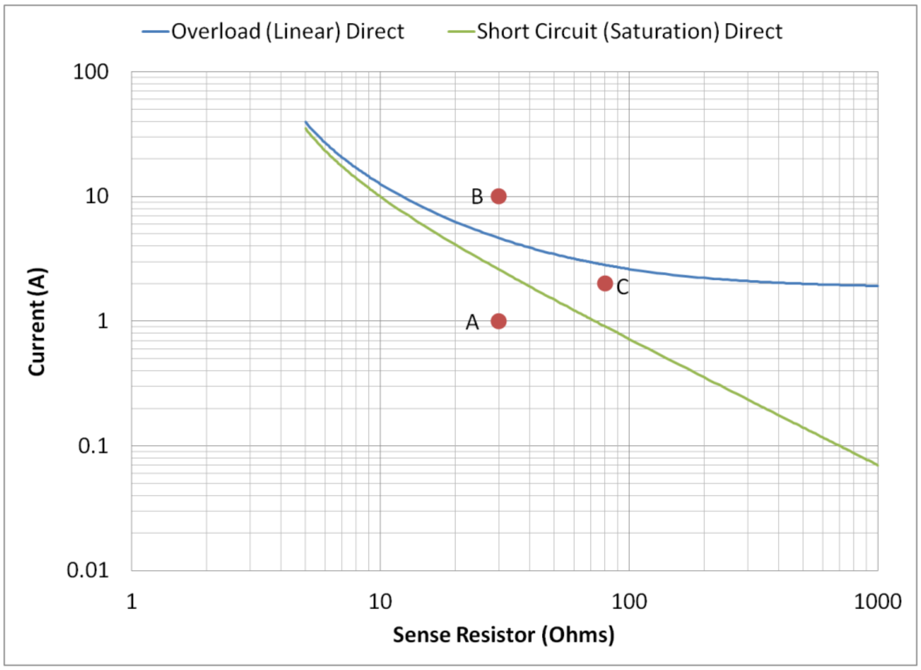

Figure 10. Overload and Short circuit currents for Direct and connection with example current points

Case 2
R_S = 80 Ω
Operation voltage = 5 V
Normal load impedance = 2.5 Ω
Load Capacitance = 10 μF

In this case the normal operating current after any initial transients should be 2 A, point C in Figure 10. This places the operating point between the Short Circuit and Over Load curves. This creates an interesting situation under a hot plug application. Before the load is plugged in the source of the SENSEFET will be at 5 V. When the load is plugged in the large capacitance creates a temporary short to ground, resulting in a large drain to source voltage on the SENSEFET, putting the SENSEFET into saturation. As the capacitor charges the voltage rises toward 5 V, but the current needs to pass through the Short Circuit curve before it reaches the expected 2 A of current. During the voltage rise the SENSEFET is in the saturated mode, meaning that the Short Circuit curve is relevant. In this case the voltage across the load will never reach 5 V because the Electronic Fuse will limit the current at the Short Circuit current value of 0.91 A for the 80 Ω R_S. There is also a dV/dt circuit limiting the current.

Summary

This Application Note has given a detailed explained of how ON Semiconductor’s Electronic Fuses limit current with the use of a SENSEFET device. The two current levels, overload and short circuit, which will trigger the Electronic Fuse to limit current are explained. Kelvin and Direct connections of the sense resistor are explained and theoretical expressions for the Overload and Short Circuit currents are derived for Kelvin and Direct connection.

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