Texas Instruments

Application Report
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Adjustable Current Limit of Smart High Side Switch

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ABSTRACT

Adjustable current limit is a unique feature in Smart High Side Switch family from Texas Instruments. It is widely used to clamp the overload current, deliver the constant current and dynamically control the power-up inrush current.

This application report introduces the principle and implementation of the function, and gives a guide on the set of the current limit value. It also provides some examples to discuss how to leverage this feature for different application scenarios.

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1 Introduction

Smart High Side Switch from Texas Instruments is a robust automotive-grade power switch family, rated at 40 V, with a wide on-resistance range and different channel-configurations. The high-accuracy current sense enables the full diagnostics and intelligent control of the load.

Besides, Smart High Side Switch from TI protects against Short-to-GND and Over-Load events through the flexibility to select current limit values for targeted thresholds. The adjustable current limit, as a unique feature in the market, improves the reliability of the whole system by limiting the overload current effectively. It also saves the front stage power budget and reduces PCB traces and connector sizes, which lower the whole system costs.

2 Function Description

2.1 Basic Implementation

The family devices have two different current-limit modes. When CL pin is tied to GND, it is the internal current limit mode, which is adaptive to the large power-up transient load. When tied through a resistor R(CL) to GND, it's the external current limit mode. The external adjustable current limit allows the flexibility to set the current limit value by applications.

The current limit block diagram is shown as Figure 1.

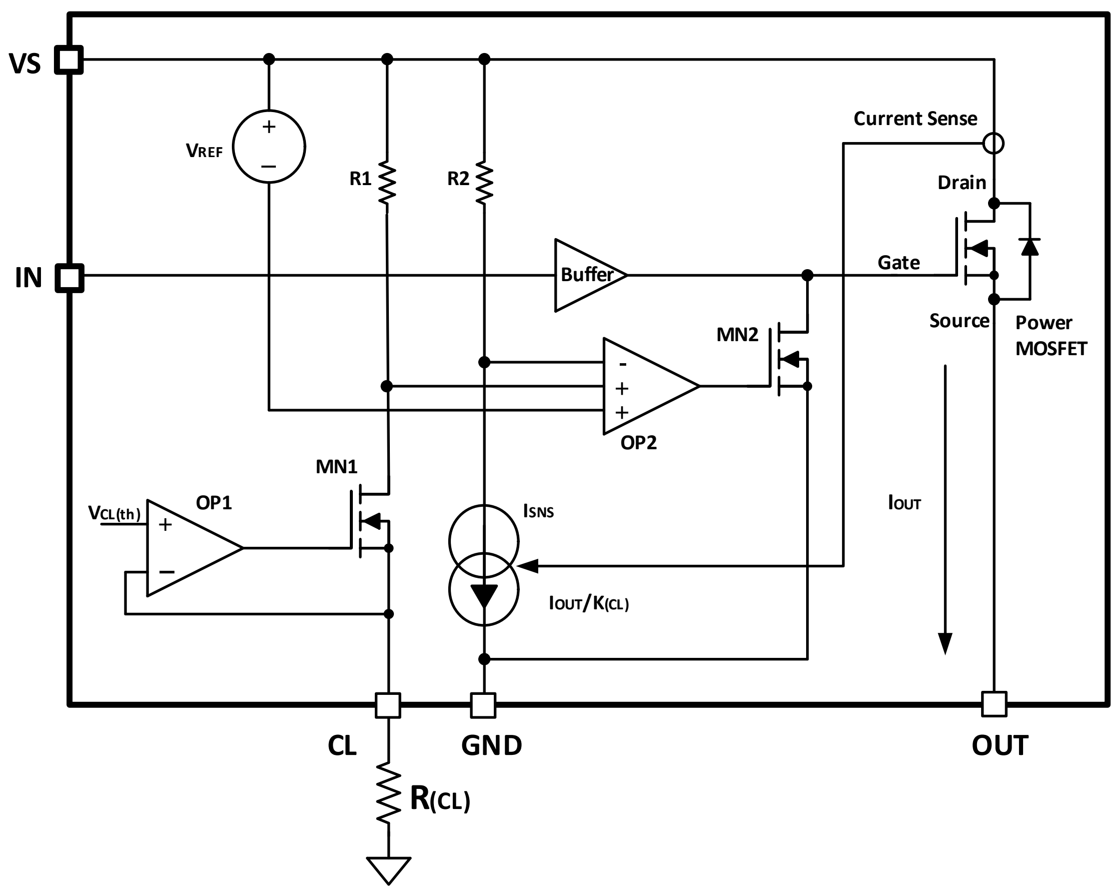


Figure 1. Internal Block Diagram of Current Limit

With the high accuracy current sense mirror, the output current is captured as Equation 1. $K_{(CL)}$ is the constant ratio of the output current (I_{OUT}) and the sense current (I_{SNS}). The voltage drop on R_2 is V_{R2}, shown as Equation 2:

$$I_{SNS} = \frac{I_{OUT}}{K_{(CL)}} \tag{1}$$

$$V_{R2} = I_{SNS} \times R_2 \tag{2}$$

- Internal Fixed Current Limit, V_{R2} compares with internal reference voltage V_{REF}, and the current limit is fixed at $I_{CL(int)}$.
- External Adjustable Current Limit, with OP_1 and MN_1, the current limit is set as shown in Equation 3. $V_{CL(th)}$ is the internal bandgap voltage. The voltage drop on R_1 ($R_1 = R_2$) is as shown in Equation 4. When the output current (I_{OUT}) increasing, if the sense current (I_{SNS}) triggers the current limit set value (I_{CL}), the OP_2 regulates $V_{R2} = V_{R1}$. The output current (I_{OUT}) is clamped as shown in Equation 5.

$$I_{CL} = V_{CL(th)} / R_{(CL)} \tag{3}$$

$$V_{R1} = I_{CL} \times R_1 = I_{CL} \times R_2 \tag{4}$$

$$I_{OUT} = K_{(CL)} \times V_{CL(th)} / R_{(CL)} \tag{5}$$

After the current limit, the operation region of the Power MOSFET changes from the linear mode to the saturated mode. The power dissipation should be considered during the system level design. The voltage drop on the Power MOSFET VDS is as shown in Equation 6. The power dissipation on the Power MOSFET PDS is as shown in Equation 7.

$$V_{DS} = V_S - I_{OUT} \times R_{OUT} = V_S - I_{CL} \times R_{OUT} \tag{6}$$

$$P_{DS} = V_{DS} \times I_{OUT} = (V_S - I_{CL} \times R_{OUT}) \times I_{CL} \tag{7}$$

Table 1 is a summary of the family devices.

Table 1. Current Limit Specifications Summary

Part Number	Internal Current Limit	$V_{CL(th)}$	$K_{(CL)}$
TPS1H100-Q1	7-13A	1.233 V	2000
TPS2H160-Q1	9-15A	0.8 V	2500
TPS4H160-Q1	8-14A	0.8 V	2500
TPS2H000-Q1	1-1.6A	0.8 V	300
TPS4H000-Q1	1-1.6A	0.8 V	300

2.2 *Current Limit Accuracy*

Besides the current limit threshold, the current limit accuracy also should be taken into consideration during system level design. Figure 2 shows the relationship of the design target (Green Line), set value (Blue Line) and the front stage power budget (Red Line). From the ±30% and ±15% tolerance comparison, it is clear that a higher accuracy means a lower front stage power budget.

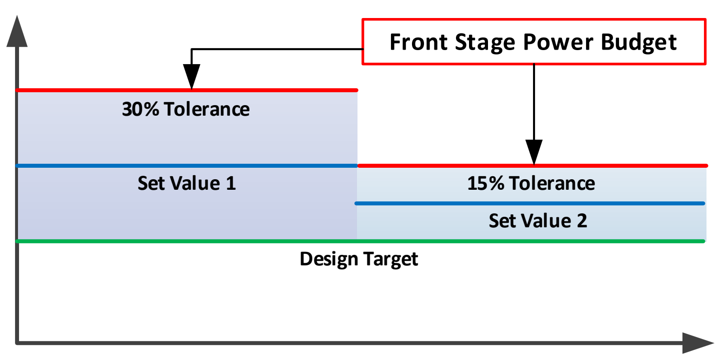


Figure 2. Comparison of Different Current Limit Accuracy

Table 2 shows the accuracy for each device in different current limit range. All the data are across the full temperature range. For detailed information, see the device-specific data sheet.

Table 2. Current Limit Accuracy Summary of Family Devices

Part Number	Current Limit Range	Current Limit Accuracy
TPS1H100-Q1	0.5-1.6A	≤ ±20%
	1.6-7A	≤ ±14%
TPS2H160-Q1 TPS4H160-Q1	0.25-0.5A	≤ ±20%
	0.5-7A	≤ ±15%
TPS2H000-Q1 TPS4H000-Q1	0.05-0.1A	≤ ±25%
	0.1-0.2A	≤ ±20%
	0.2-0.5A	≤ ±15%
	0.5-0.9A	≤ ±10%

3 Application Example

3.1 Start-Up Inrush Current Clamping

Nowadays, current limit function is implemented in most high side switches. However, the limit threshold is internally fixed, due to the legacy of driving the high wattage bulbs. For the other loads, the threshold is too big and meaningless for protections. In infotainment system, around 100 mΩ Ron device is used to drive a display module, in which the nominal current is only 1A but with about 1000 µF input cap. If using conventional high side switch, the large fixed current limit result in up to 15A inrush current violently. It is an obvious concern for the whole system design. To address the inrush current trouble, Texas Instruments innovatively introduces the adjustable current limit function in the new smart high side switch family.

The family devices are very suitable as the start-up inrush current clamper, especially driving a capacitive load. Figure 3 shows the typical block diagram in the automotive infotainment system.

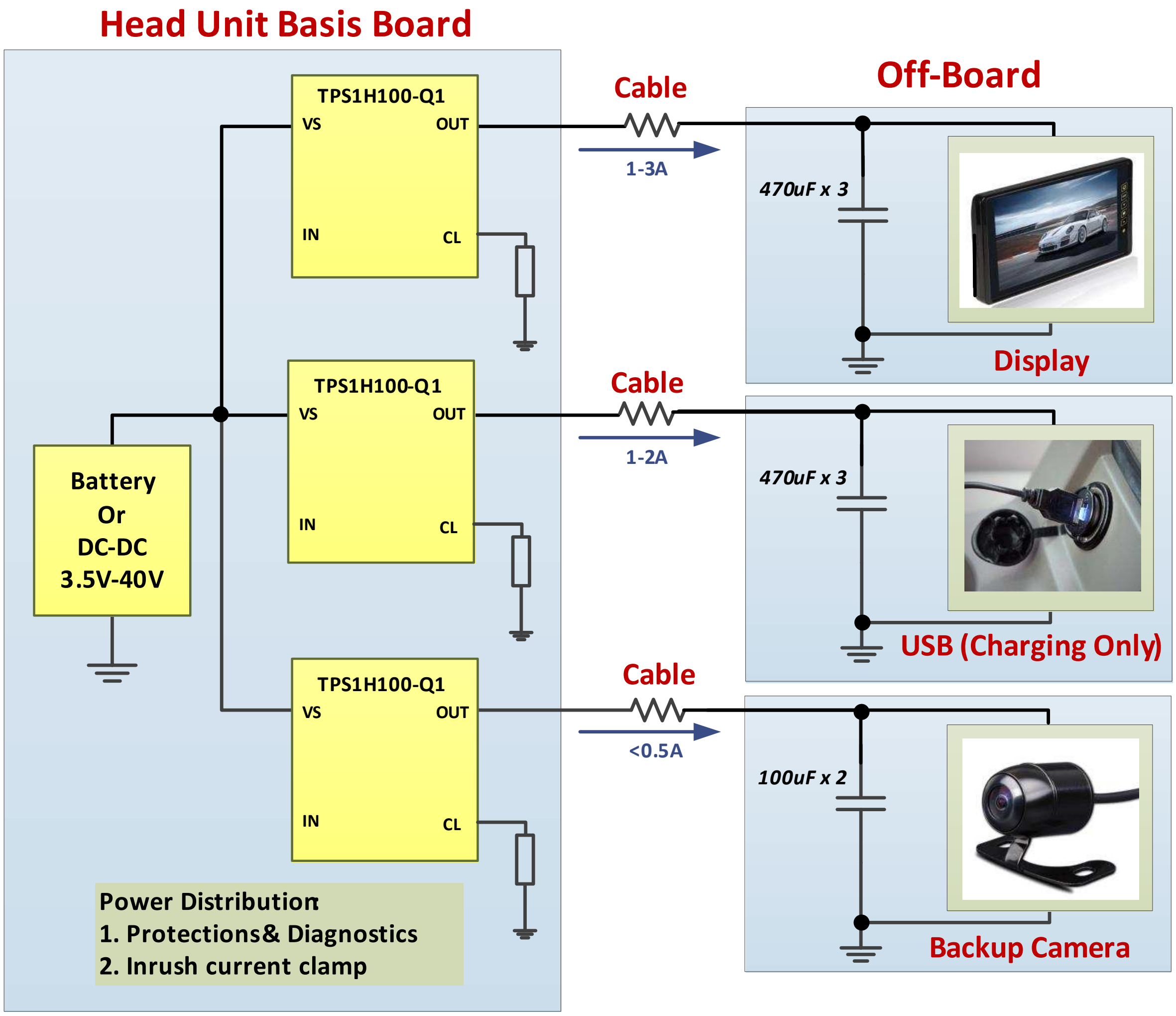


Figure 3. Using Smart High Side Switch as Inrush Current Clamper in Infotainment System

With the adjustable current limit, the family devices can clamp the inrush current effectively.

Test condition: TPS1H100-Q1, V_S = 13.5 V, I_{OUT} = 1A, output are 5 units of 470 µF electrolytic capacitors in parallel. Set the current limit threshold at 2.5A.

Figure 4 shows a zoomed-out waveform under 85°C ambient temperature. No unexpected thermal behaviors are triggered during the entire charging cycle.

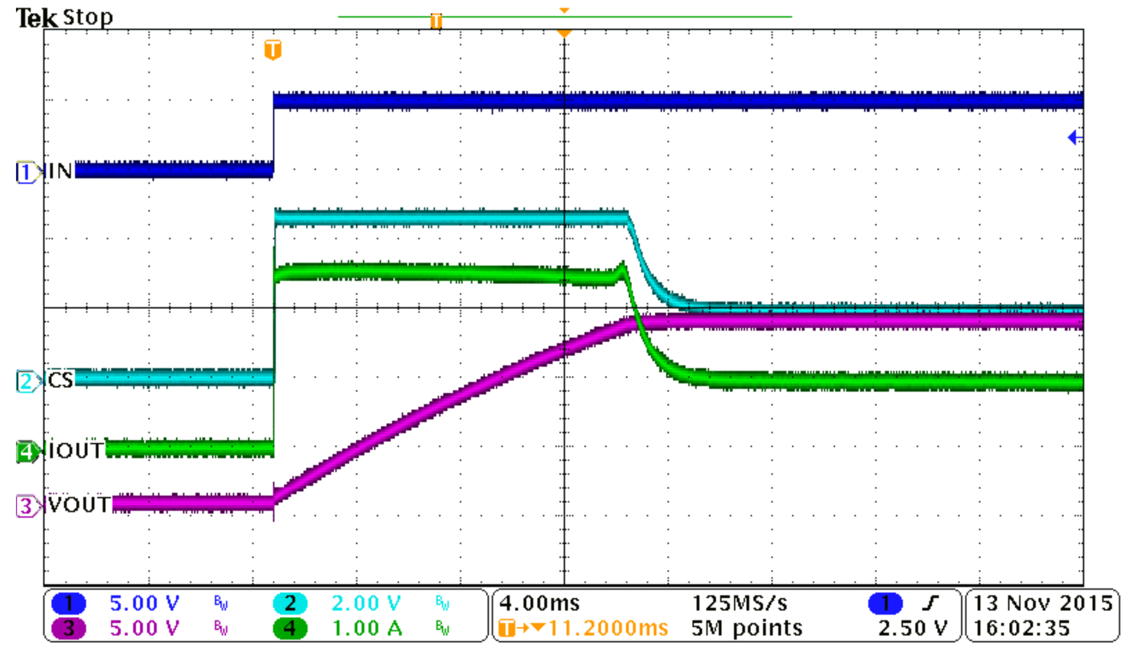


Figure 4. Zoomed-Out Waveform of Inrush Clamping

Figure 5 shows a zoomed-in waveform under 85°C ambient temperature.

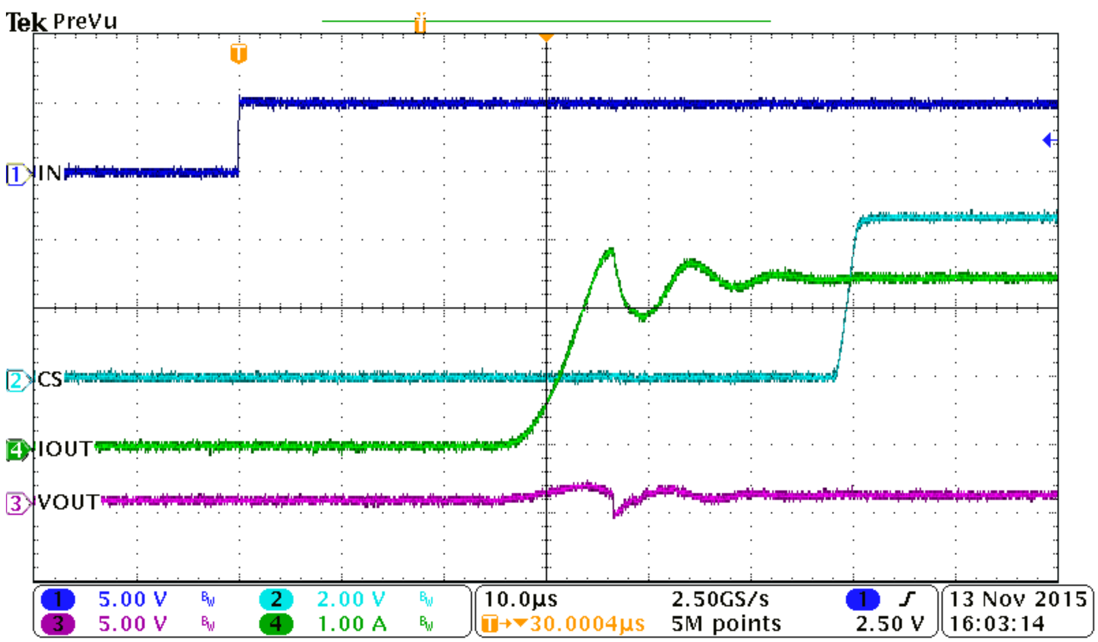


Figure 5. Zoomed-In Waveform of Inrush Clamping

3.2 Fast-Trip Response for Hard Short

Generally, for Smart High Side Switch, there are two types of load current overshoots. In addition to the inrush current during start-up (Section 3.1), the hard short (IN is active, output cable short to GND suddenly, shown as Figure 6) is also a big trouble during system level design.

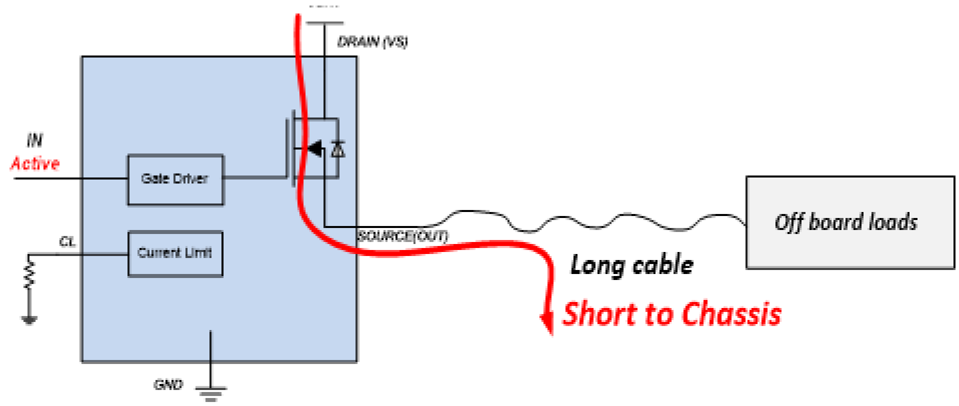


Figure 6. Hard Short

For better protection from the hard short, the family devices implement a fast-trip protection to turn off the channel immediately (response time <1 µS) ahead of current limit loop. Figure 7 shows the fast trip implementation.

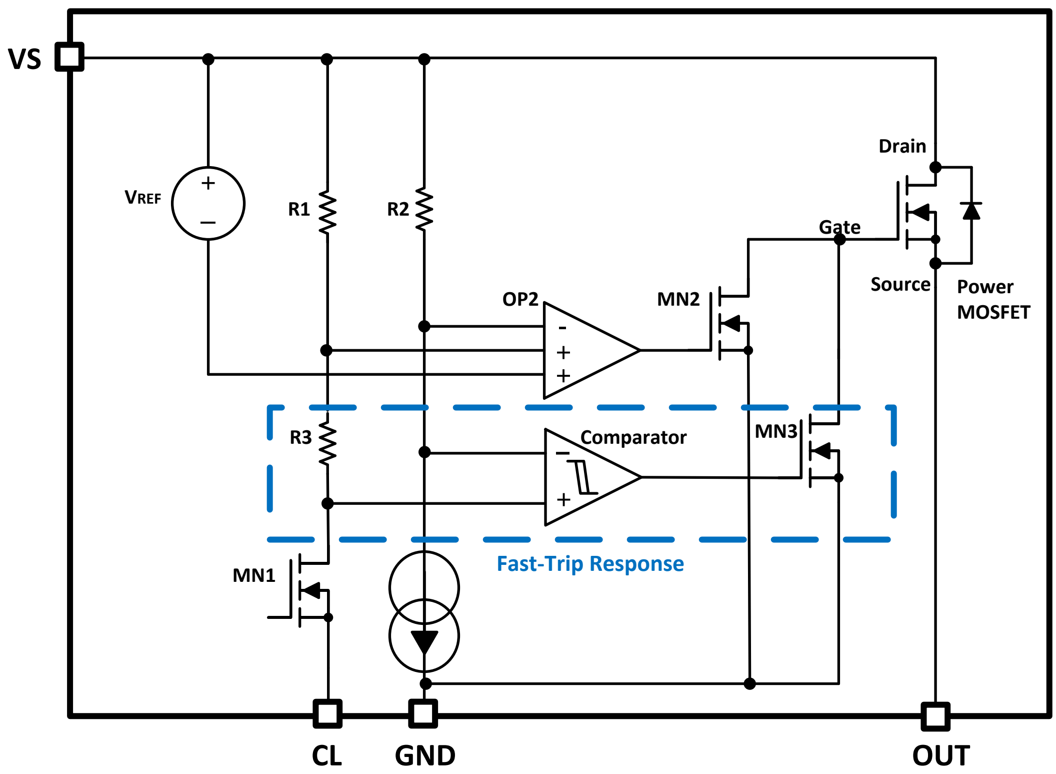


Figure 7. Internal Block Diagram of Hard Short Implementation

With the fast response, the device can achieve better overshoot current suppression performance, see Figure 8.

Test condition: TPS1H100-Q1, V_S = 13.5 V, IN is active, current limit value is 1A. Hard short happens with a cable (5 µH + 100 mΩ, according to AEC Q100-012 standard).

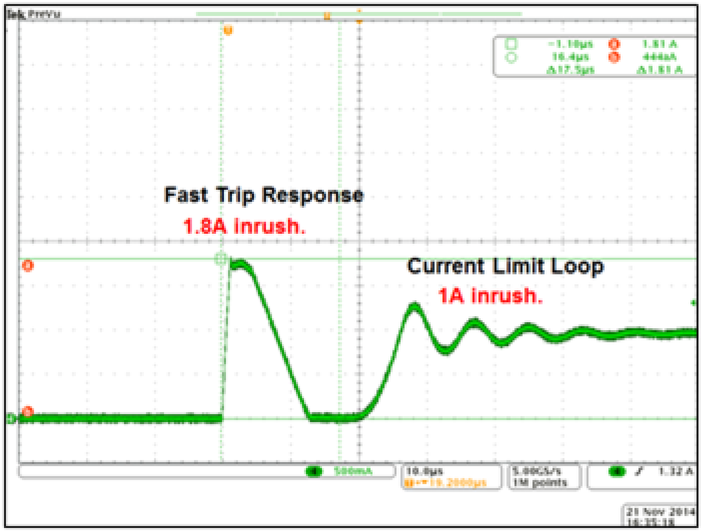


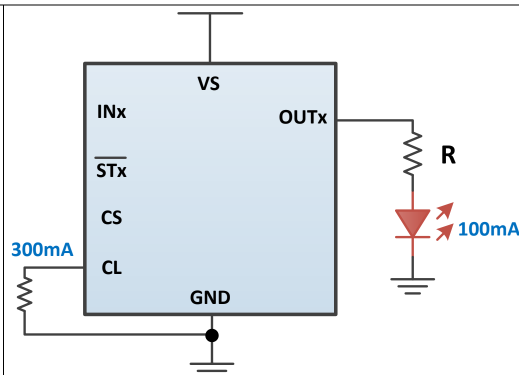
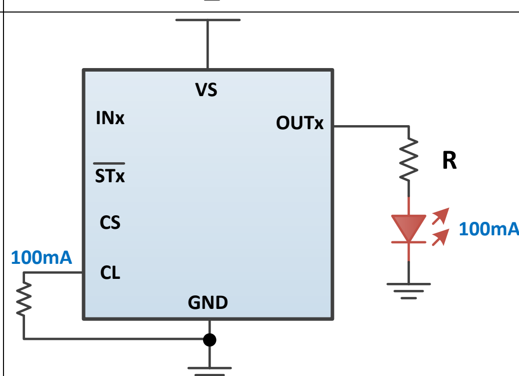
Figure 8. Hard Short Waveform

3.3 *Smart LED Driver*

With the trend of the LED replacement, the high side driven topology is popular in the market, which have both the short-to-GND proof and common-cathode connection advantage.

Benefitting from the adjustable current limit function, the Smart High Side Switch from Texas Instruments supports the connections as shown in Table 3.

Table 3. Driving LED Topologies

Non-Constant Current		• $V_{DS} = R_{ON} \times I_{LED}$ • $P_{DS} = V_{DS} \times I_{LED}$ • Full Diagnostics are shown in the *Fault* table in the device-specific data sheet.
Constant Current		• $V_{DS} = V_S - I_{LIM} \times R - V_{LED}$ • $P_{DS} = V_{DS} \times I_{LIM}$ • $\overline{STx}$ = LOW when normal operation. • $\overline{STx}$ = HIGH when Open load / Short to battery.

3.4 Dynamic Inrush Current Control

When powering up, some loads call a big inrush current for the fully turn-on. The bulbs require >10 times of the nominal current for fast turn-on, and for some inductive loads (solenoid, relay and motor), around 2-6 times of the nominal current is needed for the right turn-on. After the powering up stage, a lower and reasonable current limit is the target for the better protection, especially when short to GND occurs. For this dynamic limit request, Figure 9 shows the target curve.

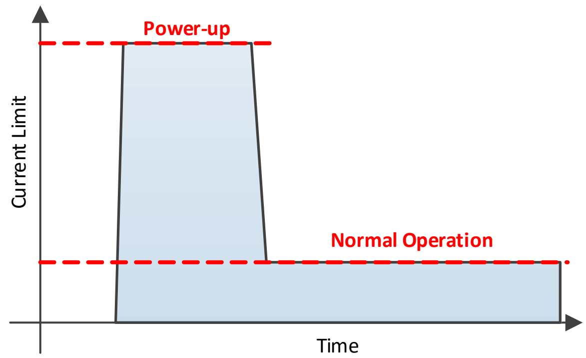


Figure 9. Dynamic Current Limit Control

With some simple external circuitry, the family devices can achieve the functions easily. Figure 10 shows the one recommended connection. When powering up, MCU signal short the CL pin to GND with the internal current limit. After the certain period, switch to the external current limit value.

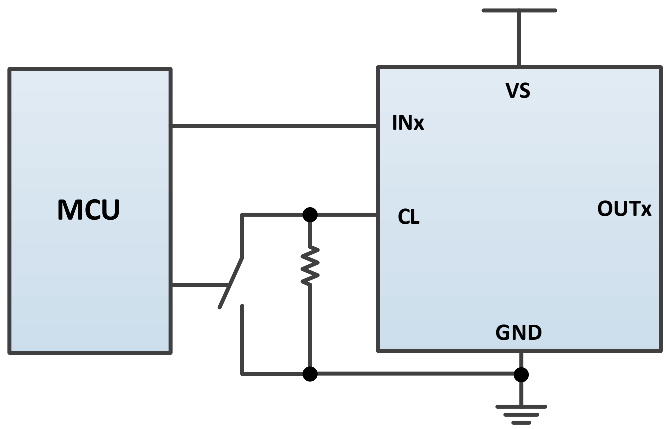


Figure 10. External Circuitry of Dynamic Current Limit Control

4 Summary

Smart High Side Switch is the device with protection and diagnosis features, with which the system can easily realize the high reliability and intelligent fault detection. It's widely used in automotive and industrial applications.

One common design trouble for such application is the big overload current, mostly resulted by the abrupt low impedance in two scenarios: driving a big capacitive load or hard short. To overcome this barrier, more than enough front stage power budgets must be taken into consideration by using conventional high side switches. To address this, Texas Instruments innovatively introduces the adjustable current limit function in the new smart high side switch family. It improves the reliability of whole design and saves the system level costs.

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