

AN1212: Advanced Load Driving Considerations for the Si834x Isolated Smart Switch

Output circuits in industrial programmable logic controllers (PLCs) can be routinely subjected to adverse load conditions. PLC outputs often drive relay coils or other inductive loads that can generate potentially dangerous voltage spikes and must discharge significant energy from their magnetic fields when switched off. Loads such as lamp filaments may require amps of inrush current, and short-circuited outputs must also be tolerated. These adverse load conditions can damage the PLC output switch device, and damage may spread to the host controller interface, potentially putting the PLC controller and possibly system operators at risk, if adequate protection mechanisms are not in place.

The Si834x Isolated Smart Switch devices incorporate a rich set of protection mechanisms and diagnostic reporting capabilities to help ensure long, safe, reliable operation of PLC systems. The Si834x devices offer galvanic isolation to insulate the low voltage PLC controller circuitry, and users, from transients and fault conditions that may be present on the PLC output circuits. An integrated “smart” multi-voltage demagnetization clamp limits voltage spikes and absorbs demagnetization energy from inductive loads, and protection mechanisms such as temperature sensing, dissipated energy estimation, current monitoring, and undervoltage shutdown are included to help PLC systems handle adverse load conditions.

KEY POINTS

- Galvanic isolation insulates low-voltage host interface from industrial loads
- Integrated “smart” multi-voltage demagnetization clamp
- Short-circuit and over-current protection
- Undervoltage fault detection
- Open-circuit detection
- Diagnostic reporting

1. Introduction

The Si834x Isolated Smart switch devices are designed for use in industrial applications such as Programmable Logic Controller (PLC) output circuits. PLC output circuits typically provide switching of 24 VDC supplies to control industrial loads like relays, motor actuators, or lamps. The Si834x isolated switches allow logic signals from low voltage processors to control switching of the higher-voltage PLC outputs while providing galvanic isolation between the logic inputs and the PLC outputs. Galvanic isolation provides protection for the processors and human operators on the low voltage side of the circuit from the higher voltages and possible transients or fault conditions that may arise on the output side of the PLC equipment.

PLC outputs can be exposed to a wide variety of load conditions that can present many challenges for traditional switch circuits. For example, PLC outputs often drive relay coils or other inductive loads which store energy in their magnetic field while the switch is in the “on” state. The interruption of current when the switch turns off can often generate enough “inductive kick” or “flyback” voltage to damage the switch unless some form of voltage “clamping” is implemented. Care must be taken when implementing demagnetization clamp circuits to ensure that absorption of the coil's demagnetization energy does not cause overheating in the clamp. PLC output circuits should also be designed to protect themselves from overheating when the output is accidentally shorted. On the other hand, PLC output may also be used to illuminate light bulbs, which can draw amps of initial “inrush” current before the filament heats up, so these loads may initially look very much like a short circuit.

The Si834x isolated smart switch devices incorporate a number of innovative protection and diagnostic capabilities which facilitate driving of difficult industrial loads, and which distinguish this family of switches from competing devices. The Si834x 4-channel switches deliver up to 700 mA ($I_{O(ON)}$) continuously per channel, meeting and exceeding the IEC 61131-2 requirements for 500 mA drive capability. An innovative “smart” multi-voltage demagnetization clamp is included on-chip to protect against the over-voltage conditions and absorb the demagnetization energy that can result from driving inductive loads such as relays, solenoids and motors. This integrated demagnetization clamp dynamically switches between operation at 2.1 V (V_{CLMPL}) or 17.5 V (V_{CLMPH}), based on sensed operating current, temperature, and supply voltage. A special “Inrush” mode of operation accommodates up to 8 A (I_{OPCL}) of peak inrush current for loads such as lamps. Inrush mode is complemented by a “Safe Start” mode of operation which uses an integrated power estimation technique to prevent excessive power dissipation or overheating when exposed to a short circuited output or other elevated current conditions for extended time periods. The Si834x on-chip diagnostics also detect and report open-circuit output conditions back to the host.

The low-voltage logic interface side of the Si834x operates at a VDD1 supply range of approximately 2.25 to 5.5 V, and the switch side of the Si834x operates over a VDD2 supply range of approximately 9 to 32V. Undervoltage protection is provided for both the VDD1 and the VDD2 supplies. In addition, an overvoltage condition on the VDD2 supply will constrain operation of the clamp to help avoid excessive power dissipation.

PLC systems may require sourcing or sinking output switch configurations, depending on the application. The Si834x devices are available in both sourcing and sinking switch configurations, as depicted in the figure below. The sourcing configuration operates as an open-source output for high-side switching. The sinking configuration uses an open-drain output for low-side switching. Both the sourcing and sinking configurations of the Si834x isolated smart switch provide galvanic isolation between the low-voltage logic interface and the switch outputs.

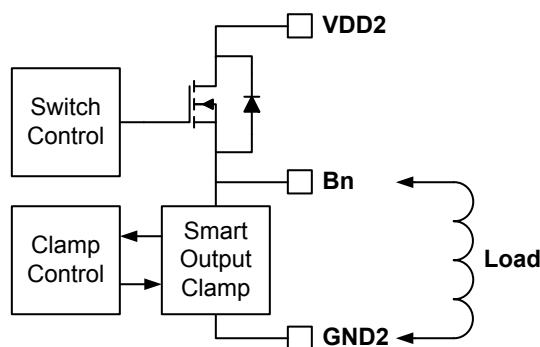


Figure 1.1. Si834x Sourcing Device

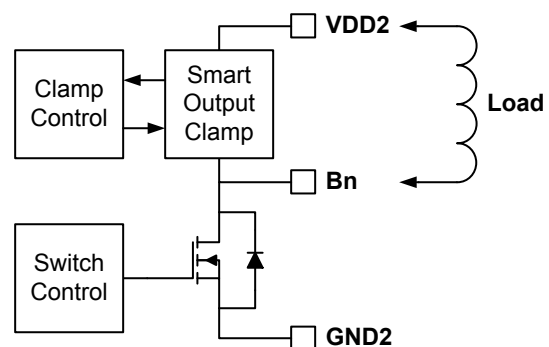


Figure 1.2. Si834x Sinking Device

The balance of this application note provides more detailed information about the advanced switch protection and diagnostic features of the Si834x family of isolated smart switches. Section 2 provides an overview of the various sensing and protection mechanisms implemented in the Si834x isolated smart switch devices. Section 3 describes the integrated “smart” multi-voltage demagnetization clamp, and section 4 presents a brief description of the state machine that is involved in the implementation of these protection mechanisms. The descriptions in the following sections generally apply to the default behavior of one channel of a 4-channel sourcing

configuration part. Some of the default behavior characteristics for parts with a SPI interface may be changed by the host controller through the SPI interface (see data sheet for more details on configuration options for the SPI interface).

2. Temperature, Power, Current, and Supply Voltage Monitoring Mechanisms

On-chip thermal sensors provide an important safeguard against excessive junction temperatures in semiconductor devices. Competing devices often rely solely on “thermal shutdown” mechanisms, triggered by on-chip thermal sensors, for protection of their switches against short-circuit or over-current load conditions. A typical approach is to allow the switch to operate in a current-limited state until the thermal limit is reached, turn the switch off until thermal hysteresis is satisfied, then turn the switch back on and repeat. The average switch die temperature for these devices under continuing short-circuited output conditions will be quite high (thermal limit temperature - hysteresis/2), which can limit operation of other channels and potentially reduce the operating life of the device.

Rather than relying solely on thermal sensors, the Si834x uses a sophisticated combination of on-chip thermal sensors, time-integrated power estimation, current sensing techniques, and an integrated smart multi-voltage demagnetization clamp to ensure device protection under a wide variety of operating and load conditions. Protection is effectively implemented by transitioning between operating states based on both configured device settings and sensed operating conditions. During initial switch turn on (i.e., “Safe Start” state) the Si834x relies on an “integrated power estimation” technique to protect against excessive power dissipation due to short circuits or other over-current load conditions. Once the switch is safely turned on (i.e., in the “Switch On” state), “Switch-On current monitoring” is implemented to protect against short circuits and over-current conditions. The on-chip thermal sensors are relied on primarily to protect the switches from excessive temperature due to prolonged operation with out-of-specification load conditions, where temperature rises relatively slowly. This approach allows the Si834x to quickly detect and react to a variety of adverse load conditions, or fault conditions, without requiring the die temperature to rise to the thermal shutdown trip point.

The Si834x’s integrated monitoring and protection mechanisms allow a number of warning and/or fault conditions to be reported to the host interface for diagnostic purposes. In general, these diagnostic indicators are, by default, cleared automatically when the associated condition is no longer present. However, there are also options that allow the indications to behave in a “sticky” manner (i.e., remain set until the host has actively reset them). The behavior of the driver will be the same whether the indicators are automatically cleared or sticky; for example, a driver channel that would return to normal operation after a fault condition is automatically cleared will still return to normal operation after the fault conditions are no longer present if the fault indication is sticky. Please refer to the Si834x data sheet for details on the behavior of diagnostic indicators. Note that this document assumes that all diagnostic indications are cleared automatically.

The following paragraphs describe some of the key sensing and protection mechanisms implemented in the Si834x design.

2.1 On-Chip Thermal Sensors

The Si834x devices include on-chip thermal sensors for each switch channel. The thermal protection mechanism implemented with these sensors has a nominal over-temperature threshold (T_{OT}) of 165 °C with hysteresis (T_{HYS}) of 33 °C.

If the temperature on a given channel reaches 165 °C (T_{OT}), then an “Over-Temperature Constraint” (OT_CNSn) warning will be reported for that channel via the logic interface. In addition, to prevent additional temperature rise and speed thermal recovery, any other channels that are not already “On” (i.e., not already in the “Switch On” state) will be prevented from turning on, and the smart clamps for all channels will operate in “constrained” (clamp voltage = V_{CLMPL}) mode, for as long as the OT_CNSn condition persists. When the temperature of the affected channel has dropped below about 130 °C ($T_{OT} - T_{HYS}$), the OT_CNSn will be cleared and all channels will resume normal, non-constrained operation. If the host interface indicates that any other channels should be on, they will be turned on (transitioned to “Safe Start” state, followed by “Driver On” state – See 4. Si834x Internal State Machine for details) at this time.

If the temperature on all channels of the device reach 165 °C (i.e., OT_CNSn condition is present on all channels), then an “Over-Temperature Shutdown” (OT_SD) fault will be reported via the logic interface, and all channels of the device will be automatically “Shut Down” (transitioned first to “Safe Stop” state, then to “Switch Off” state - see section 4 for more details). When the temperature on any channel drops below 130 °C (i.e., OT_CNSn condition is no longer present), the “Over-Temperature Shutdown” (OT_SD) fault indication will be cleared. However, all channels will be prevented from turning back on, and the smart clamps for all channels will continue to operate in “constrained” mode (clamp voltage = V_{CLMPL}), until the temperatures for all channels have dropped below about 130 °C. When all channels have dropped below 130 °C, all channels will resume normal, non-constrained operation, and any channels that the host controller dictates should be on will be turned back on at this time.

2.2 Dissipated Energy Estimation

In operating states where a quick response to adverse load conditions is desired, the Si834x uses an estimation of average dissipated energy as a predictor of switch junction temperature. This allows identification of, and protection against adverse load conditions without having to wait until over-temperature events are detected, resulting in a faster response to short-circuit conditions than could be achieved with standard thermal sensors alone.

Estimation of dissipated energy is accomplished by monitoring the time spent under various power-dissipation conditions. The switch's VDS voltage is sensed, and the current limiting conditions for the various switch states are known, so instantaneous power can be estimated. Time integration of instantaneous power is achieved using counters that count up or down at rates appropriate for the power dissipation level. This effectively provides a short-term running time average of the energy dissipated in the switch. Limiting the dissipated energy of the switch effectively limits junction temperature rise. This prevents damage to individual switch circuits experiencing over-current fault conditions, and also prevents faults on individual channels from causing excessive rise in overall die temperature that might result when using slower thermal sensors. The dissipated energy estimation technique is particularly effective during initial switch turn-on, where turning the switch on into a shorted load can cause high power dissipation and rapid switch junction temperature rise. The Si834x state machine uses a combination of dissipated energy estimation and “switch-on” current monitoring to limit power dissipation and thermal rise when driving shorted loads (See 4. [Si834x Internal State Machine](#) for more details).

2.3 Switch-On Current Monitoring

In operating states that have the switch turned on, current sensing is accomplished by measuring the VDS voltage across a second lower-current “replica” switch. The replica switch is designed to respond to process, supply and temperature variations in the same way as the actual channel output switch. This approach provides a fast and accurate representation of the switch current without imposing the power dissipation penalty associated with use of a shunt resistor for current sensing.

In general, when the current monitoring on any channel in the “Switch On” state indicates a current exceeding 1.15 A (I_{OCLT}), the switch current is limited to about 0.88 A (I_{OCL}), an over-current condition is detected, and the channel transitions immediately to the “Safe Start” state. If the over-current condition persists for 155 μ s (T_{OCL}) in “Safe Start” operation, the “Over-Current Shutdown” (OC_SDn) fault for that channel is reported through the logic interface, and the channel is automatically “Shut Down” (transitioned first to “Safe Stop” state, then to “Switch Off” state - see 4. [Si834x Internal State Machine](#) for more details).

2.4 Switch-Off Current Monitoring

Current is monitored when the switch is “off” in order to assess the amount of current flowing in the on-chip smart demagnetization clamp. The smart clamp dynamically switches its operating voltage based on the sensed current. When the switch is off, current is sensed by measuring the voltage across a shunt current-sense resistor (approximately 1 Ω). A voltage comparator is used to determine when the current is above or below the Demagnetization Clamp Current Threshold (I_{CLMPT}) of 400 mA. See 3. [Operation of the “Smart” Multi-Voltage Demagnetization Clamp](#) for details on operation of the smart multi-voltage demagnetization clamp.

2.5 Open-Circuit Diagnostic Feature

The Si834x open-circuit diagnostic feature allows assessment and reporting of open-circuit load conditions. Open-circuit assessment is only performed when switch is off. An on-chip current source of less than 100 μ A ($I_{O(OFF)}$) is applied to the channel output when the switch is off, and the resulting load voltage is measured to determine the approximate load resistance. If the sensed load resistance (R_L) exceeds the Load Resistance Threshold for Open-Circuit Diagnostic (R_{LMAX}), then the Open-Circuit Warning (OPEN_WRNn) is reported to the host controller. The Load Resistance Threshold for Open-Circuit Diagnostic (R_{LMAX}) is set at approximately 35 k Ω (min) for VDD2 between 9 V and 16 V, and at 100 k Ω (min) for VDD2 greater than 16 V.

2.6 VDD1 Voltage Monitoring and Undervoltage Shutdown

The Si834x “logic supply”, VDD1, is monitored to protect against operation with insufficient supply voltage. VDD1 “undervoltage shutdown” occurs at an undervoltage threshold of about 2V ($VDD1_{UV}$) with hysteresis of 50 mV ($VDD1_{HYS}$). When an undervoltage condition is sensed, the transmission of an on-state condition from the low-voltage interface logic is suspended, so all channels transition to “Safe Stop” and then to “Driver Off” state, as if a host command to turn off the channel had been received.

A VDD1 undervoltage shutdown condition is reported via the FLT pin, provided that sufficient VDD1 voltage is still available (See the Si834x data sheet for more information regarding device behavior when VDD1 is “unpowered”). There is no corresponding SPI register indication for VDD1 undervoltage.

Note that, while VDD1 undervoltage shutdown helps protect the device from VDD1 undervoltage conditions, device damage may occur when the VDD1 supply voltage is excessive, or when reverse polarity supplies are applied to VDD1 (see the Si834x data sheet for more details).

2.7 VDD2 Voltage Monitoring, Low-Voltage Warning, Undervoltage Shutdown, and Overvoltage Constraint

The Si834x “switch supply”, VDD2, is monitored for both undervoltage and overvoltage conditions. A “mild” undervoltage condition will result in a VDD2 Low-Voltage Warning being reported to the host controller, while a severe undervoltage condition will result in a VDD2 Undervoltage Shutdown. A VDD2 overvoltage condition will result in operational constraints to help prevent excessive power dissipation in the device.

A VDD2 low-voltage condition occurs when the VDD2 supply voltage falls between approximately 8.5 V ($V_{DD2_{UV9}}$) and 18.25 V ($V_{DD2_{UV18}}$). The VDD2 low-voltage condition results in the VDD2 Low-Voltage warning (V_{DD2_LOW}) being reported to the host controller. The output switches and smart demagnetization clamps for each channel continue to operate normally under VDD2 low-voltage conditions.

A VDD2 undervoltage shutdown occurs when the VDD2 supply voltage falls below approximately 8.5 V ($V_{DD2_{UV9}}$). When a VDD2 shutdown occurs, both the VDD2 Low-Voltage warning (V_{DD2_LOW}) and the VDD2 Out-of-Specification fault condition (V_{DD2_OS}) will be reported to the host controller, and all channels will be safely “shut down” (channels are transitioned first to the “Safe Stop” state, then to the “Switch Off” state) and prevented from turning back on (See section 4 for more details). The smart demagnetization clamps for each channel operate normally. After VDD2 rises back above 8.5 V (note there is some hysteresis for the $V_{DD2_{UV9}}$ threshold), the VDD2 Out-of-Specification fault condition (V_{DD2_OS}) indication is cleared, and all channels return to normal operation. When VDD2 rises above $V_{DD2_{UV18}}$, the V_{DD2_LOW} indication is cleared. Note that if VDD2 continues to fall below the VDD2 undervoltage threshold ($V_{DD2_{UV9}}$), the smart clamp voltage will eventually become indeterminate, and a communication error ($COMM_ERR$) will be reported to the logic interface. See the Si834x data sheet for more information regarding device behavior when VDD2 is “unpowered”.

A VDD2 overvoltage condition is detected when the VDD2 supply voltage exceeds approximately 33.5 V ($V_{DD2_{OV32}}$). When the VDD2 overvoltage condition is detected, the “VDD2 Out of Specification” (V_{DD2_OS}) diagnostic indication is reported to the host controller, and “VDD2 Overvoltage Constraint” operation is enforced on all channels. During “VDD2 Overvoltage Constraint” operation, the demagnetization clamps for all channels operate at 2.1 V (V_{CLMPL}) to minimize on-chip power dissipation during load demagnetization, but channels are otherwise allowed to operate normally. When the VDD2 supply falls back below approximately 33.5 V (note there is some hysteresis for the $V_{DD2_{OV32}}$ threshold) the V_{DD2_OS} flag is cleared and the clamps return to normal dynamic operation. Note that, while VDD2 Overvoltage Constraint operation helps minimize power dissipation in the device during overvoltage conditions, device damage may occur when the VDD2 supply voltage is excessive, or when reverse polarity supplies are applied to VDD2 (see the Si834x data sheet for more details).

2.8 Demagnetization Clamp

The Si834x includes an on-chip “smart” multi-voltage demagnetization clamp to protect the switch from the “flyback” or “inductive kick” voltage that can result from switching inductive loads, and to safely absorb the demagnetization energy stored in the magnetic field of the load. Operation of the clamp is described in [3. Operation of the “Smart” Multi-Voltage Demagnetization Clamp](#).

3. Operation of the “Smart” Multi-Voltage Demagnetization Clamp

The Si834x devices include an integrated high-efficiency multi-voltage clamp to absorb the demagnetization energy, and limit the voltage spikes that result from switching off with inductive loads. This “smart” active clamp design has a dynamically controlled operating voltage, providing an attractive combination of low power dissipation and excellent demagnetization speed.

PLC outputs often drive inductive loads like relay coils. When the output is turned on, voltage from the external supply is applied across the relay coil, and the current ramps up as energy is being stored in the coil’s magnetic field. When the current flowing in the coil is interrupted, a voltage, sometimes referred to as a “flyback voltage” or “inductive kick”, is induced across the coil (for an ideal inductor, the induced voltage is $V_L = L di/dt$). This induced voltage has the opposite polarity of the supply voltage that was applied across the coil when the switch turned on, and the induced voltage appears at the switch output after the switch turns off. Even relatively small 24 V relay coils may have inductances of over 1 henry, and can easily generate enough “inductive kick” to destroy a switch if no clamp is present.

Clamping is required to limit the “inductive kick” when switching the output off, and to provide a current path for demagnetization of the coil. To demagnetize the coil, the clamp must dissipate the energy stored in the coil’s magnetic field (for an ideal inductor, the energy, W , stored in the magnetic field is $W = 1/2 L \times I^2$). IEC 61131-2-compliant PLC output circuits are expected to support short-term “overload” currents of at least twice their “rated” operating current, so a 500 mA-rated output may be delivering 1A or more at the moment it is switched off.

The simplest clamp circuit is a diode placed across the relay coil. When the PLC output is on, this diode is reverse biased, and does not conduct. When the output turns off, the diode becomes forward biased by the voltage induced in the coil, and provides a path for the coil current to continue flowing for demagnetization. The voltage across the coil is limited to the diode’s forward voltage drop, thus protecting the switch. The power dissipated in the clamping diode is that forward voltage multiplied by the demagnetization current, which is sometimes referred to as the “flyback current”. If 1 amp was flowing in the coil when the output was switched off, the peak power dissipated in the clamping diode would typically be below 1 watt, which is quite manageable. However, this low-power approach has the disadvantage of demagnetizing the coil rather slowly. This limits the maximum switching speed of the circuit, but more importantly, slow coil demagnetization can also result in increased arcing across the relay contacts, which reduces the operating life of the relay device. Additional information regarding relay operating life may be found in the publication “Coil Suppression Can Reduce Relay Life” at https://www.te.com/commerce/DocumentDelivery/DDEController?Action=schrtrv&DocNm=13C3264_App-Note&DocType=CS&DocLang=EN.

Clamping at higher voltages will speed up the demagnetization and extend the relay life, but there are diminishing returns for clamping voltages above 15 to 20 V, and the peak power dissipated in the clamp increases linearly with voltage making higher voltages impractical. Experimentation has shown that limiting the load voltage to approximately 17.5 V is effective for a variety of common PLC load conditions. The Si834x provides an active clamp that dynamically switches between operation at 2.1 V (V_{CLMPL}) and at 17.5 V (V_{CLMPH}) to provide a combination of low power dissipation and fast demagnetization.

Some competing integrated PLC output devices utilize avalanche breakdown of the output switch to provide clamping. In this case, the external supply is included in the flyback current path as illustrated in Figure 1. To limit the coil voltage to 17 V in a circuit with a 24 V supply, for example, the voltage across the output would have to be clamped at 41 V.

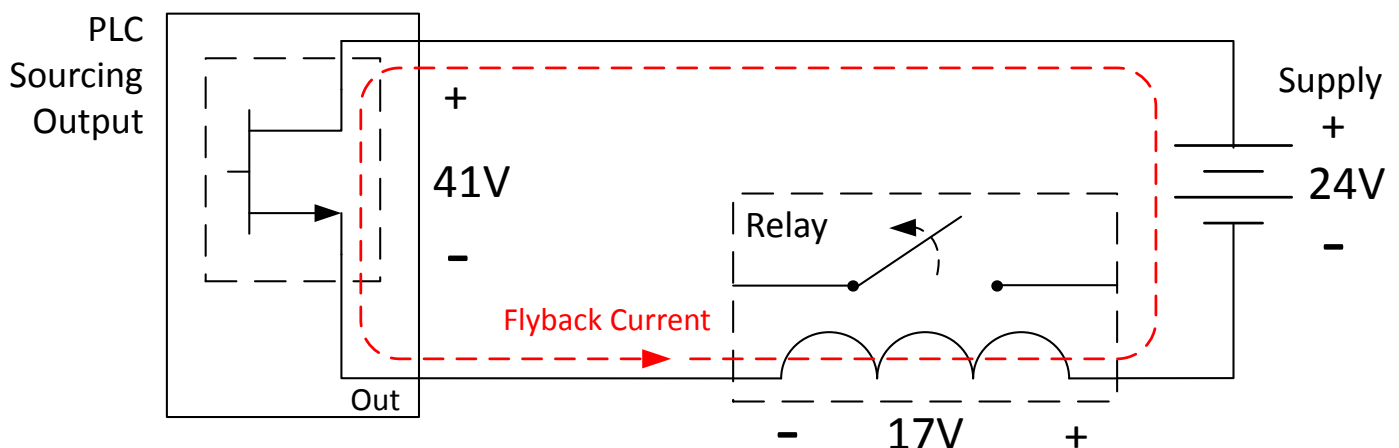


Figure 3.1. Example of Solution with Clamping Implemented in Output Driver Device

If 1 A was flowing in the inductor when the output was switched off, the peak power dissipation in the device (now acting as a clamp) would be about 41 watts. This kind of power dissipation leads to large packages and thermal concerns, especially for devices which may have multiple channels that could be switching simultaneously.

The Si834x clamp is implemented independently from the output switch, providing a flyback current path that does not include either the switch or the external supply. The Si834x current sourcing output configuration is depicted in the figure below.

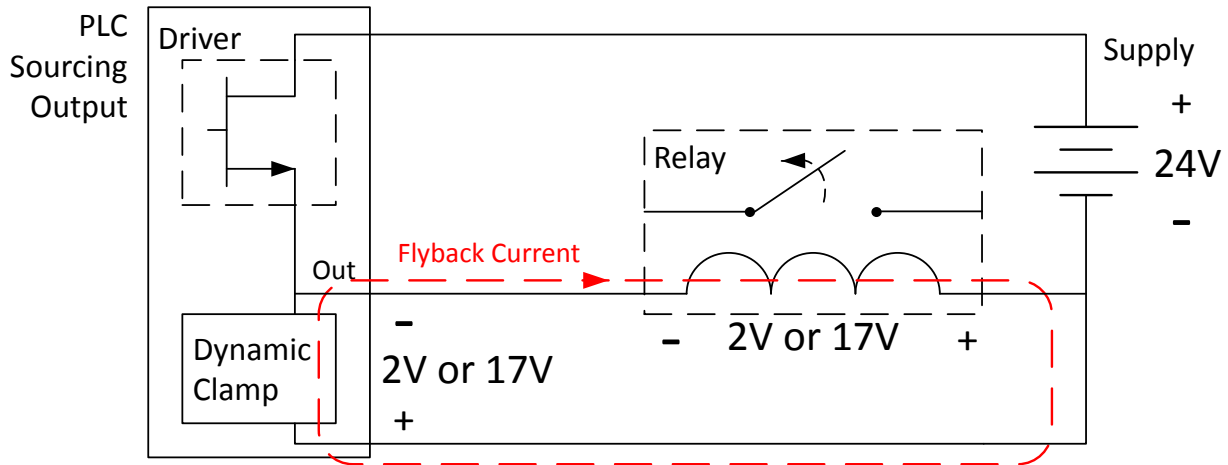


Figure 3.2. Si834x Active Dynamic Clamp (Sourcing Output Configuration)

The active clamp takes only a few microseconds to turn on, and a passive clamping mechanism limits the output voltage to 20V during turn-on. For currents above 400 mA, the active clamp operates initially at 2.1 V (V_{CLMPL}), minimizing power dissipation as demagnetization of the coil begins. The Si834x senses the current through the clamp, and when the current drops to about 400 mA, the clamp switches to 17.5 V operation to rapidly discharge the remaining magnetic field. A relay coil with valid impedance will release cleanly during this rapid discharge period. If a 1 amp current was flowing in the coil when the switch turned off, the passive clamp would dissipate about 44 W ($1 \text{ A} \times (24 \text{ V} + 20 \text{ V})$) for only a few microseconds, before the active clamp would take over. The peak power in the active clamp would only be about 2.1 W during the initial high-current demagnetization, increasing to about 7 W when the current drops to 400 mA.

Note that the Si834x also senses on-chip temperature, and if an over-temperature condition is detected, the clamp voltage will remain at the 2.1 V (V_{CLMPL}) setting rather than switching to 17.5 V (V_{CLMPH}) operation when the current drops to 400 mA.

The clamp is designed to limit “inductive kick” voltages and to demagnetize inductive loads when the switch is turning off. During normal operation, the switch is turned off under control of the host controller. However, the Si834x will also switch off automatically under certain fault conditions, including detection of an over-current condition. Figure 3 illustrates the clamp operation when driving an “out-of-spec” load that has a low enough coil resistance to cause an over-current condition.

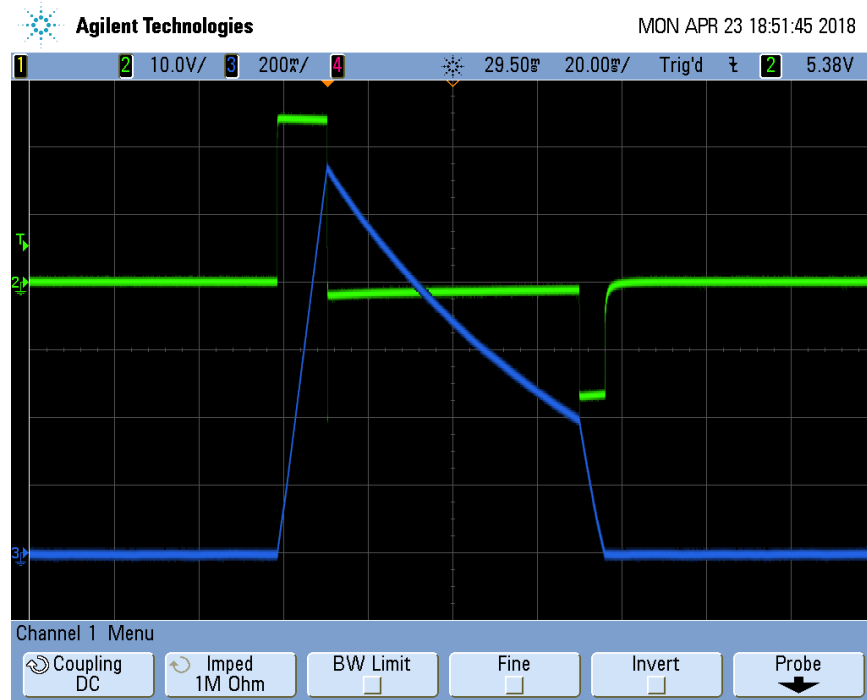


Figure 3.3. Active Clamp Operation for Overcurrent Condition

When the switch is turned on, the output voltage, captured on channel 2 in green, steps from 0V to 24 Vdc. The output current, captured on channel 3 in blue, ramps linearly as the magnetic field builds up in the inductive load. The current in this “out-of-spec” load continues to ramp past the 1 A “temporary overload” level specified for a 500 mA-rated output. The Si834x detects an over-current condition when the current reaches approximately 1.1 A, and the part automatically switches to the “Safe Stop” state as described in the “Operating Modes” section of this document. Switching to “Safe Stop” mode shuts the switch off, and this results in a reverse-bias “inductive kick” voltage being generated by the inductive load. It takes several microseconds for the active clamp, which is set to 2.1 V operation in the “Safe Stop” state, to engage. The voltage on the output is initially clamped to -20 V by the Si834x passive clamp until the active clamp engages. After engaging, the active clamp holds the voltage at -2.1 V as the load current begins to ramp down during initial coil demagnetization.

When the current reaches 400 mA, the part automatically switches to the “Switch Off” state as described in section 4. The clamp operates at -17.5 V in the Switch Off state, so the voltage at the switch output changes from -2.1 V to -17.5 V. The current drops much faster at this point, as the clamp quickly dissipates the remaining energy in the coil’s magnetic field.

In this example, the current flowing when the switch shuts off is larger than would be seen during normal operation. The energy stored in the load’s magnetic field, and dissipated by the Si834x clamp, is thus much higher than would be seen during normal switching operation. This illustrates the effectiveness of the Si834x dynamic active clamp in protecting the output circuitry.

4. Si834x Internal State Machine

The internal operation of the Si834x is controlled by a state machine that dynamically switches between five operating states based on settings from the logic interface and on sensed operating conditions. The five basic operating states of the Si834x are the Switch Off state, the Safe Start state, the Switch On state, the Inrush state, and Safe Stop state. The state machine is designed to check for acceptable load conditions before turning the switch on for continuous operation. It is also designed to differentiate between a short-circuited load and a high inrush load like a lamp filament. The state machine also effectively controls the operating voltage of the demagnetization clamp.

One key goal of the state machine is to limit the amount of time spent driving a short-circuited load, while also being able to effectively drive a high-inrush load like a lamp filament. The switch turn-on process begins with the Safe Start state. If the initial load current is less than 700 mA in the Safe Start state, the driver is transitioned directly to the Switch On state.

However, when turning on into a short-circuited load (less than about 4 Ω), the Safe Start state will limit the switch current to 700 mA ($I_{O(ON)}$) for 155 μs (T_{OCL}), after which time the switch will be “shut down” (transitioned first to “Safe Stop” state, then to “Switch Off” state) for 850 μs ($T_{OCLP} - T_{OCL}$), and then transitioned back to the Safe Start state to repeat the cycle. This “pulsed 700 mA current” cycle will repeat for up to 6 ms (t_{OCPD}) to verify that the high current is not a transient condition, after which time the switch will transition to the Inrush state. The Inrush mode determines whether this is a high-inrush load or a short. For the short-circuit case, the current will be greater than 8 A (I_{OPCL}), and the state machine will report the “Over-Current Shutdown” (OC_SDn) fault through the logic interface, and shut down the channel for a 500 ms (t_{OPRD}) “cool-down” period before repeating the process. This “pulsed” current approach keeps the average power dissipation (and resulting die temperature) very low during short-circuit conditions, and allows the part to return to normal operation if/when the short is removed.

The turn-on process with a high-inrush load, like a lamp filament, begins much like the short-circuit case. A lamp filament may present an initial (cold) load of only ~ 4 to 24 Ω , so start up will begin with 6 ms of “pulsed 700 mA current” as described above for the short circuit case. However, once in the Inrush state, the inrush current for the lamp filament load will be less than 8 A (not a short). In this case, the Inrush state will then check if the current is still greater than 1 A after a 20 ms (T_{OPCL}) delay. If the current remains above 1 A, (possibly a resistive short), then the “Over-Current Shutdown” (OC_SDn) fault is reported through the logic interface, and the channel is shut down for a 500 ms (t_{OPRD}) “cool-down” period before repeating the process. However, if the current drops below 1 A (a “high-inrush” load like a lamp filament), the state machine transitions to the Switch On state.

If a short circuit occurs sometime after the channel has already turned on (state machine is already in the Switch On state), a current of greater than 1.1 A (I_{OODT}) will be detected in the Switch On state, and the state machine will transition to the Safe Start state, where current limiting at 700 mA ($I_{O(ON)}$) for 155 μs (T_{OCL}) will result in an Over-Current Shutdown” (OC_SDn) indication being sent to the host controller, and the channel will be “shut down” (transition to the Safe Stop state, followed by the Switch Off state for 500 ms (t_{OPRD})).

The five basic operating states of the Si834x state machine are described in sections [4.1 "Switch Off" State](#) through [4.5 "Safe Stop" State](#). Section [4.6 Basic State Machine Operation](#) describes basic operation of the state machine, including response to over-temperature conditions. An example of the state machine operation is given in [4.7 Overcurrent Shutdown \(OC_SDn\) Example](#).

4.1 "Switch Off" State

The Switch Off state is entered at power-up, and after the “Safe Stop” state. Key characteristics of the Switch Off state include:

- The switch is “Off”.
- The demagnetization clamp for each channel normally operates at 17.5 V (V_{CLMPH}) in the Switch Off state, but the clamps for all channels will operate at 2.1 V (V_{CLMPL}) when the “Over-Temperature Constraint” (OT_CNSn) is active on any channel.
- An on-chip current source of less than 100 μA ($I_{O(OFF)}$) is applied to the channel output in the Switch Off state to determine if the output is open-circuit (see [2.5 Open-Circuit Diagnostic Feature](#)).

4.2 "Safe Start" State

The Safe Start state effectively checks to see if the load current is low enough to transition to the Switch On state, or high enough to transition to the Inrush state.

Key characteristics of the Safe Start state include:

- The demagnetization clamp for each channel operates at 2.1 V (V_{CLMPL}).
- The switch output current is limited to 700 mA ($I_{O(ON)}$) mA.

A simplified set of rules for the Safe Start state is as follows:

- If switch current is less than 700 mA ($I_{O(ON)}$) after settling time of 6 μ s (t_{OCL}), then go to the "Switch On" state.
- If switch current is 700 mA ($I_{O(ON)}$) for 155 μ s (T_{OCL}) AND the previous state was "Switch Off", then go to Safe Stop, followed by the "Switch Off" state for 850 μ s ($T_{OCLP} - T_{OCL}$) μ s, and then return to "Safe Start" again.
 - If this "pulsed 700 mA current" cycle repeats for $> t_{OCPD}$ (~ 6 ms), then go to the "Inrush" state.
- If switch current is 700 mA ($I_{O(ON)}$) for 155 μ s (T_{OCL}) AND the previous state was "Switch On", then send Over-Current Shutdown" (OC_SDn) indication to host controller, and go to Safe Stop, followed by "Switch Off" state for 500 ms (t_{OPRD}).

4.3 "Switch On" State

The Switch On state is the state used to drive typical loads. The Switch On state is normally entered from the Safe Start state. The output operates with source resistance of about 145 m Ω (R_{ON}), resulting in very low power dissipation.

A key characteristic of the Switch On state is that the demagnetization Clamp is disabled.

A simplified rule for the Switch On state is:

- If switch current is greater than 1.15 A (I_{OCLT}), then go to the "Safe Start" state.

4.4 Inrush State

The Inrush state provides support for high-inrush-current loads, such as lamp filaments, and differentiates between high-inrush loads and short-circuited loads.

Key characteristics of the Inrush state include:

- The demagnetization clamp is disabled.
- The output current is limited to 8 A (I_{OPCL}).

A simplified set of rules for the Inrush state is as follows:

- If (when) current is less than 1 A, then go to "Switch On" state.
- If current is greater than 8 A (I_{OPCL}) after settling time of 12 μ s (t_{OPCT}), then Over-Current Shut Down condition (OC_SDn) is indicated via logic interface, and go to the Safe Stop state, followed by the Switch Off state for 500 ms (t_{OPRD}), and then go to "Safe Start".
- If current is greater than 1 A after 20 ms (T_{OPCL}), then set Over-Current Shut Down condition (OC_SDn), and go to "Safe Stop" followed by "Switch Off" for 500 ms (t_{OPRD}), and then go to "Safe Start".

4.5 "Safe Stop" State

The Safe Stop state is used to limit power dissipation in the demagnetization clamp during initial demagnetization of inductive loads (see 3. Operation of the "Smart" Multi-Voltage Demagnetization Clamp).

Key characteristics of the Safe Stop state include:

- The switch is Off.
- The demagnetization clamp for each channel normally operates at 2.1 V (V_{CLMPL}).

A simplified rule for the Safe Stop state is:

- If demagnetization clamp current is less than 400 mA, then go to the "Switch Off" State.

4.6 Basic State Machine Operation

The Si834x powers-up in “Switch Off” state. A host command to “turn on” a channel will cause that channel to switch to the “Safe Start” state, and a host command to “turn off” a channel will cause that channel to switch to the “Safe Stop” state.

An Over-Temperature Constraint (OT_CNSn) condition on any channel will:

- Force any channels not already in “Switch On” state to transition to “Safe Stop” state.
- Constrain Clamp operation (set clamp voltage = V_{CLMPL}) for all channels.
- Prevent any channels from “turning on” (see [2.1 On-Chip Thermal Sensors](#)).

An Over-Temperature Shut-Down (OT_SD; all channels at OT_CNSn) will:

- “Shut down” all channels (transition first to “Safe Stop”, then to “Switch Off” state).
- Constrain Clamp operation (set clamp voltage = V_{CLMPL}) for all channels.
- Prevent any channels from “turning on” (see [2.1 On-Chip Thermal Sensors](#)).

A VDD1 Undervoltage condition will:

- “Shut down” all channels (transition first to “Safe Stop”, then to “Switch Off” state) (see [2.6 VDD1 Voltage Monitoring and Undervoltage Shutdown](#) for more details).

A VDD2 Low Voltage Warning (VDD2_LOW) condition will:

- Have no effect on normal operation (VDD2_LOW is a diagnostic indication only) (See [2.7 VDD2 Voltage Monitoring, Low-Voltage Warning, Undervoltage Shutdown, and Overvoltage Constraint](#) for more details).

A VDD2 Undervoltage Shutdown Fault Condition (VDD2_LOW AND VDD2_OS) condition will:

- “Shut down” all channels (transition first to “Safe Stop”, then to “Driver Off” state).
- Constrain Clamp operation (set clamp voltage = V_{CLMPL}) for all channels.
- Prevent any channels from “turning on” (see [2.7 VDD2 Voltage Monitoring, Low-Voltage Warning, Undervoltage Shutdown, and Overvoltage Constraint](#) for more details).

A VDD2 Overvoltage Constraint condition on any channel will:

- Constrain Clamp operation (set clamp voltage = V_{CLMPL}) for all channels (see [2.7 VDD2 Voltage Monitoring, Low-Voltage Warning, Undervoltage Shutdown, and Overvoltage Constraint](#) for more details).

4.7 Overcurrent Shutdown (OC_SDn) Example

This section reviews the Over-Current Shutdown (OC_SDn) example from the Si834x data sheet in the context of the Si834x state machine. The figure below depicts the behavior of the control signal (An), the channel n output voltage (V_{Bn}), the channel n output current (I_{Bn}), and the Over-Current Shutdown diagnostic indicator (OC_SDn) during an over-current shutdown event that occurs while driving an inductive load.

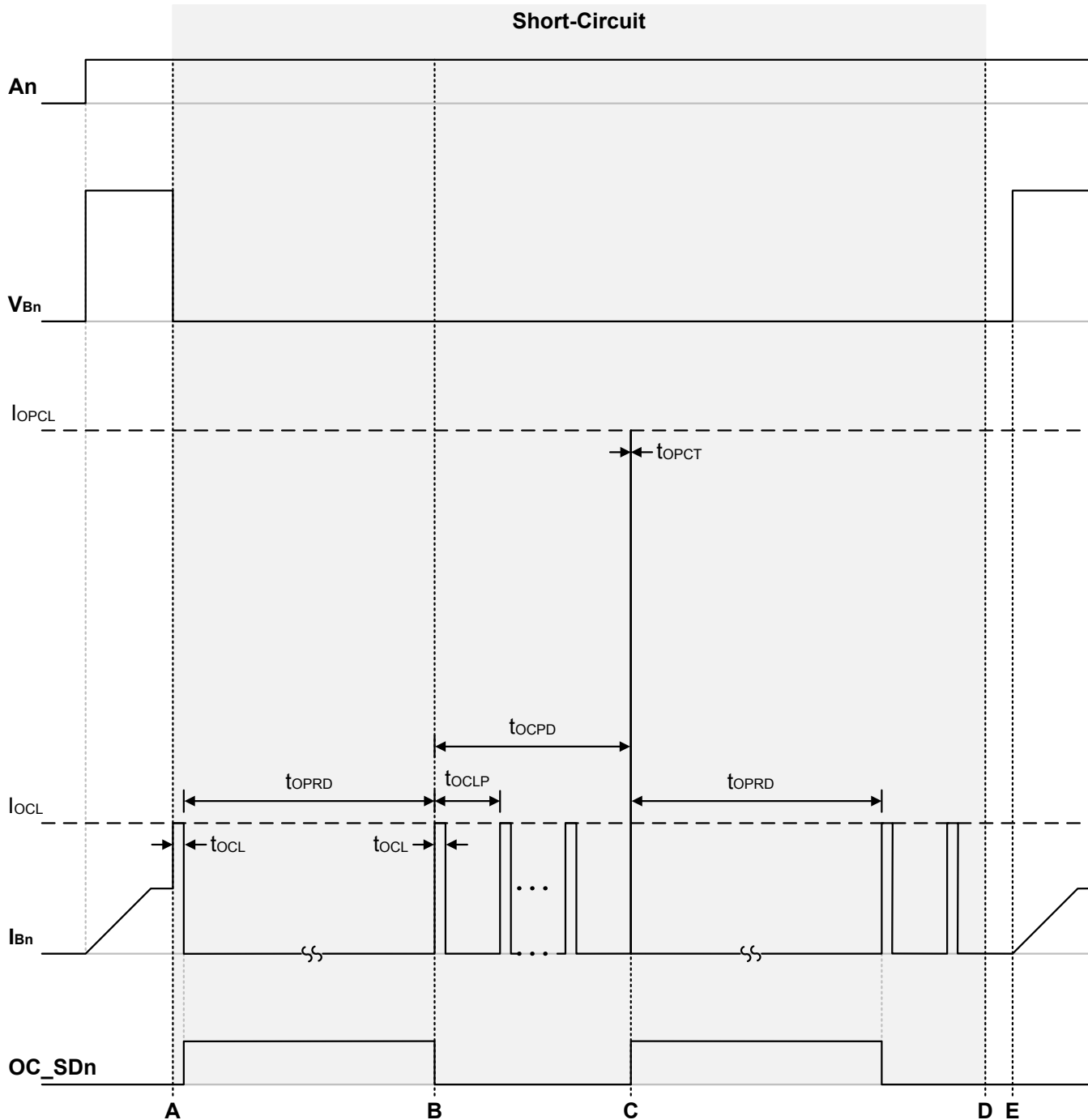


Figure 4.1. Overcurrent Shutdown Behavior

The portion of the above figure to the left of marker A depicts a normal channel turn-on. The Si834x powers-up in the Switch Off state, so no V_{Bn} voltage or I_{Bn} current is indicated here, although a current of less than 100 μA may be applied to the output in the Switch Off state for open-circuit detection (see 2.5 Open-Circuit Diagnostic Feature and 4.1 "Switch Off" State for details).

When the An control signal goes high to turn the channel on, the Si834x channel transitions first to the Safe Start state (see 4.2 "Safe Start" State), where voltage V_{Bn} is applied. Because the sensed current is less than 700 mA in Safe Start, the channel transitions to the Switch On state. The current ramps up until the magnetic field of the inductive load is fully charged.

At the time indicated by marker A, a dead short is placed on the channel's output. The "Switch On Current Monitoring" (see [2.3 Switch-On Current Monitoring](#)) indicates that the current has exceeded the over-current threshold, I_{OCLT} , so the switch current is limited to I_{OCL} , and the channel transitions Safe Start state. In Safe Start mode (See [4.2 "Safe Start" State](#)), the output is current limited for 155 μs (T_{OCL}), and the previous state was the "Switch On" state, so OC_SDn is triggered, and the channel is shut down (transitioned first to the Safe Stop, then to Switch Off state) for 500 ms (t_{OPRD}).

After the 500 ms "cool down" (marker B), OC_SDn is released, and the channel switches back to the Safe Start state (see [4.2 "Safe Start" State](#)) to recheck the load conditions. Because the output short-circuit is still present, the output will current limit again for 155 μs . The previous state was "Switch Off", so the channel is now switched first to the Safe Stop state, then to the Switch Off state for 850 μs ($T_{OCLP} - T_{OCL}$) μs , then finally back to the Safe Start state, where the cycle is repeated repeats for 6 ms (t_{OCPD}). After 6 ms of "current pulsing", the channel is switched to the Inrush state, to differentiate between a "high inrush" load (lamp filament) and a short.

The channel switches to the Inrush state (see [4.4 Inrush State](#)) at marker C. The shorted output condition is still present, so the output is current limited to 8 A (I_{OPCL}) for 12 μs (t_{OPCT}) in the Inrush state, after which OC_SDn is set true again, and the channel is transitioned first to the Safe Stop state, followed by the Switch Off state for 500 ms (t_{OPRD}).

After the 500 ms "cool down", OC_SDn is released, the channel switches back to the Safe Start state, and the "current pulsing" load testing begins, just as it did earlier at marker B. However, in the middle of the load test current pulsing, at marker D, the short-circuited load condition is removed. When the T_{OCLP} timer expires at marker E, and the channel switches back to the Safe Start state for the next load test, the sensed current is less than 700 mA, and the channel switches to the Switch On state.

4.8 Short Circuit Load Example

The figure below illustrates the behavior of the Si834x Smart Switch compared to competing solutions when driving a short circuited load.

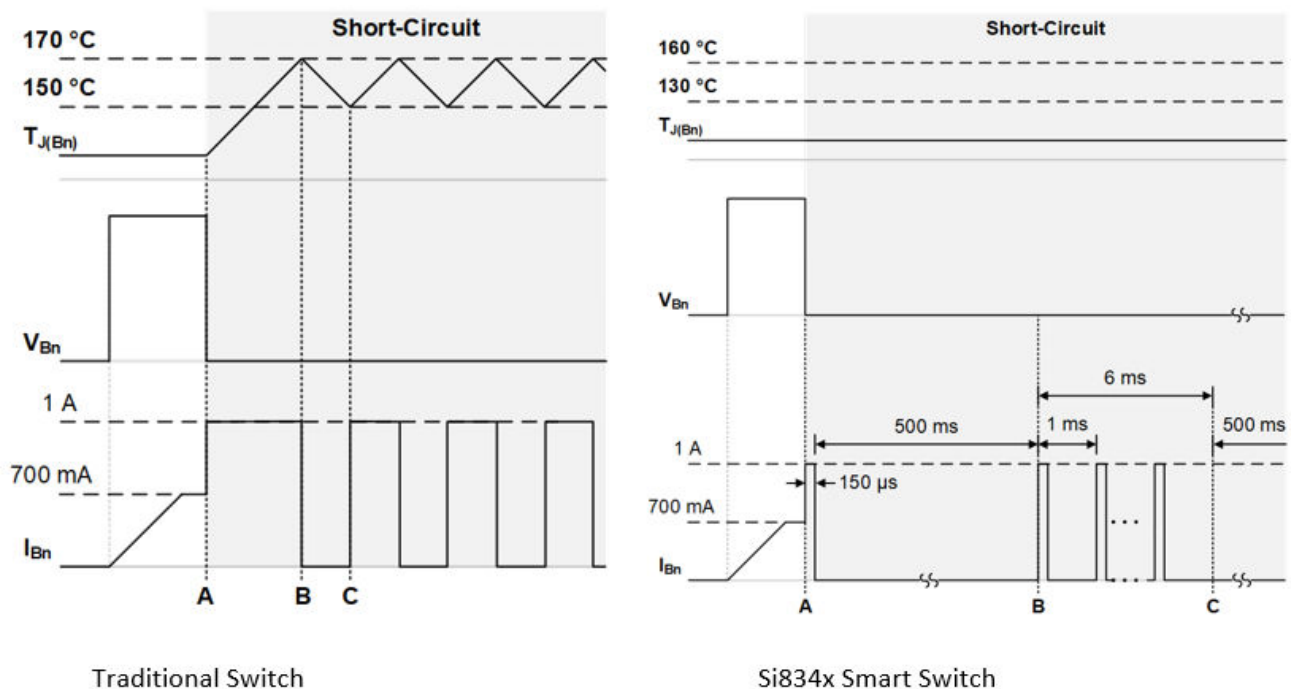


Figure 4.2. Comparison of Si834x vs. Traditional Switch under Short-Circuit Load Conditions

The traditional approach for protecting a smart switch against over-current conditions relies heavily on thermal switch protection, current measurements, and controlling the impedance of the smart switch. This method is shown on the left. In this diagram, the switch is turned on and the load current initially ramps to 700 mA. At marker A, a cable is crimped to the load and a 0 Ω short is created. The switch will measure a current above 1 A and immediately increase the switch impedance to limit current to just 1 A through the short circuit. With a much higher impedance, power dissipation is drastically increased, and the temperature of the switch rapidly rises. At marker B, the thermal protection is tripped because of the short circuit, and the channel is immediately shut-down. This reduces power dissipation and the switch temperature falls until it reaches a safe level, shown at marker C. At this point, the output is immediately turned back on, and if the short circuit remains, the process repeats, driving the device temperature back to the protection limit. In this way, the traditional switch oscillates off and on, and the device temperature oscillates at the thermal limit. This is not a good condition for the long term reliability of the switch, and is an extremely inefficient use of power.

To avoid this undesirable behavior, the Si834x Smart Switch utilizes a dissipated energy estimation technique as described in [2.2 Dissipated Energy Estimation](#). The resulting Si834x behavior is shown on the right. Prior to the marker, the Si834x is delivering 700 mA to the load, just as in the previous case. At marker A, a 0 Ω short is created on the output and is immediately detected when the current exceeds about 1 A. Just like a traditional smart switch, the Si834x smart switch increases its impedance to limit current to roughly 1 A. Unlike a traditional smart switch, the power is estimated based on the known current and voltage and the channel is turned off within a set amount of time. After a delay period, at marker B, the channel is tested for the short circuit again by turning on the channel for short, controlled pulses (about 6 pulses). None of these pulses are long enough to dissipate a sizable amount of power, and so the temperature of the switch remains relatively unchanged. At marker C, this process is repeated. This will go on indefinitely, as long as the over-current condition remains.

Because of this non-thermal approach to over-current protection, the Si834x remains at a safe temperature, protecting long-term reliability of the device, reducing power consumption, and simplifying the required thermal solution while keeping device manufacturability high.

5. Summary

The Si834x family of Isolated Smart Switches provide a variety of protection mechanisms and diagnostic indications to ensure reliable operation under a wide variety of industrial load conditions. An integrated “smart” multi-voltage demagnetization clamp protects the switch output from “inductive kick” voltages and safely absorbs demagnetization energy from switching of inductive loads. Power supply monitoring and undervoltage shutdown mechanisms are included to help protect against power supply failures. Other advanced protection mechanisms, including on-chip thermal sensors, dissipated energy estimation, and driver-on current monitoring, help prevent excessive power dissipation when driving short-circuited loads, and keep the Si834x die temperatures lower than many competing parts under adverse operating conditions.



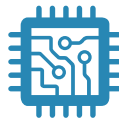
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