*Application Report*
*SLOA236–November 2016*

# *Short-to-Battery Protection Strategies for Class-D Amplifiers*

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## ABSTRACT

This document introduces the potential faults that can occur in class-D amplifier solutions, and describes how most faults are intrinsically protected for and how to extend coverage to protect against all short-circuit faults. Of particular focus is the case when an output is shorted to a battery voltage higher than the device supply voltage. This fault allows the parasitic body diode found in the H-Bridge to conduct large fault currents. Preventing damage to the amplifier and other system components is crucial in environments where safety is paramount, such as automotive environments. This application report proposes protection strategies and selection guidance to avoid damaging the class-D device and other system devices.

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# 1 Introduction to Problem

With class-D amplifiers, short-circuit faults in the output H-bridge result in dangerous current paths. This type of fault occurs when either the positive or negative outputs (OUTP or OUTN, respectively) are shorted to the power supply, PVCC, or are shorted to ground. This short causes large currents to flow because PVCC is shorted to ground when an H-bridge switch conducts. A short-circuit fault can also occur when both outputs are mutually shorted to each other. In an automotive application, the long wires between the class-D amplifier and the speaker increase the chance that an output pin could become shorted during speaker installation, maintenance, or a collision.

Texas Instruments's class-D amplifiers, such as the TPA3111D1-Q1 or TAS5421-Q1 device, protect against short-circuit faults by sensing the current through each switch in the H-bridge output. If the current exceeds a safe threshold, the gate drives are disabled and the output pins are put into a high impedance state.

A special case of a short-circuit fault occurs when an output is shorted to a voltage higher than the amplifier input voltage, PVCC. In a car, this could be the battery voltage. Nominally, the car battery voltage will be 12 V and when charged via the alternator, it will be around 14 V. If the voltage regulator between the alternator and the battery fails, the battery could be as high as 18 V. If this battery voltage exceeds the voltage at the PVCC pin, the parasitic body diode in the shorted output will begin to conduct. If PVCC is powered by the battery, then the fault only is dangerous when the amplifier is unpowered which can occur even if the outputs are put into a High-Z state. Figure 1 shows the path of the current.

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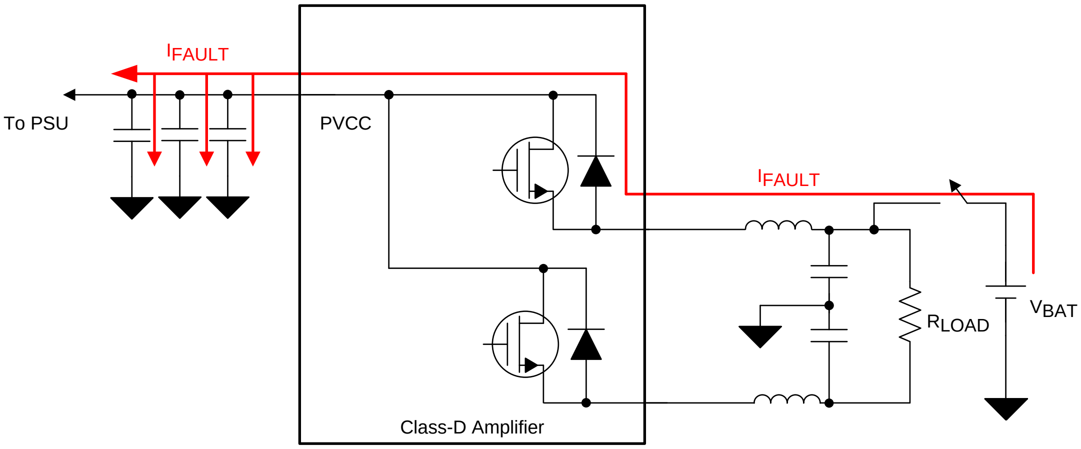

**Figure 1. Fault Current Path During Short-to-Battery**

The large capacitance on the PVCC pin and higher voltage difference cause a large fault current to flow which charges the PVCC voltage up to the battery voltage. With large enough capacitance or voltage difference, this fault current can destroy the class-D device. Furthermore, any other devices connected to the power-supply circuit will be exposed to the high voltage which can cause additional failures. The worst case scenario occurs when there is a maximum voltage difference between the battery voltage and PVCC, which occurs when the device is unpowered.

While this special case of a short-circuit fault is not inherently protected for in TI's amplifiers, several steps are proposed in this document to address the fault. The first step provides basic protection for the power-supply pin of the device. The second step builds on the suggestions of the first step to fully protect the amplifier. Finally, the alternate solutions propose changes to the protection scheme described in steps one and two.

## 2 Step 1: Basic Protection

### *2.1 PVCC Protection Diode Selection*

The first step to protect the system is to protect the power supply. Reverse-voltage protection is readily achieved with a diode. The protection requirements for the diode depend on the class-D device used with the diode. For both the TPA3111D1-Q1 and TAS5421-Q1 device, the worst-case condition is when the battery is at 18 V and the PVCC pin is unpowered. The peak inverse-voltage rating of the diode should be at least 18 V, although 30 V provides a good protection margin. This voltage rating is sometimes listed as the repetitive peak-reverse voltage, $V_{RRM}$, in data sheets. Table 1 lists the diode parameters important to this protection scheme.

**Table 1. Key Diode Parameters**

| Symbol | Parameter Name | Definition |
|---|---|---|
| $V_{RRM}$ | Maximum repetitive peak-reverse voltage | This parameter specifies the maximum reverse bias the diode can sustain before breakdown occurs. |
| $V_F$ | Forward voltage drop | This parameter specifies the forward-voltage drop across the diode, but only for a specific temperature and forward current. This parameter is useful in Step 1, but not in Step 2. TI recommends referencing the typical IV curve in the data sheet for this value. |
| $I_{FSM}$ | Maximum forward surge current | This parameter specifies the maximum surge current that can flow for 8.3 ms before the device fails thermally. |
| $I_{F(AV)}$ | Average forward current | This parameter specifies the maximum current that can flow through the diode repetitively before the junction fails thermally. This parameter is sometimes referred to as $I_O$ in data sheets. |

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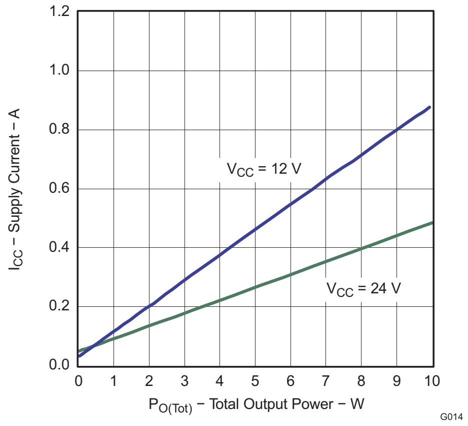
When the circuit is not in a fault state, the selected diode must sustain the average forward current drawn by the amplifier at the highest power output. Figure 2 shows the supply current, $I_{CC}$, versus the total output power, $P_{O(Tot)}$, for the TPA3111D1-Q1 Device. Using the plot that was generated for the selected impedance of the speaker is important.

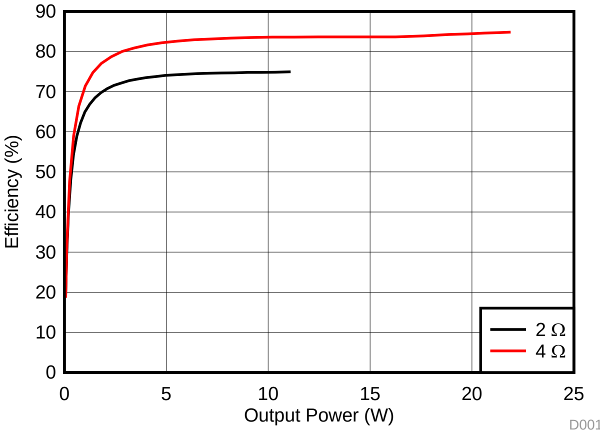


Gain = 20 dB $Z_L$ = 8 Ω +66 µH

**Figure 2. Supply Current versus Output Power for the TPA3111D1-Q1**

For a supply voltage of 12 V, the supply current is less than 1 A. In this case, the chosen diode should have an average forward current rating greater than 1 A. If the application calls for a PVCC voltage of 8 V, which is the recommended minimum voltage for the TPA3111D1-Q1 device, margin should be added for the additional supply-current.

While the data sheet for the TAS5421-Q1 device does not contain a plot of $I_{CC}$ versus $P_{O(Tot)}$, it does contain a plot of efficiency versus output power, $P_O$, as shown in Figure 3.



$V_{(PVDD)}$ = 14.4 V Gain = 26 dB $f_{SW}$ = 400 kHz $T_A$ = 25ºC

**Figure 3. Efficiency versus Output Power for TAS5421-Q1**

Use Equation 1 to calculate the input current, $I_{in}$, from this plot.

$$I_{in} = \frac{P_O}{V_I \times \eta}$$

where

- $V_I$ is the input voltage.
- $\eta$ is the efficiency. (1)

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For a 4-Ω load operating at 22 W and a $V_I$ value of 14.4 V, the device is 85% efficient. The supply current for this boundary case is 1.8 A. The rated average forward current of the diode should be greater than 2 A to support those operating conditions.

Meeting the reverse voltage and forward current ratings are not the only requirements for selecting the power-supply protection diode. Minimizing impact to system efficiency is also required which can be accomplished by selecting the diode that has the smallest forward voltage, $V_F$, at the maximum supply current of the device. The smallest $V_F$ ensures that the power loss from the diode is mitigated in normal operation. Schottky diodes have much lower forward voltages than their silicon counterparts, but also have higher reverse leakage currents. If minimizing reverse leakage current during a short-to-battery fault is critical to protect the power supply, a silicon diode should be used. Otherwise, a Schottky diode will provide a more efficient solution.

For this protection diode, the SL34 and SL44 diodes are the most efficient diodes of those tested. The SL34 diode is recommended because it meets the voltage and current requirements. Furthermore, this diode is smaller than the SL44 diode.

## 2.2 PVCC Capacitance Selection

Selection of the capacitance at the PVCC pin is critical to ensure stability and noise decoupling during normal operation. The class-D amplifier is a switching device and switches large currents each period. Long traces connecting the power supply to the PVCC pin increase stray inductance. The power supply is not a low impedance source because of this inductance and the switching speed. For this reason, a bulk capacitor is added near the PVCC pin in addition to the noise decoupling capacitors. The bulk capacitor is able to provide most of the switching current to the amplifier as well as handle load transients.

Having a large bulk capacitance helps ensure proper operation; however, it also means more charging current is drawn through the body diode in a short-to-battery fault. In addition to larger peak fault currents, the duration of the charging pulse is extended by large bulk capacitance values which further endangers the device. A solution to the large inrush current caused by the bulk capacitance is to reduce the bulk capacitance at the PVCC pin by placing it before the power-supply protection diode.

While lowering the bulk capacitance at the PVCC pin is appropriate, lowering it too much can cause a different issue during the fault. If the capacitance is too small, it will have a smaller charge current but it will also charge faster. This higher rate of current change increases the voltage across the inductance on the shorted output. The inductance could be from the reconstruction filter or it could be the stray inductance of the output wire. The voltage spike from this inductance adds to the shorting battery voltage. If the voltage after the body diode exceeds the maximum voltage allowed at the PVCC or PVDD pin, then the device may fail from an overvoltage condition. The absolute maximum voltage at the PVCC pin for the TPA3111D1-Q1 device is 30 V, and the absolute maximum voltage at the PVDD pin for the TAS5421-Q1 device is 40 V.

If the device is turned on when a short-to-battery fault occurs, the amplifier is again in danger of overvoltage. When the shorted output is switched low to ground, the battery is shorted through the series inductance to ground. This short circuit is detected at some threshold and the outputs are put into a high impedance state. The stored energy of the inductor must dissipate however, and the inductor produces a voltage spike to keep the current flowing through the body diode into the power supply capacitance. Use Equation 2 to calculate the value of the peak inductor voltage.

$$V_{pk} = I_{OC}\sqrt{\frac{L}{C}} \tag{2}$$

The overcurrent threshold, $I_{OC}$, is directly related to how much energy is stored in the inductance, L. To reduce the voltage change on the power pin, a larger capacitance, C, is required. Use Equation 3 to calculate the capacitance for the TAS5421-Q1 device with an $I_{OC}$ of 3.5 A.

$$C = \frac{I_{OC}^2 \times L}{(\mathrm{PVDD_{max}} - \mathrm{PVDD})^2} = \frac{3.5^2\ \mathrm{A} \times 32\ \mu\mathrm{A}}{(30\ \mathrm{V} - 12\ \mathrm{V})^2} = 1.21\ \mu\mathrm{F} \tag{3}$$

The inductance of 32 µH is composed of a 22-µH filter and a worst-case stray inductance of 10 µH from long speaker wires. This PVDD capacitance is the value needed to ensure that the voltage peak does not exceed the absolute maximum value of 30 V. A larger capacitance adds margin to the overvoltage protection but also increases the fault current.

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### 2.2.1 Decoupling Capacitor Selection

Ceramic decoupling capacitors are required to support the higher frequency current demands of the H-bridge structure of a class-D amplifier. These capacitors should be placed as close to the power pins as possible to reduce any stray inductance which may impede their operation. The capacitors should be placed on the cathode of the power-supply protection diode. For a more complete explanation of decoupling selection and formulas refer to *Input and Output Capacitor Selection* (SLTA055) and *Power supply decoupling and audio signal filtering for the Class-D audio power amplifier* (SLYT199).

For the TPA3111D1-Q1 device, a decoupling capacitance of 20 µF is recommended. Because this device has two pin sets of PVCC and GND, TI recommends splitting the decoupling between two 10-µF ceramic capacitors on each power pin set. For the TAS5421-Q1 device, a 22-µF ceramic capacitor should be added to the only power pin of the device. In both cases, the value of the ceramic capacitor can derate with the applied DC voltage. The absolute maximum-voltage ratings used should be selected such that the value of the capacitor at the applied PVCC pin is still correct.

### 2.2.2 Bulk Capacitor Selection

The bulk capacitance is the element that keeps the average supply voltage stable. This capacitance is typically electrolytic. This capacitor has some voltage ripple because the charge flow; however, the worse cause of voltage ripple is from the high parasitic ESR found in electrolytic capacitors. The $I^2$ESR power losses decrease system efficiency and heat the capacitor. Too much heat dissipation from a high ESR could drastically shorten the lifetime of the capacitor. The selected electrolytic capacitor must be rated for the root-mean-square (rms) current of the bulk capacitor, $I_{C(RMS)}$. Additionally, the voltage rating of the capacitor must be greater than the supply voltage.

Based on the same conditions shown in the previously described example, the $I_{C(RMS)}$ current used in the TPA3111D1-Q1 and TAS5421-Q1 devices is nearly 600mA rms and 800mA rms, respectively. The ripple-current rating takes into account the heating caused by the ESR and represents the thermal failure threshold. To reduce short-to-battery fault current, the bulk capacitance on the PVCC pin should be as low as possible while still meeting the ripple current rating.

The 146CTI series of low impedance, electrolytic capacitors from Vishay offers several options. For use with the TPA3111D1-Q1 device, the 33-µF, 35-V capacitor has a rated ripple current of 650mA rms. For more ripple current margin, the 47-µF, 35-V capacitor with a 700mA rms rating could be selected. This class-D amplifier has two sets of PVCC pins, so providing the decoupling and bulk capacitors to each pair of PVCC pins is important. Finally, a bulk capacitance with a value of 100µF, 35 V can be added to the anode of the power-supply protection diode to increase the bulk capacitance for normal operation. Figure 4 shows the solution described so far. The smaller 1000-pF and 0.1-µF capacitances are for further decoupling and high frequency current switching. These capacitors should be placed as close to the PVCC pins as possible.

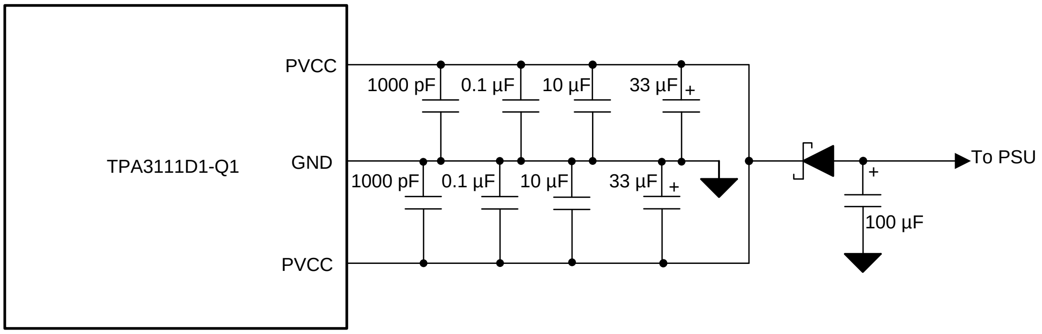

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Figure 4. TPA3111D1-Q1 Capacitance Selection and PSU Protection

For use with the TAS5421-Q1 device, the 220-µF, 35-V capacitor is rated for 900mA rms. This capacitor can be placed on the anode of the power-supply protection diode. A smaller 100-µF, 35-V capacitor can be placed on the PVDD pin to provide some bulk capacitance directly on the PVDD pin. The 220-µF capacitor still provides lower impedance to the ripple current and therefore supports more of the ripple current. Figure 5 shows the solution described so far.

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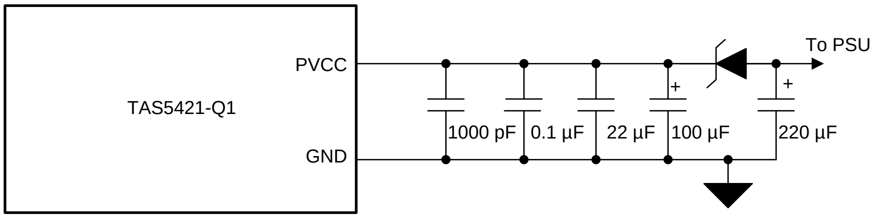

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Figure 5. TAS5421-Q1 Capacitance Selection and PSU Protection

## 3 Step 2: Schottky Diode Current Shunt

The diode and capacitor selection outlined in Step 1 helps protect the power supply and balances short-to-battery current with nominal performance and stability. The capacitance at the PVCC or PVDD pin of the amplifier is still large enough that the fault current can destroy the device if it flows entirely through the body diode. This second step builds on the first step by adding a Schottky diode in parallel with each body-diode output, as shown in Figure 6.

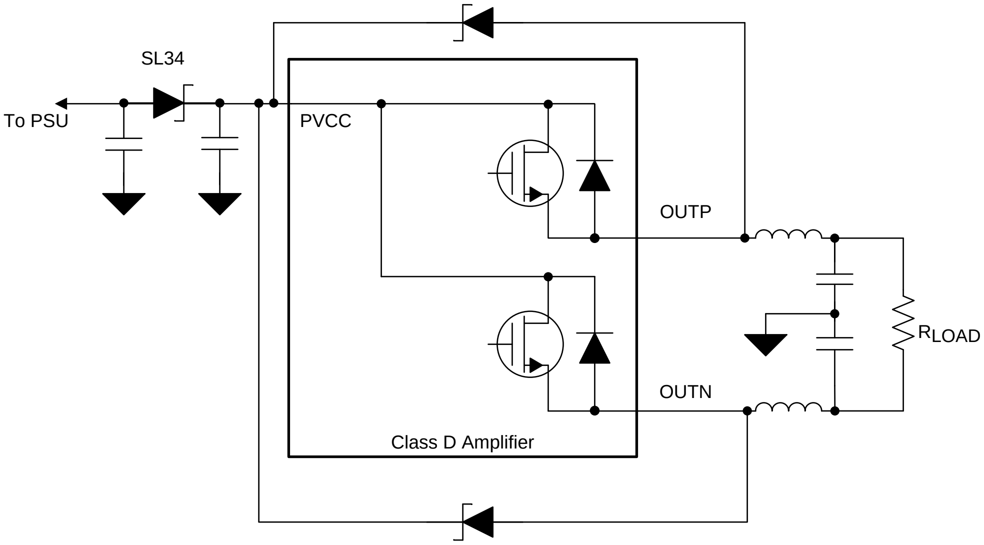

Figure 6. Parallel Schottky Diodes Added to Each Output

The parallel Schottky diodes allow for a shunt path during a short to battery and conduct most of the fault current, therefore helping to protect the device.

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## 3.1 Current Sharing among Parallel Diodes

Figure 7 shows the equivalent circuit when the fault occurs in an output and no load is present.

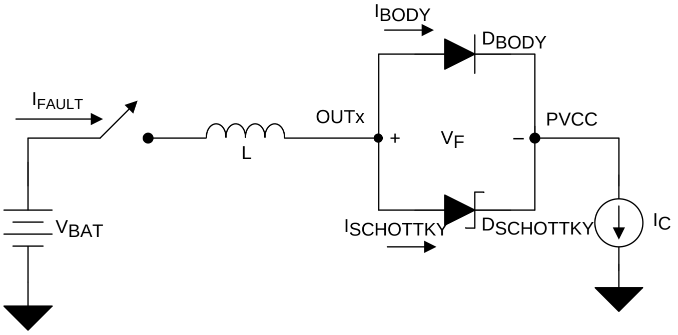

**Figure 7. Equivalent Circuit of the Short-to-Battery Fault**

The profile of the capacitor current is the independent current sink that determines how much current flows from the battery at any given time. The branch currents, $I_{BODY}$ and $I_{SCHOTTKY}$, for the body and Schottky diodes must share the capacitor current. Stated for any time, t, with Kirchoff's Current Law (KCL), Equation 4 must be true.

$$I_C(t) = I_{SCHOTTKY}(t, V_F) + I_{BODY}(t, V_F) \tag{4}$$

Because capacitor current varies as the independent quantity, the voltage, $V_F$, across both diodes must change to satisfy KCL. Diode current depends nonlinearly with $V_F$ so finding a solution for a given capacitor current requires iteration which makes current sharing predictions harder. However, if two diodes of constant forward voltages are put in parallel, the solution is simple. The diode with a lower forward voltage conducts all of the current flowing through the parallel network. Schottky diodes generally have lower forward voltage than the body diode, which is a silicon diode. Ideally, the Schottky diode will conduct all of the fault current, but, in reality, this is not the case.

As the current through a diode increases, the series resistance of the semiconductor material and Ohmic contacts cause IR-drops which reduces the voltage applied to the rectifying junction. Therefore, for the same current to flow through a diode, the voltage across the terminals must increase to counteract the IR-drop. When the capacitor current increases, the voltage across the Schottky and body diodes also increases. During the capacitor current pulse, the $V_F$ voltage can increase enough to allow the body diode to conduct significant current. When selecting the Schottky diode, focus on minimizing the time the body diode spends conducting current and minimizing the peak body current.

## 3.2 Schottky Diode Selection

### 3.2.1 Survivability

The selected Schottky diode must not fail during a fault, but it must also be rated for normal amplifier operation. For normal operation, the diode becomes reverse biased every time the output is pulled low by the H-bridge. Therefore the rating for the reverse voltage, $V_{RRM}$, must be greater than the supply voltage.

During the short-to-battery fault, the diode must be able to support a large current pulse. The data sheet parameter that specifies this rating is the maximum forward surge current, $I_{FSM}$. As previously stated, the fault current depends on the supply pin capacitance. To test this protection scheme, a TPA3111D1-Q1 EVM was modified to include 100-µF bulk capacitance on the PVCC pin. The device was unpowered and an 18-V fault was applied to an output. Figure 8 shows an oscilloscope capture of the fault with a B240Q diode. The peak current from that test case was 30 A, but this value depends on the capacitance.

The analysis of Figure 8 is as follows:

- The PVCC voltage is a diode drop below OUTN because the short circuit causes the diodes to conduct from the OUTN pin to the PVCC pin.
- The fault current is equal to: $I_{FAULT} = I_{BODY} + I_{SCHOTTKY}$
- In this case, the body diode still conducts a significant amount of current, meaning that a different

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Schottky diode should be selected.

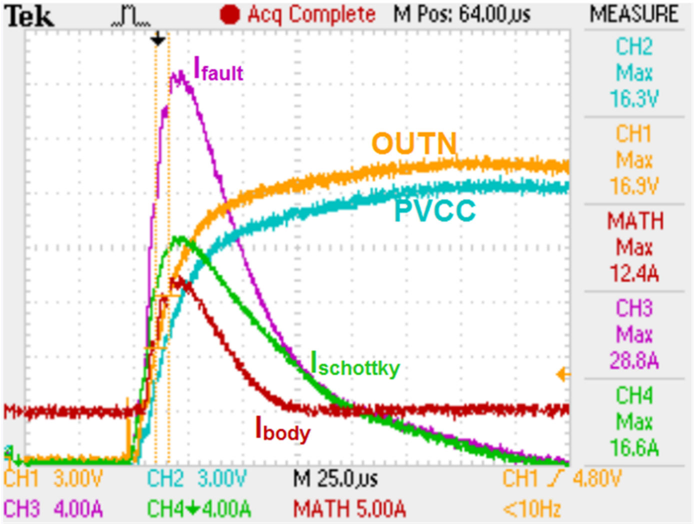

**Figure 8. Fault Voltages and Currents With B240Q Diode Under Test**

### 3.2.2 Performance

The performance a Schottky diode in the protection scheme is directly proportional to the percentage of fault current that flows through it and not the body diode. To gauge the effect of Schottky diode characteristics on performance and provide a recommendation, eight different Schottky diodes were tested. Table 2 lists the ratings and extracted parameters. For more information on how to extract the parameters from the data sheet of a diode, see Appendix A.

**Table 2. Sampled Schottky Diode Ratings and Parameters**

| Diode Name | $I_{F(AV)}$ (A) | $I_{FSM}$ (A) | $V_{RRM}$ (V) | $V_{knee}$ (V) | $I_{knee}$ (A) | Slope (mV/decade) |
|---|---|---|---|---|---|---|
| B240Q-13-F | 2 | 50 | 40 | 0.35 | 0.7 | 247 |
| PMEG4010ETP | 1 | 50 | 40 | 0.35 | 0.3 | 407 |
| SL13HE3_A/H | 1.5 | 50 | 30 | 0.4 | 0.7 | 412 |
| SL34A-TP | 3 | 80 | 40 | 0.3 | 0.6 | 432 |
| SL44HE3_A/H | 4 | 150 | 40 | 0.25 | 0.6 | 391 |
| SS15HE3_A/H | 1 | 40 | 50 | 0.48 | 0.7 | 452 |
| SSA24 | 2 | 50 | 40 | 0.38 | 0.3 | 340 |
| SSA34HE3_A/H | 3 | 75 | 40 | 0.38 | 1 | 477 |

The parameters $V_{knee}$, $I_{knee}$ and slope are all extracted from the IV curve of the diode in the diode data sheet. The knee voltage is roughly the point where the diode starts conducting a significant current, $I_{knee}$. The slope is an approximation of how much the forward voltage of the Schottky diode increases if the current through it increases by a factor of ten. In general, a diode with a lower slope performs better because the body diode does not conduct as much current if $V_F$ does not increase much. Also, a lower knee voltage and higher knee currents mean that the Schottky diode can solely conduct a larger amount of the fault current pulse.

As previously mentioned, this Schottky diode set was tested with an unpowered TPA3111D1-Q1 EVM, an 18-V fault voltage, and nearly 100 µF of capacitance on the PVCC pin. These tests were conducted at 20°C. Figure 9 shows the amount of the capacitor current that the body diode conducted at each point during the pulse.

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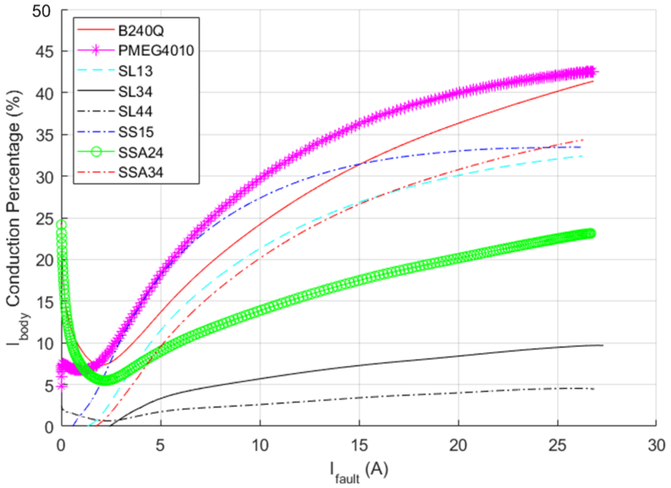

**Figure 9. Body Current Sharing versus Fault Current Across Schottky Diodes**

The top-performing Schottky diodes were the SL34 and SL44 diodes. Both diodes conducted at least 90% of the peak fault current. For the TPA3111D1-Q1 device, TI recommends using the SL34 diode for the parallel-protection diodes. The SL34 diode is a smaller footprint but has plenty of margin on forward surge current. While the TAS5421-Q1 device was not tested with this set of diodes, the increase in the peak fault current caused by the 22-µF extra supply capacitance can be supported by the SL34 and SL44 diodes. The SL34 diode is recommended but the SL44 diode can be used depending on what level of body current is acceptable. For either device, the user should verify that their system is adequately protected in each fault case. For details on testing the protection scheme, see Section 3.3.

### 3.2.3 Choosing Other Diodes

If another diode other than the recommended SL34 or SL44 diodes must be selected, follow the available guidelines. These guidelines outline the requirements of data sheet parameters required to survive normal operating conditions as well as fault conditions. The guidelines also recommend how to choose diodes based on the extracted parameters outlined in Appendix A. Table 3 lists the guidelines.

**Table 3. Survival and Performance Guidelines for Schottky Diode Selection**

| Symbol | Parameter Name | Guideline |
|---|---|---|
| **Survivability Requirements** | | |
| $V_{RRM}$ | Maximum reverse repetitive voltage | The $V_{RRM}$ voltage must be higher than the maximum supply voltage used. A $V_{RRM}$ of 30 V or 40 V is recommended but higher blocking usually increases the voltage drop in forward bias, thus reducing shunt performance. |
| $I_{FSM}$ | Maximum forward surge current | The $I_{FSM}$ must be higher than the worst-case peak fault current. The peak current value depends on the inductance in the path as well as supply pin capacitance. An $I_{FSM}$ of at least 30 A is recommended. A larger rating increases the diode size for better thermal impedance. |
| **Performance Recommendations** | | |
| $V_{knee}$ | Knee voltage | The $V_{knee}$ voltage should be as low as possible so that the high-level injection region begins earlier. |
| $I_{knee}$ | Knee current | The $I_{knee}$ current should be as high as possible to conduct a larger percentage of the peak fault current at the start of the high-level region. |
| $m_{SCHOTTKY}$ | High-level injection region slope | The slope, $m_{SCHOTTKY}$, represents the average increase in the voltage drop of the Schottky diode for a decade increase in forward current. This value should be as low as possible so that the body diode turns on as slowly as possible. |

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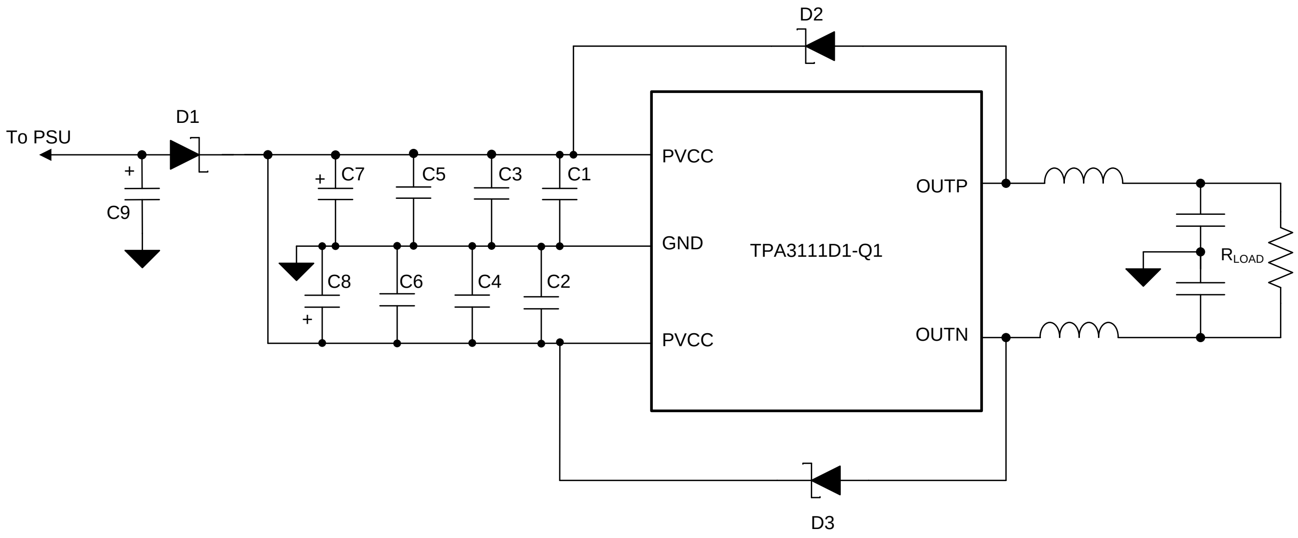
### 3.2.4 Full Protection Solutions

Figure 10 shows a complete protection scheme for the TPA3111D1-Q1 device.



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| Component | Device Value |
|---|---|
| C1, C2 | 1000 pF, 35 V ceramic |
| C3, C4 | 0.1 µF, 35 V ceramic |
| C5, C6 | 10 µF, 50 V ceramic |
| C7, C8 | 33 µF, 35 V electrolytic |
| C9 | 100 µF, 35 V electrolytic |
| D1, D2, D3 | SL34 Schottky Diode |

**Figure 10. Full Protection Scheme for the TPA3111D1-Q1**

Figure 11 shows a frequency sweep of total harmonic distortion and noise (THD+N) for a TPA3111D1-Q1 device with the protection scheme. The modifications from the protection scheme did not significantly affect the performance of the amplifier.

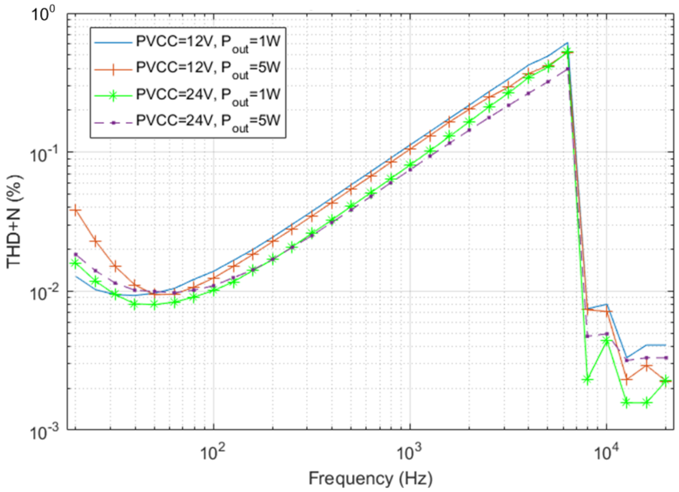

**Figure 11. THD+N versus Frequency on Protected TPA3111D1-Q1, $R_{LOAD}$ = 4 Ω**

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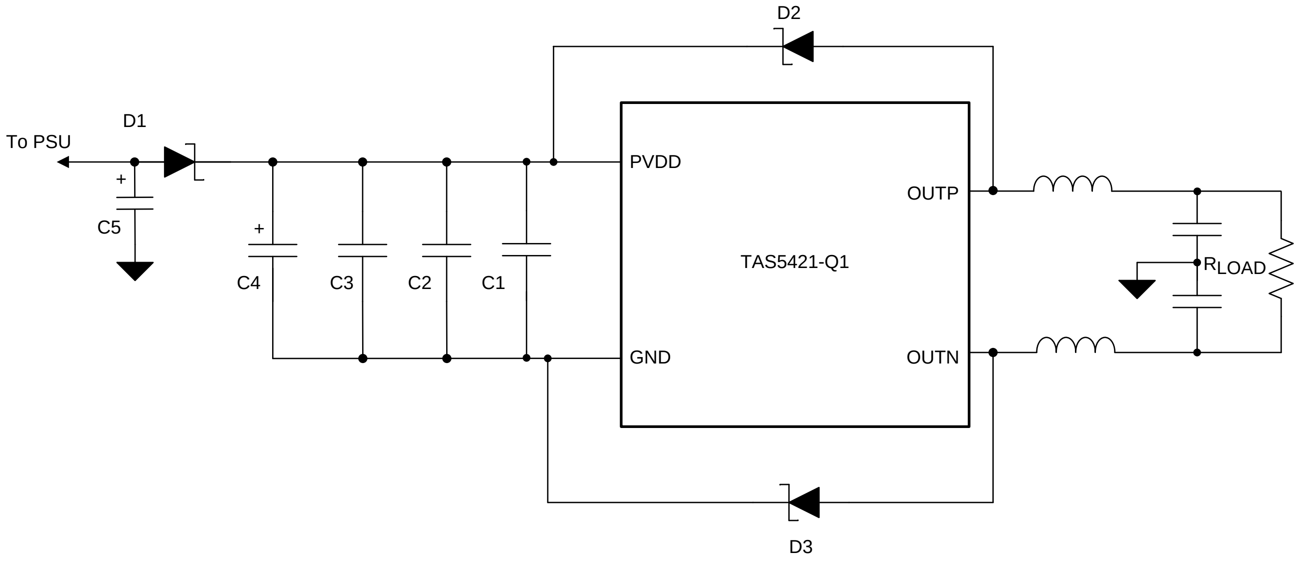
Figure 12 shows a complete protection scheme for the TAS5421-Q1 device.



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| Component | Device Value |
|---|---|
| C1 | 1000 pF, 35 V ceramic |
| C2 | 0.1 µF, 35 V ceramic |
| C3 | 22 µF, 50 V ceramic |
| C4 | 100 µF, 35 V electrolytic |
| C5 | 220 µF, 35 V electrolytic |
| D1, D2, D3 | SL34 Schottky Diode |

**Figure 12. Full Protection Scheme for the TAS5421-Q1**

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### *3.3 Protection Verification*

The recommended protection scheme was only tested on the TPA3111D1-Q1 device at 25°C. The protection scheme must be tested at the expected temperature extremes of the application. Figure 13 shows the general test setup.

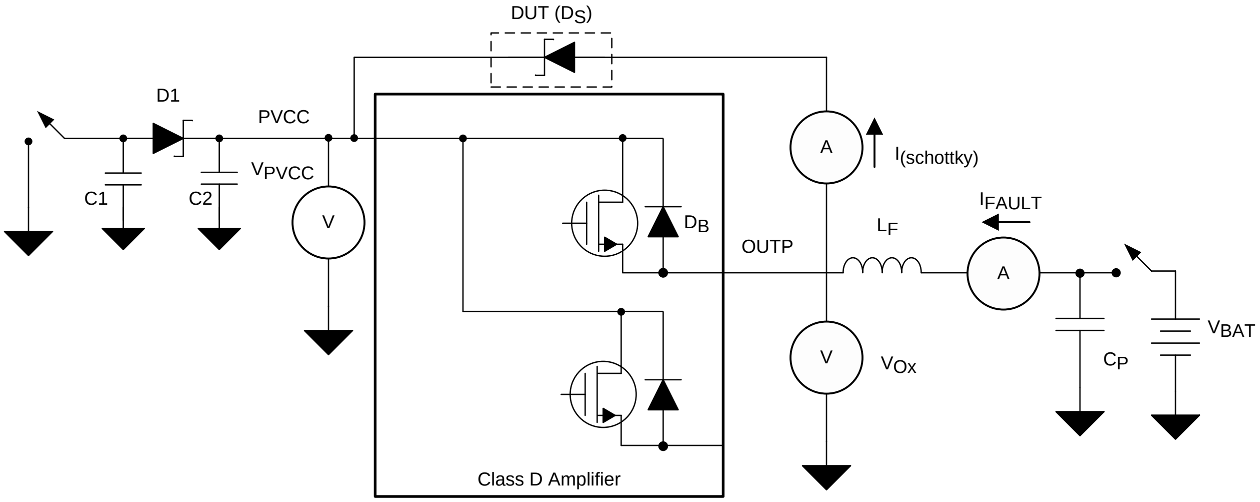

**Figure 13. General Test Setup for Protection Verification**

The critical measurements that must be taken are the $I_{SCHOTTKY}$ and $I_{FAULT}$ currents. Using these measured currents, the body current for any point of time during the fault can be calculated by subtracting the Schottky-current channel from the fault-current channel. Measuring these currents noninvasively is important. Inserting a series resistance to measure the voltage differential affects the results of the test. A resistance for fault-current measurement can dominate the stray resistance and artificially limit the fault current. If the Schottky branch current is measured with a resistor, it will perform worse as the voltage across both the parallel diodes must increase further. Therefore TI recommends measuring these currents with wire loops and a Hall-Effect current probe.

The other measurements that should be taken are the voltage at the supply pin and the voltage at the output pin. The voltage at the PVCC pin should be monitored to ensure it does not exceed the maximum rating for the amplifier. The voltage at either the positive output (OUTP) or negative output (OUTN) can be measured to find the voltage across the parallel-diode network during the fault. The diode voltage is not immediately helpful to verifying the protection scheme is sufficient; however, it can be used later to confirm that the IV curve of the Schottky diode under test matches the data sheet, or to characterize the body diode.

Before testing, make sure that the circuit is setup as shown in Figure 13. The power-supply connection on the anode of D1 should be grounded. The capacitances at the anode and cathode of D1, represented by C1 and C2, should be configured based on the recommendations in Step 1. Any output pin can be used for this test because the body diodes do not vary significantly in the same amplifier. The output LC filter may or may not be present in the design, so be sure to test the protection scheme with whichever output setup is specified in the design.

When performing the testing, begin with the fault voltage at 10 V which ensures that the Schottky diode under test is conducting the majority of the fault current at lower currents. If the Schottky diode does not conduct most of the current and an 18-V fault is induced, the body diode of the amplifier may conduct too much current and damage the device. If the Schottky diode performs well at 10 V, induce an 18-V fault to test the protection scheme. The goal of this verification is to minimize the body current and to minimize the time the current conducts. Finally, unground the power supply pin and check to make sure the amplifier is performing correctly after the 18-V fault occurs.

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# 4 Alternative Solutions

## *4.1 Increasing System Efficiency by Using a Smart Diode*

One way to alter the proposed protection scheme is to change the diode used for power-supply protection, as suggested in Step 1. Schottky diodes were selected over silicon diodes for their lower forward voltage at a given current and temperature. Despite this advantage, the power loss in the diode reduces system efficiency which reduces the benefits of using a class-D amplifier. For a TAS5421-Q1 device operating at maximum output power, the device draws 1.8 A. The recommended SL34 diode has a forward voltage of 400 mV at this current and therefore the amplifier operating at 22 W dissipates 720 mW in just the input diode.

The system could become more efficient if the diode power losses were replaced by the on-resistance losses of a MOSFET. Replacing the losses is possible with the LM74610-Q1 smart diode controller from TI. When combined with an external N-channel MOSFET and bootstrap capacitor, this controller uses the voltage across the body diode of the external FET to turn on the gate of the transistor. The controller requires no quiescent current to operate because the diode-voltage drop is boosted through charge pump to an appropriate gate voltage. Figure 14 shows a typical configuration. The input voltage would connect to the power supply and the output would connect to the supply pin of the amplifier.

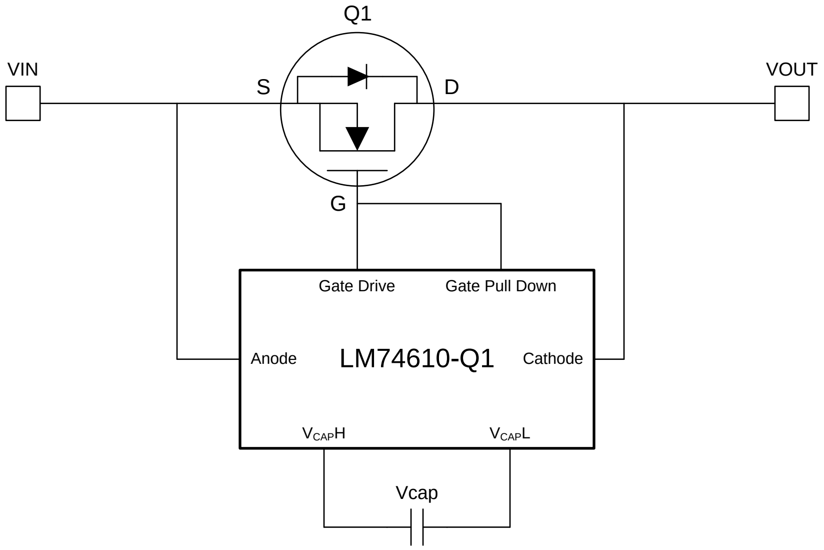

**Figure 14. Typical Configuration of Controller and External Components**

The controller can handle up to 45-V reverse voltage between the cathode and anode pins. The maximum drain-to-source voltage of the MOSFET must also be greater than the 30-V protection rating determined in Step 1. Additionally, the maximum drain current of the external MOSFET must be greater than 1 A for the TPA3111D1-Q1 device and 2 A for the TAS5421-Q1 device. For higher efficiency, the on resistance, RDS(on), of the MOSFET should be as low as possible. For more information on selecting the bootstrap capacitor and MOSFET, refer to Reference 3.

The MOSFET channel is not conducting 100% of the time. The external body diode must initially conduct current until the charge pump capacitor voltage is high enough to turn on the gate. Driving the gate eventually depletes the bootstrap capacitor and the channel turns off. The body diode must conduct again to restart the cycle. Figure 15 shows this cycle.

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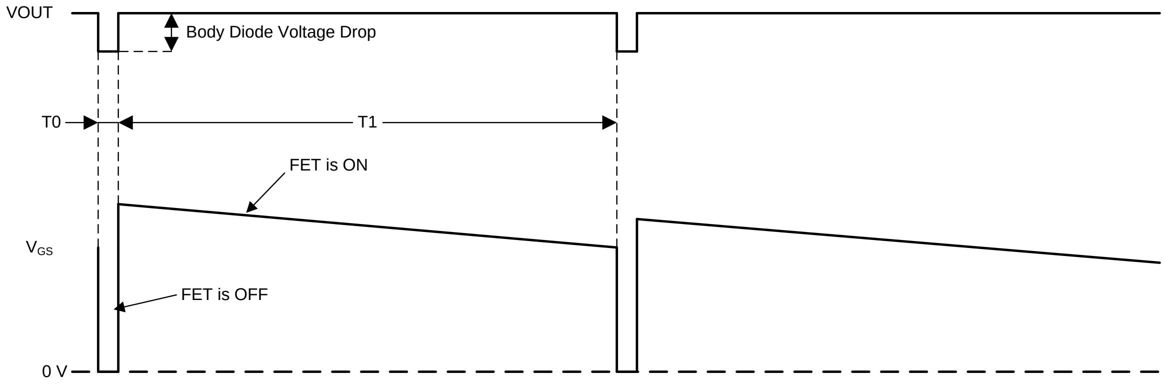

Figure 15. Output-Path Duty Cycle

The diode conducts only 2% of the time, but can cause an output-voltage ripple. With proper decoupling, this ripple will not impact the amplifier. The use of the LM74610-Q1 smart diode controller still helps protect the power supply unit during a fault, but also increases the system efficiency.

## 5 Summary

Faults can occur in automotive class-D amplifiers from maintenance or collisions. While most faults are protected on the TPA3111D1-Q1 and TAS5421-Q1 amplifiers, the short-to-battery fault can still damage the device and other system components if the battery voltage is higher than the supply pin voltage. This damage is because of a large capacitance on the supply pin charging through a body diode of the H-bridge output of the amplifier.

In Step 1, the power supply unit and other system components were protected by adding a power-supply protection diode. The SL34 Schottky diode was recommended because it meets the fault protection criteria and performs well in normal operation. Next, the supply pin bulk capacitance was reduced to reduce the peak fault current. Because the bulk capacitance of the supply pin could only be reduced so far before over-voltage became problematic, additional protection is required to support the current.

Step 2 employs a Schottky diode in parallel with each body diode of the output. Ideally, the Schottky diode will shunt the entire fault current away from the body diode because it has a lower voltage drop. Realistically, the voltage drop increases as a diode conducts more current. Therefore selecting a Schottky diode that conducts as much current as possible at the lowest voltage drop possible is necessary. The diode should also slowly increase the forward voltage when the forward current increases. The SL34 diode conducted more than 90% of a 28-A peak fault current when tested with the TPA3111D1-Q1 device. As such, TI recommends using the SL34 diode for parallel shunt protection.

The protection scheme can be further modified by replacing the power-supply protection diode with an N-channel MOSFET and the LM4610-Q1 smart diode controller. This change mitigates the system efficiency drop caused by a Schottky diode, but it also offers the necessary protection during a short-to-battery fault. As with the original scheme, a modified scheme must also be tested to ensure adequate protection in a short-to-battery fault.

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## 6 References

1. *Selecting TVS diodes for reverse polarity in automotive applications* (Mathew Jacob)
2. *Lost Secrets of the H-Bridge, Part I: Ripple Current in Inductive Loads* (Jason Sachs, July 2013)
3. *LM74610-Q1 Zero IQ Reverse Polarity Protection Smart Diode Controller* (SNOSCZ1)
4. *Lab IV. Silicon Diode Characteristics* (Jeong-Bong Lee)
5. *Input and Output Capacitor Selection* (SLTA055)
6. *Power supply decoupling and audio signal filtering for the Class-D audio power amplifier* (SLYT199)
7. *TAS5421-Q1 22-W Mono Automotive Digital-Audio Amplifier With Load Dump and I2C Diagnostics* (SLOS814)
8. *TPA3111D1-Q1 10-W Filter-Free Mono Class-D Audio Power Amplifier With Speakerguard™* (SLOS759)

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## Appendix A

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# Diode Parameter Extraction from Data Sheet

To qualitatively rank Schottky diodes for use in short-to-battery protection, extracting parameters from the data sheet of the diode is helpful. This appendix explains the theory behind extracting these parameters.

The Shockley diode equation shows an exponential relationship between $I_D$ and $V_F$ and is modeled with Equation 5.

$$I_D = I_{(sat)} \left( e^{\frac{V_F}{\eta V_T}} - 1 \right)$$

where

- $I_{(sat)}$ is the saturation current.
- $\eta$ is the ideality factor.
- $V_T$ is the thermal voltage defined as: $V_T = \frac{kT}{q}$

  where
  - k is the Boltzmann constant.
  - T is the temperature in Kelvin.
  - q is the charge of an electron. (5)

By using logarithms, this equation can be manipulated to give a linear relationship between logarithmic current and linear voltage as shown in Equation 6.

$$\log_{10}(I_D) = \frac{1}{2.303 \times \eta V_T} V_F + \log_{10}(I_{(sat)}) \quad (6)$$

If this manipulation were plotted, the result would be a straight line; however, in reality, this is not completely the case. Figure 16 shows the IV curve given by the data sheet for the SL13 Schottky diode.

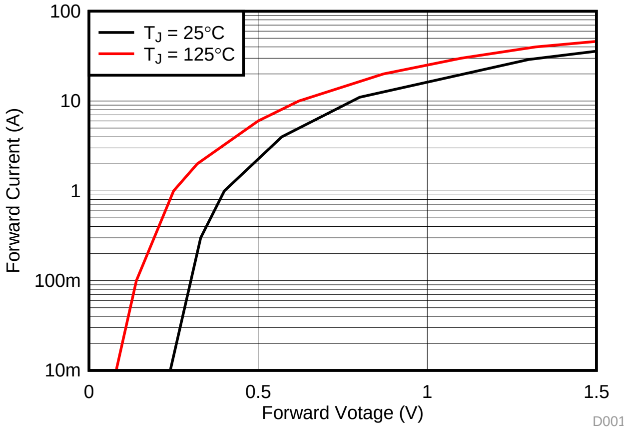

**Figure 16. SL13 Diode IV Curve**

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For the 25°C curve, the increase in current with $V_F$ appears to follow the Shockley equation until the current reaches 1 A. For this region of operation, the current is small enough that the series resistance of the diode does not affect the voltage applied to the semiconductor junction. The Shockley equation for diode current is correct over this first region. The region beyond 1 A is known as the high-level injection region (refer to Reference 4). In this region, the resistances of the silicon and Ohmic contacts cause a significant drop in voltage that is applied to the junction. As a result, the $V_F$ voltage that is applied across the entire diode package must increase to allow the same level of current to flow as predicted in the Shockley equation. Thus, the IV curve is no longer the linear relationship between linear voltage and logarithmic current.

The nonideal series resistance causes the voltage of the Schottky diode to increase faster as the current through it increases. This increase in voltage is problematic when trying to minimize the voltage applied to the body diode and the level of conduction. Another complication is evident when trying to encapsulate the behavior of a diode with a single equation. A diode can be better modeled using a composite equation, but characterizing each component equation for a data sheet is unrealistic—especially across different temperatures. The typical IV curves are expected results only, not a contract of how a device will actually perform.

At a minimum, data sheets include the typical IV curve, and might include a maximum $V_F$ value for a specified current and temperature. These single data points are not helpful in a dynamic situation, such as the short-to-battery fault. To gauge how well one Schottky diode performs relative to other diodes, a simple and consistent method of parameter extraction is necessary. This appendix details how to extract the three parameters that can be used to rank diode performance which are $V_{knee}$, $I_{knee}$, and slope (m).

## A.1 $V_{knee}$ and $I_{knee}$ Determination

The first step is to determine the coordinates of the knee point on the IV curve of the diode. The knee point is the voltage and current at which the first region ends and the high-level injection region begins. Determining this point can be accomplished by drawing a line of best fit to determine where the linear first region ends. A pencil and straight edge can be used, but an image editing tool such as Microsoft Paint, GIMP, or Inkscape may provide more consistent results when performing multiple extractions.

The SS15 Schottky diode provides a good example of parameter extraction from the SS15 data sheet. The first region is identified with a gray line of best fit as shown in Figure 17. Start drawing the line where the IV curve intersects the x-axis. Be careful not to extend the line above the curve because the endpoint of this line determines the knee point. Stop drawing the line before the typical curve departs too far from the ideal curve.

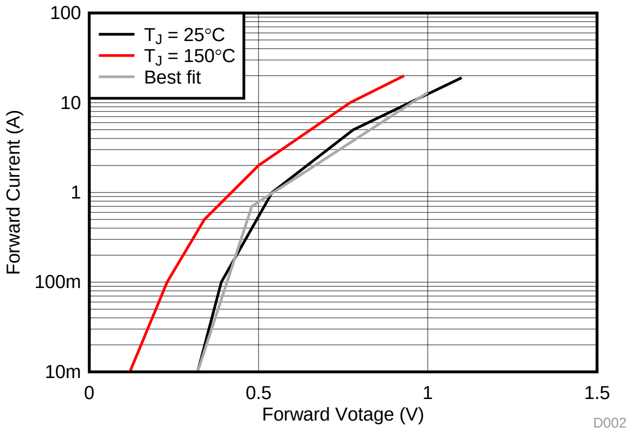

**Figure 17. Region 1 Identification for the SS15 Diode**

When the line of best fit for the first region is drawn, the coordinates of the knee point are the current and voltage values at the end of the line. For the SS15 at 25°C, the knee voltage is approximately 0.48 V and the knee current is approximately 0.7 A.

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## A.2 Slope Determination

Next, the slope parameter, m, provides a value that can estimate the average increase in diode voltage with an increase in current during such a transient. Let the starting point used for the slope calculation be the knee point. The knee point provides a starting point of where the linearized Shockley equation can no longer predict how the diode voltage changes with large currents. The endpoint can be set as the current when the diode voltage is 1 V. Although this point is arbitrarily chosen, it provides a consistent way to determine slope across different diodes. For the SS15, Figure 18 shows the start and end points for slope determination.

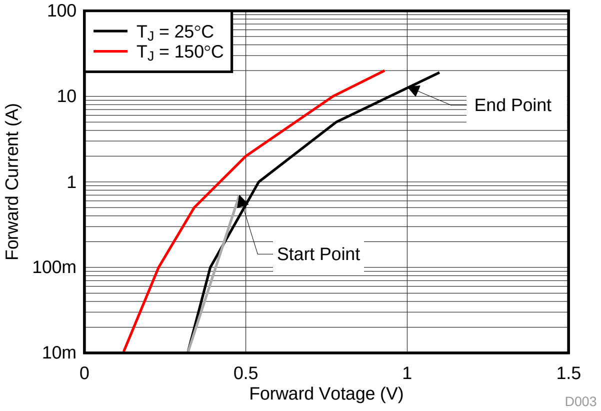

**Figure 18. Start and End Points for Slope Determination**

The endpoint in this case is 10 A at a voltage of 1 V across the SS15 diode. The slope, m, can then be found using Equation 7. The units are in millivolts per decade of current change. For the SS15 diode, the slope is 452 mV/decade.

$$m = 1000 \times \frac{V_{(end)} - V_{(start)}}{\log_{10}\left(\frac{I_{(end)}}{I_{(start)}}\right)} \tag{7}$$

## A.3 Special Considerations

In some cases, the data sheet does not provide enough information on the diode IV curve to perform an extraction. This lack of information may occur in the range of voltages or currents covered as well as the curves across temperatures. Three options can be pursued when this lack of information occurs. First, contact the manufacturer and ask for additional coverage of the IV curve. Second, do not use the diode as the limited current. Voltage ranges may indicate the diode is already insufficient for the required protection. Third, extrapolate the missing curve information enough to complete the parameter extraction, as shown in Figure 19.

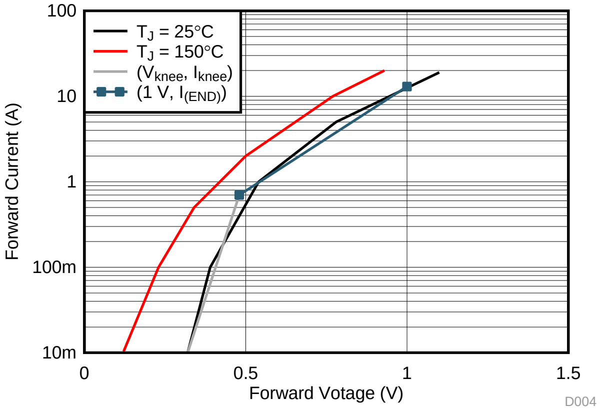

**Figure 19. Extrapolation of the B150Q IV Curve Using Microsoft Paint**

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## Appendix B

SLOA236–November 2016

# Qualitative Diode Comparisons

Many of the variables used in this appendix are extracted directly from an IV curve in a data sheet. For details on how these parameters are extracted, refer to Appendix A. This appendix describes a method of approximating the amount of current shared between a parallel body diode and Schottky diode based on three simple parameters. This methodology has only been tested with the TPA3111D1-Q1 amplifier.

## B.1 Parameter Limitations

The extracted parameters are useful for approximating changes during a current transient, but they have their limitations. Only one slope is determined across a wide voltage range because multiple slope determinations would increase the parameter extraction time and increase the complexity of the current sharing model. The downside of using only one slope is that a large error between the average slope estimation and the actual curve becomes an even larger error in a linear current scale. This error reduces the quantitative accuracy of current sharing predictions. The characterization accuracy of the body diode also limits the quantitative accuracy of the model.

Assuming the single slope did not hinder accuracy, the arbitrary selection of the endpoints used to find the slope may reduce accuracy. A better way to select these endpoints to increase quantitative accuracy may be available, but the present method provides a reasonable qualitative approach. The protection scheme must ultimately be tested by the user to see if it is adequate for the design.

## B.2 Simplified Current Sharing Model

For two parallel diodes, the current through the network is determined by the capacitor current required to charge the supply pin to nearly the battery voltage during a fault. Using the KCL equation, the relationship of the branch currents to capacitor current is expressed in Equation 8. By using the three extracted parameters, a simplified exponential model can be substituted for each branch current term as shown for a given time in Equation 9.

$$I_C(t) = I_{SCHOTTKY}(t, V_F) + I_{BODY}(t, V_F) \tag{8}$$

$$I_C = I_{knee(SCHOTTKY)}\left(10^{\frac{V_F - V_{knee(SCHOTTKY)}}{m_{(SCHOTTKY)}}}\right) + I_{knee(BODY)}\left(10^{\frac{V_F - V_{knee(BODY)}}{m_{(BODY)}}}\right) \tag{9}$$

For a given capacitor current, the amount of current conducted by the Schottky diode is determined by only the knee point voltage and current as well as the slope, $m_{SCHOTTKY}$. The exponential form of each branch term roughly resembles the Shockley diode equation. Equation 9 also provides a clear set of performance predictions. For the Schottky diode to conduct most of the capacitor current, it should have a large knee current, a low knee voltage, and a low slope.

To analyze the simplified model, the three parameters are needed for the body diode. The current sharing tests performed in Step 2 were only performed for the TPA3111D1-Q1 amplifier. Using the data from 30 different diode tests to create an average IV curve, that body diode of the device can be approximated by the IV curve shown in Figure 20.

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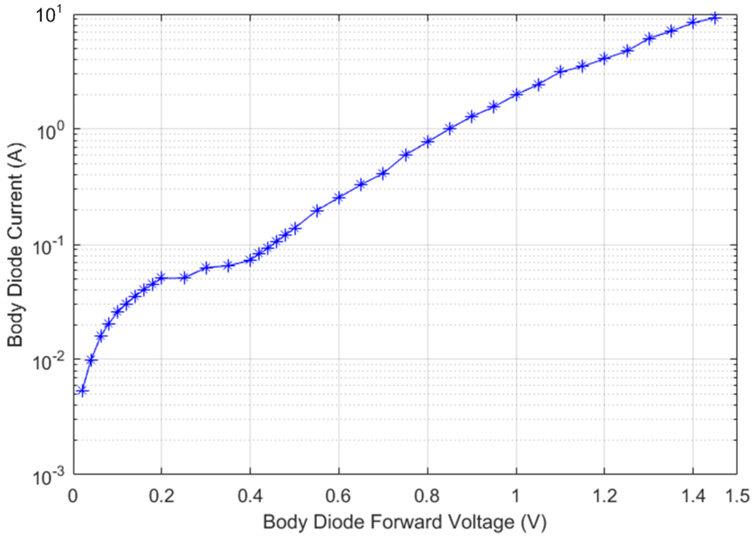

**Figure 20. TPA3111D1-Q1 Body Diode IV Average Characterization**

Extracting the parameters from this IV curve is less straightforward, but the parameters can be estimated as:

- $V_{knee}$ = 225 mV
- $I_{knee}$= 5 mA
- $m_{BODY}$ = 297 mV/decade

Using these parameters, numerically solving for the $V_F$ voltage across both diodes required to conduct the capacitor current for some instant of time is possible. Based on the $V_F$ voltage, both branch terms can be compared to the total current. A good diode selection maximizes $I_{SCHOTTKY}$ (t, $V_F$) and minimizes $I_{BODY}$ (t, $V_F$). Therefore, by ramping the capacitor current from 1 A to 30 A, the performance of each Schottky diode can be predicted. The predicted conduction of the body diode is shown in Figure 21 for each Schottky diode tested.

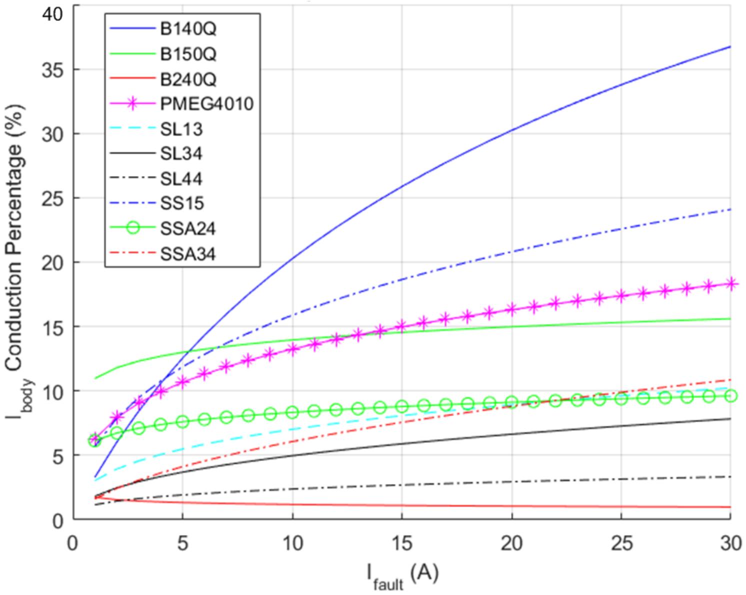

**Figure 21. Predicted Body Diode Conduction versus Fault Current**

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Figure 22 shows the experimental rankings of body diode sharing for the 10-V tests. Figure 23 shows the rankings for the 18 V tests.

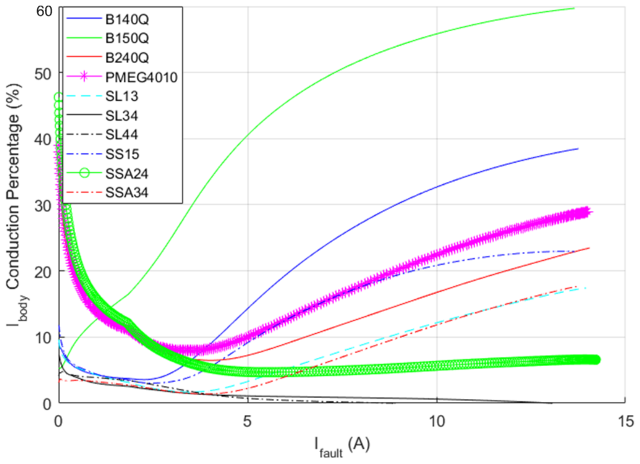

**Figure 22. Experimental Sharing Results for $V_{BAT}$ = 10 V**

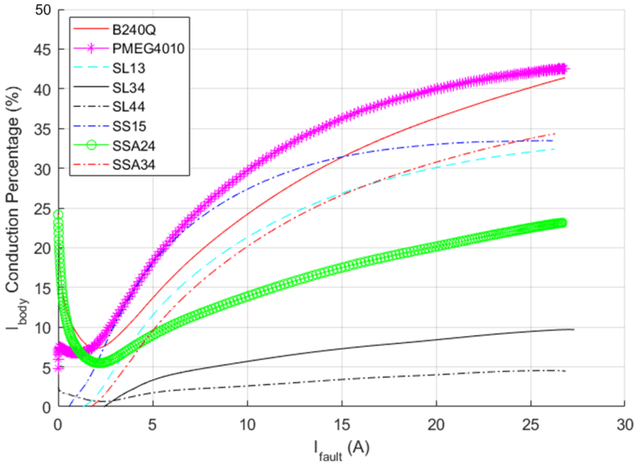

**Figure 23. Experimental Sharing Results for $V_{BAT}$ = 18 V**

The results for the B140Q and B150Q diodes are not shown in Figure 23 because they already showed excessive body-diode conduction during the 10-V tests. Testing those diodes at a battery voltage of 18 V would have damaged the device. The B150Q and B140Q diodes conducted 40% and 60% of a 15-A fault current, respectively. Table 4 lists a side-by-side ranking of the diode performance.

**Table 4. Body Conduction Rankings for Maximum Fault Current**

| Conduction Rank | Model Predictions | 10-V $V_{BAT}$ Tests | 18-V $V_{BAT}$ Tests |
|---|---|---|---|
| 1 (lowest $I_{BODY}$ | B240Q(1) | SL44(2) | SL44(2) |
| 2 | SL44(2) | SL34(2)(2) | SL34(2)(2) |
| 3 | SL34(2) | SSA24(2)(3) | SSA24(2)(3) |
| 4 | SSA24(2)(3) | SSA34(2) | SSA34(2) |
| 5 | SSA34(2) | SL13(2) | SL13(2) |
| 6 | SL13(2) | B240Q(1) | SS15 |
| 7 | B150Q(1) | SS15 | B240Q(1) |
| 8 | PMEG4010(3) | PMEG4010(3) | PMEG4010(3) |
| 9 | SS15 | B140Q | — |
| 10 (highest $I_{BODY}$) | B140Q | B150Q(1) | — |

(1) The parameter extraction required 400 mV extrapolation to reach 1 V.

(2) Top-performing diode

(3) The parameter extraction required 200 mV extrapolation to reach 1 V.

The B240Q and B150Q diodes require 40% of the IV curves to be extrapolated when extracting the parameters. This large information gap could explain why the B240Q diode did not perform the best and the B150Q diode performed the worst. The SSA24 and PMEG4010 diodes require 20% of the curves to be extrapolated.

Despite the simplified current-sharing model being quantitatively inaccurate, it was able to successfully predict the order of the top five best performing diodes (see Table 4). This conclusion discounts the B240Q diode because of a lack of information. Given diodes with at least 800 mV of IV curve information, the simplified current sharing model will be able to qualitatively predict the order of performance. Using this model, users can compare Schottky diodes to find which will perform the best in this protection application. The actual quantitative effectiveness is hard to predict solely on the IV curve given in a data sheet and limited body diode characterization. For this reason, the user must still test the protection scheme to ensure it is adequate.

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## B.3 Percent Sharing Contours

Knowing that the current sharing model is qualitatively correct, the effects of each parameter on the approximate body conduction percentage can be evaluated. For a fixed capacitor-fault current of 30 A and fixed body-diode parameters, Equation 9 only varies with $V_{knee(SCHOTTKY)}$, $I_{knee(SCHOTTKY)}$, and $m_{SCHOTTKY}$. Because the body current percentage is a function of three variables, it must be plotted by setting one variable constant and allowing the other two to vary. In this case, $V_{knee}$ is constant so that $m_{SCHOTTKY}$ and $I_{knee}$ can vary. This variance creates a three-dimensional surface which can be usefully represented as a contour plot. By creating a contour plot for a discrete set of $V_{knee}$ values, it is possible to see how body current sharing percentages vary across the three parameters. The six contour plots that follow were taken for 50 mV increments of $V_{knee}$.

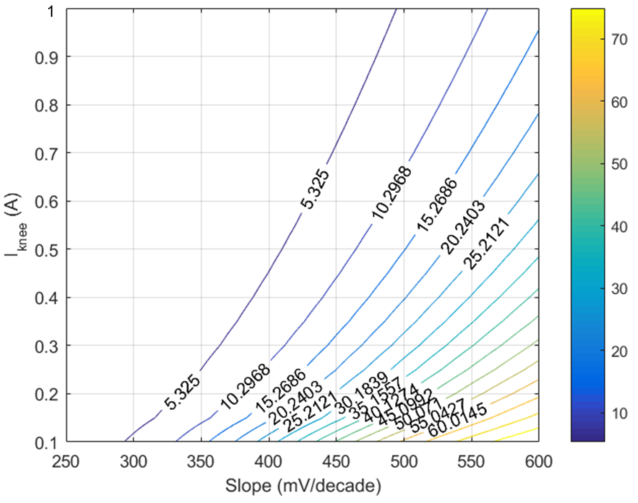

**Figure 24. Body Conduction Percent of Contour, $V_{knee}$ = 250 mV, $I_{FAULT}$ = 30 A**

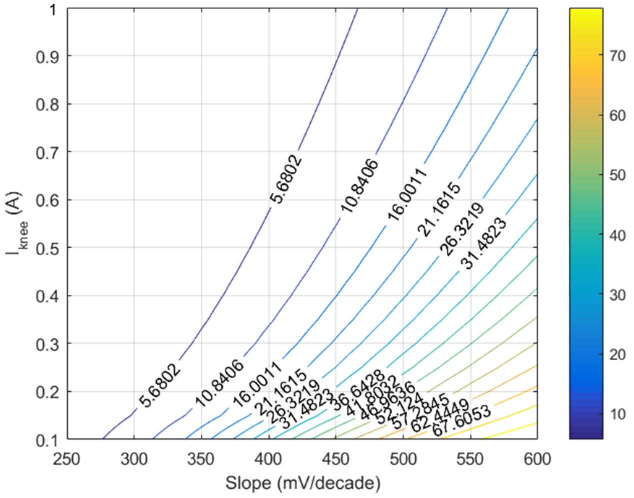

**Figure 25. Body Conduction Percent of Contour, $V_{knee}$ = 300 mV, $I_{FAULT}$ = 30 A**

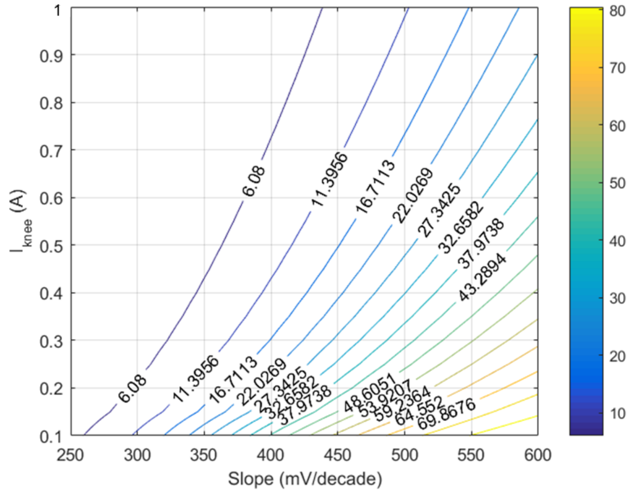

**Figure 26. Body Conduction Percent of Contour, $V_{knee}$ = 350 mV, $I_{FAULT}$ = 30 A**

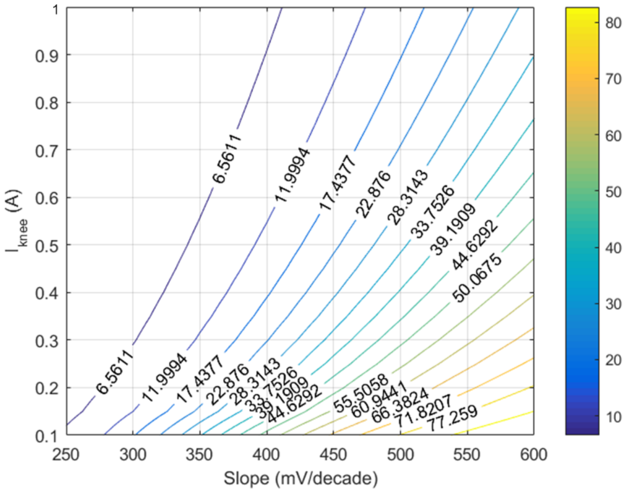

**Figure 27. Body Conduction Percent of Contour, $V_{knee}$ = 400 mV, $I_{FAULT}$ = 30 A**

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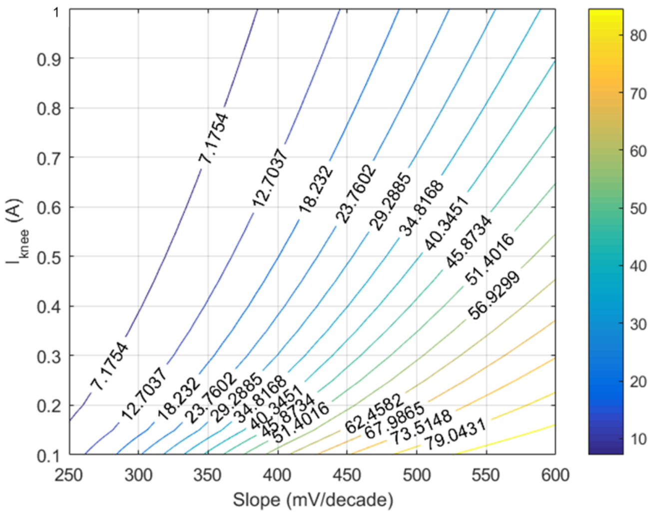

**Figure 28. Body Conduction Percent of Contour, $V_{knee}$ = 450 mV, $I_{FAULT}$ = 30 A**

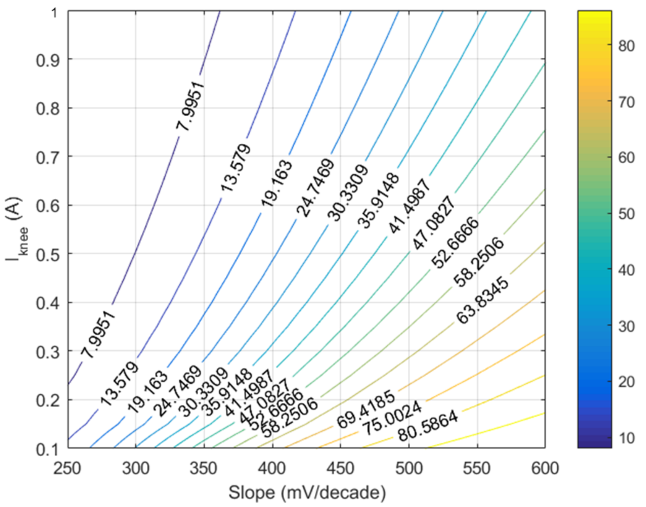

**Figure 29. Body Conduction Percent of Contour, $V_{knee}$ = 500 mV, $I_{FAULT}$ = 30 A**

## B.4 Selection Example Using Contours

The body conduction contours provide a way to evaluate two Schottky diodes in a side-by-side comparison. This comparison is especially useful when evaluating Schottky diodes outside of the tested set.

This example uses the SL34 and SSA34 diodes. The SL34 diode has the following parameters:

- $V_{knee}$ = 300 mV
- $I_{knee}$ = 0.6 A
- $m_{SCHOTTKY}$ = 432 mV/decade

The SSA34 diode has the following parameters:

- $V_{knee}$ = 380 mV
- $I_{knee}$ = 1 A
- $m_{SCHOTTKY}$ = 452 mV/decade

The SL34 diode has a knee voltage almost 100 mV less than the SSA34 diode and its slope is slightly less, too. Both of those parameters suggest that the SL34 diode may be the better device, but how does the lower knee-current of SL34 change the performance? To figure this out, the contour plots can be used. First, use the $V_{knee}$ = 300 mV contour to plot where the SL34 diode lies as shown in Figure 30.

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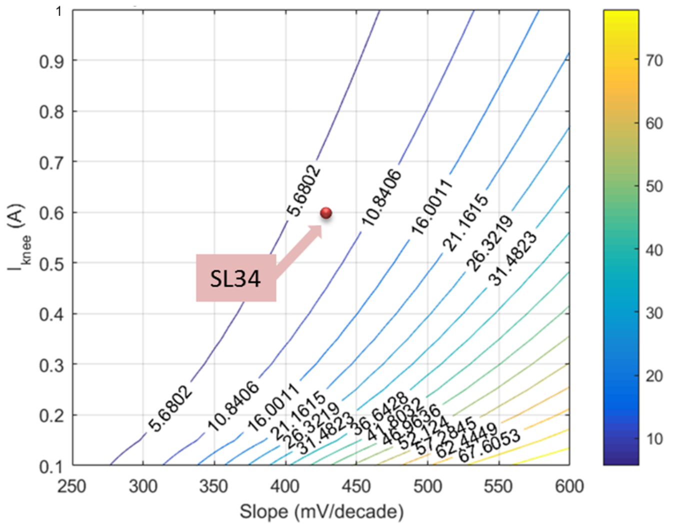

**Figure 30. SL34 Contour Placement, $V_{knee}$ = 300 mV, $I_{FAULT}$ = 30 A**

When plotted, the SL34 diode can be shown that it lets between 5.6% and 10.8% of a 30-A fault current flow through the body diode. This plotting is not quantitatively accurate, but it can be compared to the SSA34 plotting to rank relative performance. The knee voltage of the SSA34 diode is closer to 400 mV than 350 mV, so the diode is plotted on the 400 mV contour in Figure 31.

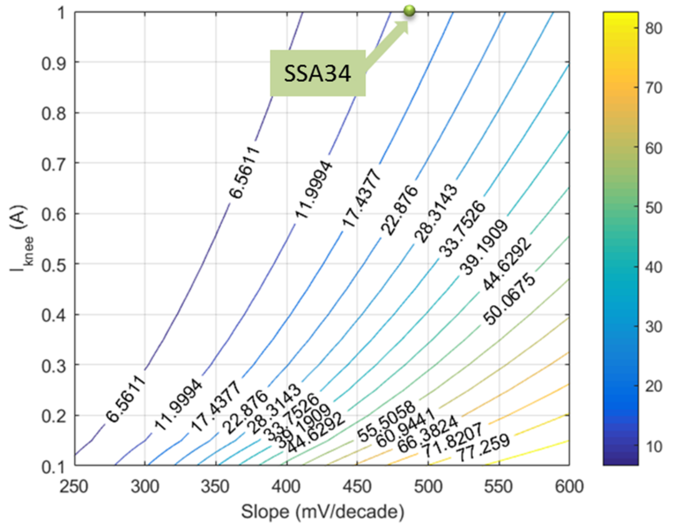

**Figure 31. SSA34 Contour Placement, $V_{knee}$ = 400 mV, $I_{FAULT}$ = 30 A**

Based on Figure 31, the SSA34 diode allows 12% to 17.4% of a 30-A fault current to flow through the body diode. Again, these percentages are quantitatively inaccurate; however, they do show that relative to each other, the SL34 diode performs better. The experimental results confirm the qualitative predictions of the simplified current sharing model. The SL34 diode allows approximately 10% of the fault current to flow through the body diode while the SSA34 diode allows approximately 35%.

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