Industrial Smart High Side Switches
Driving, Protecting, and Diagnosing Loads

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APP-PSIL-PS
Power Switches | Use Cases

Common Design Challenges

Input Power Protection
- Reverse current blocking
- Current limiting
- Overvoltage protection
- Inrush current control
- Surge immunity
- Reverse Polarity Protection

Power Distribution
- Power Sequencing
- Inrush current control
- Power Muxing/Powering Oring

Output Power Protection
- Current limiting
- Inductive load driving

Learn more at: Products → Power Management → Power Switches → Power Switches portal Page
Agenda

• What is a Smart High Side Switch?

• Where do I use a Smart High Side Switch?

• Applications of a Smart high-side switch
  – Capacitive/Inductive Load Driving
  – Short Circuit/Overload Protection
  – Diagnostics

• Smart high-side switch vs. low-side switch
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• Smart high-side switch vs. low-side switch
What is a smart high side switch?

- A smart high-side switch is a power management device that connects to a power supply input and switches on/off downstream loads, protects against faults, and provides output diagnostics.

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Device</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 100mA</td>
<td>TPS4H000</td>
<td>4-CH, 40V, 1Ω, TSSOP</td>
</tr>
<tr>
<td>≤ 500mA</td>
<td>TPS1H200</td>
<td>1-CH, 40V, 200mΩ, TSSOP</td>
</tr>
<tr>
<td>≤ 750mA</td>
<td>TPS4H160</td>
<td>4-CH, 40V, 160mΩ, TSSOP</td>
</tr>
<tr>
<td></td>
<td>TPS27S100</td>
<td>1-CH, 40V, 100mΩ, TSSOP</td>
</tr>
<tr>
<td>≤ 2A</td>
<td>TPS27S100</td>
<td>1-CH, 40V, 100mΩ, TSSOP</td>
</tr>
</tbody>
</table>

Learn More: 11 Ways to Protect Your Power Path
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Where do we use a smart high side switch?

- Smart high side switches are ON/OFF switches that sit on the high-side of the load.

- Smart high side switches are used anywhere where output power protection is required.

- Any system powering an off-board load runs the risk of a load failure that the primary board cannot control:
  - Short-Circuit
  - Load Current Overload
  - Inductive Kickback
  - Inrush current
Where are **Smart high side switches** used?

- **Factory Automation and Control**: Digital outputs provide power to sensors, motors, and valves throughout the factory floor.

- **Motor Drives**: Brakes, sensors, and general purpose I/O’s communicate between the motor drive and the motor.

- **Building Automation**: Centralized building control systems distribute power to subsystems like fire, alarm, and HVAC systems.

- **Communication Infrastructure**: Distributed 5G antennae arrays must be powered from the substation supply.

**Distributed Power Outputs**
Agenda

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• Applications of a Smart high-side switch
  – Capacitive/Inductive Load Driving
  – Short Circuit/ Current Limiting Protection
  – Diagnostics

• Smart high-side switch vs. low-side switch
Smart High side switch | Applications

Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

Short Circuit and current limiting protection improves system reliability and reduces system costs

Integrated current sense and open-load detection enables the detection and diagnosis of faults
Smart High side switch | Applications

Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

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Integrated current sense and open-load detection enables the detection and diagnosis of faults
As the current flows through the inductor, energy is stored in it according to
\[ E = \frac{1}{2}LI^2 \]

When the high-side switch opens, the current through the inductive load jumps from I to 0A

An inductor wants to resist the change in current so a large negative voltage transient appears at the output of the switch according to the below equation

\[ V = -L \times \frac{dI}{dt} \]

**What is the high-side switch’s role in driving inductive loads?**

- TI’s smart high-side switches have an integrated VDS clamp which clamps the negative voltage swing to a safe level to prevent damage to its output.
- Depending on the load, it also helps to dissipate the energy stored in the inductive element by turning on its MOSFET and dissipating the energy through it.

**Inductive Load Examples**

- Long Cables
- Solenoids
- Relays
- Electric Motors
Large bulk capacitors are often used to stabilize the voltage at the input of modules which can be as high as 5 mF.
Inrush current is the transient current drawn by load capacitance of a system when first turned on. If the inrush current is high, the power supply voltage may droop and components can be damaged.

Typical high side switches set the current limit high to avoid limiting during inrush, however this does not provide protection against inrush current.
TI Smart High Side Switches enable systems to limit the inrush current through the adjustable current limit $I_{\text{LIM}}$.

**Advantages:**
- **High Reliability** – protects power supply during short circuit or inrush current, prevents upstream supply collapse
- **Lower System Costs** – Reduces the PCB trace and connector size as well as reduces the input power supply

### Table:

<table>
<thead>
<tr>
<th>On Resistance</th>
<th>Maximum DC Current</th>
<th>Typical Fixed $I_{\text{LIM}}$</th>
<th>TI Adjustable $I_{\text{LIM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 mΩ</td>
<td>12 A</td>
<td>90 A</td>
<td>Down to 6.4 A</td>
</tr>
<tr>
<td>16 mΩ</td>
<td>8 A</td>
<td>60 A</td>
<td>Down to 4.4 A</td>
</tr>
<tr>
<td>50 mΩ</td>
<td>4 A</td>
<td>30 A</td>
<td>Down to 1.6 A</td>
</tr>
<tr>
<td>100 mΩ</td>
<td>3 A</td>
<td>25 A</td>
<td>Down to 0.5 A</td>
</tr>
</tbody>
</table>
How is $I_{CL\_lim}$ set?

An external resistor generates a reference current from an internal reference voltage that is compared to $I_{LOAD}$.

During current limiting, the FET regulates the $R_{DS\_ON}$ to increase the $V_{DS}$ and create a constant current source.

$$I_{CL\_lim} = \frac{V_{CL\_th}}{R_{CL}} = \frac{I_{out\_lim}}{K}$$
High Side Switch | Capacitive Load

Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

The max charging current is set by the current limit ($I_{INRUSH}=I_{CL}$), linearly charging the capacitor.
- Peak current from transient overshoot is limited to <4A due to the Smart High Side Switch
- Lower charging current results in lower peak currents during inrush which minimizes supply droop and reduces component current handling requirements.
- Charging time is increased as a function of the lower current limit

$$I_{INRUSH} \approx C_{LOAD} \times \frac{dV_{OUT}}{dt}$$

$I_{CL} = I_{INRUSH}$, where $I_{CL}$ equals the current of the high-side switch

$$dt \approx C_{LOAD} \times \frac{V_{OUT}}{I_{CL}} \approx 2 \text{ ms}$$

330 µF charged to 13.5V with 3.5A current limit
While the Smart High Side Switch is current limiting there is a large amount of power dissipation. This is because $V_{DS}$ is large and the charging current is flowing through the switch.

- As the capacitance is charged, the voltage across the FET is reduced and the power dissipation is decreased.
- A higher charging current will reduce the total energy dissipated in the switch but the peak inrush and short circuit current will be increased.

$$P_D = V_{DS} \times I_{OUT}$$

TPS2H160 charging 470 $\mu$F to 24V, 500mA current limit
High Side Switch | Load Driving

- Transient thermal impedance models can predict thermal shutdown point
- Charging large value caps at high currents can result in thermal shutdown, however auto-recovery mode permits full charging.
- Thermal model and power dissipation model will be available to use in the next few months.

TPS2H160 2ch charging 2200 µF

Current Limit = 3.0A

Thermal simulation

\[ T_J > T_{SD} \], so we see a shutdown
Charging time
- Determined by current limit, capacitive load, and supply voltage
- Lower charging time makes it faster to charge up off board loads
- Also can vary based on other type of loads on the rail (i.e. resistive, buck start up, etc…)

Maximum Inrush Current
- Determined by current limit
- Lower current limit saves system costs and enhance reliability during short circuit events

Switch Power Dissipation
- Determined by current limit, capacitive load, and supply voltage
- Lower power dissipation avoids switch shut downs that slow down charging and well as lower charging efficiency
Smart High side switch | Applications

- Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting
- Short Circuit and current limiting protection improves system reliability and reduces system costs
- Integrated current sense and open-load detection enables the detection and diagnosis of faults
High Side Switch | Short Circuit

- Short Circuit protection for outputs prevents damage caused when the output has a low impedance path to ground.

- This is typically a customer requirement and cause serious damage if the protection is not implemented properly.

Short Circuit and current limiting improves system reliability and reduces system costs.
Short Circuit and current limiting improves system reliability and reduces system costs.

Power dissipation before hitting ILIM is:

\[ P_{DIS} = I^2 \times R_{ON} \]

Total Energy Dissipation from cable demagnetization is:

\[ E_D = \frac{1}{2} L \times I_0^2 \times \left( \frac{V_{CLAMP}}{V_{CLAMP} - V_{BAT}} \right) \]

<table>
<thead>
<tr>
<th>Energy dissipation during turn-off, ( E_{TOFF} )</th>
<th>Single pulse, one channel, ( L_{OUT} = 5 ) mH, ( T_{J,\text{start}} = 125^\circ \text{C} )</th>
<th>100(2)</th>
<th>mJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy dissipation during turn-off, ( E_{TOFF} )</td>
<td>Repetitive pulse, one channel, ( L_{OUT} = 5 ) mH, ( T_{J,\text{start}} = 125^\circ \text{C} )</td>
<td>40(2)</td>
<td>mJ</td>
</tr>
</tbody>
</table>

High Side Switch | Short Circuit
High Side Switch | Current limiting

- PLC Digital output modules provides multiple outputs which can be used to drive a range of loads (sensors, solenoids, relays, capacitive loads, etc…)

- Modules can have 8 to 32 channels to provide power to systems

- Below are some technical specifications for an example digital output module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (typ)</td>
<td>24</td>
<td>V</td>
</tr>
<tr>
<td># of Channels</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>$I_{OUT}$, per CH</td>
<td>0.5</td>
<td>A</td>
</tr>
<tr>
<td>Short-circuit threshold (typ)</td>
<td>1</td>
<td>A</td>
</tr>
</tbody>
</table>

- Looking at the specifications, many may pick the power supply requirement based on the $I_{OUT}$ load.

- Doing this, leaves out the scenarios where overload or short-circuit events can happen. If not accounted for, this could cause the upstream power supply to collapse and turn off all 16 channels of the module instead only the ones with the fault

- The adjustable current limit of TI’s high side switches can help to reduce the short circuit trip point which can help to reduce the requirements for the power supply

<table>
<thead>
<tr>
<th>Use cases</th>
<th># of channels</th>
<th>$I_{OUT}$, per CH (A)</th>
<th>Total $I_{OUT}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case #1 - nominal current</td>
<td>16</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>Case #2 - fault case</td>
<td>16</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>Case #2 - fault case w/ TPS27S100</td>
<td>16</td>
<td>0.75</td>
<td>12</td>
</tr>
</tbody>
</table>
High Side Switch | Short Circuit

Current Limit Level
- By having a low adjustable current limit, $I_{\text{PEAK}}$ is minimized which also limits the power dissipation and energy in the system.
- Lower $I_{\text{LIM}}$ shortens length of short-circuit event.
- Lower $I_{\text{LIM}}$ minimizes supply droop during short-circuit.

Clamp Voltage
- Inductive discharge energy is a function of clamp voltage, by increasing clamp voltage the energy is minimized.
- Higher clamp voltage makes a quicker demagnetization period.

Clamp Energy Maximum
- Ensure that the switch can handle the maximum short-circuit energy that is calculated.
High side switch | Applications

Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting.

Short Circuit and current limiting protection improves system reliability and reduces system costs.

Integrated current sense and open-load detection enables the detection and diagnosis of faults.
Increasing safety and reliability requirements are driving the need for smarter outputs that can detect and respond to fault conditions.

Smarter outputs enable:
- Reduce system downtime
- Smart power management

High Side Switches integrate load current sense and open load detection functionality to meet requirements.
Load Sensing
- High Side Switches can output multiple system variables to the system
  - Load Current
  - Temperature Sense
  - Supply Voltage Sense
- Values are output as an analog current on the SNS pin

<table>
<thead>
<tr>
<th>CURRENT MONITOR AND CURRENT LIMIT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{\text{MON}} )</td>
<td>Current sense current ratio</td>
</tr>
<tr>
<td>( \frac{\text{in}}{\text{A}} \text{mA} )</td>
<td>( \text{mA} )</td>
</tr>
<tr>
<td>5</td>
<td>-80</td>
</tr>
<tr>
<td>25</td>
<td>-12</td>
</tr>
<tr>
<td>50</td>
<td>-8</td>
</tr>
<tr>
<td>1</td>
<td>-5</td>
</tr>
<tr>
<td>1</td>
<td>-3</td>
</tr>
</tbody>
</table>

- Enables predictive maintenance by watching for slow current creeps
- Accurate light load diagnostics (LED’s, wire break, etc)
- Smart Power Management
- Can help to ensure valves and solenoids are turned on by reading out the notch current as the armature moves
Open load detection enables detection of broken cables or mis-wiring conditions. TI Smart High Side Switches provide both off state and off state open load detection.

**On State Detection**

If load current drops below the threshold in datasheet, the device will register a fault.

**Off State Detection**

Open Load Detection requires a pull up resistor on the output. If $V_{OUT} >$ threshold the device recognizes that there is no load attached.

Choose pull-up resistor to overcome any pulldown including leakage other than the load. (A resistor divider for $V_{OUT}$ monitoring is shown)

<table>
<thead>
<tr>
<th>Id.on</th>
<th>Open load detection threshold in ON-state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tl.on</th>
<th>Open load detection threshold de-glitch time in on state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>
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High-side vs low-side switches Comparison

- **Smart high-side switches**
  - Sit on the “high-side” of the load
    - **Pros:**
      - Provides short to ground protection
      - Provides short to supply protection through current sensing or open load detection
      - All circuitry is referenced to ground
    - **Cons:**
      - More complex designs if NMOS based
      - Generally slower switching speeds

- **Low-side switches**
  - Sit on the “low-side” of the load
    - **Pros:**
      - Provides short to supply protection
      - Simple design
      - Generally faster switching speeds
    - **Cons:**
      - Doesn’t provide short to ground protection
      - Extra components needed to implement short to ground protection
Implementing Safe Brake function in AC Inverters/Servo Drives Reference Design (TIDA-01600)

**Features**
- Galvanic isolation of signal input and holding brake output
- Holding brakes with a current of up to 2 A can be controlled via a signal input.
- Dual switch control enhancing safe operation
- TPS27S100 enables open load detection and over current protection
- High side switch failure detection
- Rapid application of the holding brake by fast reduction of the holding brake current
- Optional reduction of voltage at holding brake output
- Can withstand reverse voltage up to -40v

**Benefit**
- Single fault tolerant system
- Enhanced system reliability by avoiding electromechanical relays
- Built-in diagnostic functionality enables meeting requirements specified in EN 61800-5-2
- Enables power dissipation in the holding brake by 20-40%
- Use of load switch eliminates discrete FET and helps in system integration optimization, controlled rise time reduces inrush current and quick output discharge controls the fall time of the device

**Target Applications**
- Servo Drives, Robotics & CNC
- Holding brake controller

**Tools & Resources**
- TIDA-01600 and Tools Folder
- Design Guide
- Design Files: Schematics, BOM, Gerbers, etc. Device Datasheets:
  - ISO7142
  - TPS27S100
  - ULN2003A
  - TPS8B69-Q1
  - TVS3300
  - LM214201

**Diagram**

- MCU
- DIGITAL ISOLATOR - ISO7142
- HIGH SIDE SMART SWITCH – TPS27S100 (100mΩ)
- ULN2003A
- BRAKE COIL
- BRAKE VOLTAGE FEEDBACK
- IN-1
- IN-2
- GND
- 24VDC+
Implementing Safe Brake function in AC Inverters/Servo Drives
Reference Design (TIDA-01600)

Figure 15. Rising Edge of Brake Coil Current

Figure 25. PWM Duty Cycle Reduced From 100% to 50% at 10 kHz
Smart High side switch | Applications

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Learn More: 11 Way to Protect Your Power Path

11 Ways to Protect Your Power Path
Design Tips and Tradeoffs Using TI’s Power Switches

Chapter 10: Safely Driving an Inductive Load

Table 1. Power Switch Topology Table

<table>
<thead>
<tr>
<th>Power Distribution</th>
<th>Input Power Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density (W/m^2)</td>
<td>Power Density (W/m^2)</td>
</tr>
<tr>
<td>Input Power (kW)</td>
<td>Input Power (kW)</td>
</tr>
<tr>
<td>Input Current (mA)</td>
<td>Input Current (mA)</td>
</tr>
<tr>
<td>Output Power (kW)</td>
<td>Output Power (kW)</td>
</tr>
<tr>
<td>Output Current (mA)</td>
<td>Output Current (mA)</td>
</tr>
</tbody>
</table>

Introduction: Basics of Power Switches

Input Protection
- Gate Protection
- Gate Driver
- Gate Driver Output

Figure 1. Typical Power Switch Use Cases

Chapter 10: Safely Driving an Inductive Load

Abstract
Inductive loads are inductors, motors, electromechanical devices, and even loads connected through a long cable. Their impedance consists of both a resistance (R) and an inductive (L) in series. The PI value determines the steady-state current and the L value determines the stored magnetic energy. This stored magnetic energy in the inductor can cause system or component-level damage if not properly dissipated.

The opening or closing of a magnetic contact in a relay or switch requires the storage or dissipation of magnetic energy. In the case of an electric motor, this stored energy is necessary for mechanical rotation. Inductive loads are continuously energized and de-energized for opening or closing contacts (relay and solenoid) and operation of other electric motors. Disconnecting an inductive load from an energized state creates a high-voltage spike that can lead to system damage. Safely de-energizing an inductive load requires the implementation of an appropriate clamp.

Equation 1
\[ i(t) = \frac{V(t)}{R} - L \frac{dV(t)}{dt} \]

Challenges of Inductive Loads
The voltage across an inductive load is time-dependent. Equation 1 calculates the inductive load parameters necessary for selecting a reliable clamp.

Energizing an Inductive Load
An inductive load is energized when connected to a voltage source. The current ramps up exponentially to a steady-state value and magnetic energy is stored in the coil. Figure 1 illustrates the behavior, using a high-side switch to drive the load.

Equation 2
When energizing an inductive load in a resistor-inductor (RL) circuit, the voltage drop across the resistor affects the current. Please refer to the additional material for more information.