Application Report

How to Drive Resistive, Inductive, Capacitive, and Lighting Loads

ABSTRACT

Many system designers struggle with the challenges inherent with driving loads that are inductive or capacitive in their nature as they offer specific thermal challenges for both turn-on and turn-off. In addition as loads like LED's become more common they introduce other specific challenges like diagnostics and reliability that must be mitigated when used as an off-board load in a system. This document will analyze each of these loads beginning with a technical discussion of the underlying challenges of the load before diving into the necessity of the robust diagnostics tools that are integrated in TI's Smart High Side Switch solutions. This application note also shares Smart High Side Switch selection considerations for the given load profile

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1 Introduction

Often in systems central modules provide power to off-board loads in a number of different form factors. This occurs in situations such as a central module powering an automotive head-light, a PLC system powering a robotic arm, and a household appliance powering the indicators on the front panel. Situations where off-board loads must be driven are common in the vast majority of electrical systems and introduce specific challenges to the system designer. While it can be simple to switch enough DC power to meet the system requirements, it is much more challenging to ensure robust protection against short circuits and open circuits, provide fault indication, power up the load quickly, and enable predictive maintenance. These additional features are being increasingly requested by designs, so an engineer needs to select an output topology that enables this functionality. The best way to accomplish this is to use a Smart High Side Switch which can reliably drive off-board loads and enable numerous diagnostic and failure prevention mechanisms.

Not all off-board loads are the same. Each load profile will interact differently with the Smart High Side Switch and require different considerations to ensure robust protection. Whether the load is resistive, capacitive, inductive, or does not fall neatly into one of those categories such as LEDs will change how driving the load must be approached and designed. A proper output power protection designer needs to understand what load profile will be expected,and then understand how that impacts the design of the output stage. This document will analyze a few common load profiles and discuss the specific challenges and considerations for those loads. The load profiles that will be investigated in this document are:

1. Section 2: Driving Resistive Loads
2. Section 3: Driving Capacitive Loads
3. Section 4: Driving Inductive Loads
4. Section 5: Driving LED Loads

For each of these load types this document will give example applications with the given profile, discuss why a Smart High Side Switch offers advantages compared to traditional discrete solutions, go in depth on the technical challenges unique to that load type, and then offer guidelines for selecting the proper Smart High Side Switch for a given application.

Through a proper and thorough understanding of the impacts of a load profile on an output power stage it is possible to significantly improve functionality and reliability for a system. As designs continue to get smarter and more robust this understanding is critical for all designers.

2 Driving Resistive Loads

2.1 Background

Resistive loads are the simplest loads to drive as they follow Ohm's Law.

$$V = I * R \tag{1}$$

It's simple because the designer knows the voltage (typically 13.5V for a car battery) and the resistance of the load (by measuring it with an Ohm meter). With these two parameters they can calculate the maximum current that will be flowing through the circuit. Knowing this information is the first step in selecting the correct device to drive this load since each high side switch has an associated ON resistance that limits the amount of nominal current allowed through the device without hitting thermal shutdown. In typical applications the current through the load needs to be varied to provide the intended output. It is also important to have features such as current sensing that can correlate back to the microcontroller what current is actually going through the load. The most basic way to vary the current through the load is through pulse width modulating (PWM) the enable pin. This introduces more complications with regard to the thermal calculations.

In this section we will look into the application of resistive loads and show what relevant features are useful when driving them. We will also see how TI's Smart High Side Switches' feature set aligns well with the requirements for loads. Finally, in order to pick the correct high side switch we must learn how to calculate the power dissipation of the switch and relate that to the junction temperature and set the current limit appropriately so that the high side switch will be able to properly drive the resistive load.

2.2 Application Example

A common resistive load in a vehicle is a seat heater. A long coil is placed inside the seat and it heats up when current flows through it. The current is controlled so that the correct amount of heat is produced. A reference design of this application can be found at: Smart Power Switch for Seat Heater Reference Design.

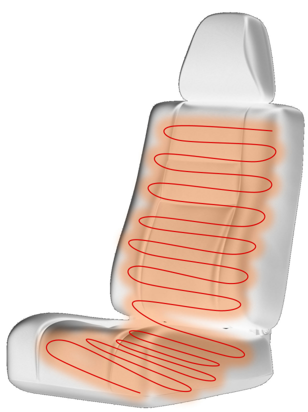

Figure 2-1. Seat Heater Resistive Load Application

In a seat heating application there needs to be discrete temperature steps in the temperature setting of the seat. All vehicles with this feature allow the user to select the correct temperature range that suits them. It can be inferred that the temperature correlates directly with the current flowing through the load and therefore to adjust the temperature the current must be varied proportionally.

$$I \propto P \propto T \tag{2}$$

To do this a microcontroller that is controlling the high side switch pulse width modulates (PWM's) the enable pin. This turns the device on and off at a fast rate that gives an effective current which can be calculated in Equation 3 based on the duty cycle D. When PWMing the enable pin there is an associated power loss that comes with turning the device on and off. This switching loss and other power calculations are explained in Section 2.4.2.

$$I = D * \frac{V}{R} \tag{3}$$

The microcontroller also needs to be measuring the current going through the high side switch in order to know what the temperature currently is in the seat. This means that the current sensing output of the high side switch needs to be accurate so that the exact temperature is known. This accurate current sensing will be discussed in Section 2.3.1.

This is an example of a seat heater load but in reality there are many different resistive loads such as incandescent lamps and industrial heaters. Each of these loads will require a different current level and therefore the short circuit protection level will also be varied. This protection level needs to be high enough to let the nominal current pass through but low enough that it does not cause damage to the system itself.

2.3 Why Use a Smart High Side Switch?

While the fundamentals of driving a resistive load are simple, there are several aspects that make using a smart high side switch the most viable option. The two main areas that differentiate smart high side switches are the accurate current sensing and the adjustable current limit.

2.3.1 Accurate Current Sensing

Most smart high side switches have a feature called current sensing that will measure the current going through the switch. This section will go through that functionality and why having it in a smart high side switch is better than discretely measuring the current.

As explained in the application section, the current flowing through the switch will be directly proportional to the temperature in the load. This means that to have a closed loop circuit where the current is being monitored and adjusted back there needs to be very low error in current measurement. Typically if the designer wants to use a load switch they will have to introduce a discrete circuit or more components to get the current to be properly measured and relayed back to the central microcontroller.

When it comes to current measurement there are many different parts that can contribute to inaccuracies in the real system. The discrete way of measuring current is using a sensing resistor and making a differential amplifier out of four resistors and an operational amplifier. In this configuration each component in the system has to have a very tight tolerance of typically less than 1%. This is to reduce the overall inaccuracy of the current sense, however comes at the expense of drastically increasing the board layout space. Additionally, the sense resistor adds more series impedance lowering the maximum amount of current in the system.

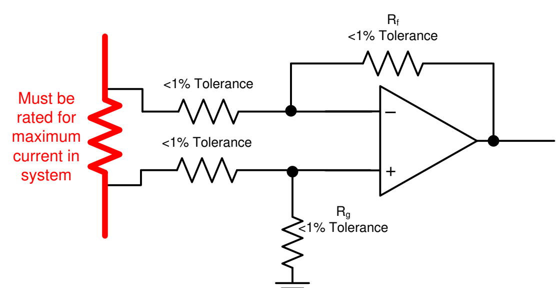

Figure 2-2. Discrete Current Measurement Implementation

TI's portfolio of high side switches have very high current sense accuracy standard on most devices. For instance, TPS1H100-Q1 has ±3% accuracy at loads ≥1A. Not only does it reduce the number of components needed in the system, it also provides less error for knowing the exact current flow through the system.

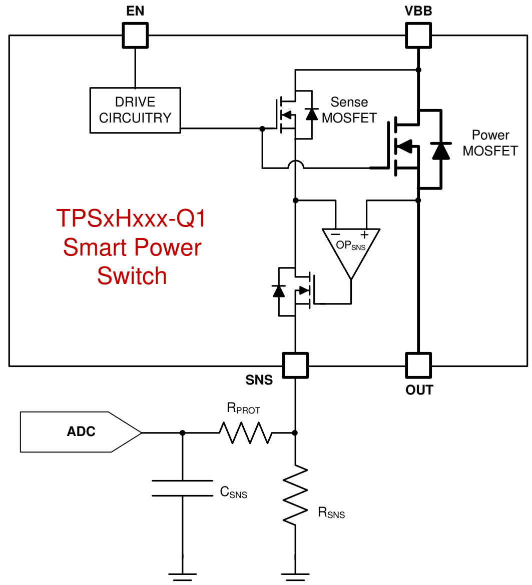

Figure 2-3. TPSxHxxx Current Sense Circuit

Figure 2-3 shows the internal circuitry used for the current sensing in TI's high side switch family of devices. Having the current sense integrated to the high side switch reduces the number of components in a system while still maintaining a high accuracy.

2.3.2 Adjustable Current Limiting

Another unique feature of TI's Smart High Side Switches is the adjustable current limit. This feature is especially relevant in heat applications where allowing large amount of currents even for short amount of times is not only damaging to the system but also the end user. Most of the time in resistive load applications the enable pin is PWMed only allowing a portion of the total current to the load. This means that even the nominal amount of current that a high side switch can handle could be a fault case and potentially damage the system or the end user.

Competition high side switches typically have a fixed current limit that is often very high relative to the nominal operating current. This means that the switch will not shut off until it reaches the current level set abnormally high or thermally shuts off. In the heater example above there could theoretically be a small resistive short that draws double the PWM current.

2.4 Selecting the Right Smart High Side Switch

The selection of a high side switch for a resistive load comes down to what features are necessary and what R_{ON} will safely drive the load.

2.4.1 Power Dissipation Calculation

The choice of the correct smart high side switch is weighted heavily by whether or not the device can provide the current required for the application without reaching thermal shutdown. For resistive load applications the first thing that needs to be done is measuring the resistance of the load. Then using Equation 1 the current can be calculated. Note that the voltage provided needs to be the maximum operating voltage desired for a specific use case. For car batteries this would be 18V and anything higher would be considered a fault case. Most resistive loads will not be ran at full current due to the PWMing of the input, but it is important to make sure that the switch will still be able to operate in this condition. This can happen during a reverse battery fault when the current cannot be regulated by the PWM. Using this current and the R_{ON} of the switch (maximum at high temperature), the power dissipated in the switch can be calculated by Equation 4.

$$P_{DIS} = I^2 * R_{ON} \tag{4}$$

To calculate the junction temperature of a device a designer can find the junction-to-ambient thermal resistance, $R_{\theta JA}$, in the Thermal Information section of the datasheet. Notice that the $R_{\theta JA}$ in the datasheet is specified for a specific board layout defined by the JEDEC standard. The thermal performance will change for different board layouts, but this gives a good first approximation. For a full calculation please run thermal simulations of the device to see what the temperature will be. Calculating the junction temperature, T_J, on a first order basis is taking the ambient temperature, T_A, plus the power dissipated times the $R_{\theta JA}$ as shown,

$$T_J = T_A + P_{DIS} * R_{\theta JA} \tag{5}$$

All of TI's Smart High Side Switches have a thermal shutdown capability. This means that when the junction temperature of the device reaches a certain temperature the device will shut off to protect itself. When a system is in normal operation it should be designed such that the switch should never reach that temperature. Using the equation above and relating the maximum junction temperature calculated with the thermal shutdown threshold in the datasheet, $T_{(SD)}$ or T_{ABS}, will let the designer know if the device will shut off because of the current required driving this load. Note that this is for the use case where there is no PWMing of the load. When the load is PWMed the current in the system is lower than the DC current calculated in the section. This means that designers can actually choose their smart high side switch based on the PWM'd current and due to TI's adjustable current limiting, can set the current limit below DC operation.

2.4.2 PWM and Switching Loss

Calculating just the power dissipation and junction temperature at steady state operation is the first step to choosing a smart high side switch to drive resistive loads. As mentioned in the application section, most resistive loads work by PWMing the switch to adjust the amount of current given to the load. This PWMing, or the turning on and off rapidly of the switch, introduces more loss in the switch that also needs to be accounted for in large load current applications. Most designers' assumption at this point would be that since the load is resistive there wouldn't be any power losses when turning it on and off because from Ohm's law the voltage is directly proportional to the current. Therefore, when the current goes to zero the voltage will follow. There are two problems with this assumption. The first is that there is no such thing as a purely resistive load as real world parasitics in the load must be accounted for and will directly affect the relationship of the voltage and current. The second, and more prominent, is that the smart high side switches are designed to have a set shape for the output voltage waveform. This means that when the system is PWMing the enable pin of the switch, the output voltage waveform will not directly mirror enable. It will instead have a different slew rate by design. It is very important and necessary that the switch does this because very quick changes in the output waveform will emit large amounts of EMI that can be disruptive especially in automotive systems. The shape of the turn on and turn off pulse is defined in the datasheet. Figure 2-4 shows an example waveform.

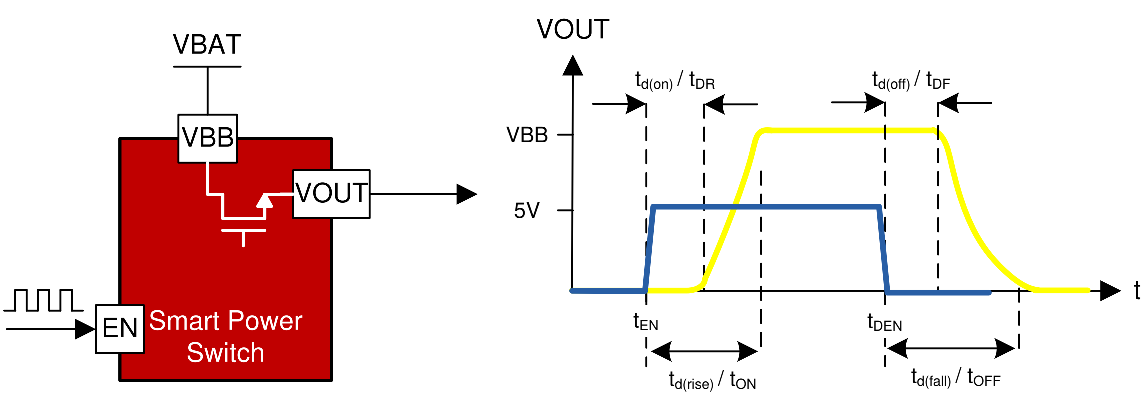

Figure 2-4. Smart High Side Switching Waveform

The smart high side switch's datasheet defines the turn on delay, $t_{d(on)}$ or t_{DR}, and the total turn on time, $t_{d(rise)}$ or t_{ON}, and the subtraction of the two gives the 10% to 90% rise time for the output device. In the same way, the turn off delay, $t_{d(off)}$ or t_{DF}, and the total turn off time, $t_{d(fall)}$ or t_{OFF}, can be used to find the 90% to 10% fall time for the output. This does not, however, tell the entire story as there are extra switching losses that happen from 0-10% and 10-0%. Using Figure 2-5 it can be seen that the switching energy loss is the area under the power dissipation curve for the turn on and turn off times.

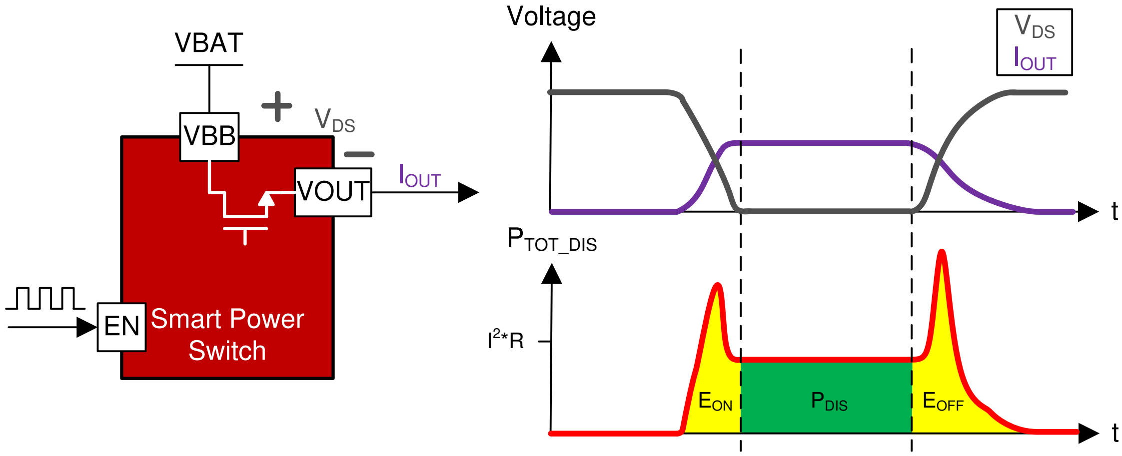

Figure 2-5. Switching Energy Losses during PWM

This image shows the voltage across the main FET, V_{DS}, of the switch and the current through the system, I_{OUT}. Underneath these waveform shows the power dissipation waveform which is the multiplication of the two waveforms above. Clearly the V_{DS} and I_{OUT} are inversely proportional. Their waveform is not linear which can be seen by the spikes on the power waveform in red for the turn on and turn off periods. Until the system gets to the steady state, the area under this curve is what is referred to as the switching on or off energies, E_{ON} and E_{OFF}. It is important to note that this is a visual representation and is not drawn to exact scale as the main energy loss will be the dissipation through the FET in most cases.

The lower the R_{ON} of the switch the more prevalent the switching losses become. Therefore, TI has provided the switching energy losses during turn off and turn on for the low R_{ON} family of devices. Taking this value, in mJ, and multiplying it by the switching frequency will give the switching energy losses.

$$P_{SW} = (E_{ON} + E_{OFF}) * f_{SW} \tag{6}$$

It is also important to note that this is the switching loss for one channel. If the device has more than one channel the switching loss plus the FET dissipation is multiplied by the number of channels

$$P_{DIS\_TOT} = \left(P_{SW\_CH} + P_{DIS}\right) * (\#\ of\ channels) \tag{7}$$

Now that when the power loss due to switching has been determined the total power dissipation in the system can be calculated to confirm that the device can drive this load successfully. This is as simple as adding up all of the switching losses and power dissipation losses for the total power dissipation and using Equation 5 to calculate the junction temperature. If the junction temperature is below the thermal shutdown threshold then the device can successfully deliver power to the load.

Table 2-1. Heater Load Example

Smart Power Switch	TPS2HB16-Q1
Resistive Load 1 , $\mathbf{R_{H1}}$	1.42 Ω
Resistive Load 2, $\mathbf{R_{H2}}$	2.6 Ω
Battery Voltage, $\mathbf{V_{BAT}}$	13.5 V
PWM Frequency 1, $\mathbf{f_{SW1}}$ / Duty Cycle, $\mathbf{D_1}$	200Hz, 50%
PWM Frequency 2, $\mathbf{f_{SW2}}$ / Duty Cycle, $\mathbf{D_2}$	100Hz, 85%
Ambient Temperature, $\mathbf{T_A}$	70°C
$R_{\theta JA}$, JEDEC	32.9 W/°C
T_{ABS}	160°C

An example would be if we have two resistive heater loads: the first one is 1.42Ω and needs to be switched at 200Hz with a 50% duty cycle and the second one is 2.6Ω and is PWMed at 100Hz with a 85% duty cycle. The battery voltage is 13.5V. Using TPS2HB16-Q1 and knowledge of resistive loads we can first calculate the steady state load current for both I_{H1} for channel 1 and I_{H2} for channel 2.

$$I_{LOAD1} = D_1 * \frac{V_{BAT}}{R_{H1}} = 4.75\ A \tag{8}$$

$$I_{LOAD2} = D_2 * \frac{V_{BAT}}{R_{H2}} = 4.41\ A \tag{9}$$

The next step is to calculate the power dissipation of the switch during normal operation for each channel using Equation 4. Note also that the R_{ON} value comes from "On Resistance (R_{ON}) vs Temperature" graph in the TPS2HB16-Q1 datasheet. The natural question that arises is if the load with the duty cycle factored in acceptable to use in power dissipation calculations. This is a question because in Figure 2-5 there is no concern about the duty cycle for the P_{DIS} potion of the energy loss. This is mitigated by the fact that this is a steady state calculation. This means that as long as the duty cycle does not change dynamically the average power dissipation through the switch will be related to the steady state current calculated with the duty cycle.

$$P_{DIS1} = I_{LOAD1}^2 * R_{ON} = (4.75\ A)^2 * 0.04\ \Omega = 0.903\ W \tag{10}$$

$$P_{DIS2} = I_{LOAD2}^2 * R_{ON} = (4.41\ A)^2 * 0.04\ \Omega = 0.778\ W \tag{11}$$

Now that the nominal power dissipation of the switch has been calculated the switching losses must be added. In the TPS2HB16-Q1 datasheet the E_{ON} is defined as 0.4mJ and the E_{OFF} is also defined as 0.4mJ. Using Equation 6 the switching loss for the device can be found.

$$P_{SW1} = (0.4\ mJ + 0.4\ mJ) * 200\ Hz = 0.16\ W \tag{12}$$

$$P_{SW2} = (0.4\ mJ + 0.4\ mJ) * 100\ Hz = 0.08\ W \tag{13}$$

This can be seen in the waveforms below. Figure 2-6 shows the switching of the R_{H1} with the blue waveform being the enable signal, the green being the VBB, the yellow is the V_{OUT} and the purple is the I_{OUT}. Also, in Figure 2-7, the V_{DS} of the switch can be seen in white and the resulting power dissipation with the switching losses is in red.

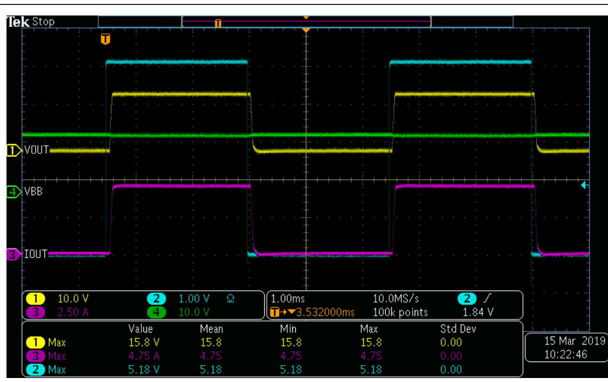

Figure 2-6. Measured Switching Waveform

Figure 2-7. Measured Switching Losses Waveform

Adding up all of the losses in the device gives the total power dissipation.

$$P_{TOT\_DIS} = (P_{DIS1} + P_{SW1}) + (P_{DIS2} + P_{SW2}) = 1.921\ W \tag{14}$$

Finally, now that the total power dissipation has been determined, the junction temperature can be calculated using Equation 5.

$$T_J = 70°C + 32.9\frac{°C}{W} * 1.921\ W = 133.2°C \tag{15}$$

This temperature is much lower than the 160°C thermal shutdown of the device meaning the TPS2HB16-Q1 can safely drive these loads.

3 Driving Capacitive Loads

3.1 Background

TI's Smart High Side Switches can be used to drive large bulk and hold-up capacitive loads that often go as high as 4 mF. Depending on the rise time at power-up, this load output capacitance can cause large inrush currents that are limited only by parasitic resistance and inductance's present in wiring and interconnections. The inrush in some scenarios can exceed 100A. High currents such as this can potentially cause input voltage supply droop which can harm or cause malfunction in other circuits in the system.

To prevent these problems a Smart High Side Switch can be used to limit the current and reduce the inrush current by linearly charging the capacitive load. Inn order to effectively drive capacitive loads with a Smart High Side Switch it is necessary to understand the impact of thermal dissipation in the switch while it is current limiting as large power levels can be observed inside the device. A proper theoretical understanding of the charging process and practical understanding for the selection a Smart High Side Switch enables an engineer to design a proper output stage that will have safe and efficient capacitive load driving with minimized system costs.

In this section we will dive in-depth to the considerations that are required when driving capacitive loads. We will initially discuss a few applications where capacitive loads are present before looking at the system advantages of a Smart High Side Switch for inrush current limiting. After that we will investigate the thermal impact capacitive load driving has in a Smart High Side Switch and how to mitigate this in a system. Finally we will discuss the selection of an appropriate high side switch for a specific load profile.

3.2 Application Examples

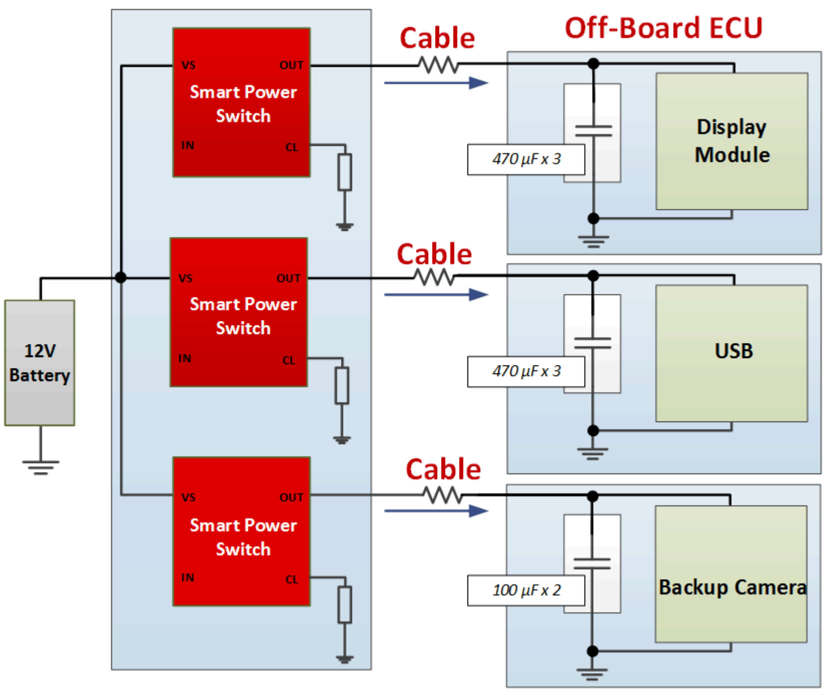

Figure 3-1. Automotive Capacitive Load Driving Example

In automotive applications like Figure 3-1, many off-board ECUs have large bulk capacitances in place to stabilize the voltage at the input. As these modules must be able to reliably operate during input voltage drops, spikes, and switching noise, the capacitor bank is required to help prevent any loss of functionality. These capacitances can range from hundreds of microfarads up to millifarads.

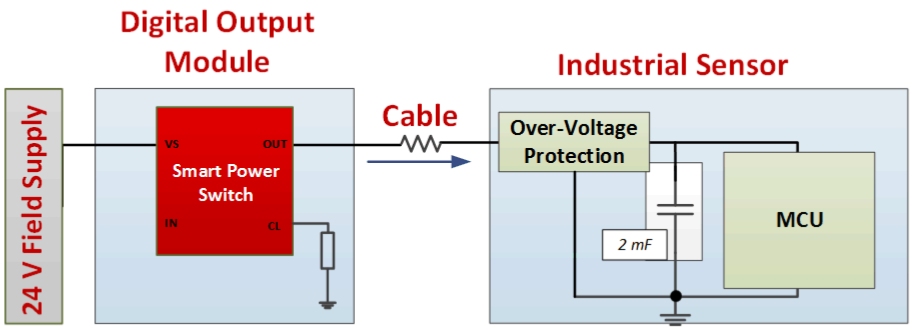

Figure 3-2. Industrial Capacitive Load Driving Example

Industrial applications such as the PLC module seen in Figure 3-2 also must be able to drive large capacitive loads. Often digital output modules are used to provide power to sensors that are protected against transient surges. The easiest way to protect the sensor from this transient surge is to use an overvoltage switch that shuts off the sensor power during the overvoltage. This means that a large capacitance must be used to provide system power until the transient surge has passed and the overvoltage protection disengages. This large capacitance adds challenges to sensor start-up and can cause inrush current problems each time the over-voltage protection disengages. Without a careful design the inrush current can cause the 24-V external field supply voltage to droop which can blow fuses elsewhere in the system and cause dangerous reverse currents from other capacitive modules attached to the same supply.

In both of these examples it is necessary for the output designer to understand the impact of the capacitive load on the system and provide an effective, reliable, and efficient method to drive the loads. In the next sections we will investigate the challenges for reliably driving a capacitive load.

3.3 Why Use a Smart High Side Switch?

3.3.1 Capacitive Load Charging

When a voltage is applied to an uncharged capacitor the capacitor will sink current until it's voltage is equal to the supply voltage. The magnitude of the inrush current is directly proportional to the rate at which the voltage across the capacitor changes with time. The resulting inrush current can be calculated by Equation 16 and be seen in Figure 3-3.

$$I_{INRUSH} = C_{LOAD} * \frac{dV}{dT} \tag{16}$$

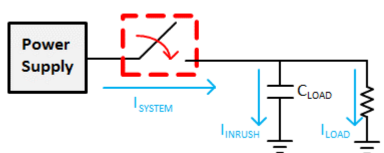

Figure 3-3. Capacitive Load Charging Diagram

When the switch is closed and the voltage is first applied to the capacitor, dV/dT is determined by the rate at which the switch in Figure 3-3 ramps up the output voltage. Depending on this rate the inrush can be very high and would only be limited by the parasitic resistance and inductance present in the routing between the switch output and the capacitor. Without anything limiting I_{INRUSH}, these high currents can lead to a voltage supply droop at the input voltage supply which could collapse due to the high level of power required. This can be seen in Figure 3-4, where charging a capacitor with a high dV/dT leads to inrush currents up to a peak of 40 A and causes a noticeable drop on the yellow input supply voltage.

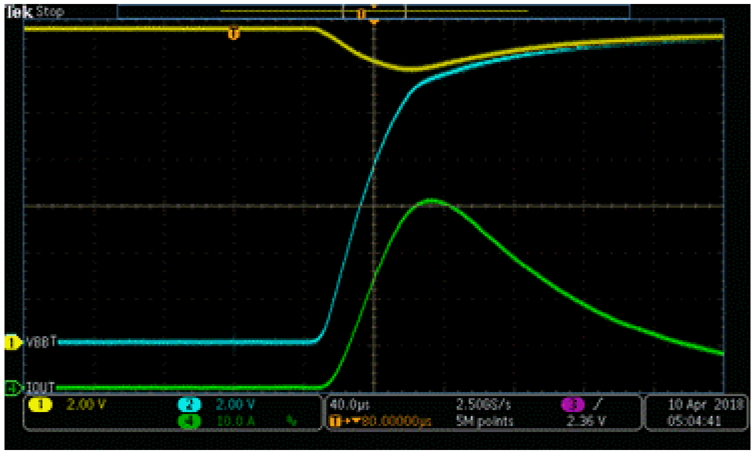

Figure 3-4. Inrush Supply Droop Example

This input supply drop means that any other systems connected to the same voltage supply must be able to operate without any variation even with an unstable supply. Additionally, the 40 A of current itself causes problems as the system must now be analyzed to make sure that there won't be any harm caused by the excessive current flow through the cables and connectors. This means more complex and expensive systems in the form of:

- Larger traces and connectors to accommodate the large current
- More powerful supply to prevent the supply droop
- Increased bulk capacitors at the input of downstream systems to enable continued device operation

To prevent these system considerations it is necessary to have a solution in place to let the system drive the capacitor and charge it at a controlled rate without allowing it to sink high levels of inrush current. In the next section we will show how this can be done with an adjustable current-limiting Smart High Side Switch.

3.3.2 Inrush Current Mitigation

A simple example of a modeled capacitive load can be seen in Figure 3-5. This circuit shows a simplified model of a switch driving a 500mA DC load at 24V with a 10µF output capacitor. This example shows the cable as 100mΩ and 5µH:

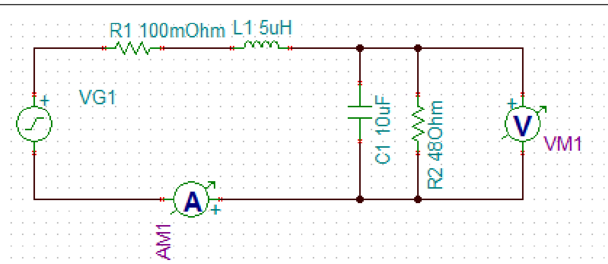

Figure 3-5. Uncontrolled Capacitor Charging Schematic

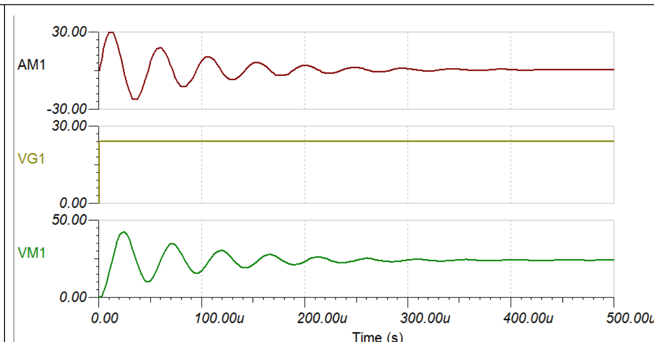

Figure 3-6. Uncontrolled Capacitor Charging Waveform

Figure 3-6 shows that an uncontrolled dV/dT leads to an inrush current that reaches nearly 30A with severe ringing. Without current limiting this is the quickest way to charge the capacitor, however for many systems this sort of inrush current is not acceptable and cannot be supported by the input power rail.

One option would be to find a way to limit this current while not impacting the system or causing the capacitor charging time to become too long. A simple solution would be for the designer to add a 12Ω current limiting resistor as seen in Figure 3-7.

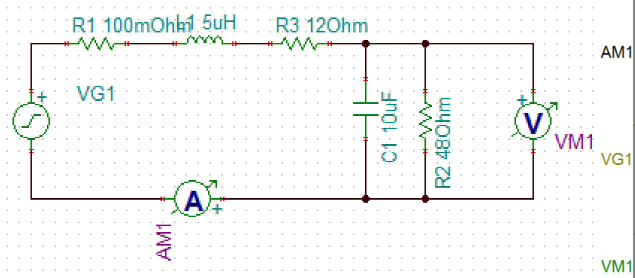

Figure 3-7. Series Resistance Capacitor Chargin Schematic

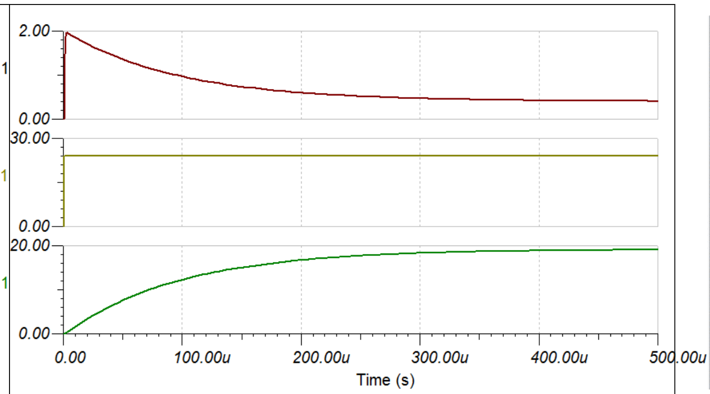

Figure 3-8. Series Resistance Capacitor Charging Simulation

The addition of a 12Ω current limiting resistor limits the peak current to less than 2A, but is not a viable solution due to the power dissipation and voltage drop over the additional 12-Ω resistance. With a 500mA DC load this adds 3W of additional power dissipation and a 6V drop over the resistor. This heat dissipation and voltage drop are not acceptable in the majority of applications.

Even for a relatively small 10µF load a better solution is needed. For larger capacitive loads these effects will be magnified further.

TI Smart High Side Switches are capable of limiting inrush current by linearly charging the capacitive load through current limiting. When charging a capacitor the Smart High Side Switch recognizes the over-current event and clamps the output current at an adjustable set point. Figure 3-9, shows where the TPS2H160-Q1 charges 470µF of capacitance with the current limit set to 1A:

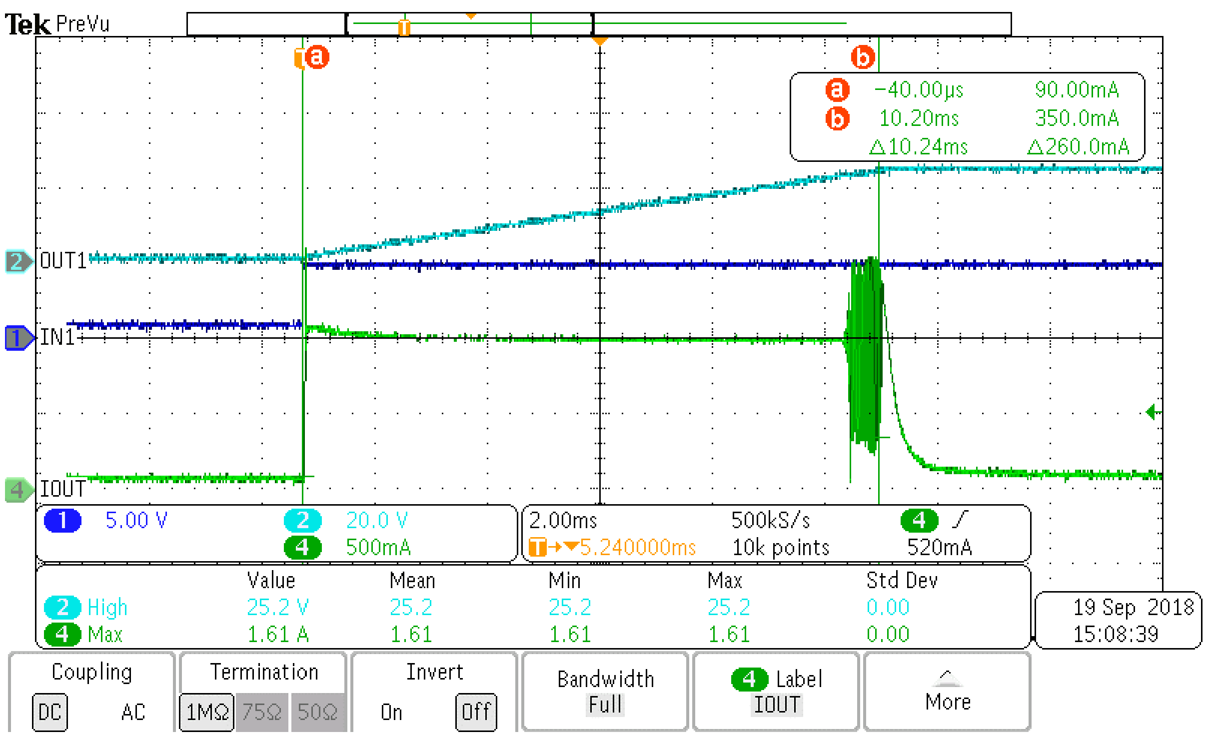

Figure 3-9. TPS2H160-Q1 Current Limiting at 1A

Now the capacitor charges fully without allowing the output current to exceed 1A and without adding significant DC series resistance to the system. Due to the FET heating up during this charging period some ringing occurs at the end because of the high temperature transition between the internal MOSFET modes of operation, however this poses no risk to the system due to the short transient length. The TPS2H160-Q1 has an on-resistance of only 160mΩ, so the same 500mA DC operating current means a power loss of only 40mW and a voltage drop of 80mV. These values are more acceptable for the system and will not cause unnecessary heat generation inside the module.

If the 1A inrush current is too significant the TPS2H160-Q1 allows the flexibility to further lower the current limit to 500mA as shown in Figure 3-10.

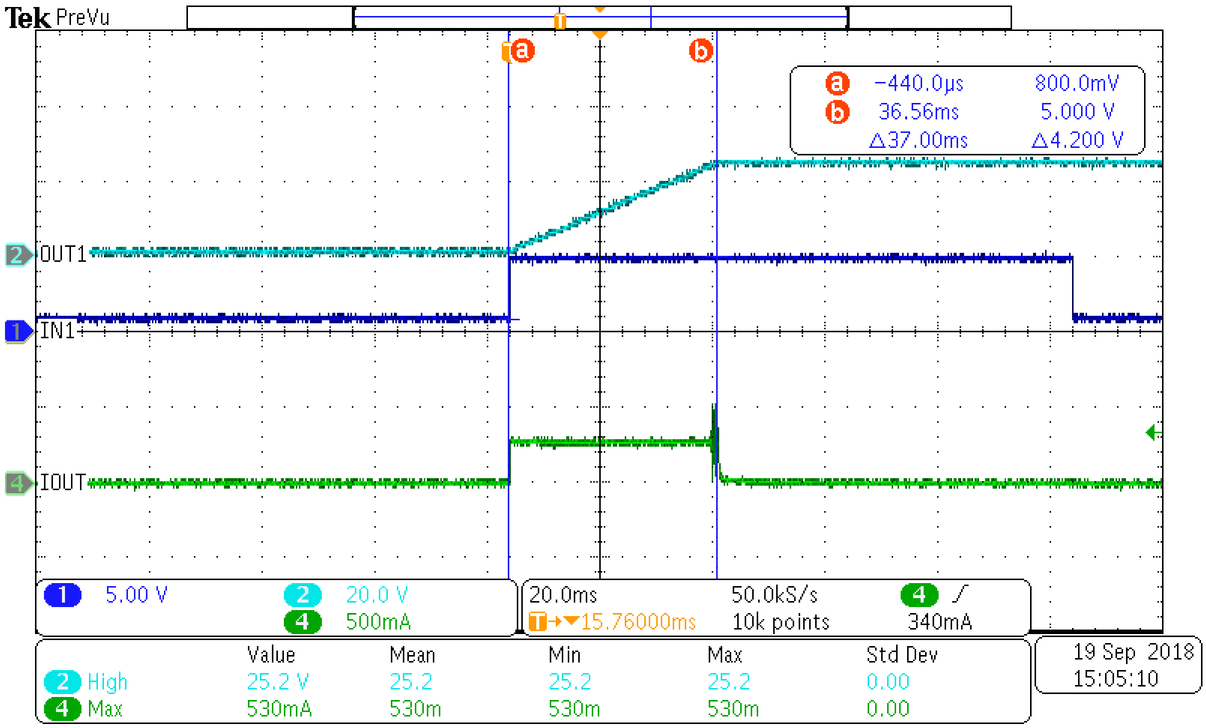

Figure 3-10. TPS2H160-Q1 Current Limiting at 500 mA

The voltage over the capacitor charges linearly with a constant current that never exceeds the set level. When taking into account the best way to limit inrush current, TI Smart High Side Switch current limiting provides a balanced solution for limiting inrush current while driving a capacitive load.

3.3.2.1 Capacitor Charging Time

Looking back at the equation for capacitor charging allows us to predict the charging profile during inrush current limiting. Rearranging Equation 16 to calculate the charging time gives us Equation 17.

$$\Delta T = C_{LOAD} * \frac{\Delta V}{I_{INRUSH}} \tag{17}$$

Equation Equation 18 shows us that Equation 17 is accurate for Figure 3-9.

$$\Delta T = 470\ \mu F * \frac{24\ V}{1\ A} = 11.28\ ms \tag{18}$$

Equation 17 shows that the lower the magnitude of the current limit set-point the longer it will take to charge the load capacitance. It is important to adjust this current limit set-point such that it appropriately balances between safely limiting current without significantly extending the charging time. This balance must be determined by looking at the specific application requirements such as system startup timing.

3.3.3 Thermal Dissipation

With large capacitive loads there are thermal considerations in the Smart High Side Switch during current limiting that must be considered. While the capacitor is charging, the Smart High Side Switch limits I_{INRUSH} by regulating the gate voltage of the MOSFET inside of the Smart High Side Switch.

Lets refer back to Equation 19 for charging a capacitor.

$$I_{INRUSH} = C_{LOAD} * \frac{dV_{CAP}}{dT} \quad (19)$$

For a regulated constant I_{INRUSH}, the capacitor needs to see a constant dV_{CAP}/dT . This means the voltage must linearly increase across the capacitor rather than the near instantaneous voltage increase that occurs with no current limiting. The voltage applied over the capacitor is V_{CAP} and is shown in Equation 20.

$$V_{CAP} = V_{SUPPLY} - V_{DS} \quad (20)$$

With a constant V_{SUPPLY}, Equation 20 shows that if V_{CAP} increases linearly, V_{DS} must be the inverse of V_{CAP} and decrease linearly. Therefore, for a constant current capacitive charging the Smart High Side Switch V_{DS} will initially be equal to V_{SUPPLY} before dropping towards zero while V_{CAP} simultaneously increases to reach V_{SUPPLY}. Figure 3-11 shows this behavior with the TPS2H160-Q1 driving a large (470µF) capacitive load to 24V with a current limit of 500mA.

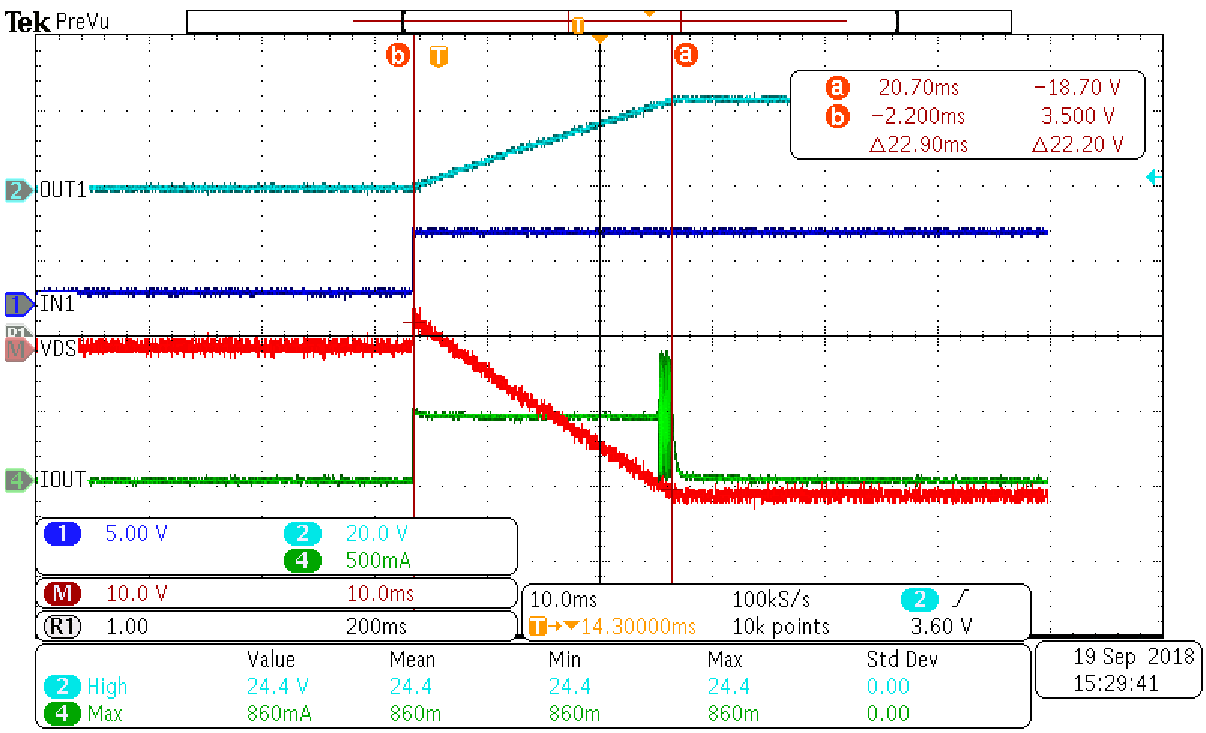

Figure 3-11. V_{DS} While Charging Capacitance

We see the Smart High Side Switch limiting the output current to 500mA as the OUT1 voltage over the capacitance linearly increases from 0V to 24V and the V_{DS} slowly decreases inversely from the supply voltage towards 0V.

During this charging period the power dissipation, P_{DIS}, in the Smart High Side Switch is calculated in Equation 21.

$$P_{DIS} = V_{DS} * I_{LIM} \quad (21)$$

The current is now limited and no longer unchecked inrush current so the equations will now consider I_{LIM} rather than I_{INRUSH}. Since I_{LIM} is constant and initially V_{DS} = V_{SUPPLY}, the peak power dissipation occurs at the beginning of the pulse and is given in Equation 22.

$$P_{PEAK} = V_{SUPPLY} * I_{LIM} \tag{22}$$

When the capacitor is fully charged, $V_{DS} \approx 0$ so $P_{DIS} \approx 0$. For a first approximation this means that the average power dissipation during the charging period is given in Equation 23.

$$P_{AVG} = \frac{1}{2}(V_{SUPPLY} * I_{LIM}) \tag{23}$$

This average dissipation will occur for a period equal to the charging period which is calculated in Equation 24.

$$\Delta T = C_{LOAD} * \frac{\Delta V_{SUPPLY}}{I_{LIM}} \tag{24}$$

In Figure 3-11 we see a peak power dissipation of 24V × 500mA = 12W, an average dissipation of 6W, and a charging time of 22.9ms. In order to have reliable operation the FET must be able to dissipate this heat over the charging time.

Lets look at what happens in Figure 3-12 when the current limit is increased to 1A.

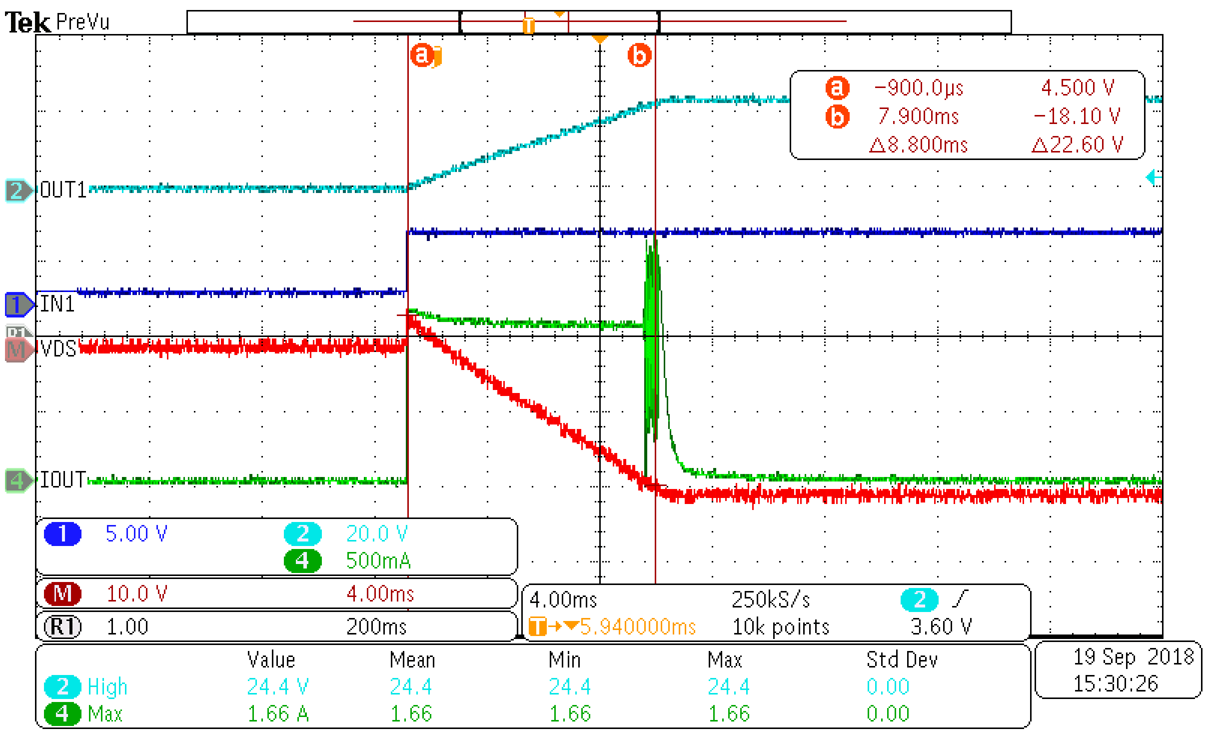

Figure 3-12. TPS2H160-Q1 Charging at 1A

The peak power dissipation has increased to 24W and the average dissipation to 12W, however the charging time has decreased to 8.8 ms. A higher current limit equates to a higher peak power dissipation with a shorter pulse while a lower current limit equates to a low peak dissipation for a longer time.

3.3.4 Junction Temperature During Capacitive Inrush

The large thermal dissipation that a High Side Switch sustains during capacitive inrush can exceed the average power dissipation of the device calculated in Power Dissipation Calculation. This leads to relibaility concerns if device junction temperatures rise above $T_{j(Max)}$ and possibly cause the device to go into Over Temperature Shutdown.

For average power consumption, we had estimated junction temperature as in Equation 4. Capacitive inrush events, however, are not steady-state conditions and are short in duration. A high-side switch may be able to tolerate higher-than-average power dissipation for short periods during inrush events due to the input-dependent thermal impedance.

Transient thermal impedance is typically modeled via a Foster RC network, shown in Figure 3-13. This model links the high-side switch junction temperature T_J to ambient temperature T_A and the response of the thermal RC network to power dissipated in the device P_{DIS}. The thermal impedance values in the model are strongly dependent on device construction and packaging. $Z_{\Theta JA}$ is defined as in Equation 25.

$$Z_{\theta JA} = \sum_{i=1}^{N} R_i (1 - e^{\frac{-t}{R_i \cdot C_i}}) \quad (25)$$

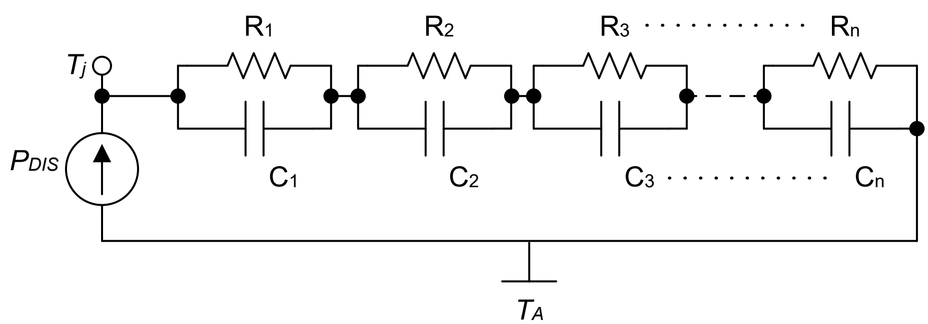

Figure 3-13. Foster Network Model of Device Thermal Impedance

This model shows us that short bursts of power have less effect on the junction temperature if the period is much less than the RC time constant, acting as a high-pass filter. For long periods of time, the thermal capacitances block the power and all the power passes through the thermal resistances $R_{1,2,3..n}$. The sum of these thermal resistances in the model is $R_{\Theta JA}$, which is specified in the device data sheets. The modeled response to a fast power transient is compared to a steady-state power dissipation in Figure 3-13.

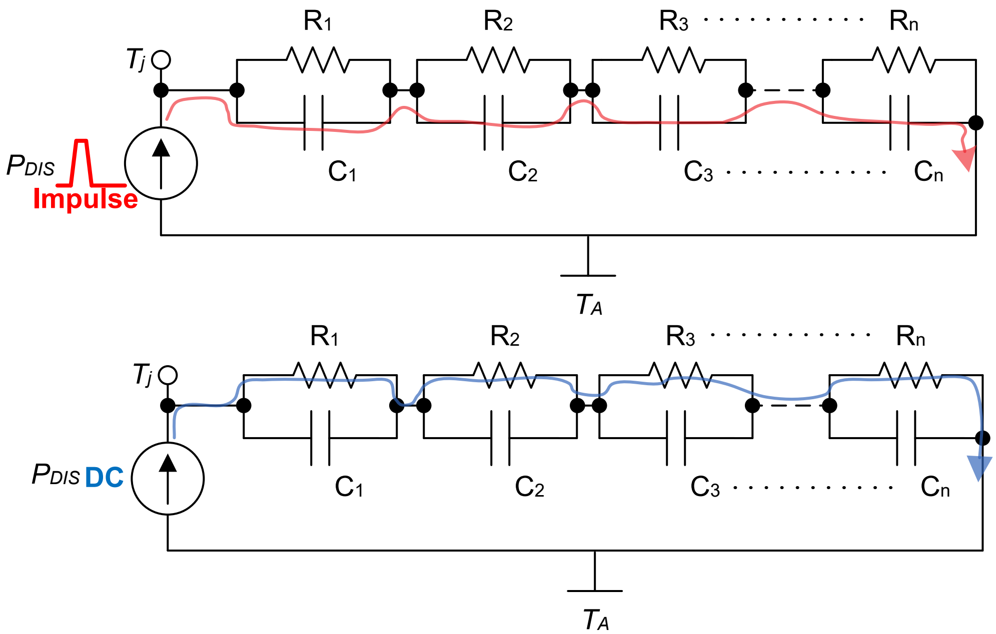

Figure 3-14. Effect of Thermal Time Constant on $R_{ΘJA}$ and Junction Temperature

During capacitive inrush, $Z_{ΘJA}$, P_{DIS}, and T_J are functions of time during, as shown in Figure 3-13. Time is on a logarithmic scale, and $Z_{ΘJA}$ is the time dependent thermal impedance of the device (between junction and ambient air). $Z_{ΘJA}$ follows an exponential decay according to the time constants of the Foster model for a particular device.

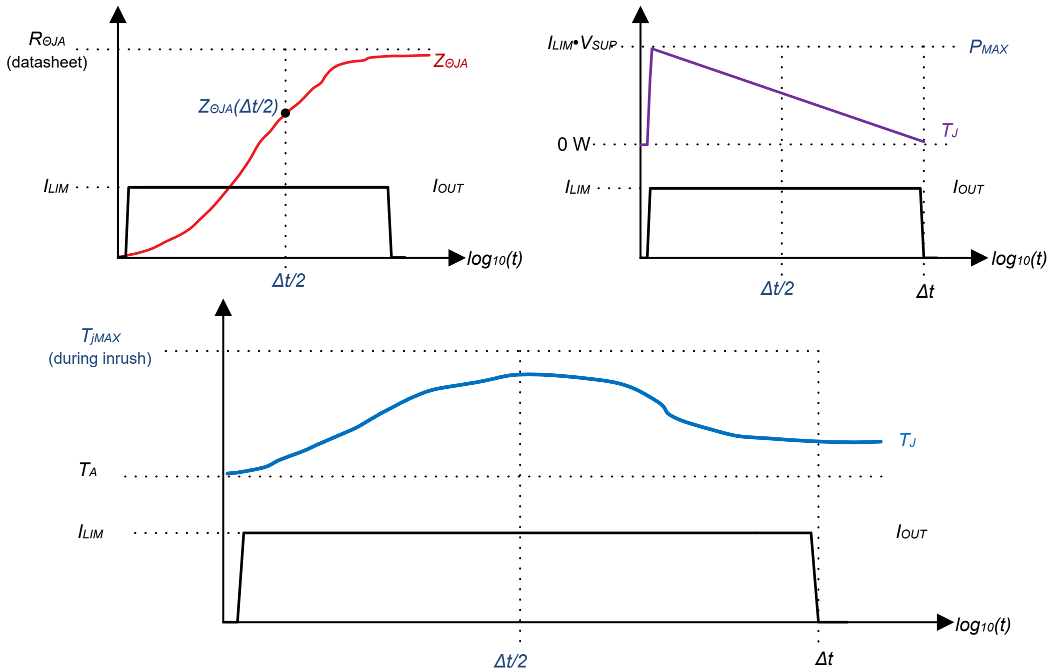

Figure 3-15. $R_{\Theta JA}$ and Junction Temperature During an Inrush Period

$Z_{\Theta JA}$ is monotonically increasing during the inrush period, Δt, but total power dissipated in the device is dropping linearly due to current limiting. The peak power dissipation $I_{LIM} \cdot V_{SUP}$ occurs at the beginning of this period, while $Z_{\Theta JA}$, the sum of decaying exponentials, peaks at the end of the inrush period.

This converse relationship causes junction temperature to peak at approximately half of the inrush period, or at Δt/2. This holds true as long the inrush period Δt is less than the effective thermal time constant of the device, or before $Z_{\Theta JA}$ plots flatten out. This is around 500 s for most high-side switches.

Mathematically, junction temperature is the convolution of $Z_{\Theta JA}$ and P_{DIS}, which are both time variant, shown in Equation 26. Evaluating this convolution to find ΔT_j is exceedingly difficult, and is best left to simulators like PSPICE if the device has a thermal-enabled model available.

$$\Delta T_j(t) = P_{DIS}(t) * Z_{\theta JA}(t) \tag{26}$$

For design purposes, we are mainly concerned with finding $T_{JMax)}$ during the inrush period rather than obtaining an expression for T_J for any point in time. This simplification allows us approximate $T_{J(Max)}$ as in Equation 27.

$$T_{j(MAX)} \approx \frac{2}{3} \cdot V_{SUP} I_{LIM} \cdot Z_{\theta JA(\Delta t/2)} + T_A \tag{27}$$

In Equation 27, $Z_{\Theta JA(\Delta t/2)}$ is the transient thermal impedance at half of the inrush period Δt calculated as in Equation 24. Then we find $Z_{\Theta JA}$ at Δt/2 from the device's transient thermal impedance curve, as shown in Figure 3-16.

Figures for transient thermal impedance $Z_{\Theta JA}$ are located in Appendix A and provided for each TI high-side switch listed in Table 3-1.

Equation 27 is accurate to within ±10% of PSPICE simulation results for $T_{J(Max)}$, but only for inrush times Δt < ~500 s, or the point at which the $Z_{\Theta JA}$ curve flattens. Beyond this point, this approximation begins to undershoot as peak temperature occurs later than Δt/2. A more advanced thermal simulation with PSPICE, Simulink, or another modeling tool should be used at that point.

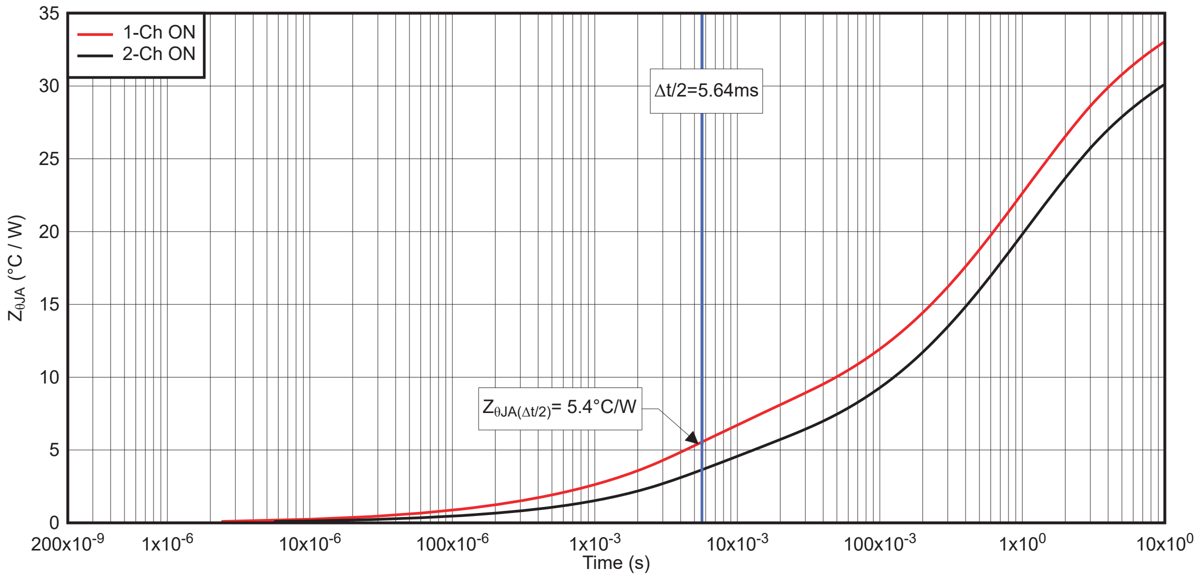

Figure 3-16. Estimating $Z_{\Theta JA(\Delta t/2)}$ from TPS2H160-Q1 Transient Thermal Impedance Curve

This procedure can be repeated for multi-channel devices using the transient thermal data $Z_{\Theta JA}$ for 2 or 4-Ch ON. However, this data should only be used for situations where both channels turn on simulatenously and the loading conditions are identical.

Adding on to our examples for TPS2H160-Q1, we can estimate $T_{J(Max)}$ during capacitive inrush. In this example, a single channel drives a 470-µF capacitive load, current limit I_{LIM} is set to 1 A, supply voltage is 24 V, and the ambient temperature is T_A = 25°C.

From Equation 18, we found the inrush period lasts Δt = 11.28 ms. Referencing the data for TPS2H160-Q1 in Appendix A, we can draw a line at Δt = 11.28 ms as in Figure 3-16 to find the values of $R_{\Theta JA}$ at half the inrush period Δt since we are only driving on one channel, $Z_{\Theta JA}$(Δt/2) = 5.4°C/W.

Current limiting is active during the inrush period and is responsible for significant power dissipation in the high-side switch. This is because current limiting is achieved through control of the FET R_{ON}. R_{ON} must be forced up to several orders of magnitude higher than the data sheet specification a the beginning of inrush, which leads to high I^2R losses in the FET channel.

Once the device turns on the FET, V_{DS} across the fet is initially V_{SUP} and reduces to nearly 0 V once the capacitor load is charged. This initial point is where the peak power dissipation occurs. In our example with TPS2H160-Q1, we had set ILIM = 1 A, so the peak power is 24 V·1 A = 24W. We can now calculate $T_{J(MAX)}$ during inrush by substituting our values for V_{SUP}, I_{LIM}, T_A, and $Z_{\Theta JA(\Delta t/2)}$ into Equation 27, shown in Equation 28.

$$T_{j(MAX)} \approx \frac{2}{3} \cdot 24\text{V} \cdot 1\text{A} \cdot 5.4°\text{C/W} + 25°\text{C} = 111.4°\text{C} \tag{28}$$

From Equation 28, we find that the $T_{J(Max)}$ ≈ 111°C at an ambient temperature of 25°C. and 111°C < 150°C, well within the specification limits for T_J. Our ΔT_J from ambient is therefore 86°C.

As this is an estimate and operating conditions may vary from the design point, it is recommended to allow for sufficient headroom between $T_{J(Max)}$ and 150°C. Not properly limiting T_J may trigger over-temperature shutdown and reduce both reliability and device lifetime.

In addition to keeping T_J < 150°C, it is recommended to keep $\Delta T_J < T_{SW}$, where T_{SW} = 60°C to prevent thermal swing shutdown during inrush. As the highest temperature will occur in the FET junction during inrush, designing for $\Delta T_J < T_{SW}$ guarantees thermal swing shutdown will not be triggered during inrush. Since T_{FET} T_{CON} are strongly time-depenedent on loading conditions over inrush, ΔT_J could also potentially be larger than T_{SW} without triggering thermal swing shutdown.

For the most accurate thermal results, it is strongly recommended to use thermal-enabled PSPICE models for TI's high-side switches which model T_J, T_{CON}, and thermal shutdown. For more information on simulating device thermals in PSPICE, please see Using PSpice Simulator to Model Thermal Behavior in TI's Smart High-Side Switches.

3.3.5 Over Temperature Shutdown

To ensure there are no failures during high power dissipation, TI Smart High Side Switches integrate two methods of over temperature protection. The first is an absolute thermal shutdown that turns off the FET when the junction temperature reaches an unsafe level, typically around 150°C. The second is a relative thermal shutdown, or thermal swing shutdowthat measures the temperature difference between the FET and the controller. This will shut the Smart High Side Switch off during large transients where the FET quickly heats up but the controller lags the FET temperature. This protection increases reliability in two primary cases:

1. **Protection against localized hot spots in the FET that are not recorded by the temperature sensor.** With only an absolute temperature shutdown you are assuming that the measurement is occurring at the hottest part of the junction, which cannot be guaranteed.
2. **Protection in short circuit situations with cable inductance.** During an output short circuit the output wants to draw very high currents so the Smart High Side Switch will clamp at the current limit until it hits thermal shutdown. Once thermal shutdown is hit the output current will immediately stop, however any output inductance that is present in a cable will attempt to continue the current flow and the Smart High Side Switch must demagnetize this inductance. For more details on demagnetizing inductive loads reference Section 4. If the Smart High Side Switch is already at its peak junction temperature this demagnetization energy will destroy the switch. By using the relative temperature of the FET to register this short circuit and shut the device down earlier the device ensures it is capable of absorbing the demagnetization energy safely.

Figure 3-17 shows the behavior of the relative thermal shutdown mechanism which shuts off the FET when T_{FET}-T_{CON}>T_{SW} where T_{SW}=60°C and turn back on below T_{SW} less a hysteresis temperature T_{HYS}. This may cause power cycling during inrush and slow load capacitor charging.

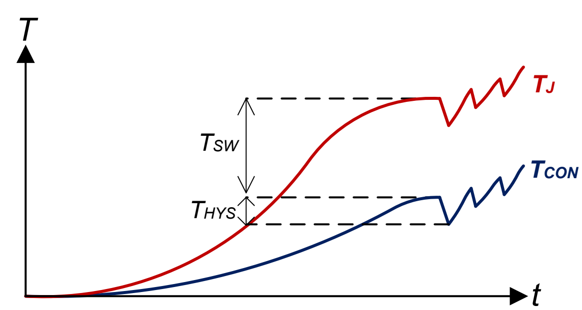

Figure 3-17. Thermal Cycling due to relative thermal shutdown mechanism

When either of these shutdown mechanisms occurs, the switch shuts off to prevent current flow to the load. By preventing current to the load, the device prevents any additional power dissipation in the Smart High Side Switch. This gives the switch time to cool down and reach a safe temperature.

During the shutdown the open FET temporarily prevents the capacitor from charging, however TI Smart High Side Switches have a fast cool-down and retry time so the charge erosion on the capacitor will be limited and upon restart the switch will continue charging. This means that if the Smart High Side Switch hits thermal shutdown it will quickly try again and resume charging the capacitor safely.

This behavior can be seen in Figure 3-18 where the TPS2H160-Q1 drives 470μF to 24V with a current limit of 2.2A. It can be observed that on two occasions the device reaches the relative temperature shutdown and temporarily disables the switch preventing current flow before re-enabling after the device has had a chance to cool down. In this way, the TI Smart High Side Switch protects itself from over-temperature stresses when driving large capacitive loads.

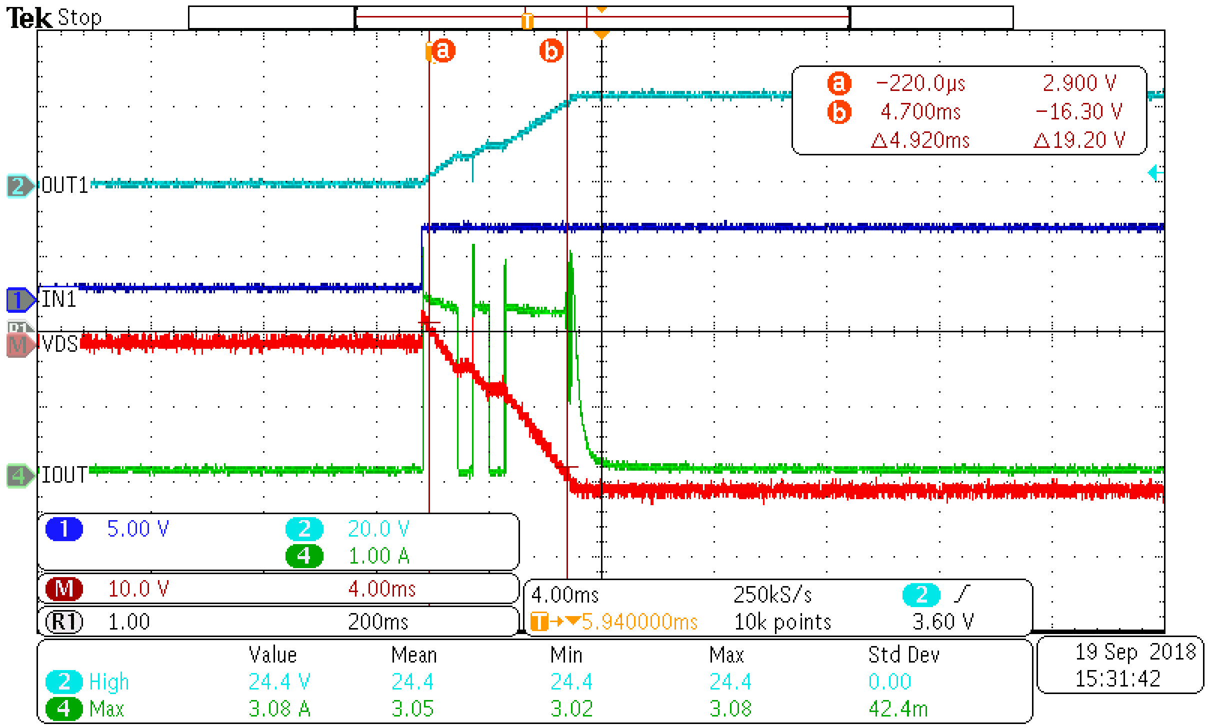

Figure 3-18. TPS2H160-Q1 Thermal Shutdown While Driving Capacitance

This analysis is important to understand while selecting a TI device for driving capacitive loads. Ideally, the Smart High Side Switch should be able to drive the load without any shutdowns, however a designer should balance the current limit set-point with the required charging time. To determine whether the device will go into thermal shutdown the best method is to test the specific load profile with a TI evaluation module, but for a detailed analysis an RC thermal model can also be used.

3.3.6 Selecting the Correct Smart High Side Switch

When selecting a Smart High Side Switch for capacitive load driving, there are two critical specifications:

1. **DC Current Range**: Ensure that the on resistance of the Smart High Side Switch is low enough to drive the required DC current without significant heating.
2. **Thermal Dissipation**: Calculate the thermal energy required for charging the capacitor and then reference the Smart High Side Switch thermal models to make sure that the device can drive the load with minimal thermal shutdowns.

Use Table 3-1 to determine the best device for your application by selecting a device that can support the maximum application DC current requirement:

Table 3-1. TI Smart High Side Switch Portfolio

<table>
<tr><th>Device</th><th>On Resistance</th><th>Max DC Current</th></tr>
<tr><td>TPS1H000-Q1</td><td>1000 mΩ</td><td>1 A</td></tr>
<tr><td>TPS2H000-Q1</td><td rowspan="2">1000 mΩ</td><td rowspan="2">0.75 A</td></tr>
<tr><td>TPS4H000-Q1</td></tr>
<tr><td>TPS1H200-Q1</td><td>200 mΩ</td><td>2.5 A</td></tr>
<tr><td>TPS2H160-Q1</td><td rowspan="2">160 mΩ</td><td rowspan="2">2.5 A</td></tr>
<tr><td>TPS4H160-Q1</td></tr>
<tr><td>TPS1H100-Q1</td><td rowspan="2">100 mΩ</td><td rowspan="2">4 A</td></tr>
<tr><td>TPS27S100</td></tr>
<tr><td>TPS1HB50-Q1</td><td rowspan="2">50 mΩ</td><td>4 A</td></tr>
<tr><td>TPS2HB50-Q1</td><td>4.5 A</td></tr>
</table>

Table 3-1. TI Smart High Side Switch Portfolio (continued)

Device	On Resistance	Max DC Current
TPS1HB35-Q1	35 mΩ	5 A
TPS2HB35-Q1		5 A
TPS1HB16-Q1	16 mΩ	7 A
TPS2HB16-Q1		7 A
TPS1HA08-Q1	8 mΩ	8 A
TPS1HB08-Q1		11 A

The maximum current listed in the table refers to nominal silicon with a JEDEC standard board. The best practice is to ensure sufficient margin to account for non-ideal layouts or higher than standard ambient temperatures. For an exact calculation, reference the data sheet $R_{\theta JA}$ specification to calculate the actual thermal diffusion for DC current flow. Once you have a selected a device that can support the output current requirements, ensure that it has the thermal dissipation capability to sufficiently dissipate the heat required for the capacitive charging.

TI Smart High Side Switches provide a reliable and efficient way to safely drive capacitive loads. While driving a capacitive load it is important to safely limit the inrush current while still minimizing the load charging time. By selecting the appropriate current limiting Smart High Side Switch it is possible to efficiently and effectively charge the capacitive load while avoiding thermal issues.

4 Driving Inductive Loads

4.1 Background

An inductive load is any load that stores magnetic energy when connected to a supply voltage. The inductive load impedance consists of both a resistance and inductance in series. Common inductive loads that can be driven by Smart High Side Switches are relays, motors, and solenoids. When they are switched off inductive loads can generate a transient negative voltage of hundreds of volts due to the stored magnetic energy in the inductance. This transient voltage can cause severe damage to the drive circuit. To prevent any potential damage, during switch-off the stored magnetic energy must be dissipated by clamping the voltage across the inductive load. TI Smart High Side Switches integrate a power clamp circuitry that protects the circuit by clamping the voltage over the switch to a set voltage and recirculating the current through the clamp. This causes the stored energy to be safely dissipated. With this large clamp voltage the demagnetization time is decreased leading to a safe and quick turn off time for inductive loads.

This document gives guidance on the important parameters and calculations for high reliability during inductive load driving. Due to the integrated clamp, TI Smart High Side Switches are generally capable of driving an inductive load with no need for external protection components like Transient Voltage Suppressor (TVS) diodes. The section will use the TPS4H160-Q1 as an example for most calculations, but the calculations and comparisons will be very similar with all TI High Side Switches if the demagnetization energy plot is available.

We will start by looking at common inductive load applications followed by deriving the critical parameters and equations that determine the inductive load demagnetization. Then we will begin looking specifically at the TPS4H160-Q1 as a case study for reading a demagnetization energy plot. Finally, we will look at several examples showing specific applications and how we can tell if the TI Smart High Side Switch is capable of demagnetizing the load.

Note

Key Design Consideration: Ensure that upon turn-off, the Smart High Side Switch is capable of dissipating the demagnetization energy that is stored within an inductive load.

4.2 Application Examples

Common inductive loads include a variety of relays and solenoids with up to 1500mH inductance and a steady state current of up to 5A. Motors and resistive loads connected with long cables, especially in industrial systems, are also inductive in their nature. One common example, seen in Figure 4-1, is driving solenoids in industrial applications like factory automation systems.

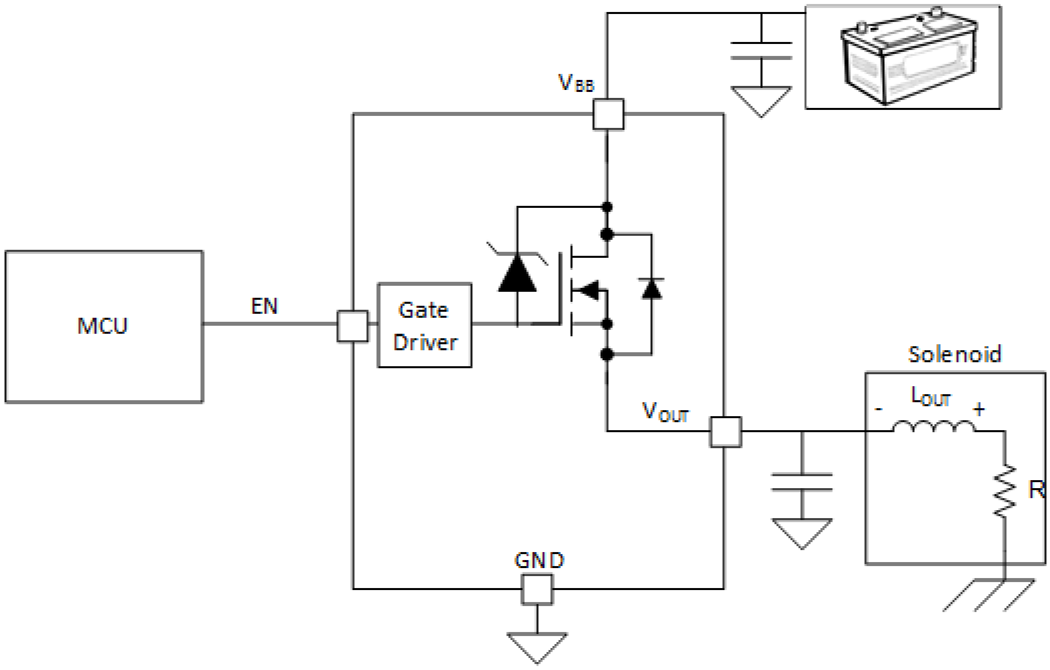

Figure 4-1. Solenoid Application Example

In this example, the Smart High Side Switch is controlling power between a car battery and a solenoid. Solenoids are needed in automotive applications to provide a large initial current to the car engine starter so their operation is critical to turning the vehicle on. The Smart High Side Switch provides a current to the inductive coil in the solenoid which will close the contacts for the primary current to start the engine. Because this solenoid is inductive in nature it must be ensured that the Smart High Side Switch can effectively manage the challenges of both turning on and turning off the solenoid. This is a critical feature of the vehicle so proper design is necessary for the switch to operate.

Solenoids are not the only common applications that have an inductive load profile. PTC Relays, valves, electric motors, and transformers will all have a predominantly inductive load to drive. For any of these loads it is essential to ensure a proper understanding of the theory and design for an output load driving stage.

4.3 Why Use a Smart High Side Switch?

An understanding of theory behind inductive load driving is critical for designing a long term reliable Smart High Side Switch solution. There are two aspects of inductive load driving to be considered: the turn-on phase and the turn-off phase.

4.4 Turn-On Phase

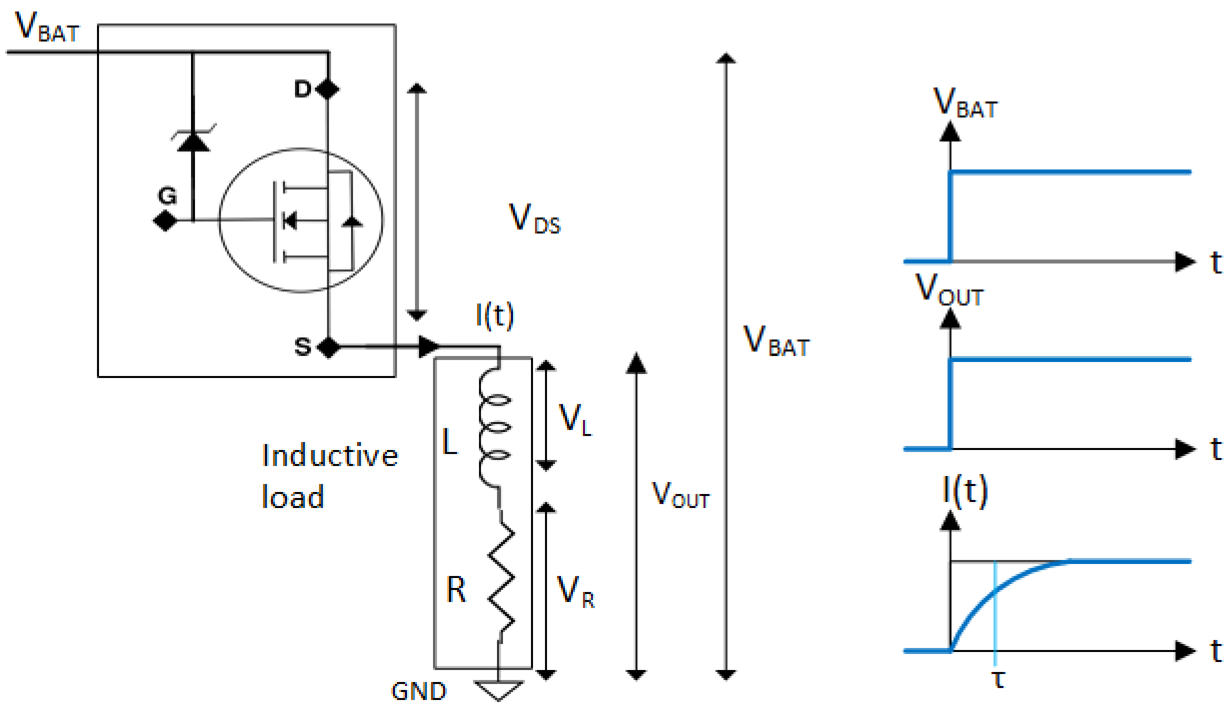

Figure 4-2. Inductive Load Turn-On Phase

The turn-on phase as shown in Figure 4-2 begins when the supply voltage V_{BAT} is initially applied to an uncharged inductive load. This causes the load current to ramp up exponentially from zero. When a step voltage V_{BAT} is applied across an uncharged inductor, the current can be calculated with Equation 29.

$$I(t) = \frac{V_{BAT}}{R}\left(1 - e^{\frac{-t}{\tau}}\right) \tag{29}$$

$$\tau = \frac{L}{R} \tag{30}$$

The time constant τ determines the slew rate of the current and is a function of the load resistance and inductance. The load profile also determines the steady state current $I_{LOAD,DC}$ through Equation 31, which is approximately reached at time t = 3τ and the stored magnetic energy E through Equation 32.

$$I_{LOAD,DC} \approx I(3\tau) \approx \frac{V_{BAT}}{R} \tag{31}$$

$$E = \frac{1}{2} L \left(\frac{V_{BAT}}{R}\right)^2 \tag{32}$$

When using a Smart High Side Switch that includes open load detection, make sure that the switch waits long enough for the current to ramp before declaring an open load. Also ensure that the Smart High Side Switch can handle the DC current flow. If the current is above the data sheet specification of the device it can cause high power dissipation inside the switch and cause a thermal shutdown.

4.5 Turn-Off Phase

Inductive loads seek to maintain continuous current flow in one direction. When an inductive load is turned off, the inductive load reverses the polarity of the applied voltage to prevent the immediate loss of current flow. That means if the voltage across the inductive load is positive during the on-phase, it will become negative when applied power is removed.

Immediately before the switch is opened, the load current I_0 is equal to $I_{LOAD,DC}$ as calculated in Equation 31. Immediately after the switch opens the inductor current will begin decaying from I_0 to zero as a continuous function. With a negative dI/dT and no applied V_{BAT}, the voltage across the inductive load will invert and a negative voltage will appear on the high side switch output. This process is shown in Figure 4-3

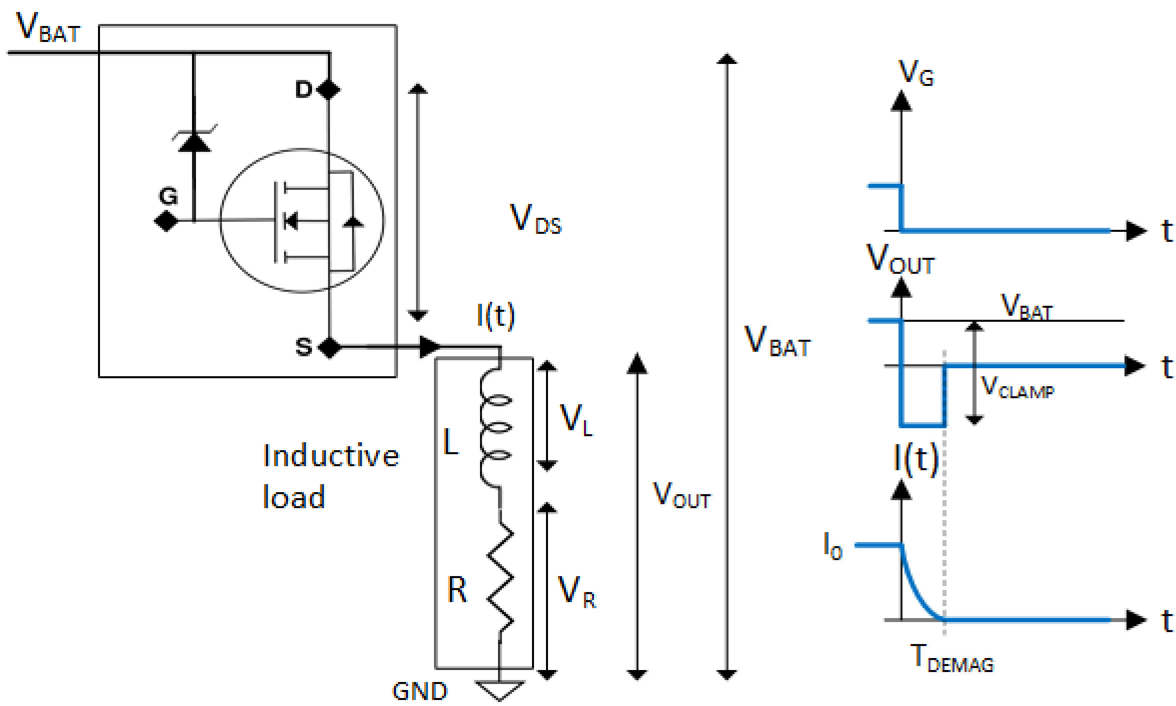

Figure 4-3. Inductive Load Turn-Off Phase

Applying Kirchhoff's voltage law gives Equation 33.

$$V_{BAT} = V_R + V_L + V_{CLAMP} \tag{33}$$

Where V_L is the voltage across the inductive element of the load, V_R is the voltage across resistive element of the load, V_{CLAMP} is the voltage across the switch FET V_{DS} during a transient voltage spike, and V_{BAT} is the supply voltage. Ohm's law for resistors and inductors are seen in Equation 34 and Equation 35:

$$V_R = R * I(t) \tag{34}$$

$$V_L = L * \frac{dI(t)}{dt} \tag{35}$$

Inserting those into Equation 33 gives Equation 36:

$$V_{BAT} = \left(R * I(t)\right) + L\frac{dI(t)}{dt} + V_{CLAMP} \tag{36}$$

Rearranging Equation 36 gives Equation 37, which is a first order differential equation for the load current.

$$I(t) + \left(\frac{L}{R} * \frac{dI(t)}{dt}\right) = -\frac{V_{CLAMP} - V_{BAT}}{R} \tag{37}$$

This is solved in Equation 38.

$$I(t) = -\frac{V_{CLAMP} - V_{BAT}}{R} + \left(\frac{V_{CLAMP} - V_{BAT}}{R} + I_0\right) e^{\frac{-t}{\tau}} \tag{38}$$

Where I_0 is the current when the switch is initially opened. Equation 38 shows that the current decays exponentially with negative slope and time constant $\tau = L/R$. This equation serves as the basis for calculating the inductive load demagnetization energy. The current has two components: on the left side of the equation is the steady state current contribution and on the right is the transient current contribution that is modified by the exponential time factor. The load is demagnetized completely when the total current is zero and the two components are equal.

Note that Equation 38 is valid only from time t = 0 until the load is completely demagnetized. This demagnetization time is calculated in the next section.

4.5.1 Demagnetization Time

The demagnetization time T_{DEMAG} is the time that the current takes to decay from I_0 to zero. This parameter is necessary to later calculate the total demagnetization energy.

To calculate T_{DEMAG}, Equation 38 can be solved for when the total current is equal to 0.

$$I(T_{DEMAG}) = -\frac{V_{CLAMP} - V_{BAT}}{R} + \left(\frac{V_{CLAMP} - V_{BAT}}{R} + I_0\right) e^{\frac{-T_{DEMAG}}{\tau}} = 0 \tag{39}$$

$$e^{\frac{-T_{DEMAG}}{\tau}} = \frac{\frac{V_{CLAMP} - V_{BAT}}{R}}{\frac{V_{CLAMP} - V_{BAT}}{R} + I_0} \tag{40}$$

$$\frac{T_{DEMAG}}{\tau} = -\ln\left(\frac{\frac{V_{CLAMP} - V_{BAT}}{R}}{\frac{V_{CLAMP} - V_{BAT}}{R} + I_0}\right) \tag{41}$$

$$T_{DEMAG} = \frac{L}{R} * \ln\left(1 + \frac{R * I_0}{V_{CLAMP} - V_{BAT}}\right) \tag{42}$$

Equation 42 shows that the demagnetization time is proportional to the time constant L/R and increases with larger I_0, lower V_{CLAMP}, and higher V_{BAT}.

4.5.2 Instantaneous Power Losses During Demagnetization

During this demagnetization time, the inductor energy is absorbed within the high side switch. The instantaneous power through the switch is calculated in Equation 43 from the voltage across the switch and the load current.

$$P_D(t) = V_{CLAMP} * I(t) \tag{43}$$

Equation 43 and Equation 38 combined give Equation 44:

$$P_D(t) = V_{CLAMP} * [-\frac{V_{CLAMP} - V_{BAT}}{R} + \left(\frac{V_{CLAMP} - V_{BAT}}{R} + I_0\right) e^{\frac{-t}{\tau}}] \tag{44}$$

After calculating the demagnetization time in Equation 42 and the instantaneous power in Equation 44, the demagnetization energy can be calculated.

4.5.3 Total Energy Dissipated During Demagnetization

During the switch off time, the demagnetization energy must be dissipated in the high side switch. In the absence of proper demagnetization the FET can be severely damaged and also can cause damage elsewhere in the system.

Selection of a high side switch can be determined once the demagnetization energy is well defined. The dissipated energy E_D is calculated in Equation 45 by integrating the instantaneous power losses $P_D(t)$ over the demagnetization time T_{DEMAG}.

$$E_D = \int_0^{T_{DEMAG}} P_D(t)\, dt \tag{45}$$

Taking Equation 45 and Equation 44 together and solving the integration gives Equation 48.

$$E_D = \int_0^{T_{DEMAG}} V_{CLAMP} * [-\frac{V_{CLAMP} - V_{BAT}}{R} + \left(\frac{V_{CLAMP} - V_{BAT}}{R} + I_0\right) e^{\frac{-t}{\tau}}]\, dt \tag{46}$$

$$E_D = \tau * V_{CLAMP} * [I_0 - \frac{V_{CLAMP} - V_{BAT}}{R} * \ln\left(1 + \frac{R * I_0}{V_{CLAMP} - V_{BAT}}\right)] \tag{47}$$

$$E_D = \frac{L}{R} * V_{CLAMP} * [I_0 - \frac{V_{CLAMP} - V_{BAT}}{R} * \ln\left(1 + \frac{R * I_0}{V_{CLAMP} - V_{BAT}}\right)] \tag{48}$$

Equation 48 allows us to calculate the inductive demagnetization energy during switch off.

In typical automotive and industrial applications where the nominal supply voltage V_{BAT} are 12 V and 24 V respectively, the term in the natural logarithm is always less than one because the maximum R × I_0 value is equal to V_{BAT}, while V_{CLAMP} will always be higher, with a typical nominal value of 60 V. This allows us to simplify Equation 48 into Equation 49.

$$E_D = \frac{L}{R} * V_{CLAMP} * [\frac{V_{BAT}}{R} - \left(\frac{V_{CLAMP} - V_{BAT}}{R}\right) * \ln\left(1 + \frac{V_{BAT}}{V_{CLAMP} - V_{BAT}}\right)] \tag{49}$$

The logarithmic term in Equation 49 can be converted to a polynomial by using the Taylor series in Equation 50.

$$\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots \tag{50}$$

This polynomial function has infinite terms but converges when x is less than 1. In industrial applications where V_{BAT} = 24 V and V_{CLAMP} = 60 V, Equation 51 calculates the values of the first few terms.

$$x = \frac{V_{BAT}}{V_{CLAMP} - V_{BAT}} = \frac{24\ V}{60\ V - 24\ V} = 0.6666$$

$$\frac{x^2}{2} = 0.2222$$

$$\frac{x^3}{3} = 0.0987$$

$$\frac{x^4}{4} = 0.05 \quad (51)$$

The signs of the terms in the Taylor series are alternating and decreasing. With estimation of less than 5% error, all terms after the second can be eliminated and Equation 49 can be simplified to Equation 54.

$$E_D = \frac{L}{R} * V_{CLAMP} * [\frac{V_{BAT}}{R} - \left(\frac{V_{CLAMP} - V_{BAT}}{R}\right) * \left(\frac{V_{BAT}}{V_{CLAMP} - V_{BAT}} - \frac{1}{2}\left(\frac{V_{BAT}}{V_{CLAMP} - V_{BAT}}\right)^2\right)] \quad (52)$$

$$E_D = \frac{1}{2} L \left(\frac{V_{BAT}}{R}\right)^2 * (\frac{V_{CLAMP}}{V_{CLAMP} - V_{BAT}}) \quad (53)$$

$$E_D = \frac{1}{2} L I_0^2 * (\frac{V_{CLAMP}}{V_{CLAMP} - V_{BAT}}) \quad (54)$$

Equation 54 allows a designer to calculate the total demagnetization energy that must be dissipated with the high side switch during an inductive turn off event. This can be compared to the Smart High Side Switch demagnetization capabilities to determine if the device can dissipate the energy alone or if an external clamp must be used to safely demagnetize the inductive load.

4.5.4 Measurement Accuracy

Let’s compare Equation 54 to measured data to verify the calculations. In this example, a pure inductor mounted on an iron core was measured precisely and a single 24-V pulse was applied and then turned off. The inductive coil had a 200 mH inductance and a 5.6 Ω series resistance.

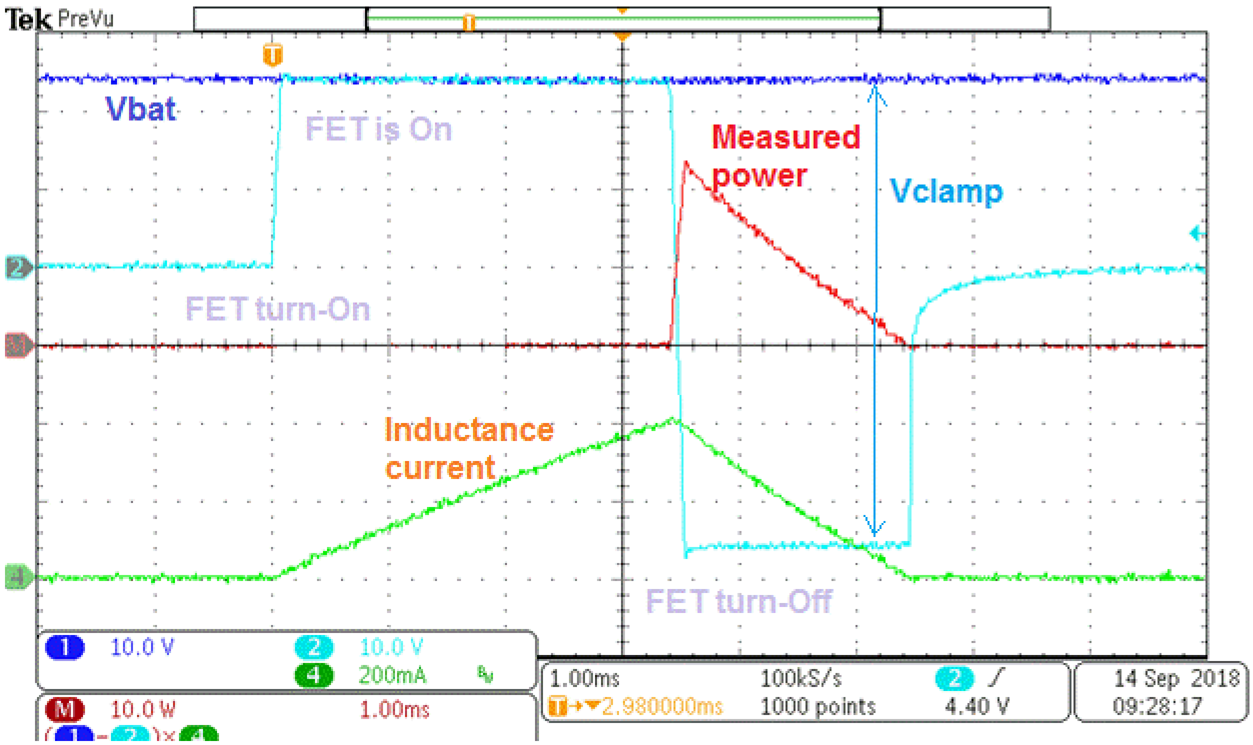

Figure 4-4. Demagnetization Energy During Inductive Turn-Off

Figure 4-4 shows both the turn-on and turn-off time. Looking at the turn-off time, we see that there is a T_{DEMAG} of 3.3 ms and an I_0 of 0.4 A. Table 4-1 compares these measured values to the values calculated from derived equations.

Table 4-1. Measured vs. Calculated Demagnetization Energy

Inductance	Peak Current	V_{SUPPLY}	V_{CLAMP}	Inductor Energy		Demagnetization Energy	Demagnetization Time
200 mH	400 mA	24 V	60 V	15.84	**Calculated**	26.4 mJ	2.13 ms
					Measured	24 mJ	2.05 ms

Table 4-1 shows the calculated demagnetization energy from Equation 54 is 26.4 mJ and the measured value is 24 mJ, less than 10% difference. This small difference is due to the approximations made during the derivation and measurement tolerances. The derived equations offer a good approximation of the inductive discharge energy.

4.5.5 Application Example

Example specifications for a few inductive loads are shown in Table 4-2. This specification is an example of a solenoid or relay that is commonly driven in automotive or industrial applications. The following example will step through determining if TPS4H160-Q1 is capable of driving these loads with no external components. Inductive load profiles will vary over temperature, so typically the profile will be specified across the operating temperature range of the system with the worst case when the system is at its lowest temperature.

Table 4-2. Inductive Load Examples

Load #	Inductance	Resistance			Switching Frequency	V_{SUPPLY}
		-40ºC	25ºC	35ºC		
1	205 mH	79 Ω	150 Ω	158 Ω	1 Hz	24 V
2	48.4 mH	50 Ω	67 Ω	69.9 Ω	1 Hz	24 V
3	35 mH	7.5 Ω	10 Ω	10.4 Ω	1 Hz	24 V

With these load profiles, we can calculate the current and stored energy during the on-state and demagnetized on transition to the off-state. These parameters allow us to choose the correct high side switch that is capable of safely dissipating the stored inductive energy during switching off.

4.5.6 Calculations

The detailed calculation is shown for Load 1, Load 2 and Load 3 can also be calculated following the same steps.

The following steps allow us to calculate the demagnetization energy of the load:

- Determine the supply voltage V_{BAT}, which is 24 V
- Calculate the worst case steady state load current. For Load 1, the worst case load current is at –40ºC, giving R = 79 Ω. The steady state current is calculated as

$$I_{OUT} = \frac{V_{BAT}}{R} = \frac{24\ V}{79\ \Omega} = 0.304\ A \tag{55}$$

- Calculate the stored energy during the on time from the inductance value:

$$E = \frac{1}{2} L * I_0^2 = \frac{1}{2} * 205\ mH * (0.304\ A)^2 = 9.46\ mJ \tag{56}$$

- Calculate the demagnetization time:

$$T_{DEMAG} = \frac{L}{R} \ln\left(1 + \frac{R * I_0}{V_{CLAMP} - V_{BAT}}\right) = \frac{205\ mH}{79\ \Omega} \ln\left(1 + \frac{24\ V}{60\ V - 24\ V}\right) = 1.32\ ms \tag{57}$$

  This means with the internal clamp at 60 V the stored energy will demagnetize in 1.32 ms
- Calculate the demagnetization energy:

$$E_D = \frac{1}{2} L \left(\frac{V_{BAT}}{R}\right)^2 * \left(\frac{V_{CLAMP}}{V_{CLAMP} - V_{BAT}}\right) = \frac{1}{2}(205\ mH)\left(\frac{24\ V}{79\ \Omega}\right)^2 * \left(\frac{60\ V}{60\ V - 24\ V}\right) = 15.76\ mJ \tag{58}$$

Load 1 has a current of 0.304 A, inductance of 205 mH and a stored magnetic energy of 9.46 mJ. The stored magnetic energy will be demagnetized over the high side switch with a total demagnetization energy that must be absorbed of 15.67mJ. Lets look to see if the TI Smart High Side Switch TPS4H160-Q1 can dissipate this energy.

The TPS4H160-Q1 is a quad channel high side switch that is widely used for driving inductive loads in both industrial and automotive systems. Like all TI Smart High Side Switches, the TPS4H160-Q1 includes an integrated inductive clamp that allows it demagnetize inductive loads without external circuitry. To determine whether this device can handle this inductive load, reference the device's demagnetization capability plot which shows the maximum load current or total energy for a given inductance. Demagnetization capability plots are available in Appendix B. The plot for the TPS4H160-Q1 is shown in Figure 4-5:

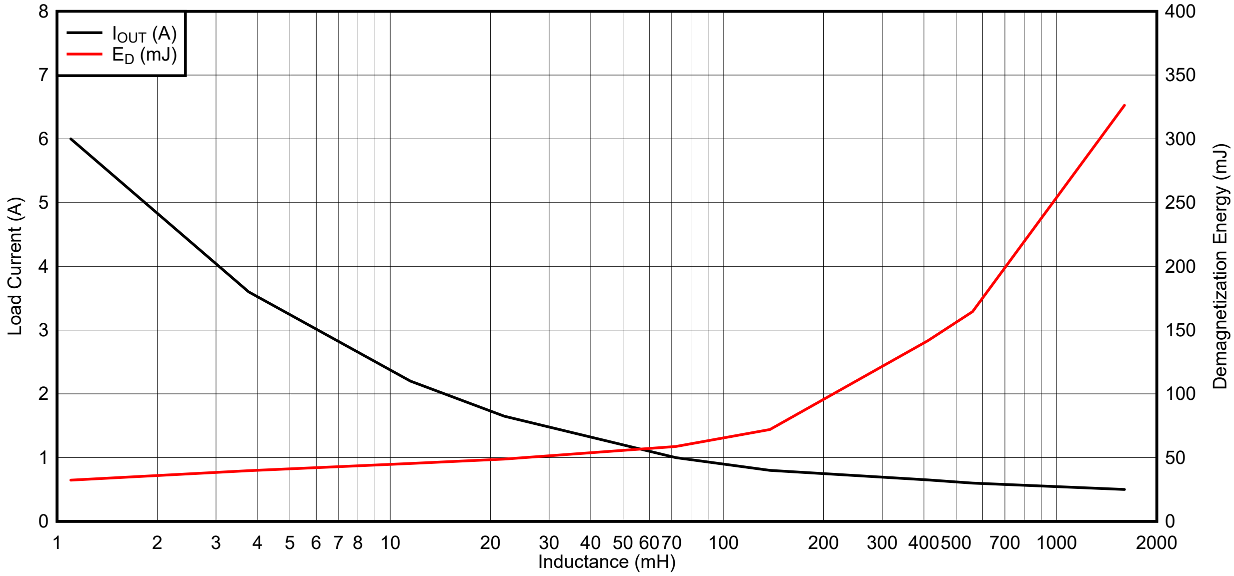

Figure 4-5. TPS4H160-Q1 Demagnetization Capability

To determine capability for the 205 mH described in Load 1, find 205 mH on the horizontal axis. Figure 4-5 shows that at 205 mH, the TPS4H160-Q1 can demagnetize 0.75 A and dissipate 90 mJ. The load calculations above gave a load current of 0.304 A and a dissipation of 15.76 mJ, so the TPS4H160-Q1 can safely demagnetize this load with significant margin.

Repeating these calculations for Load 2, which has 50 Ω resistance 48.4 mH inductance, we see a steady state current of 0.48 A and a calculated demagnetization energy of 9.29 mJ. Using Figure 4-5, we see that for 48.4 mH, TPS4H160-Q1 can demagnetize a maximum of 1.1 A and dissipate up to 55 mJ. Similar to Load 1, the device can comfortable demagnetize Load 2.

Looking at Load 3, we see that it has 7.5 Ω resistance and an inductance of 35 mH. This allows us to calculate the steady state current at 3.2 A and the demagnetization energy at 298.6 mJ. Looking at Figure 4-5, we see that for a 35 mH inductive load, the TPS4H160-Q1 can drive a maximum of 1.5 A and dissipate 50 mJ. This is lower than the calculated requirements, so the TPS4H160-Q1 cannot drive this load without an external TVS diode to clamp the inductive energy.

Note that even though the inductance for Load 3 is much lower than that of Load 1, the higher Load 3 current significantly increases the demagnetization energy that must be dissipated. This highlights the importance of knowing both the inductance and load current rather than just one or the other.

4.5.7 Measurements

To verify the calculations for Load 1, lab measurements were taken. With the Load 1 profile, the switch is turned off in Figure 4-6 to measure the demagnetization energy.

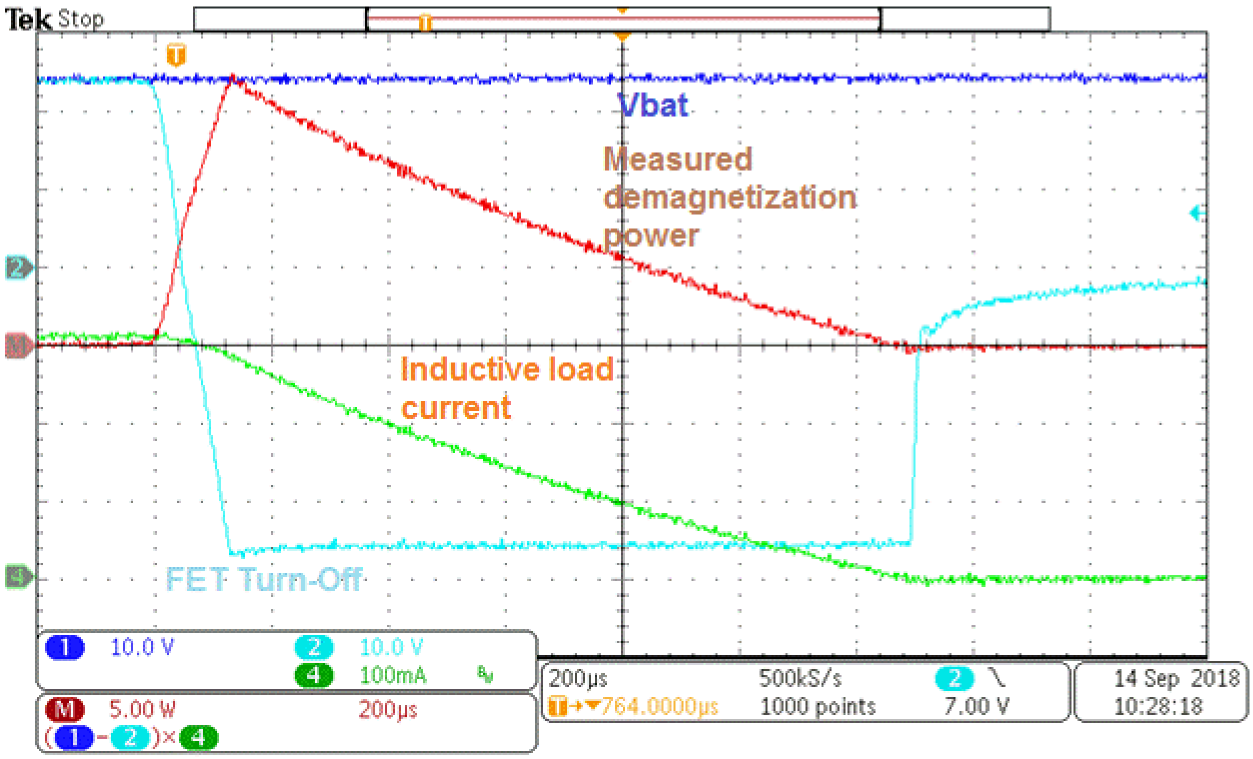

Figure 4-6. Load 1 Measured Demagnetization Energy

The peak power is 18 W and the demagnetization time T_{DEMAG} can be seen as 1.3 ms. The demagnetization energy is calculated in Equation 59.

$$E_D = \frac{1}{2} P_{PEAK} * T_{DEMAG} = \frac{1}{2} * 18\ W * 1.3\ ms = 11.7mJ \tag{59}$$

The calculated value is 15.67 mJ so the measured value is close but not exact due to variations in the inductance value and approximations in the equation derivations. It can be shown from this example that the TPS4H160-Q1 can safely demagnetize this load as shown in the calculations.

4.6 Selecting the Correct Smart High Side Switch

TI Smart High Side Switches have on-resistances that range from 4 mΩ to 1000 mΩ, giving a variety of options for different DC currents. Knowing the DC resistance and the DC current allows optimization of device selection. Once a switch has been chosen that is capable of driving the required DC current, refer to the device inductive demagnetization capability chart to ensure that it is capable of dissipating the required current for a given load profile.

Calculation of demagnetization energy is critical for selecting the right Smart High Side Switch. The calculated energy should be compared to the provided Smart High Side Switch plot that shows the maximum current or energy for a given inductance. If the demagnetization energy is within the Smart High Side Switch rated energy the part can be selected, however if the demagnetization energy is higher than the Smart High Side Switch rated energy either a more robust device must be selected or an external TVS must be used.

5 Driving LED Loads

5.1 Background

LEDs are finding an increasing use in automotive and industrial lighting applications replacing incandescent bulbs. Compared to traditional bulbs, LED lighting improves power efficiency while delivering a similar rated light output. Consequently, LEDs are now being used in headlamps, rear lighting, interior lighting, and indicator lighting. In these applications, Smart High Side Switches can be used to drive LED strings or to provide power to standalone LED driver modules. The Smart High Side Switch should be chosen based on the functionality needed, primarily considering protection, diagnostics, and load current requirements. The Smart High Side Switch must be able to drive the LED DC current load as well as manage the challenges posed by the input capacitance and parasitic resistance of lighting modules.

In this section we will discuss the various LED load driving application types. We will dive into the load characteristics and how they impact the choice of the appropriate Smart High Side Switch. Two important diagnostic features for LED loads will be highlighted: load current sensing and open load detection. These two features offer improved functionality to improve reliability and provide feedback to enable simpler system maintenance. We will also discuss the ability to set an adjustable low current limit threshold since LED loads typically have lower maximum DC current compared to other common load types. This adjustable current limit improves short circuit protection, protects against slow current creeping, and lowers the cost of cables and connectors. Finally, we will discuss how to use this information to select the appropriate Smart High Side Switch.

Note

Key Design Consideration: Enabling diagnostic features like open load detection, LED failure detection, and short circuit protection to improve system functionality.

5.2 Application Examples

A typical application that requires a Smart High Side Switch driving various types of LED lighting loads is shown in Figure 5-1. The LED loads fall into two broad categories:

1. LED Direct Drive
2. LED Module (with or without a separate MCU)

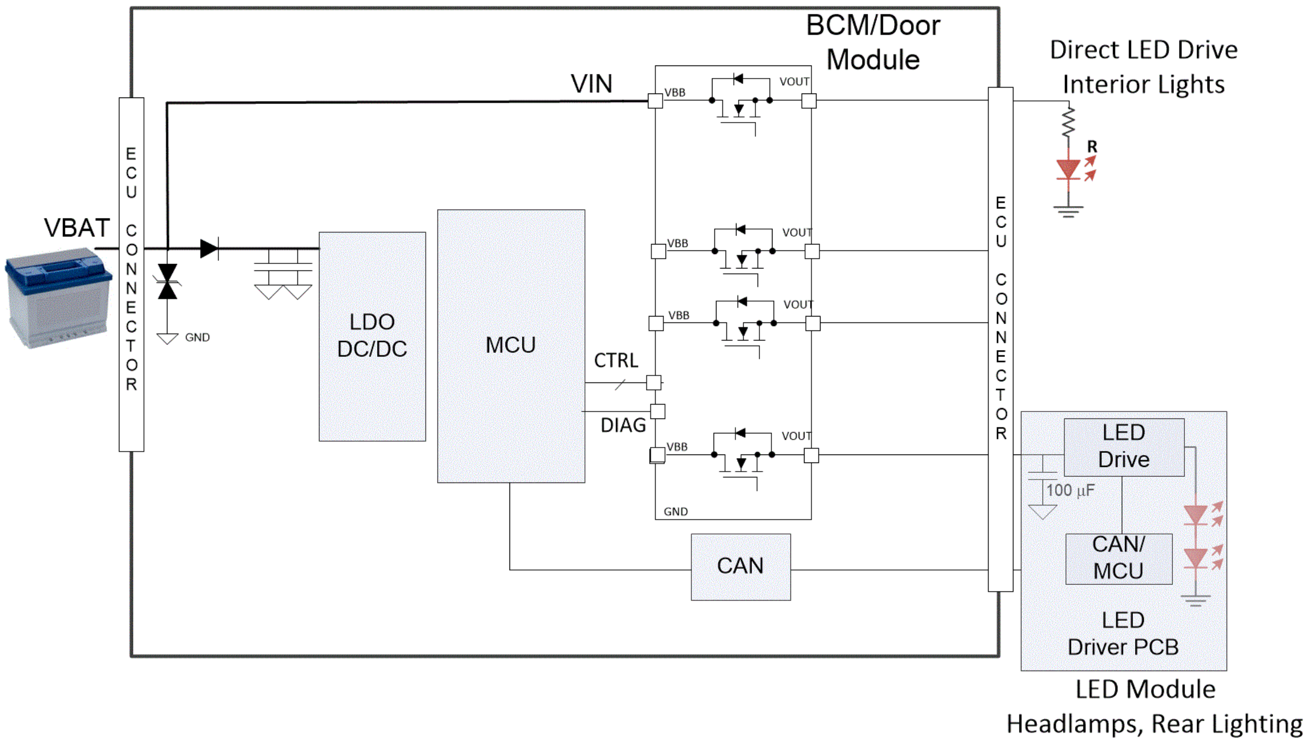

Figure 5-1. Application Examples of Smart High Side Switches Driving LED Loads

The direct LED drive offers a cheaper solution with less control while the LED module offers a constant current solution for a more accurate LED drive. Automotive systems are increasingly using LEDs to replace traditional bulbs, whether in head lights, interior lighting, or heads-up-displays. In industrial applications, LEDs are regularly used as indicators or lighting. The choice between direct LED driving or an LED module will depend on the specific application requirements. In either case the LED will require a Smart High Side Switch to provide power and diagnostic functionality.

5.3 LED Direct Drive

In this application the Smart High Side Switch directly drives the LED and a series resistor that sets the current in the LED string. The Smart High Side Switch provides a constant voltage source, but since the light output is dependent on the current in the LED string pulse width modulation of the switch can be employed to keep the current constant over varying supply voltages. A PWM frequency greater than 120 Hz is applied to the Smart High Side Switch input to vary the duty cycle of switching and modulate the LED current. The choice of Smart High Side Switch is driven primarily by the power dissipation in the switch that occurs while driving the LED current. For directly driving LEDs the primary design factor is the R_{ON} of the switch. Ensure that the R_{ON} of the switch is low enough that the Smart High Side Switch will not have issues dissipating the power caused by your DC LED current. Single channel or multi-channel devices can be used depending on the total power dissipation in the switch and the heat dissipation of the PCB.

5.4 LED Modules

Smart High Side Switches are often used in a central module to control the battery input current flow into a LED driver module as shown in Figure 5-1. In each case, the current in each of the LED strings or arrays is controlled by the LED lighting module rather than directly from the Smart High Side Switch. In the simplest case, there is no additional MCU in the LED module and the LEDs are either discrete ON/OFF only or are controlled through a separate PWM signal. In more sophisticated modules the central module can communicate the light pattern and intensity over protocols like CAN or LIN.

LED modules typically include switching DC/DC converters that convert the input battery voltage into a controlled source. In most cases there will be significant input capacitance (of the order of 100 µF-300 µF) at the input to the switching converter. In order to choose the right Smart High Side Switch and its configuration when driving

LED modules with large capacitance please refer to the capacitive load driving section of this document in Section 3.

5.5 Why Use a Smart High Side Switch?

TI Smart High Side Switches can be used to provide power to LED modules by either directly driving LEDs or by driving LED modules. The use of multiple Smart High Side Switches in a control module to power multiple LED modules is shown in Figure 5-2.

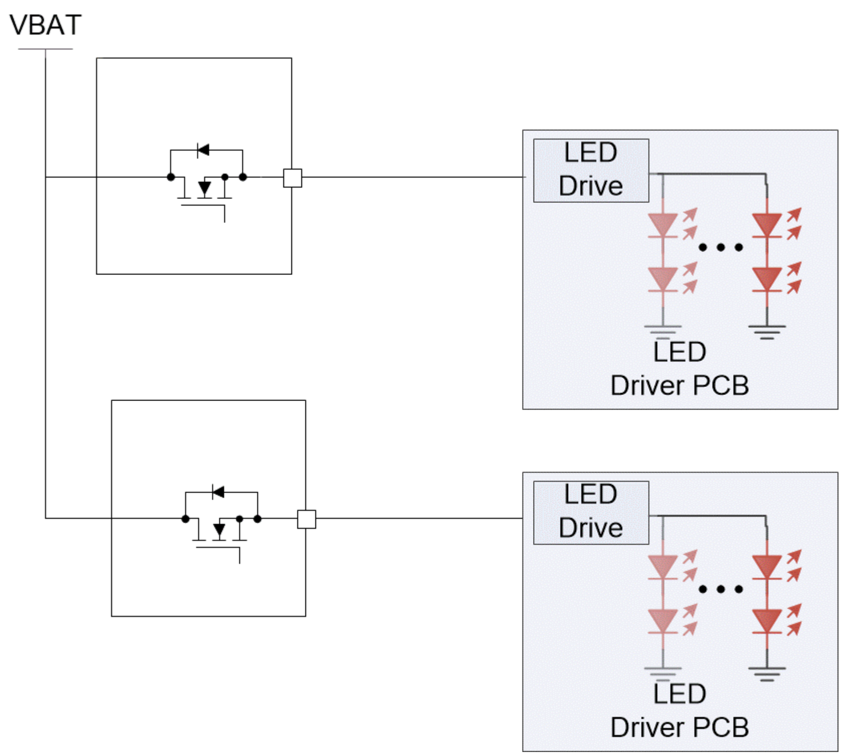

Figure 5-2. Smart High Side Switches Powering LED Modules

The Smart High Side Switch in the control module serves three primary functions:

1. Provide diagnostic features like open load detection
2. Enable LED failure recognition through load current sensing
3. Serve as a constant current source for direct drive LED's

The diagnostics are especially important in modules without an MCU and where no information on the status of the lights can be obtained from the LED lighting ECUs.

5.6 Open Load Detection

As systems become more intelligent it is important to have robust diagnostic features. One common issue is open loads created by wire breaks, mis-wiring, or open circuit failures. It is desirable that systems would be able to independently diagnose these failures and report the issue back to a microcontroller. TI Smart High Side Switches enable open load detection and reporting both when the switch is turned on and off. Open load detection, including external circuitry, is shown in Figure 5-3.

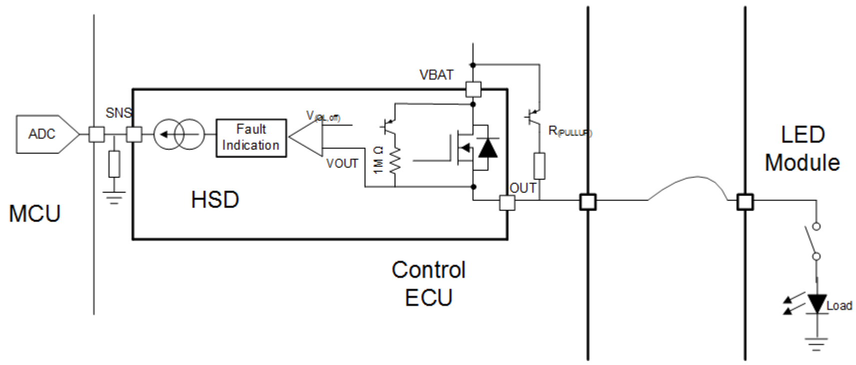

Figure 5-3. Open Load Detection Schematic

Open load detection requires a pull-up resistance from the output to the battery. This pull-up resistance can be either external or integrated into the Smart High Side Switch. This large pull-up means that when a load is attached it will pull the switch output close to 0 V, but when no load is attached the output will be pulled close to the supply voltage. The Smart High Side Switch then measures the output voltage and reports an open load if it measures a voltage close to the supply.

When the switch is turned on, the internal Smart High Side Switch current sense diagnostic will notify on open load condition as the output current will go to zero. TI devices have very high current sense accuracy at the low currents. This accuracy can range down to a few milliamps of current accuracy so the current drop out can be easily measured. Some TI devices like TPS1H200-Q1 and TPS1H000-Q1 do not provide an analog sense current output; instead they will trigger a FAULT signal when the current falls below the open load detection threshold.

When the switch is turned off the devices will still detect for open load and report out through a FAULT signal or the current sense output. One disadvantage of open load detection is that the pull-up resistor adds a current path that will put a small amount of current through the LEDs even when the switch is turned off which can sometimes cause a dim LED glow.

5.7 Load Current Sensing

Open load detection can determine if there is a broken wire or faulty module, however it cannot determine a partial failure. In many applications LEDs are configured as multiple strings in parallel as shown in Figure 5-2. In this case it is important to know if any of the LED strings in the array are non-functional even if the remainder of the strings continue to work. TI Smart High Side Switches can determine this by using an accurate load current measurement to sense an absolute change in output current that comes with a partial open that is caused by a string failure. This information can then be used to communicate a partial failure to a MCU.

For example, consider the case of driving a parallel array of six LED strings with each string drawing a current of 50 mA. In order to recognize the open failure of one of the six parallel strings, the load current has to be sensed within ±16% accuracy. For best practices this means an accuracy within ±10%, however the system can be assumed to have an additional ±5-6% variability in common LED string current draw, ADC digitization, and other parasitic elements. This means that the Smart High Side Switch current measurement must be accurate within ±3-4% in the load current range. The current sense accuracy of devices like the TPS2H160-Q1 and the TPS2H000-Q1 match this requirement and are capable of providing an absolute current measurement with enough accuracy to diagnose a single LED string failure. Table 5-1 shows the two parts and their current sense accuracy for the given load current.

Table 5-1. Maximum Current Sense Accuracy at Typical Multi-String Array Load Currents

Device	Load Current	Current Sense Accuracy
TPS2H160-Q1	300 mA	±4%
TPS2H000-Q1	60 mA	±3%

Load current sensing enables increased diagnostic abilities by giving a designer the ability to ensure that the entire LED array is functional rather than just parts of it. This in turn improves overall system reliability and helps for predictive maintenance.

5.8 Constant Current Source

For the best LED performance it is best to use a constant current source, however often in systems with no LED drive module the only source available is a constant voltage source. Using a TI Smart High Side Switch a designer is able to create a constant current drive mode by forcing the device into current limit regulation mode. The current limiting feature is discussed more in depth in the capacitive driving section of this document in Section 3 as well as in the *Adjustable Current Limit of Smart High Side Switches* application note. The current limit threshold is set by an external resistor from the CL pin and should be chosen as equal to nominal LED current. Doing this ensures that the Smart High Side Switch will regulate the input voltage to provide a constant current source as long as the supply is capable of providing the power required. Figure 5-4 shows a switch in constant voltage mode on the left and a switch in constant current mode on the right.

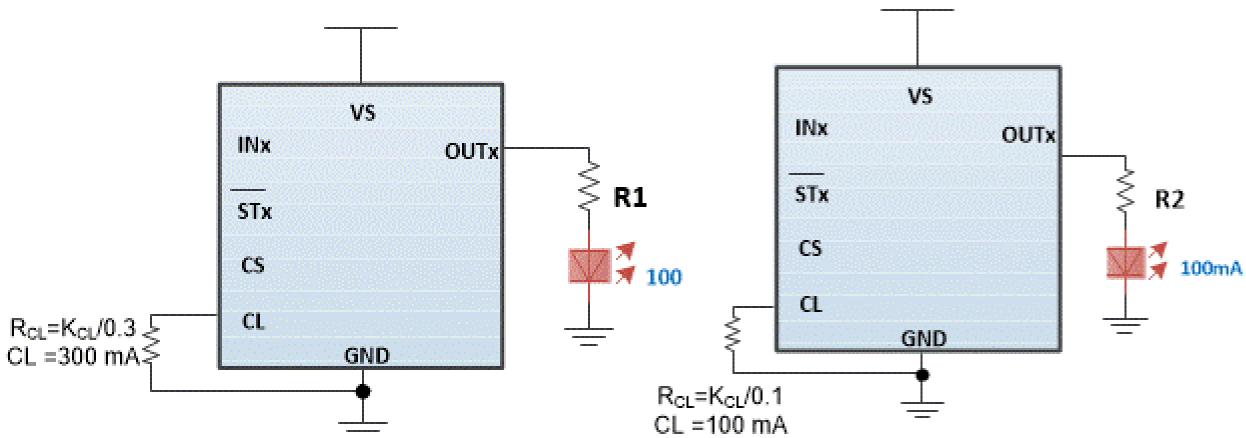

Figure 5-4. Driving LED in Constant Output Voltage and Constant Current Mode

On the left, the LED is nominally operated at 100 mA, but because it is regulated by the resistor that current will increase with an increasing supply voltage. On the right, if the supply voltage increases the switch will increase its resistance to maintain a 100 mA output current.

To operate the switch in constant current mode it must be ensured that the switch has enough room to regulate the source. For example, if the LED string consists of five LED's each with a 0.7-V drop and require 100-mA current (typical for a LED automotive interior light) then the total voltage over the string will be 3.5 V. If the minimum supply is 8 V then the resistor R2 should be chosen so that the supply can always supply 100 mA. In this case if R2 is less than 45 ohm then even at the minimum input supply voltage the LED string will still maintain 100 mA. When the supply is nominally at its value of 13.5 V the switch and the resistor will dissipate more heat to regulate the current flow as calculated in Equation 60. In this case the total DC dissipation should not cause thermal issues so the LEDs will be driven by the Smart High Side Switch creating a constant current source.

$$P_R = I_{LED}^2 * R = (100\ mA)^2 * 45\ \Omega = 450\ \text{mW} \tag{60}$$

$$P_{SWITCH} = I_{LED} * V_{DS} = I_{LED} * (V_S - V_R - V_{LED}) = (100\ mA) * (13.5\ V - 4.5\ V - 3.5\ V) = 550\ mW \tag{61}$$

5.8.1 Selecting the Correct Smart High Side Switch

With LED loads and modules increasingly finding use in automotive and industrial applications, TI Smart High Side Switches are well suited to meet the needs for driving LED loads with reliable diagnostics. Table 5-2 shows a few of the key design parameters that must be considered when selecting a Smart High Side Switch to drive an LED load:

Table 5-2. Smart High Side Switch Design Considerations

Design Parameter	Design Consideration
On Resistance (R_{ON})	Low enough R_{ON} to limit the total power dissipation to meet the PCB thermal requirements.
Current Limit (I_{LIM})	I_{LIM} above the DC load current. In case LED modules with input capacitance, choose I_{LIM} to match the charging time requirements.

Table 5-2. Smart High Side Switch Design Considerations (continued)

Design Parameter	Design Consideration
Current Sense Accuracy	Current Sense Accuracy that meets requirements within the load current range.

With proper design, a Smart High Side Switch can provide diagnostics and reliable protection for LED loads. TI offers a wide variety of switches with different on-resistances and diagnostic features to meet the requirements for any LED driving application.

6 Appendix

6.1 Transient Thermal Impedance Data

The following figures model transient junction-to-ambient resistance ($R_{j\Theta A}$) for each device in Table 3-1. Figures for multi-channel devices assume uniformly distributed power in each channel that is ON and include effects of mutual self-heating between channels

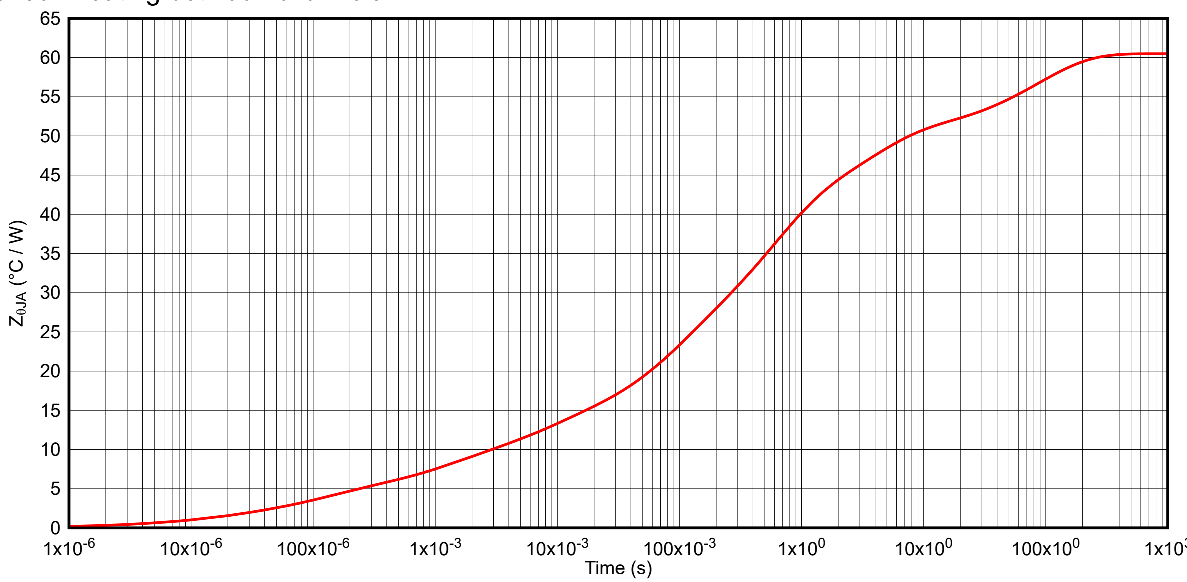

Figure 6-1. TPS1H000-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

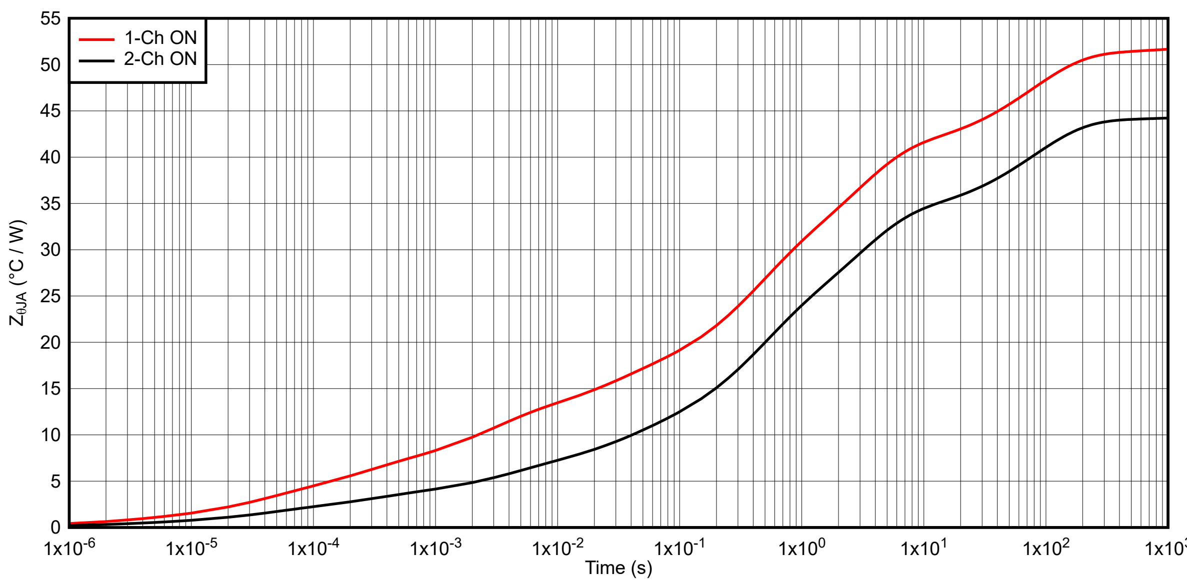

Figure 6-2. TPS2H000-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

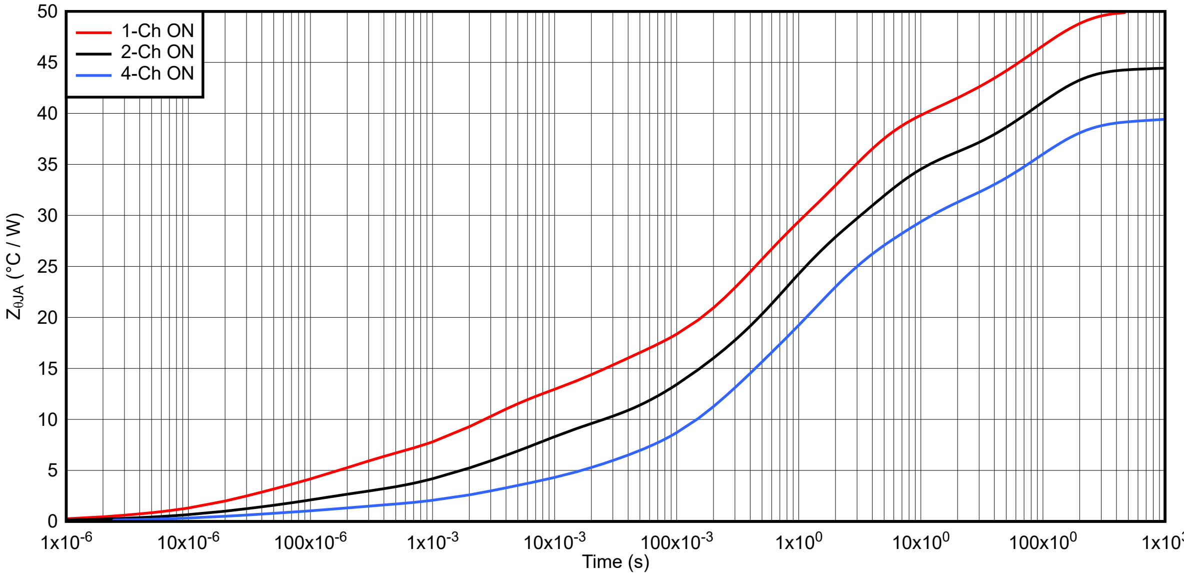

Figure 6-3. TPS4H000-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

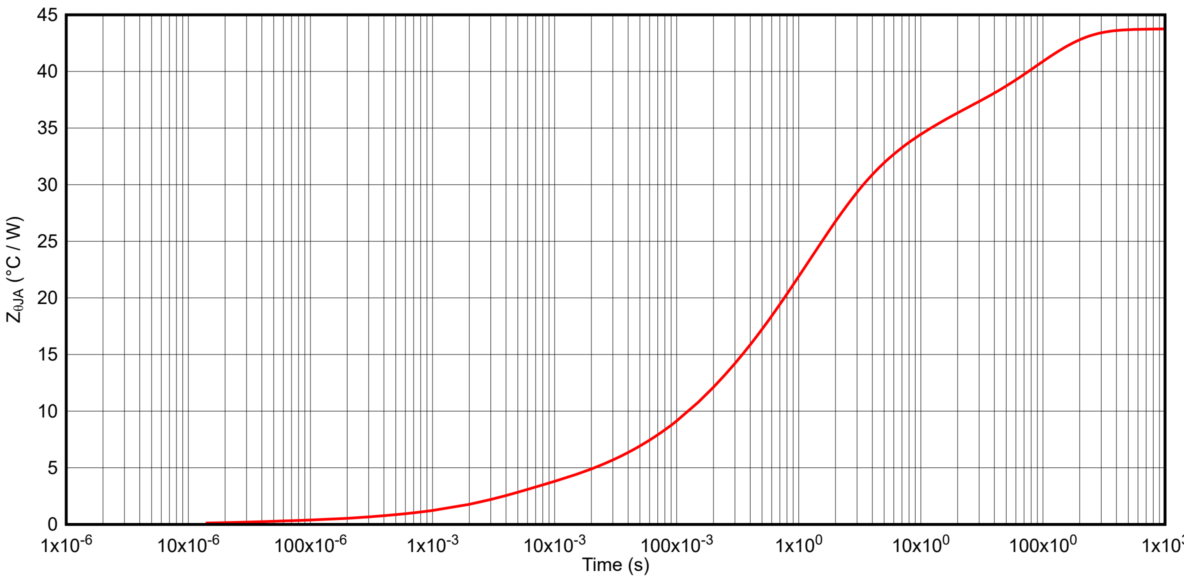

Figure 6-4. TPS1H100-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

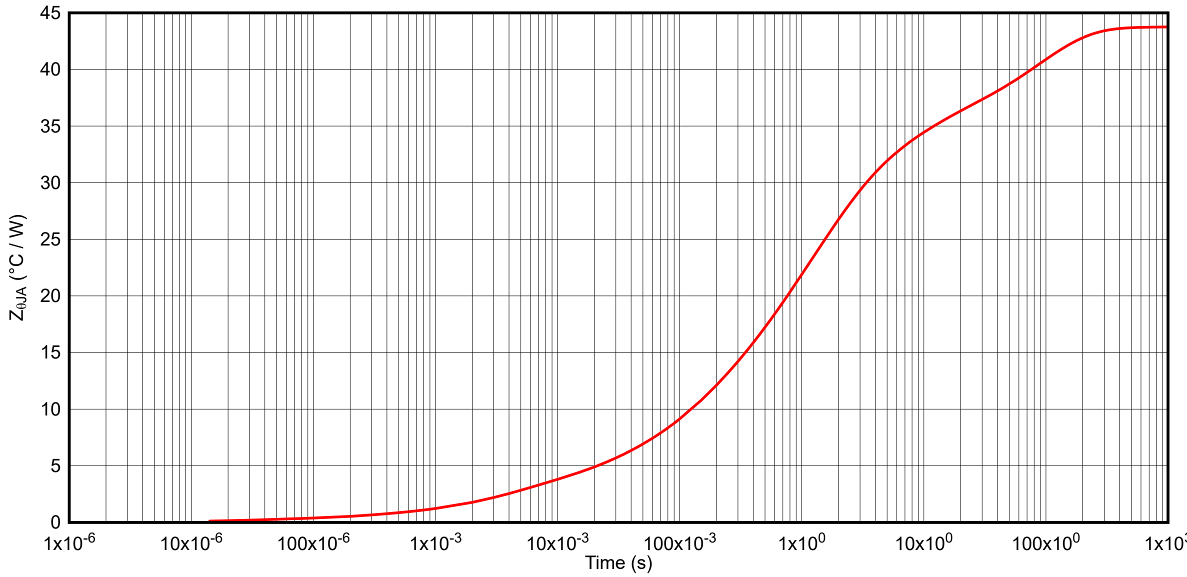

Figure 6-5. TPS1H200-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

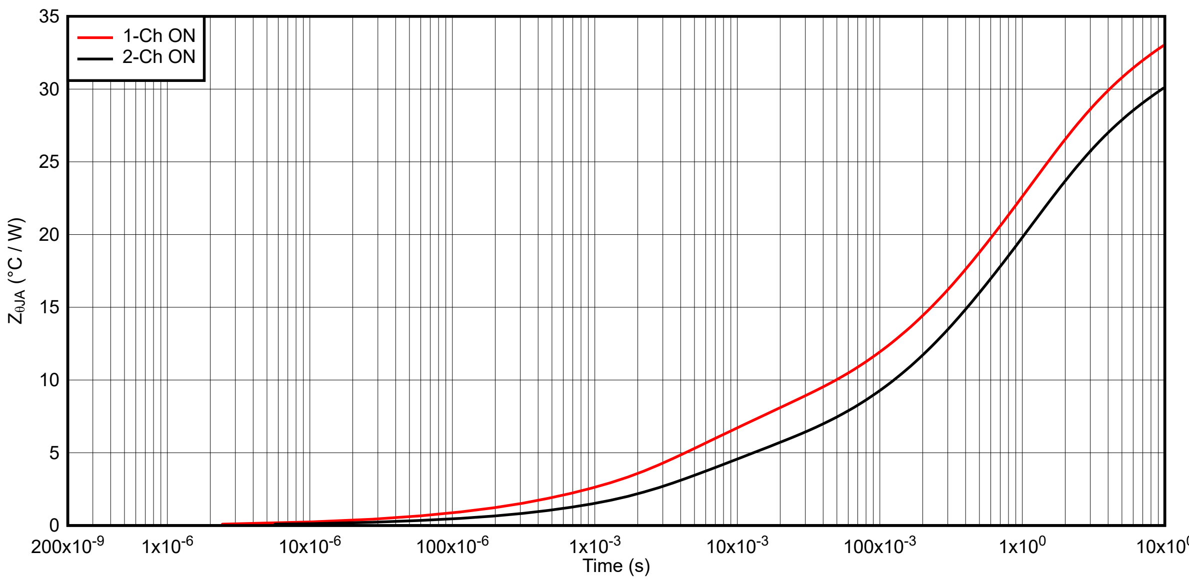

Figure 6-6. TPS2H160-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

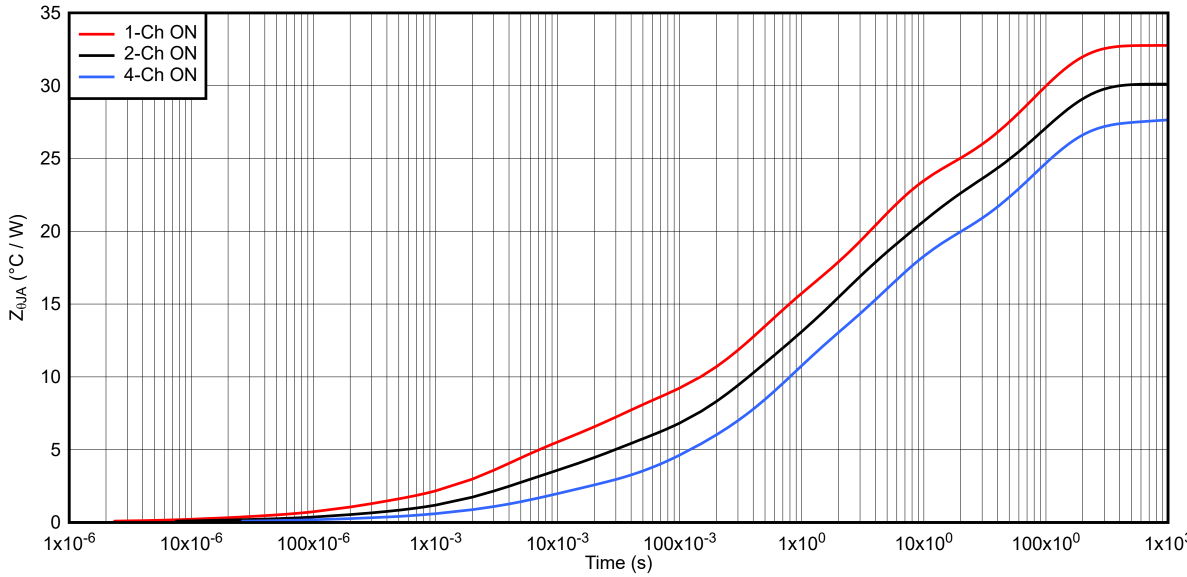

Figure 6-7. TPS4H160-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

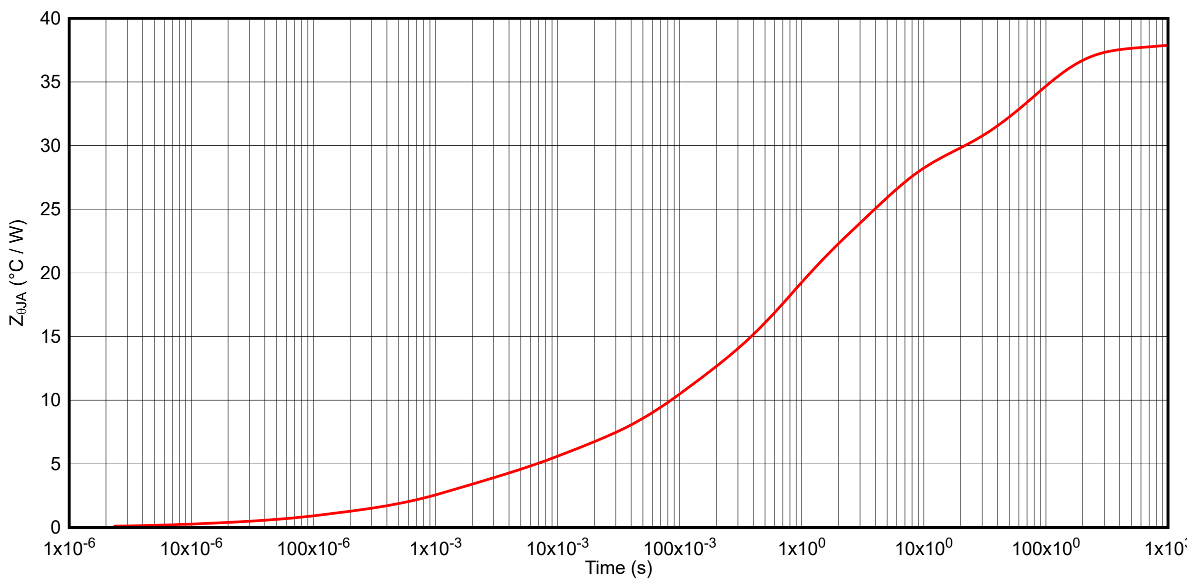

Figure 6-8. TPS1HB50-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

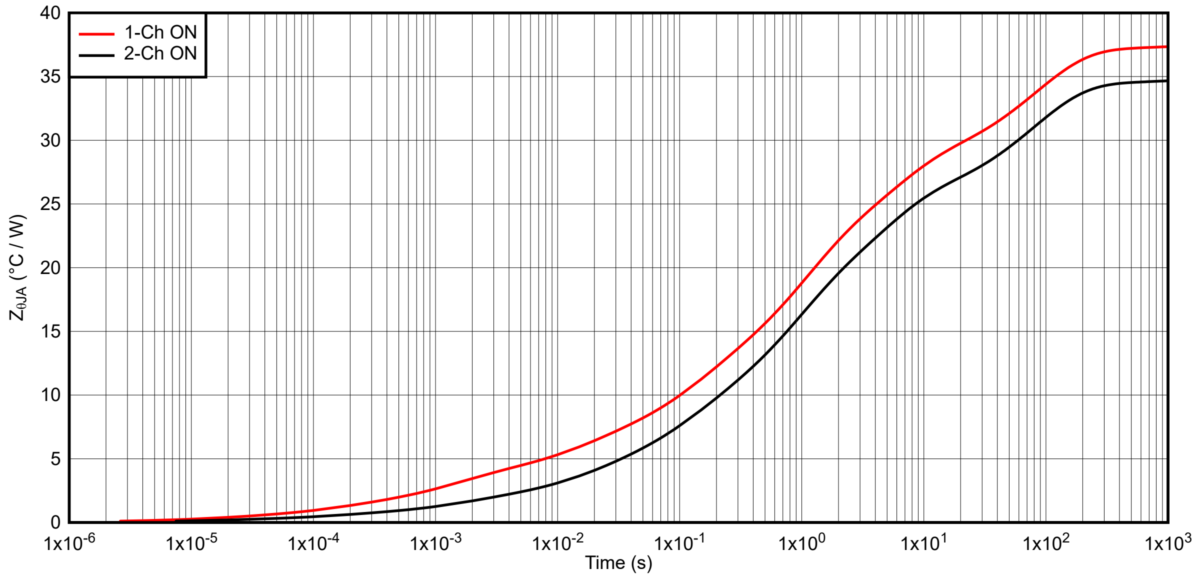

Figure 6-9. TPS2HB50-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

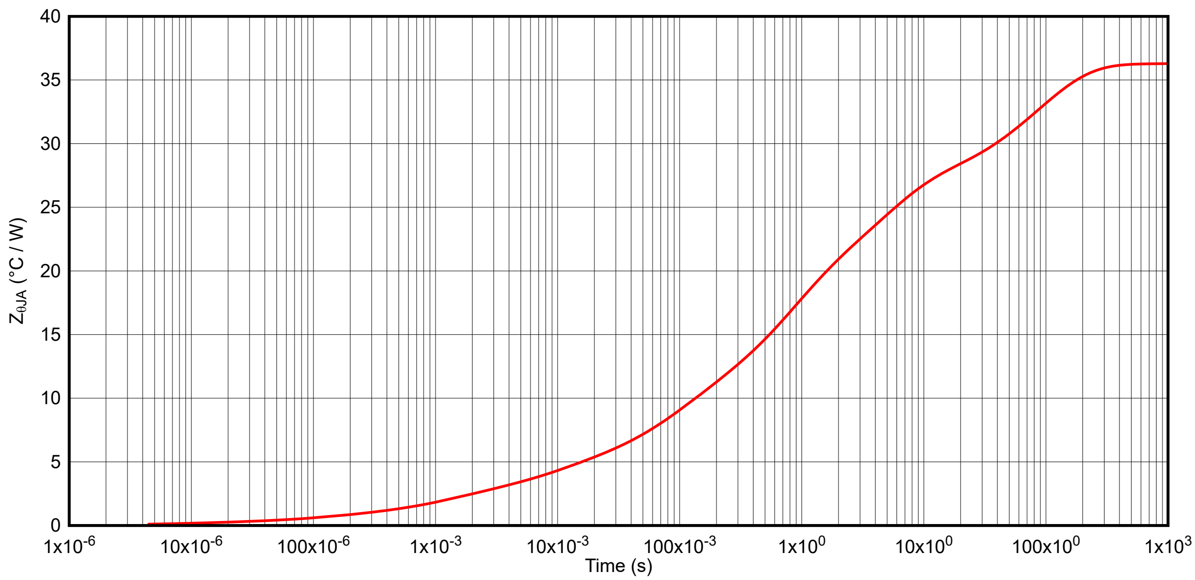

Figure 6-10. TPS1HB35-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

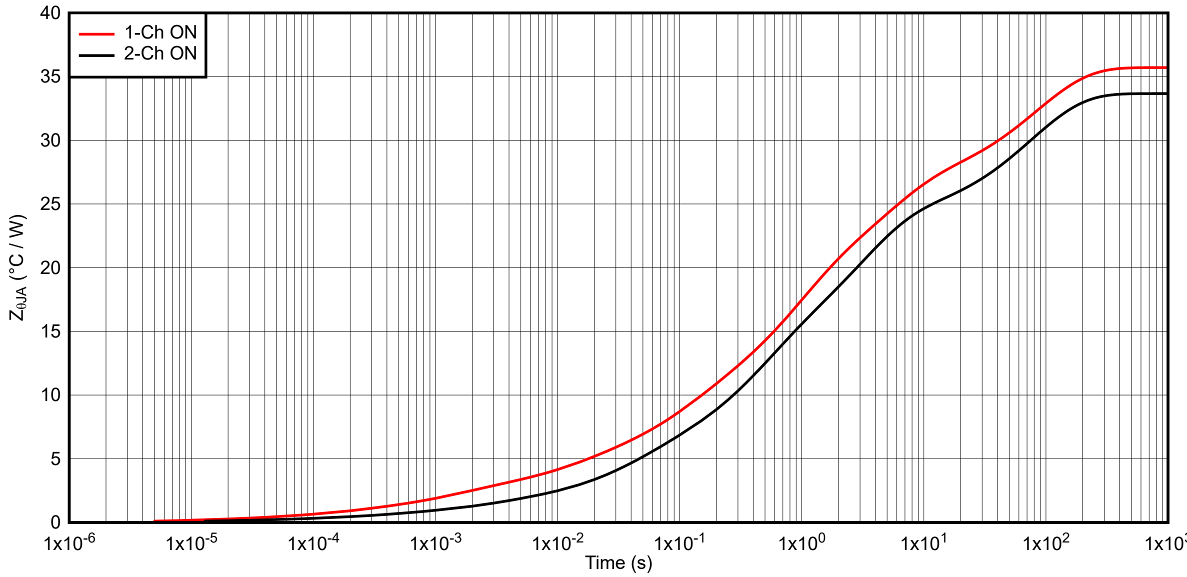

Figure 6-11. TPS2HB35-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

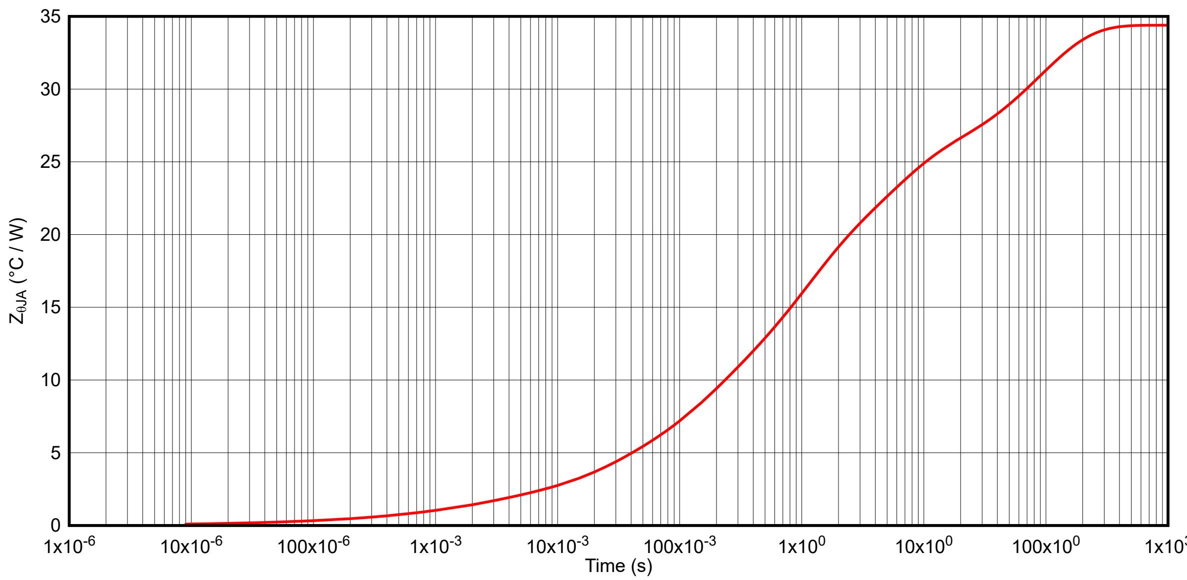

Figure 6-12. TPS1HB16-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

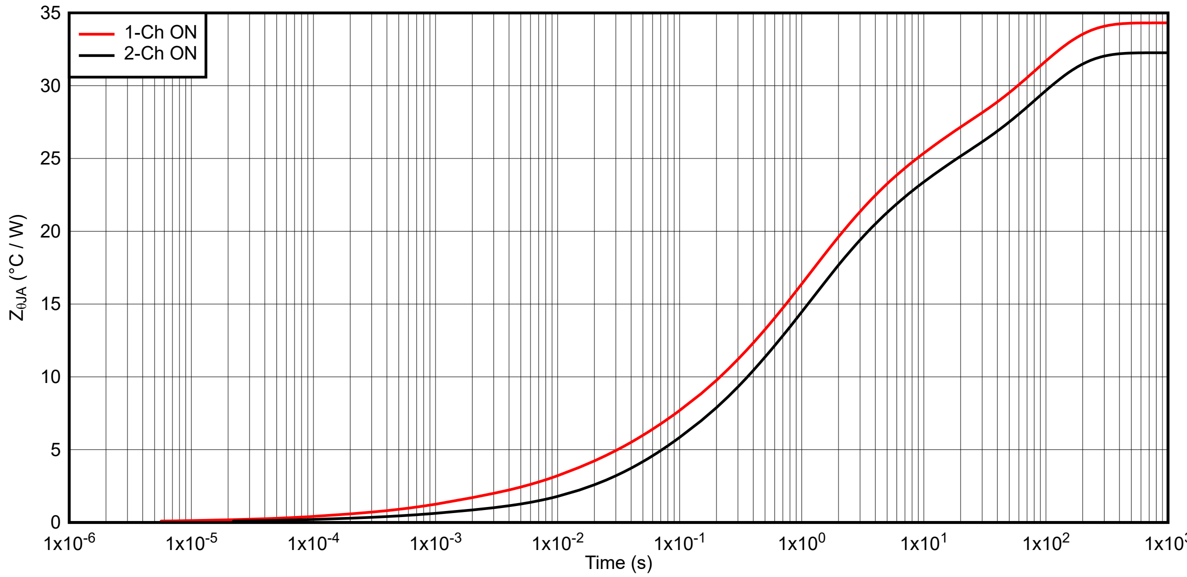

Figure 6-13. TPS2HB16-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

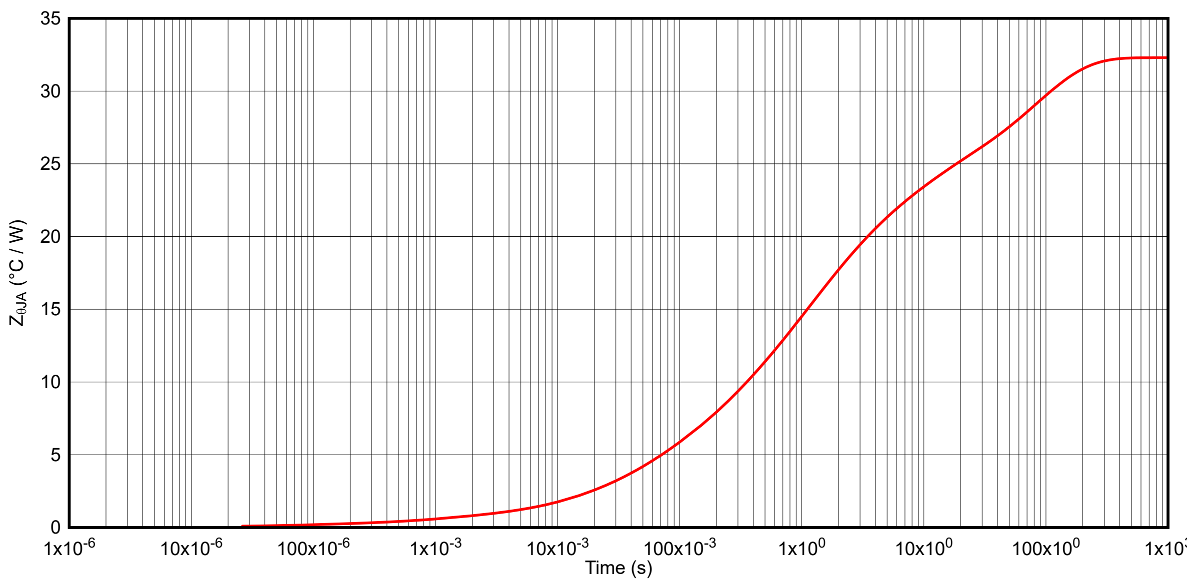

Figure 6-14. TPS1HA08-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

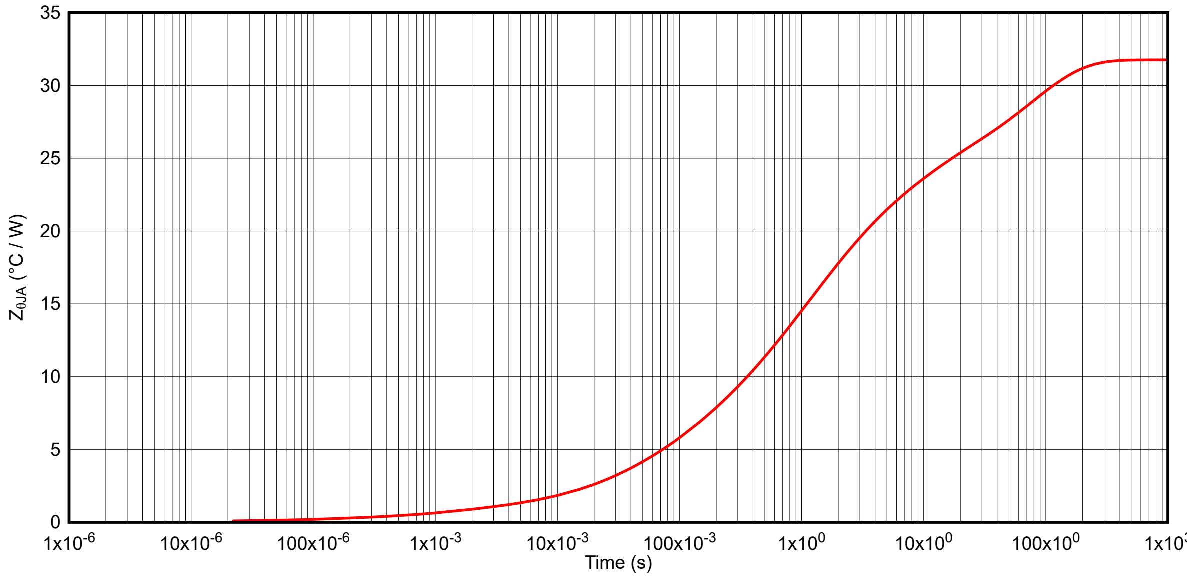

Figure 6-15. TPS1HB08-Q1 Transient Thermal Impedance $Z_{\Theta JA}$

6.2 Demagnitization Energy Capability Data

The following figures depict the demagnetization energy capability for multiple TI Smart High Side Switches.

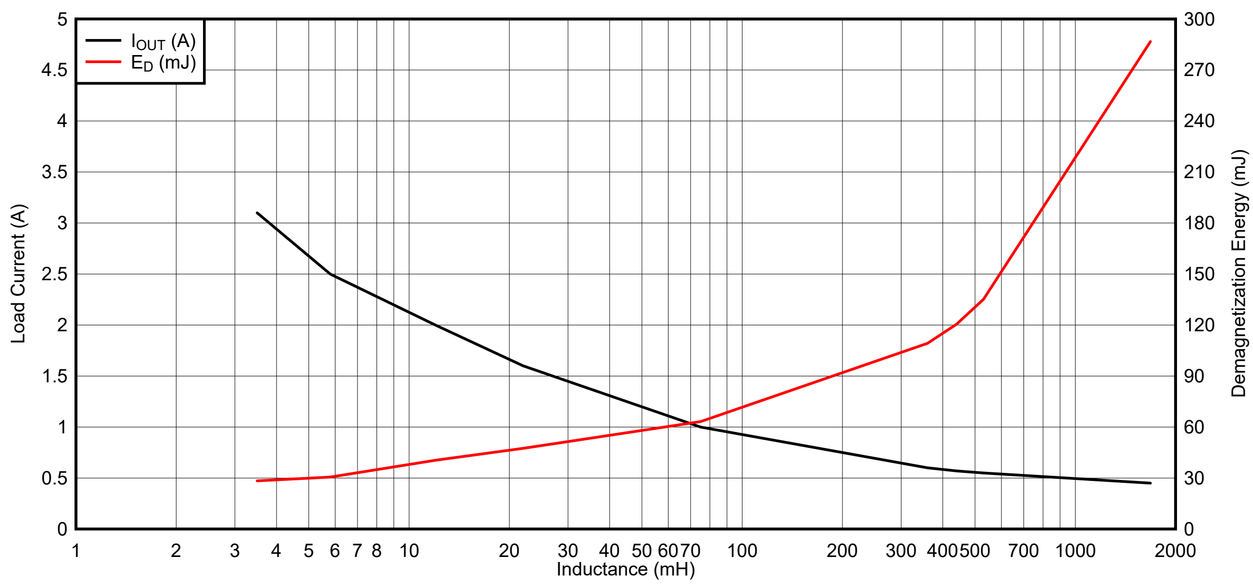

Figure 6-16. TPS1H200-Q1 Demagnetization Energy Capability

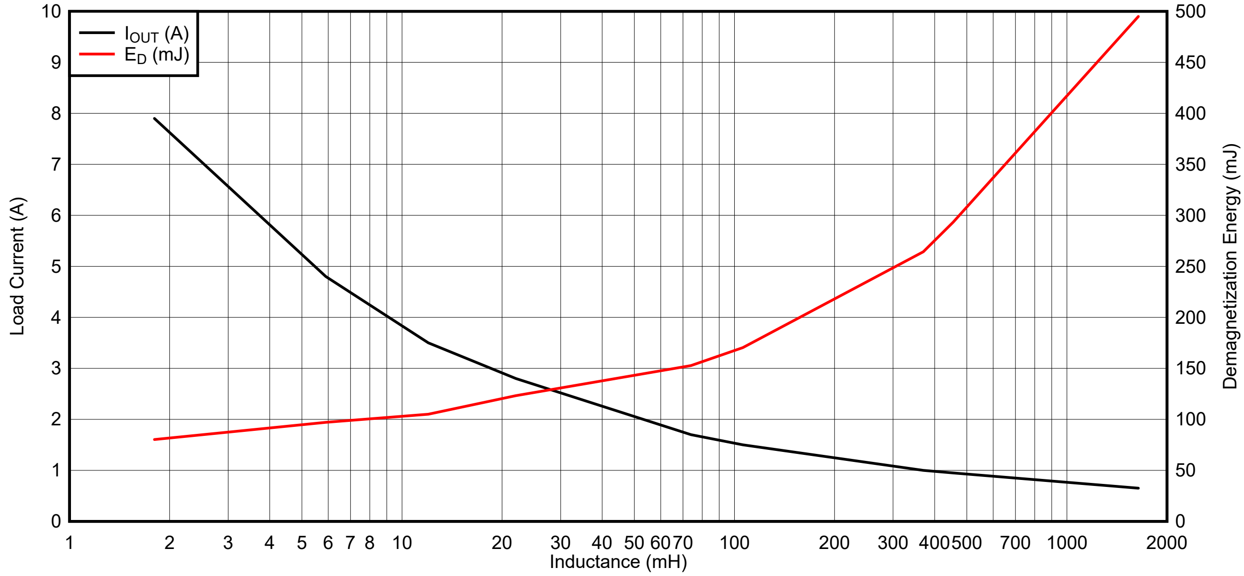

Figure 6-17. TPS1HA08-Q1 Demagnetization Energy Capability

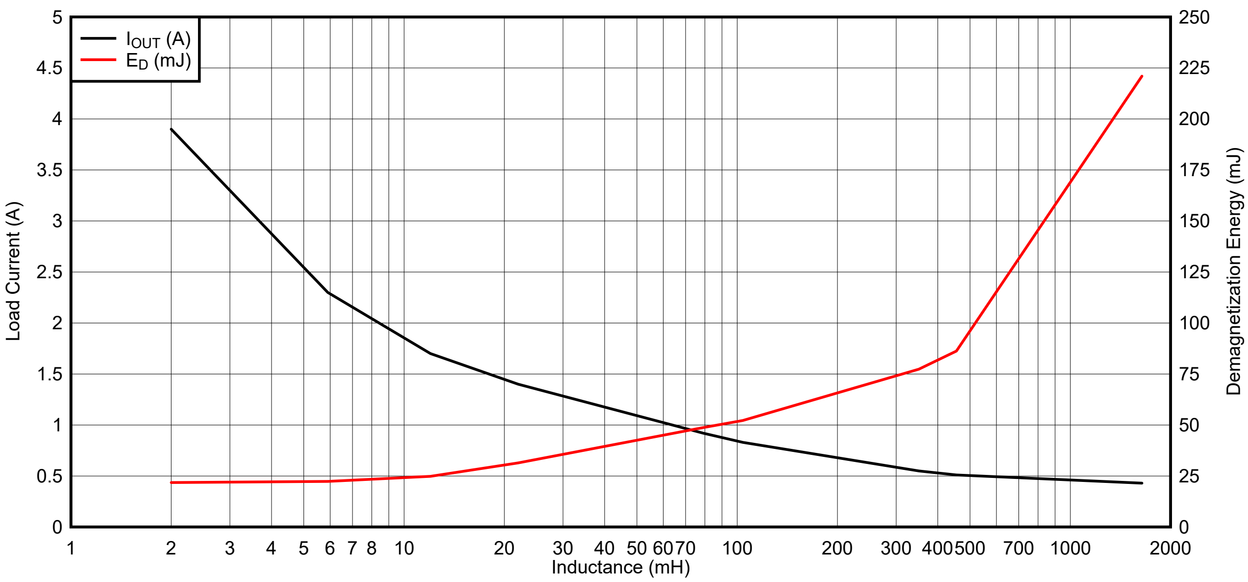

Figure 6-18. TPS2HB50-Q1 Demagnetization Energy Capability

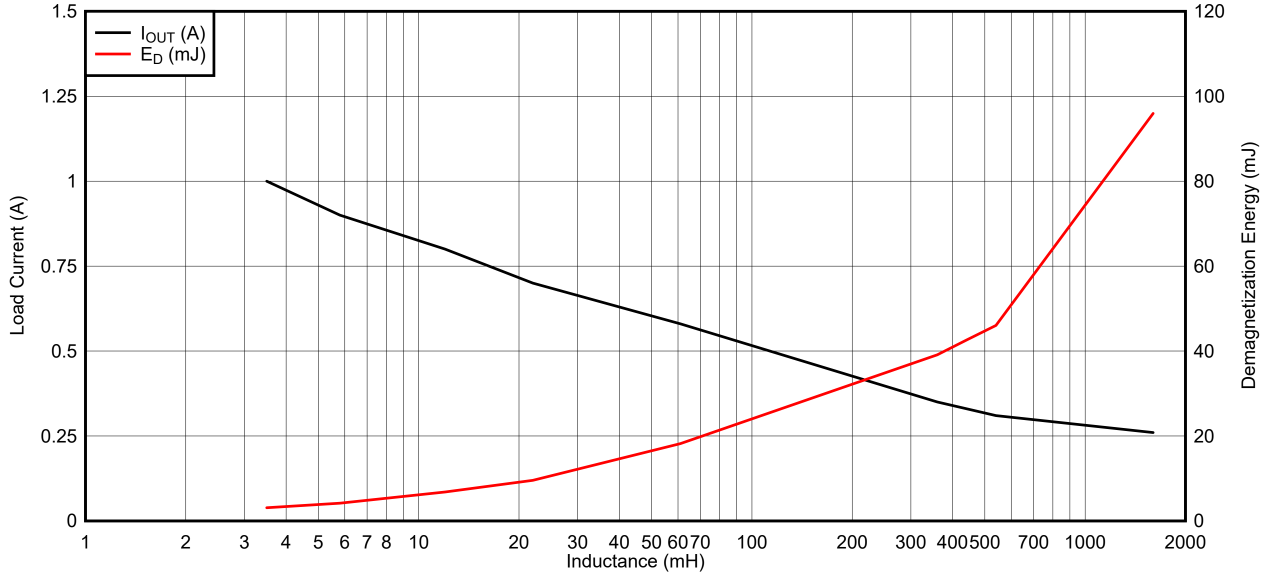

Figure 6-19. TPS4H000-Q1 Demagnetization Energy Capability

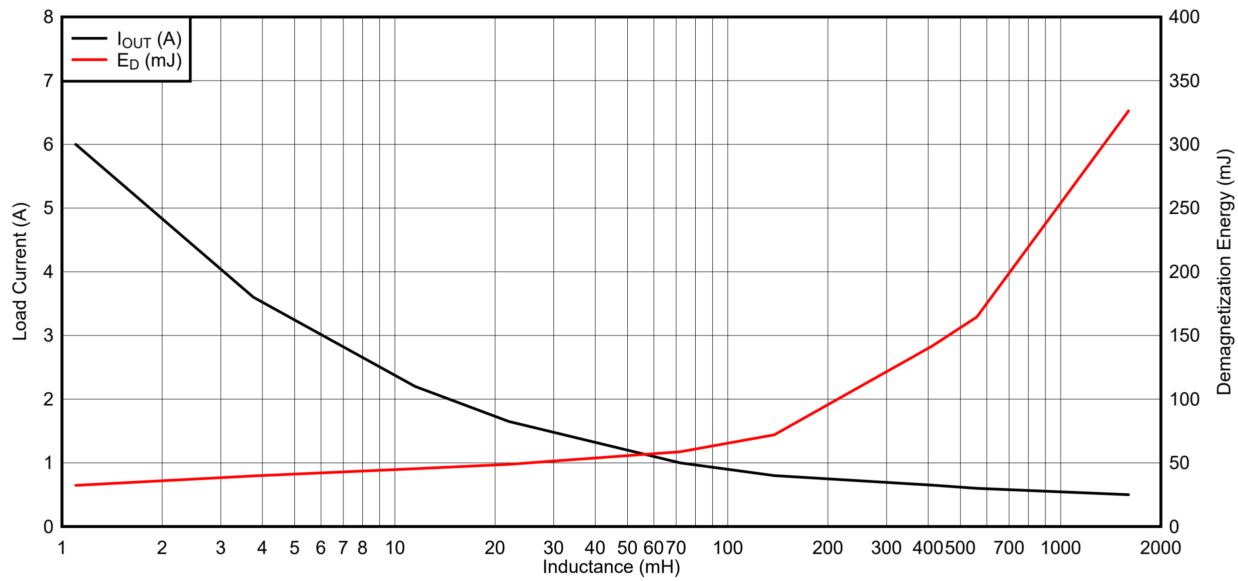

Figure 6-20. TPS4H160-Q1 Demagnetization Energy Capability

7 References

For more information on TI Smart High Side Switches, reference the following documents:

1. Texas Instruments, *Adjustable Current Limit of Smart High Side Switches App Note*
2. Texas Instruments, *High-Side Switches Paralleling Channels App Note*
3. Texas Instruments, *Basics of Power Switches App Note*
4. Texas Instruments, *Short-Circuit Reliability Test for Smart High Side Switches App Note*
5. Texas Instruments, *TPS2H160-Q1 Product Folder*
6. Texas Instruments, *TPS1H100-Q1 Product Folder*

8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision D (February 2021) to Revision E (March 2021) — **Page**

- Deleted *TPS2HB50-Q1 Demagnetization Energy Capability* image........ 42

Changes from Revision C (December 2020) to Revision D (February 2021) — **Page**

- Added *Junction Temperature During Capacitive Inrush* section........ 17
- Added *Transient Thermal Impedance Data* section........ 42

Changes from Revision B (August 2020) to Revision C (December 2020) — **Page**

- Updated capacitive load calculations........ 11

Changes from Revision A (April 2019) to Revision B (August 2020) — **Page**

- Added demagnetization energy plots to appendix section........ 42
- Added demagnetization energy plots to appendix section........ 49