

TPS1HC04-Q1 4.9mΩ Single-Channel Automotive Smart High-Side Switch

1 Features

- Single-Channel smart high-side switch with full diagnostics
 - Control using GPIO pins
 - Open-drain status output
 - Current sense analog output: sense accuracy $< \pm 9\%$ at $\geq 5A$
- Wide operating voltage: 3V to 28V
- Low R_{ON} : 4.9mΩ typical, 8mΩ max at 150°C
- Ultra-low standby current: $< 1.4\mu A$ at 85°C
- Adjustable current limit with and without thermal regulation
 - Current limit range: 15A to 45A
- Protection
 - Overload and short-circuit protection
 - Undervoltage lockout (UVLO)
 - Thermal shutdown and swing with self recovery
 - Integrated output clamp to demagnetize inductive loads
 - Loss-of-GND, loss-of-battery, and reverse battery protection
- Diagnostics
 - Global fault report for fast interrupt
 - Overcurrent and short-to-ground detection
 - Open-load and short-to-battery detection
- Qualified for automotive applications
 - AEC-Q100 qualified with the following results:
 - Temperature grade 1: $-40^{\circ}C$ to $125^{\circ}C$ ambient operating temperature range
 - Passed electrical transient disturbance immunity tests (ISO7637-2 and ISO16750-2)
- Small footprint: 11-pin wettable flank VQFN-HR 2.2mm x 3.6mm, 0.55mm pitch
- **Functional Safety Capable**
 - Documentation available to aid functional safety system design

2 Applications

- Zone control module
- Body control module
- Incandescent and LED lighting
- Front door module
- Seat heater

3 Description

TPS1HC04-Q1 is a single-channel, smart high-side switch, with integrated NMOS power FET and charge pump, designed for 12V automotive battery systems. The low on-resistance (4.9mΩ) minimizes device power dissipation when driving a wide range of output load current up to 15A DC.

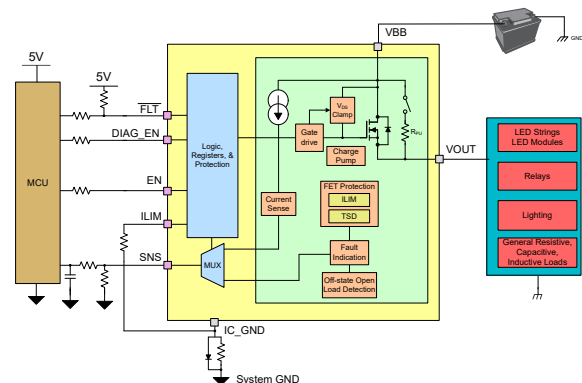
The device integrates protection features such as thermal shutdown, output clamp, and current limit. TPS1HC04-Q1 implements an adjustable current limiting circuit that improves the reliability of the system by reducing inrush current when driving large capacitive loads and minimizing overload current. The adjustable current limit can be adjusted from (15A to 45A) using an external resistor on the ILIM pin. The device offers both thermal-regulated current limiting for capacitive loads at startup and non-regulated current limiting for motor inrush or bulb applications.

The device also provides an accurate current sense that allows for improved load diagnostics such as overload and open-load detection, enabling better predictive maintenance. TPS1HC04-Q1 is available in a 11-pin, 2.2mm x 3.6mm VQFN-HR wettable-flank package with 0.55mm pitch, minimizing the PCB footprint.

Package Information

PART NUMBER	PACKAGE ⁽¹⁾	PACKAGE SIZE ⁽²⁾
TPS1HC04-Q1	VAH (VQFN-HR, 11)	2.2mm x 3.6mm

- (1) See the orderable addendum at the end of the data sheet.
- (2) The package size is a nominal value and includes pins.



Typical Application Schematic

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4 Device Comparison Table

TPS1HC04-Q1 is part of a high current, smart high-side switch family, which has multiple device versions. The following tables shows the details of the versions and which versions are going to be available for each device.

Table 4-1. Version Table

VERSION ⁽²⁾	SLEW RATE	OPEN LOAD DETECTION DELAY
P	Nominal (0.45V/μs)	0.4ms delay
M ⁽¹⁾	Nominal (0.45V/μs)	2.4ms delay
D ⁽¹⁾	Slow (0.06V/μs)	0.4ms delay
B ⁽¹⁾	Slow (0.06V/μs)	2.4ms delay

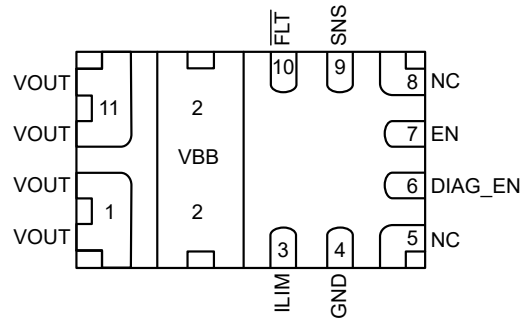
(1) Device in preview. Please contact TI for more information.

(2) All versions are GPIO controlled.

Table 4-2. Device Comparison Table

PART NUMBER	PLANNED VERSIONS	NUMBER OF CHANNELS	ON-RESISTANCE at 25°C	ADJUSTABLE CURRENT LIMIT RANGE	OVERCURRENT BEHAVIOR
TPS2HC08-Q1	P, D, M, B	2	9.5mΩ	7.5A - 25A	• Current limiting with thermal regulation when external resistor is used on ILIM pin
TPS2HC16-Q1	P, M	2	18.7mΩ	5A - 15A	
TPS1HC08-Q1	P, D, M	1	9.8mΩ	10A - 25A	
TPS1HC04-Q1	P, D	1	4.9mΩ	15A - 45A	
TPS1HC03-Q1	P, D, M	1	3.2mΩ	20A - 55A	• Current limiting with no thermal regulation when ILIM pin = GND
TPS1HC16-Q1	P	1	16mΩ	7A - 17A	
TPS2HC30-Q1	P	2	30mΩ	3.5A - 11A	

5 Pin Configuration and Functions



NC – No internal connection

Figure 5-1. VAH Package TPS1HC04-Q1 Top View

Table 5-1. Pin Functions

PIN		TYPE	DESCRIPTION
NO.	NAME		
1	VOUT	Power	Output of high side switch, connect to load
2	VBB	Power	Power supply.
3	ILIM	Input	Adjustable current limit. Connect a resistor from the pin to GND to set the current limit.
4	GND	Power	Ground of device. Connect to resistor-diode ground network to have reverse battery protection
5	NC	N/A	No internal connection
6	DIAG_EN	Input	Enable-disable pin for diagnostics, internal pulldown
7	EN	Input	Input control for channel activation, internal pulldown
8	NC	N/A	No internal connection
9	SNS	Output	Analog current sense output corresponding to load current. Connect R_{SNS} to ground to convert to a voltage. Also shows fault status by going high
10	FLT	Output	Open drain global fault output. Referred to \overline{FAULT} , \overline{FLT} , or fault pin
11	VOUT	Power	Output of high side switch, connect to load

6 Specifications

6.1 Absolute Maximum Ratings

Over operating free-air temperature range (unless otherwise noted)⁽¹⁾

		MIN	MAX	UNIT
Maximum continuous supply voltage, V _{BB}			28	V
Load dump voltage, V _{LD}	ISO16750-2:2010(E)		35	V
Reverse polarity voltage	Maximum duration of 3 minutes and with the application circuit	-18		V
Enable pin current, I _{EN}	Enable pin current, I _{EN}	-1	20	mA
Enable pin voltage, V _{EN}		-1	7	V
Diagnostic Enable pin current, I _{DIAG_EN}		-1	20	mA
Diagnostic Enable pin voltage, V _{DIAG_EN}		-1	7	V
Sense pin current, I _{SNS}		-150	10	mA
FLT pin current, I _{FLT}		-30	10	mA
FLT pin voltage, V _{FLT}		-0.3	V _{BB}	V
ILIM pin current, I _{LIM}	ILIM pin current, I _{LIM}	-30	10	mA
ILIM pin voltage, V _{LIM}	ILIM pin voltage, V _{LIM}	-0.3	V _{BB}	V
Reverse ground current, I _{GND}	V _{BB} < 0V		-50	mA
Energy dissipation during turnoff, E _{AS}	Single pulse, V _{BB} = 13.5V, I _{OUT} = 5mA, T _{J,start} = 125°C, nominal slew rate (version P, M)		181 ⁽²⁾	mJ
Energy dissipation during turnoff, E _{AR}	Repetitive pulse, V _{BB} = 13.5V, I _{OUT} = 15A, T _{J,start} = 125°C, nominal slew rate (version P, M)		28 ⁽²⁾	mJ
Maximum junction temperature, T _J			150	°C
Storage temperature, T _{stg}		-65	150	°C

- (1) Operation outside the Absolute Maximum Ratings may cause permanent device damage. Absolute Maximum Ratings do not imply functional operation of the device at these or any other conditions beyond those listed under Recommended Operating Conditions. If used outside the Recommended Operating Conditions but within the Absolute Maximum Ratings, the device may not be fully functional, and this may affect device reliability, functionality, performance, and shorten the device lifetime.
- (2) For further details, see the section regarding switch-off of an inductive load.

6.2 ESD Ratings

			VALUE	UNIT
V _(ESD)	Electrostatic discharge ⁽¹⁾	Human-body model (HBM), per AEC Q100-002 Classification Level 2 ⁽²⁾	±2000	V
			±4000	
		Charged-device model (CDM), per AEC Q100-011 Classification Level C5	±750	

- (1) All ESD strikes are with reference from the pin mentioned to GND
- (2) AEC-Q100-002 indicates that HBM stressing shall be in accordance with the ANSI/ESDA/JEDEC JS-001 specifications.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)⁽¹⁾

		MIN	MAX	UNIT
V _{VBB_NOM}	Nominal supply voltage ⁽¹⁾	4	18	V
V _{VBB_EXT}	Extended supply voltage ⁽²⁾	3	28	V
V _{VBB_SC}	Short circuit supply voltage capability		24	V
V _{EN}	Enable voltage	-1	5.5	V
V _{DIAG_EN}	Diagnostic Enable voltage	-1	5.5	V

6.3 Recommended Operating Conditions (continued)

over operating free-air temperature range (unless otherwise noted) ⁽¹⁾

		MIN	MAX	UNIT
V _{SNS}	Sense voltage	-1	5.5	V
T _A	Operating free-air temperature	-40	125	°C

- (1) All operating voltage conditions are measured with respect to device GND
- (2) Device will function within extended operating range, however some timing parametric values might not apply. See the respective sections for what voltages are used. Additionally more explanation can be found in [Power Supply Recommendations](#)

6.4 Thermal Information

THERMAL METRIC ^{(1) (2)}		TPS1HC04-Q1		UNIT
		VAH		
		11 PINS		
R _{θJA}	Junction-to-ambient thermal resistance	42.7		°C/W
R _{θJC(top)}	Junction-to-case (top) thermal resistance	39.2		°C/W
R _{θJB}	Junction-to-board thermal resistance	9.6		°C/W
ψ _{JT}	Junction-to-top characterization parameter	2.0		°C/W
ψ _{JB}	Junction-to-board characterization parameter	9.6		°C/W
R _{θJC(bot)}	Junction-to-case (bottom) thermal resistance	8.0		°C/W

- (1) For more information about traditional and new thermal metrics, see the [SPRA953](#) application report.
- (2) The thermal parameters are based on a 4-layer PCB according to the JESD51-5 and JESD51-7 standards.

6.5 Electrical Characteristics

V_{BB} = 6V to 18V, T_J = -40°C to 150°C (unless otherwise noted); Typical application is V_{BB} = 13.5V, R_{LIM} = Open (unless otherwise specified)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
INPUT VOLTAGE AND CURRENT							
V _{UVLOR}	VBB undervoltage lockout	Measured with respect to device GND pin	VBB rising threshold	3.7	3.85	4.0	V
V _{UVLOF}			VBB falling threshold	2.8	2.9	3.0	V
V _{DET1}	VBB detection 1 threshold	Active, diagnostic, or standby state	VBB rising threshold	19	20.5	22.5	V
			VBB falling threshold	18.4	19.5	20.7	V
V _{DET2}	VBB detection 2 threshold	active state	VBB rising threshold	24.5	26	28	V
			VBB falling threshold	22.5	24	26	V
V _{HV_R}	VBB high voltage wakeup threshold	VBB voltage to transition from sleep to standby state	VBB rising threshold	20.9	25	28.1	V
V _{HV_F}		VBB voltage to transition from standby to sleep state	VBB falling threshold	18			V
V _{Clamp}	VDS clamp voltage	VBB ≥ V _{DET1}	T _J = 25°C			37	V
			T _J = -40°C to 150°C	31		42	V
		VBB < V _{DET1}	T _J = -40°C to 150°C	24		35	V
I _{SLEEP}	Standby current (total device leakage including MOSFET channel)	V _{EN} = V _{DIAG_EN} = 0V, V _{OUT} = 0V	T _J = 25°C			1.2	µA
			T _J = 85°C			1.4	µA
			T _J = 150°C			12	µA

6.5 Electrical Characteristics (continued)

V_{BB} = 6V to 18V, T_J = -40°C to 150°C (unless otherwise noted); Typical application is V_{BB} = 13.5V, R_{LIM} = Open (unless otherwise specified)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
I _{OUT(SLEEP)}	Output leakage current	V _{EN} = V _{DIAG_EN} = 0V, V _{OUT} = 0V	T _J = 25°C		0.02	0.5	μA
			T _J = 85°C			0.7	μA
			T _J = 150°C			6	μA
I _{DIAG}	Diagnostic state current consumption	V _{EN} = 0V, V _{DIAG_EN} = 5V, V _{OUT} = 0V, I _{SNS} = 0A			1.4	2.4	mA
		V _{EN} = 5V, V _{DIAG_EN} = 0V, V _{OUT} = 0V, I _{SNS} = 0A			1.4	2.4	mA
I _Q	Quiescent current	V _{EN} = V _{DIAG_EN} = 5V, I _{OUT} = 0A			1.7	2.6	mA
t _{STBY}	Standby mode delay time	V _{EN} = V _{DIAG_EN} = 0V, V _{BB} < V _{HV_F} to standby		15	20	23	ms
RON CHARACTERISTICS							
R _{ON}	On-resistance	3V ≤ V _{BB} ≤ 28V, I _{OUT} = 1A	T _J = 25°C		4.9	5.2	mΩ
			T _J = 150°C			8	mΩ
R _{ON(REV)}	On-resistance during reverse polarity	-18V ≤ V _{BB} ≤ -6V	T _J = 25°C		4.9	5.3	mΩ
			T _J = 150°C			8.1	mΩ
I _{L(NOM)}	Continuous load current	T _{AMB} = 85°C			15		A
V _F	Source-to-drain body diode voltage	V _{EN} = 0V I _{OUT} = -1A		0.15	0.6	0.8	V
CURRENT SENSE CHARACTERISTICS							
V _{BB_ISNS}	V _{BB} headroom needed for full current sense and fault functionality ⁽²⁾	V _{DIAG_EN} = 3.3V		5.3			V
		V _{DIAG_EN} = 5V		6.5			V
K _{SNS}	Current sense ratio I _{OUT} / I _{SNS} across I _{OUT}	V _{BB} > V _{BB_ISNS} , V _{EN} = V _{DIAG_EN} = 5V	I _{OUT} = 5A		6000		A/A
					-9	9	%
			I _{OUT} = 2A		6011		A/A
					-17	15	%
			I _{OUT} = 1A		6030		A/A
					-25	25	%
			I _{OUT} = 500mA		6053		A/A
					-38	38	%
SNS CHARACTERISTICS							
I _{SNSleak}	I _{SNS} fault high-level	V _{DIAG_EN} > V _{IH,DIAG_EN}		5.5	7.4	9.5	mA
I _{SNSleak_disabled}	I _{SNS} leakage (Diagnostics disabled)	V _{DIAG_EN} = 0V	Force 0V on SNS Pin	-100	1	100	nA
CURRENT LIMIT CHARACTERISTICS							
R _{LIM}	RLIM Short Circuit Detection Range				16.67		kΩ
	RLIM Open Detection Range				50		kΩ
I _{CL_FLT_Trip}	Ratio of Current at which fault assertion happens to actual current limit ⁽²⁾	T _J = -40°C to 150°C	R _{LIM} = 16.67kΩ to 50kΩ	74	80		%
K _{CL}	Current Limit Ratio ⁽¹⁾	T _J = -40°C to 150°C	R _{LIM} = 16.67kΩ	607.5	750	952.5	A * kΩ
			R _{LIM} = 25kΩ	607.5	750	952.5	A * kΩ
			R _{LIM} = 50kΩ	637.5	750	862.5	A * kΩ
I _{CL}	I _{CL} Current Limit Threshold	T _J = -40°C to 150°C	R _{LIM} = GND		45		A
			R _{LIM} = OPEN		15		A

6.5 Electrical Characteristics (continued)

V_{BB} = 6V to 18V, T_J = –40°C to 150°C (unless otherwise noted); Typical application is V_{BB} = 13.5V, R_{LIM} = Open (unless otherwise specified)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
I _{CB}	Peak current threshold when short is applied while switch enabled ⁽²⁾	R _{LIM} = 16.67kΩ to 50kΩ	T _J = –40°C		49		A
			T _J = 25°C		50		A
			T _J = 150°C		51		A
I _{CL_HV}	I _{CL} current limit derating at high voltage ⁽²⁾	T _J = –40°C to 150°C	V _{BB} < V _{DET1}		I _{CL}		A
			V _{DET1} ≤ V _{BB} < V _{DET2}		(I _{CL})/2		A
			V _{BB} ≥ V _{DET2}		(I _{CL})/3		A
I _{CL_LNPK}	Linear mode peak ⁽²⁾	T _J = –40°C to 150°C	R _{LIM} > 25kΩ		1.45 × I _{CL}		A
			R _{LIM} ≤ 25kΩ		1.45 × I _{CL}	I _{CB}	A

FAULT CHARACTERISTICS

V _{OL}	Open-load detection voltage (V _{BB} - V _{OUT} voltage)	V _{EN} = 0 V, V _{DIAG_EN} = 5V, diagnostic state	1.5	2.2	2.9	V
R _{PU}	Open-load (OL) detection internal pull-up resistor per channel	V _{EN} = 0 V, V _{DIAG_EN} = 5V, (V _{BB} - V _{OUT} = 2.7V)		90		kΩ
t _{OL}	Open-load (OL) detection deglitch time	V _{EN} = 0 V, V _{DIAG_EN} = 5V, When V _{BB} - V _{OUT} < V _{OL} , duration longer than t _{OL} . Openload detected.	200		550	μs
t _{OL1}	OL and STB indication-time from EN falling	V _{EN} = 5V to 0V, V _{DIAG_EN} = 5V I _{OUT} = 0mA, V _{OUT} = V _{BB} - V _{OL}	150		550	μs
t _{OL2}	OL and STB indication-time from DIA_EN rising	V _{EN} = 0V, V _{DIAG_EN} = 0V to 5V I _{OUT} = 0mA, V _{OUT} = V _{BB} - V _{OL}	200		4900	μs
T _{ABS}	Thermal shutdown ⁽²⁾		150	165	180	°C
T _{REL}	Relative thermal shutdown			85		°C
T _{HYS}	Thermal shutdown hysteresis			28		°C
V _{FLT}	FLT low output voltage	I _{FLT} = 2.5mA			0.2	V
t _{FAULT_FLT}	Fault indication-time ⁽²⁾	V _{DIAG_EN} = 5V, time between fault and FLT asserting			20	μs
t _{FAULT_SNS}	Fault indication-time ⁽²⁾	V _{DIAG_EN} = 5V, time between fault and I _{SNS} settling at I _{SNSFH}			30	μs
t _{RETRY_WIN DOW}	Initial retry time window			40		ms
t _{RETRY_INT}	Retry time in initial retry window	Time from thermal shutdown to switch re-enable	100	160	300	μs
t _{RETRY_EXT}	Retry time in extended overcurrent		50	80	150	ms

EN PIN CHARACTERISTICS

V _{IL_EN}	Input voltage low-level	No GND Network			0.8	V
V _{IH_EN}	Input voltage high-level		1.5			V
V _{IHYS_EN}	Input voltage hysteresis			320		mV
R _{EN}	Internal pulldown resistor		150	200	500	kΩ
I _{IL_EN}	Input current low-level ⁽²⁾	V _{EN} = 0.8V	1.6	4	5.5	μA
I _{IH_EN}	Input current high-level ⁽²⁾	V _{EN} = 5V	19	25	35	μA

DIA_EN PIN CHARACTERISTICS

V _{IL_DIAG_EN}	Input voltage low-level	No GND Network			0.8	V
V _{IH_DIAG_EN}	Input voltage high-level		1.5			V

6.5 Electrical Characteristics (continued)

V_{BB} = 6V to 18V, T_J = -40°C to 150°C (unless otherwise noted); Typical application is V_{BB} = 13.5V, R_{LIM} = Open (unless otherwise specified)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
V _{IHYS, DIAG_EN}	Input voltage hysteresis			320		mV
R _{DIAG_EN}	Internal pulldown resistor		100	200	500	kΩ
I _{IL, DIAG_EN}	Input current low-level ⁽²⁾	V _{DIAG_EN} = 0.8V	1.6	4	5.5	μA
I _{IH, DIAG_EN}	Input current high-level ⁽²⁾	V _{DIAG_EN} = 5V	19	25	35	μA

- (1) To calculate I_{CL} from K_{CL} use equation I_{CL} = K_{CL} / R_{LIM}
(2) Parameter specified by design; not subject to production test.

6.6 SNS Timing Characteristics

V_{BB} = 6V to 18V, V_{EN} = 5V, V_{DIAG_EN} = 5V, R_{SNS} = 1kΩ, T_J = -40°C to +150°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
SNS TIMING - CURRENT SENSE						
t _{SNSION1}	Settling time from rising edge of DIAG_EN ⁽¹⁾	V _{DIAG_EN} = 0V to 5V, I _{OUTX} = 1A			20	μs
		V _{DIAG_EN} = 0V to 5V, I _{OUTX} = 50mA			20	μs
t _{SNSION2}	Settling time from rising edge of EN and DIAG_EN, 50% of V _{DIAG_EN} , V _{EN} to 90% of I _{SNS}	V _{EN} = V _{DIAG_EN} = 0V to 5V, I _{OUT} = 1A			170	μs
		V _{EN} = V _{DIAG_EN} = 0V to 5V, I _{OUT} = 50mA			170	μs
t _{SNSION3}	Settling time from rising edge of EN with DIAG_EN = HI; 50% of V _{EN} to 90% of I _{SNS}	V _{EN} = 0V to 5V, V _{DIAG_EN} = 5V, I _{OUT} = 1A			110	μs
t _{SNSIOFF}	Settling time from falling edge of DIAG_EN; 50% of V _{DIAG_EN} to 5% of I _{SNS} ⁽¹⁾	V _{EN} = 5V, V _{DIAG_EN} = 5V to 0V, I _{OUT} = 1A			20	μs
t _{SETTLEH}	Settling time from rising edge of load step ⁽¹⁾	I _{OUT} = 50mA to 1A			20	μs
t _{SETTLEL}	Settling time from falling edge of load step ⁽¹⁾	I _{OUT} = 1A to 50mA			20	μs

- (1) Parameter specified by design; not subject to production test

6.7 Switching Characteristics

V_{BB} = 13.5V, R_L = 10Ω, T_J = -40°C to +150°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
t _{DR}	Channel Turn-on delay time	50% of EN to 20% of V _{OUT} from standby state	6	12	30	μs
		50% of EN to 20% of V _{OUT} from sleep state	10	45	70	μs
t _{DF}	Channel Turn-off delay time	50% of EN to 80% of V _{OUT}	35	80	121	μs
SR _R	V _{OUT} rising slew rate	20% to 80% of V _{OUT} , 0.9 Ohm load (version D, B)	0.02	0.04	0.07	V/μs
		20% to 80% of V _{OUT} , 0.9 Ohm load (version P, M)	0.3	0.45	1	V/μs
SR _F	V _{OUT} falling slew rate	80% to 20% of V _{OUT} , (version D, B)	0.02	0.04	0.07	V/μs
		80% to 20% of V _{OUT} , (version P, M)	0.3	0.4	0.6	V/μs
t _{ON}	Channel Turn-on time	50% of EN to 80% of V _{OUT} , from standby state	15	30	90	μs
		50% of EN to 80% of V _{OUT} , from sleep state	35	60	110	μs

6.7 Switching Characteristics (continued)

V_{BB} = 13.5V, R_L = 10Ω, T_J = –40°C to +150°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
t _{OFF}	Channel Turn-off time	50% of EN to 20% of V _{OUT}	50	90	130	μs
t _{ON} – t _{OFF}	Turn-on and off matching ⁽¹⁾	1ms enable pulse	–75		40	μs
		200μs enable pulse	–100		40	μs
Δ _{PWM}	PWM accuracy - average load current ⁽¹⁾	200μs enable pulse (1ms period)	–45		25	%
		≤500Hz, 50% Duty cycle	–12		12	%
E _{ON}	Switching energy losses during turn-on	V _{BB} = 18V, R _L = 2.1Ω, 0% to 100% of V _{OUT}		0.57		mJ
		V _{BB} = 18V, R _L = 2.1Ω, 10% to 90% of V _{OUT}		0.51		mJ
E _{OFF}	Switching energy losses during turn-off	V _{BB} = 18V, R _L = 2.1Ω, 100% to 0% of V _{OUT}		0.72		mJ
		V _{BB} = 18V, R _L = 2.1Ω, 90% to 10% of V _{OUT}		0.68		mJ

(1) Parameter specified by design; not subject to production test.

6.8 Typical Characteristics

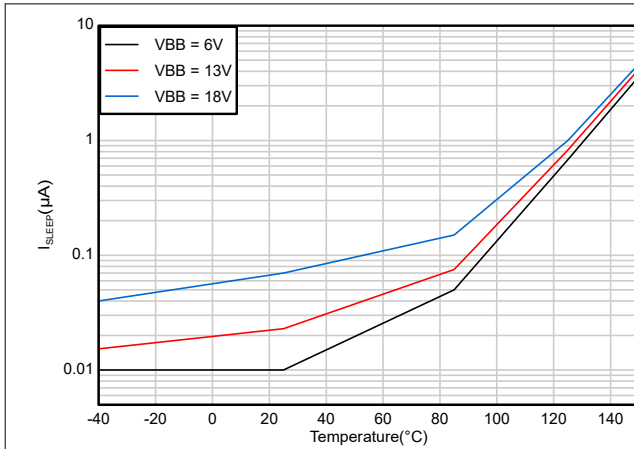


Figure 6-1. Standby Current (I_{SLEEP}) vs Temperature

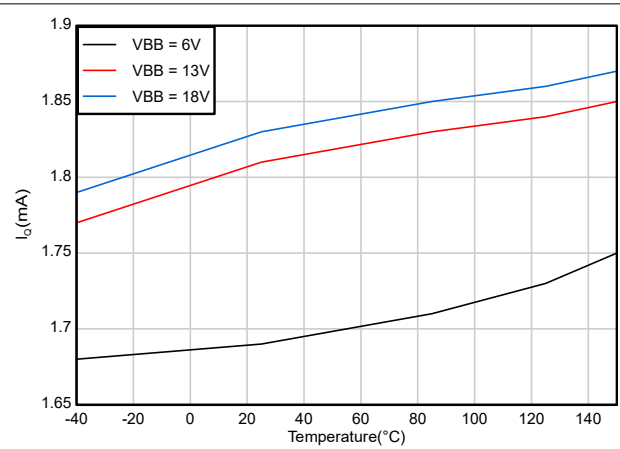


Figure 6-2. Quiescent Current (I_Q) vs Temperature

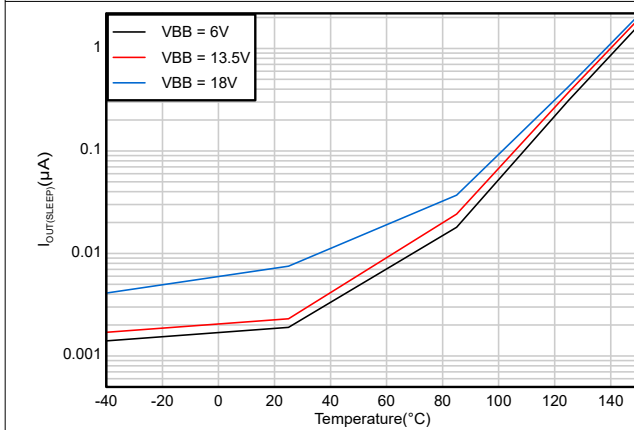


Figure 6-3. Output Leakage Current ($I_{OUT(SLEEP)}$) vs Temperature

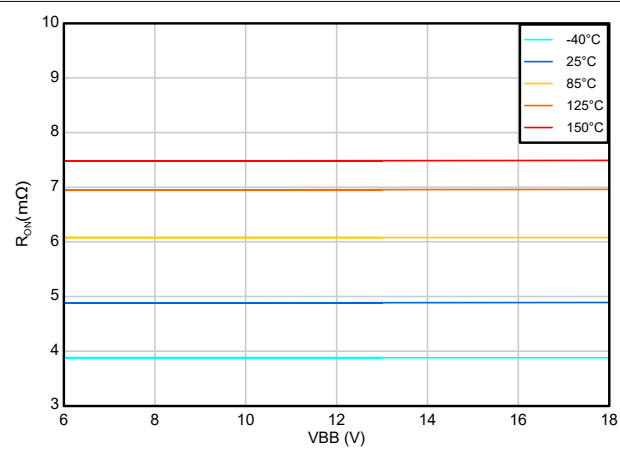


Figure 6-4. On-resistance (R_{ON}) vs VBB

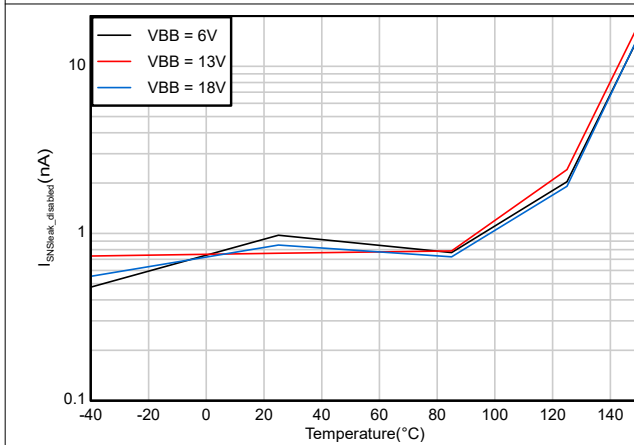


Figure 6-5. I_{SNS} leakage with Diagnostics disabled vs Temperature

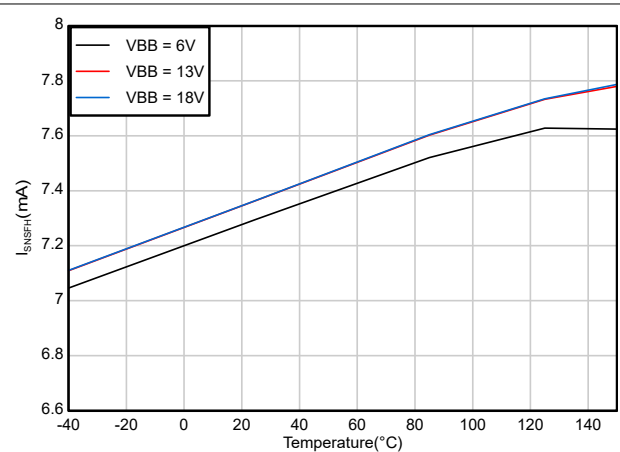


Figure 6-6. I_{SNS} fault high-level current vs Temperature

6.8 Typical Characteristics (continued)

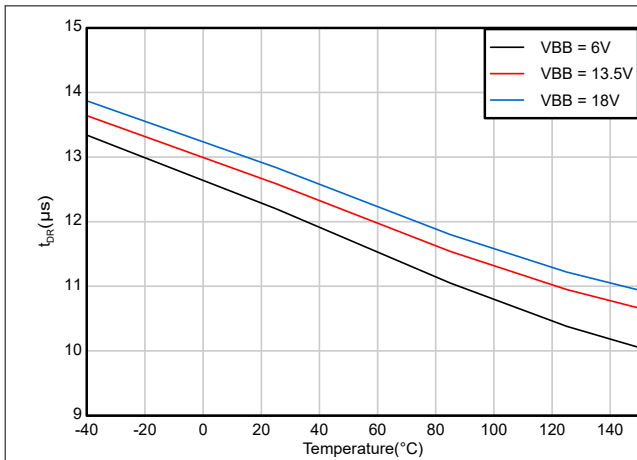


Figure 6-7. Channel Turn-on Delay Time (t_{DR}) vs Temperature

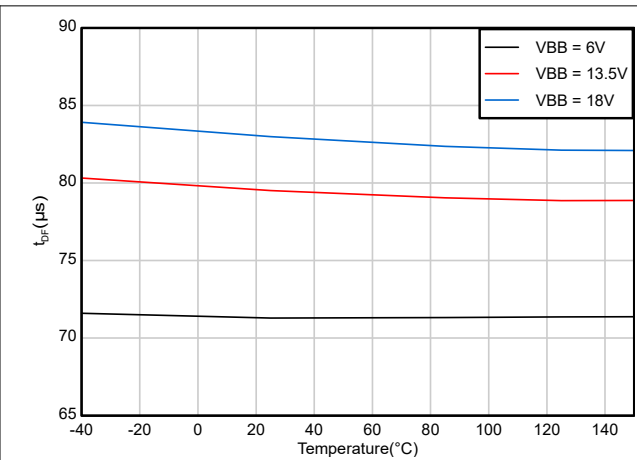


Figure 6-8. Channel Turn-off Delay Time (t_{DF}) vs Temperature

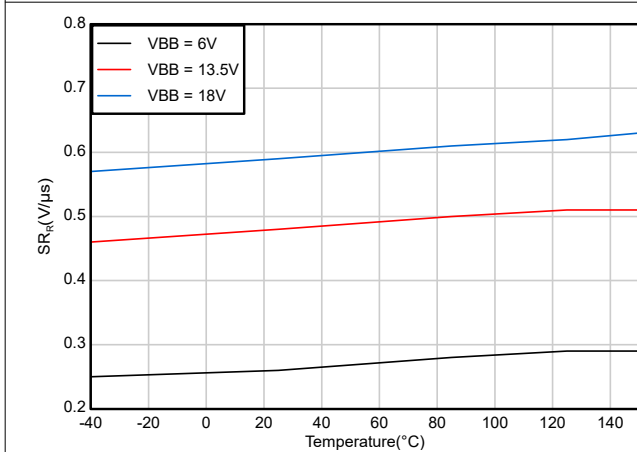


Figure 6-9. VOUT Rising Slew Rate (SR_R) vs Temperature (P, M version)

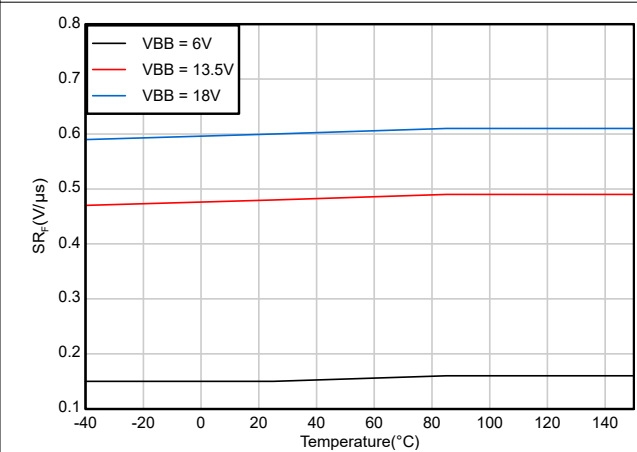


Figure 6-10. VOUT Falling Slew Rate (SR_F) vs Temperature (P, M version)

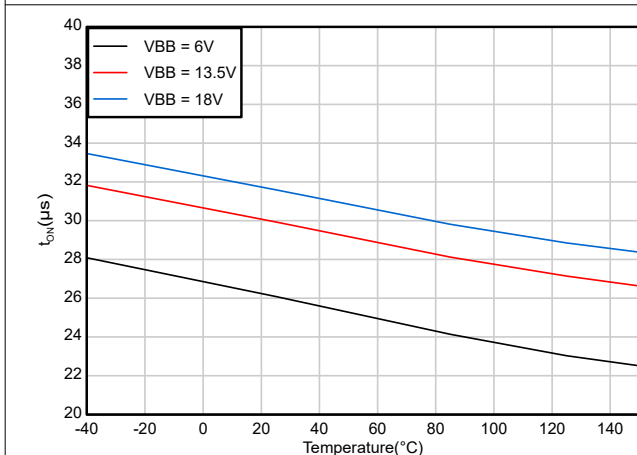


Figure 6-11. Channel Turn-on Time (t_{ON}) vs Temperature

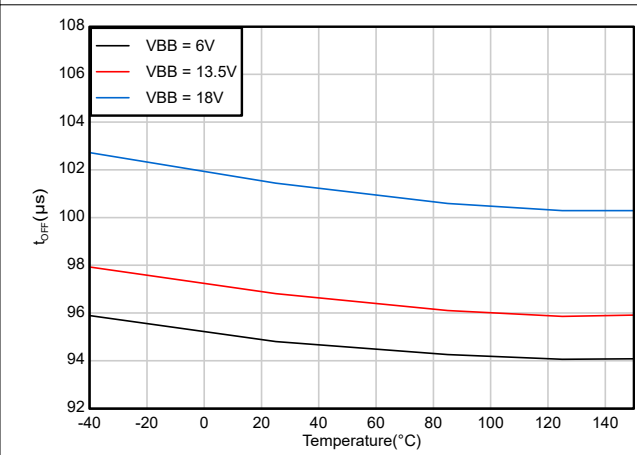


Figure 6-12. Channel Turn-off Time (t_{OFF}) vs Temperature

6.8 Typical Characteristics (continued)

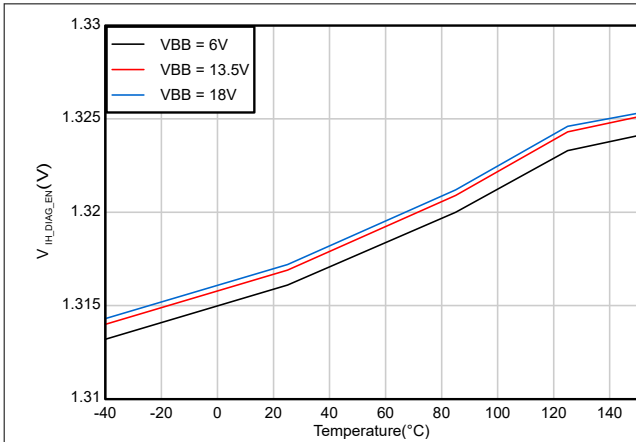


Figure 6-13. DIAG_EN Input Voltage High Level vs Temperature

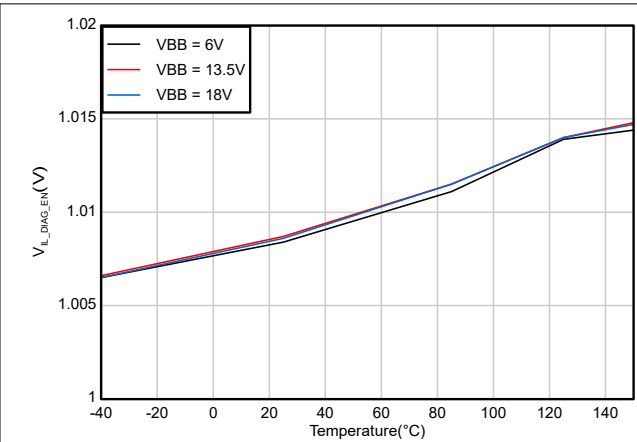


Figure 6-14. DIAG_EN Input Voltage Low Level vs Temperature

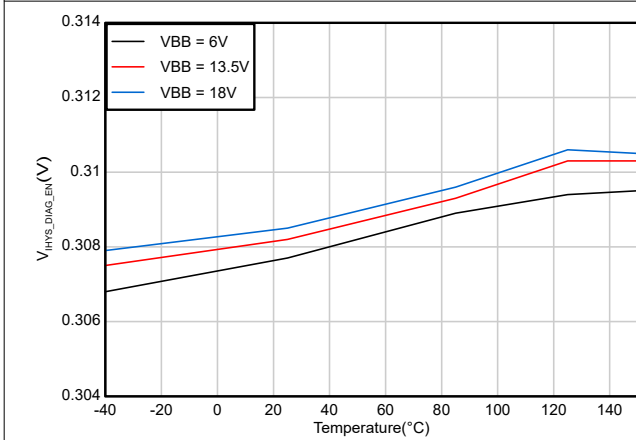


Figure 6-15. DIAG_EN Input Voltage Hysteresis vs Temperature

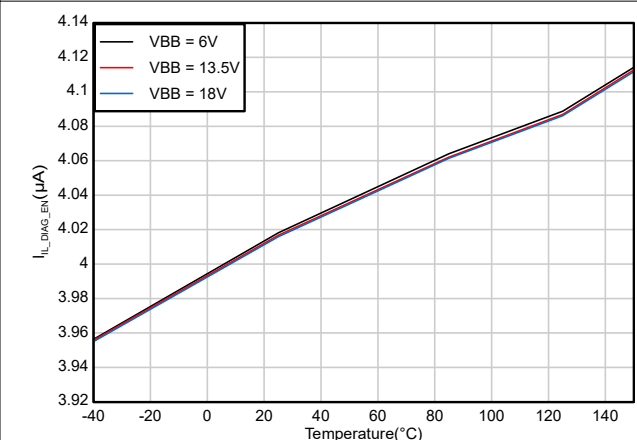


Figure 6-16. DIAG_EN Input Current Low Level vs Temperature

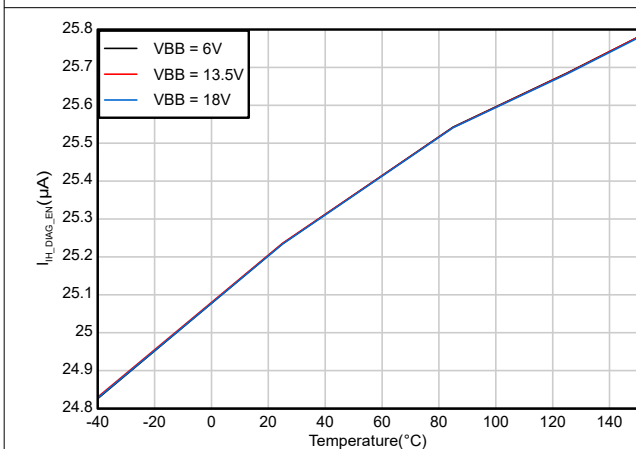


Figure 6-17. DIAG_EN Input Current High Level vs Temperature

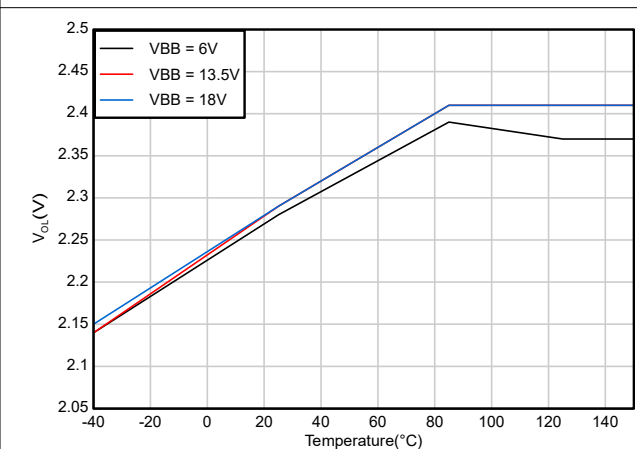


Figure 6-18. Open-Load Detection Voltage (V_{OL}) vs Temperature

6.8 Typical Characteristics (continued)

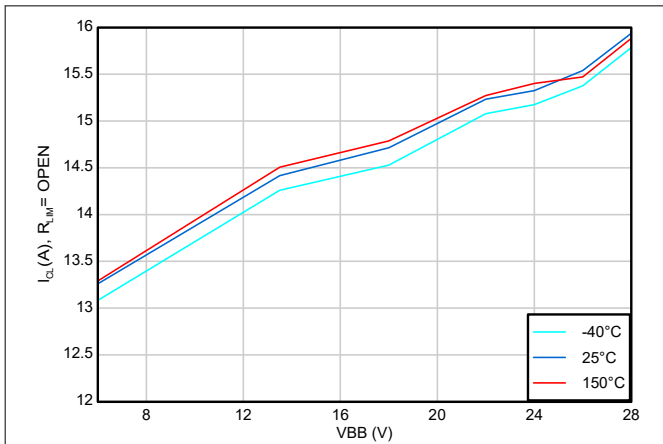


Figure 6-19. Current Limit Regulation Level (I_{CL}) vs V_{BB} , $R_{LIM} = OPEN$

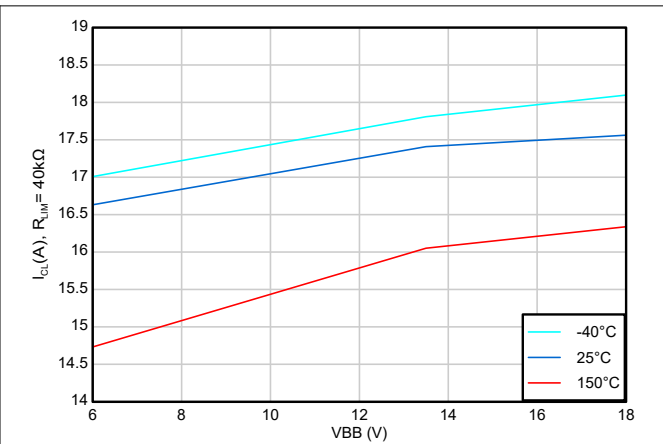


Figure 6-20. Current Limit Regulation Level (I_{CL}) vs V_{BB} , $R_{LIM} = 40k\Omega$

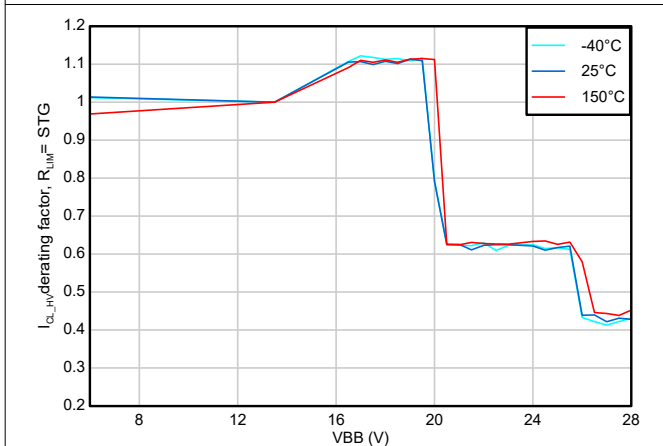


Figure 6-21. Current Limit Derating factor (I_{CL_HV}) vs V_{BB} , $R_{LIM} = STG$

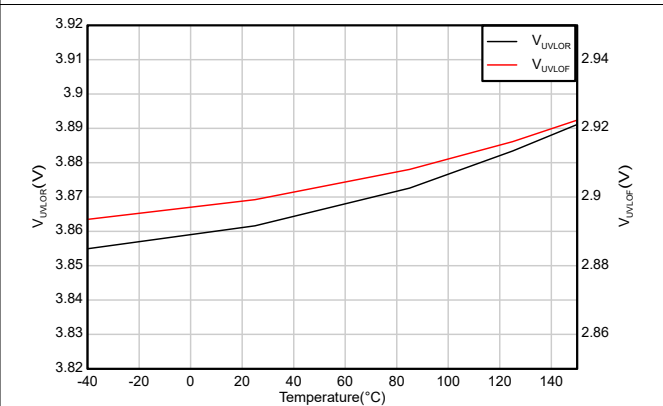


Figure 6-22. Undervoltage Lockout Thresholds (V_{UVLOR} , V_{UVLOF}) vs Temperature

7 Parameter Measurement Information

For reference purposes throughout the data sheet, current directions on the respective pins are as shown by the arrows in Figure 7-1. All voltages are measured relative to the ground plane.

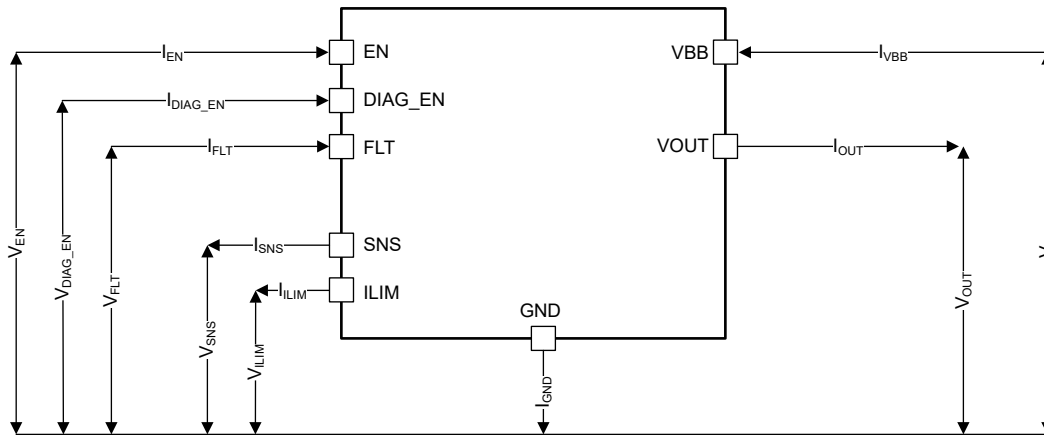
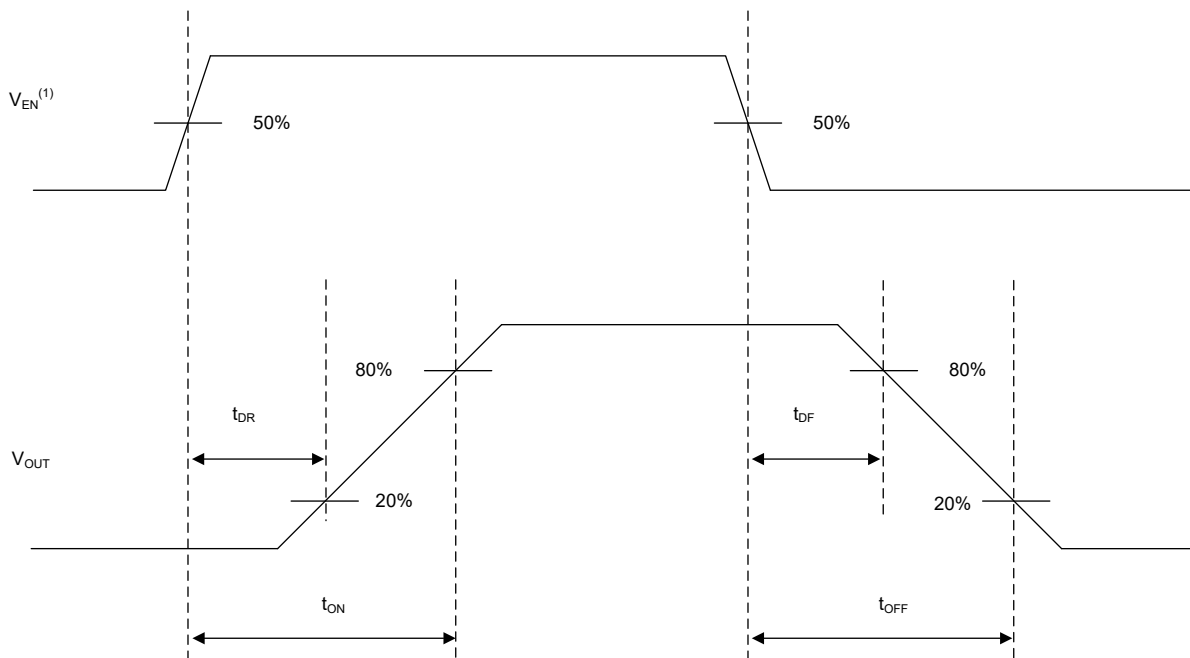


Figure 7-1. Voltage and Current Conventions



Rise and fall time of VEN is 100 ns.

Figure 7-2. Switching Characteristics Definitions

8 Detailed Description

8.1 Overview

The TPS1HC04-Q1 is a single-channel, fully-protected, high side power switch with integrated NMOS power FET and charge pump. Full diagnostics and high-accuracy current-sense features enable intelligent control of the load. The device offers two pins to support both digital status and analog current-sense output. The current-sense output can be set to high-impedance state when diagnostics are disabled, which can enable multiplexing of the MCU analog interface between multiple devices.

The device has dedicated logic pin to enable the FET and a separate DIAG_EN pin to enable the diagnostic output. With diagnostics enabled, the analog current sense is output on the SNS pin. The device also implements a global $\overline{\text{FLT}}$ pin with an open-drain structure, to be used as an interrupt to the MCU. When a fault condition occurs, the pin is pulled down to GND. An external pullup is required to match the microcontroller supply level.

High-accuracy current sensing allows for better real-time monitoring and more-accurate diagnostics without additional in-line calibration. A current mirror is used to source $1 / K_{\text{SNS}}$ of the load current, which is reflected as voltage across a resistor on the SNS pin. The SNS pin can also report a fault by sourcing a current of I_{SNSFH} out of the SNS pin. During fault the SNS pin voltage is represented by $I_{\text{SNSFH}} \times R_{\text{SNS}}$. If this voltage violates the acceptable voltage range of the MCU ADC, an external Zener diode or resistor divider on the SNS pin has to be connected.

The device also offers a programmable current-limit function which greatly improves the reliability of the whole system by clamping the inrush current effectively at start-up when charging large capacitances or during short-circuit conditions. The high-accuracy current limit of the device can be set using an external resistor between 15A to 45A. The device also offers current limit settings with and without thermal regulation. The thermal regulated current limit can be useful when charging large capacitors at startup. The current limit setting without thermal regulation is useful for loads such high motor stall currents or bulb loads.

A voltage clamp is built in to address switching off the energy of inductive loads, such as relays, solenoids, pumps, motors, and so forth. With the benefits of process technology and excellent IC layout, the TPS1HC04-Q1 device can achieve excellent power dissipation capacity, which can help save the external free-wheeling circuitry in most cases. For more details, see Inductive-Load Switching-Off Clamp.

The TPS1HC04-Q1 device can be used as a high side power switch for a wide variety of resistive, inductive, and capacitive loads, including bulbs, LEDs, relays, solenoids, and heaters.

8.2 Functional Block Diagram

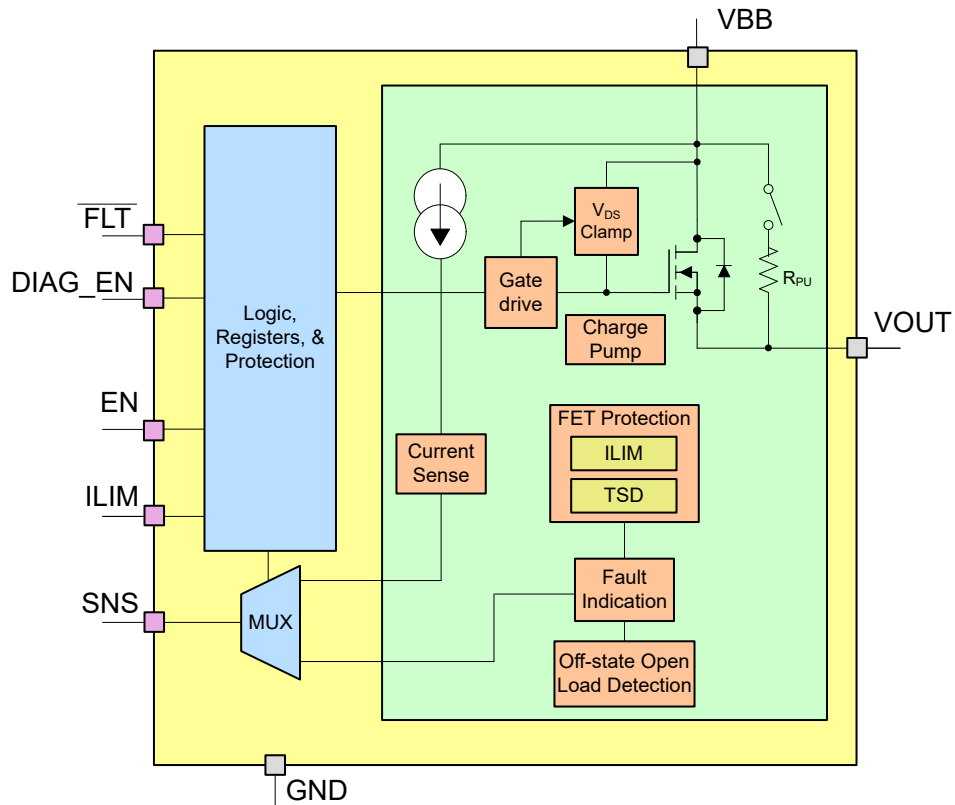


Figure 8-1. Functional Block Diagram

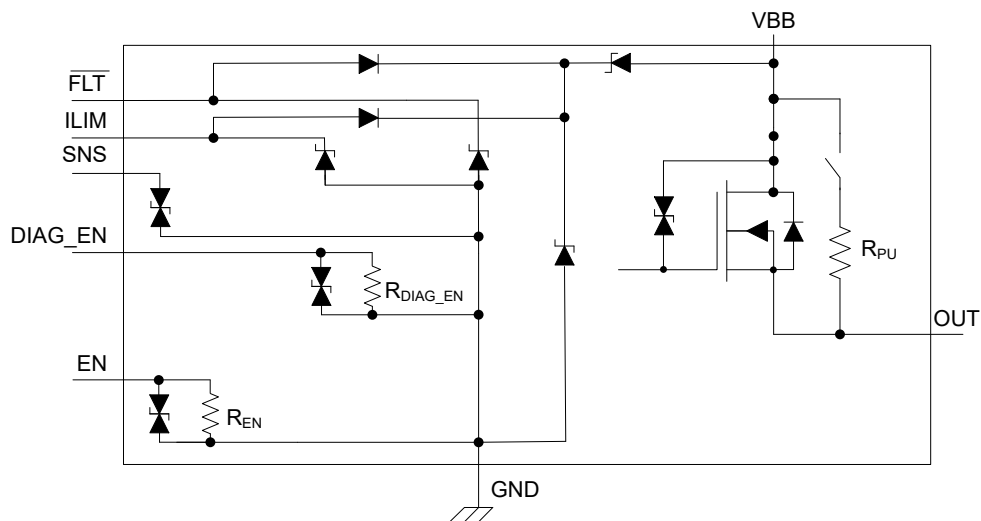


Figure 8-2. Internal Diodes Diagram

The above figure shows the internal diodes structure of the device. There are back-to-back diodes connected between GND pin and low voltage IO pins to provide voltage clamp along with the internal pull-down resistor to keep pins in known state. The $\overline{\text{FLT}}$ and ILIM pins have internal protection structure to withstand voltage up to VBB, making it robust against adjacent pin short. A drain-to-source clamp structure, comprising back-to-back zener and diode, is also implemented across the power switch to protect against inductive energy demagnetisation.

8.3 Feature Description

8.3.1 Input Voltage Thresholds

The device has below input voltage thresholds:

- VBB undervoltage lockout thresholds (V_{UVLOR} , V_{UVLOF}) determines device turn on and off voltages.
- VBB detection 1 thresholds (V_{DET1}) determines device VDS clamp voltage (V_{clamp}) switching and I_{CL} and I_{CB} foldback across VBB.
- VBB detection 2 thresholds (V_{DET2}) determines I_{CL} and I_{CB} foldback across VBB.
- VBB high voltage wakeup thresholds (V_{HV_R} , V_{HV_F}) determines device transition from standby to sleep state. In case V_{HV_R} threshold value is higher than (V_{DET1} or V_{DET2}) rising threshold, the V_{HV_R} threshold also determines the VDS clamp voltage (V_{clamp}) switching.

8.3.2 Accurate Current Sense

The high-accuracy current-sense function allows a better real-time monitoring effect and accurate diagnostics without further calibration. A current mirror is used to source $1 / K_{SNS}$ of the load current, flowing out to the external resistor between the SNS pin and GND, and reflected as voltage on the SNS pin.

K_{SNS} is the ratio of the output current and the sense current. The accuracy values of K_{SNS} quoted in the electrical characteristics do take into consideration temperature and supply voltage. Each device is internally calibrated while in production, so post-calibration by users is not required.

The sense resistor value, R_{SNS} , can be chosen to maximize the range of currents needed to be measured by the system. The R_{SNS} value must be chosen based on application need. The minimum R_{SNS} value is bounded by the ADC minimum acceptable voltage, $V_{ADC,min}$, for the minimum load current needed to be measured by the system, $I_{LOAD,min}$. The maximum R_{SNS} value is bounded by the ADC maximum acceptable voltage, $V_{ADC,max}$, for the I_{SNSFH} (check [Electrical Characteristics](#) for the minimum specification) during fault condition. The SNS pin current during fault condition, I_{SNSFH} should be significantly higher than the SNS pin current at maximum load current ($I_{LOAD,max}$), to provide sufficient headroom voltage (V_{HR}) to determine difference between the maximum readable current and a fault condition. Use [Equation 1](#) to calculate the value of R_{SNS} without any external zener diode or resistor divider on SNS pin.

$$\frac{(V_{ADC,min} \times K_{SNS})}{I_{LOAD,min}} \leq R_{SNS} \leq \frac{V_{ADC,max}}{I_{SNSFH}} \quad (1)$$

To get better resolution in current sense voltage, an external Zener diode or resistor divider can be connected to the SNS pin to clamp the SNS pin voltage to ADC maximum acceptable voltage, $V_{ADC,max}$ during the fault condition. In this case, user needs to select R_{SNS} resistor to achieve required headroom voltage (V_{HR}) between the maximum readable current and a fault condition. Use [Equation 2](#) to calculate the value of R_{SNS} in this scenario.

$$\frac{(V_{ADC,min} \times K_{SNS})}{I_{LOAD,min}} \leq R_{SNS} \leq \frac{((V_{ADC,max} - V_{HR}) \times K_{SNS})}{I_{LOAD,max}} \quad (2)$$

In some applications, where there is a higher load current range the above applicable boundary equation can only satisfy either the lower or upper bound. In these cases, more emphasis can be put on the lower measurable current values which increases R_{SNS} . Likewise, if the higher currents are of more interest the R_{SNS} can be decreased. In case a GND network is used for reverse polarity protection, the voltage drop across the GND network has to be taken into account to ensure that the SNS pin voltage does not exceed the maximum acceptable ADC voltage.

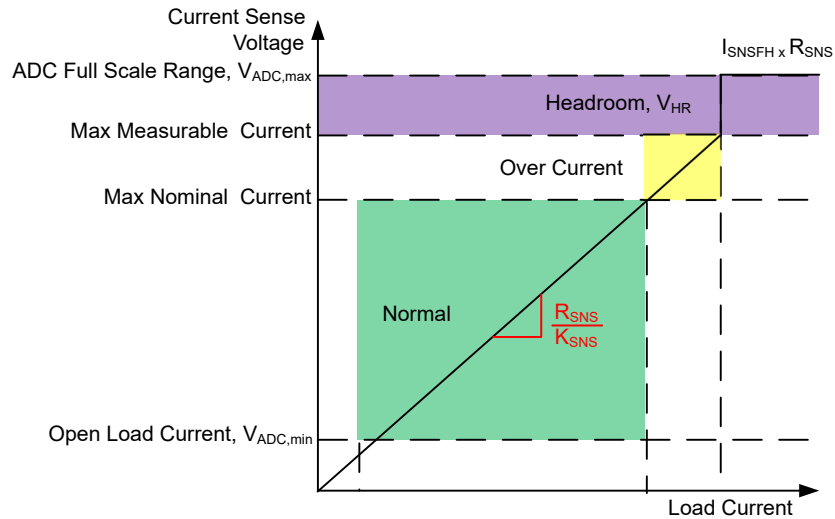


Figure 8-3. Voltage Indication on the Current-Sense Pin

The maximum current the system wants to read, $I_{LOAD,max}$, must be below the current-limit threshold because after the current-limit threshold is tripped the SNS pin current goes to I_{SNSFH} . Figure 8-4 shows the SNS pin behavior for 5A load step on the device with $1k\Omega R_{SNS}$



Figure 8-4. SNS Pin Voltage with Varying Load Current ($R_{SNS} = 1k\Omega$)

8.3.2.1 SNS Response Time

Some applications can operate with a high frequency, low duty cycle PWM. Such applications require fast settling of the SNS output. For example, a 250Hz, 5% duty cycle PWM has an on-time of only $200\mu s$. The microcontroller ADC can sample the SNS signal after the defined settling time. The following figures shows response time of SNS signal with EN and DIAG_EN being pulled high respectively. The fast response time of the device SNS signal easily allows current sense read by ADC in such applications.

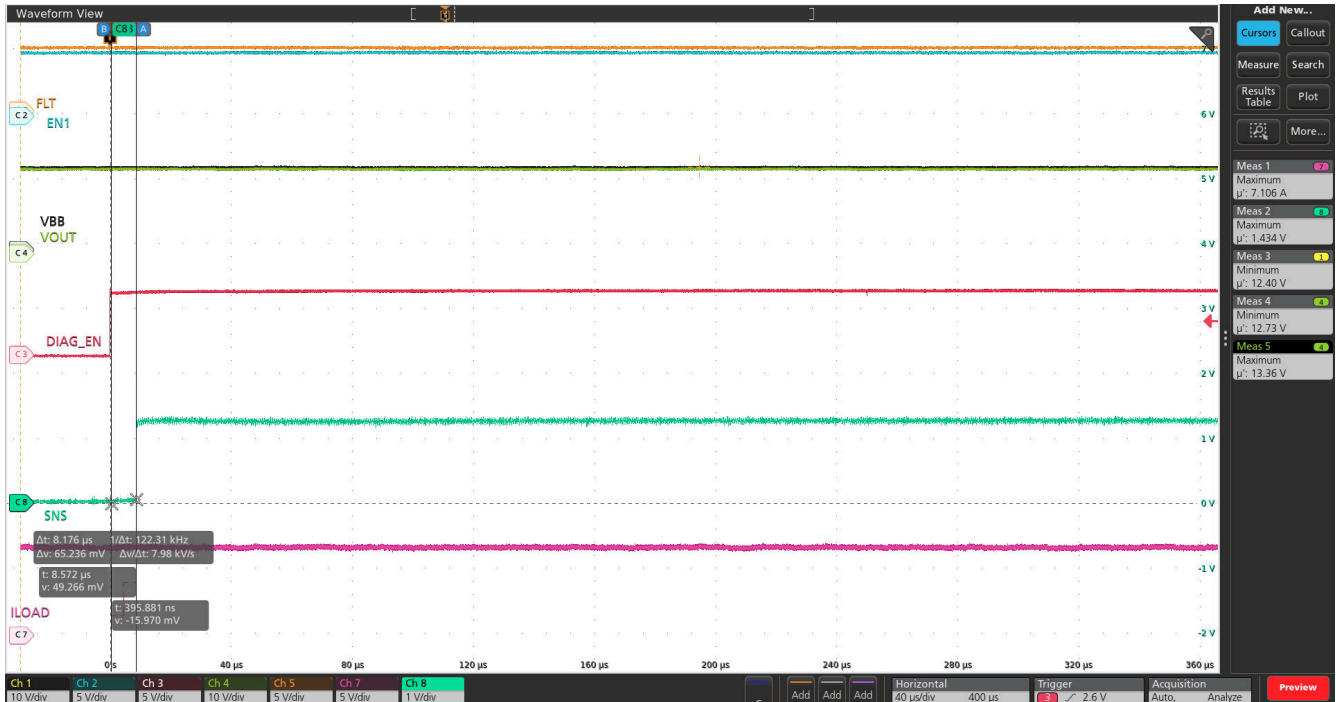


Figure 8-5. SNS Response Time with DIAG_EN ($t_{SNSION1}$)



Figure 8-6. SNS Response Time with EN ($t_{SNSION3}$)

Note

Rise and fall times of control signals are 100ns. Control signals include: EN and DIAG_EN.

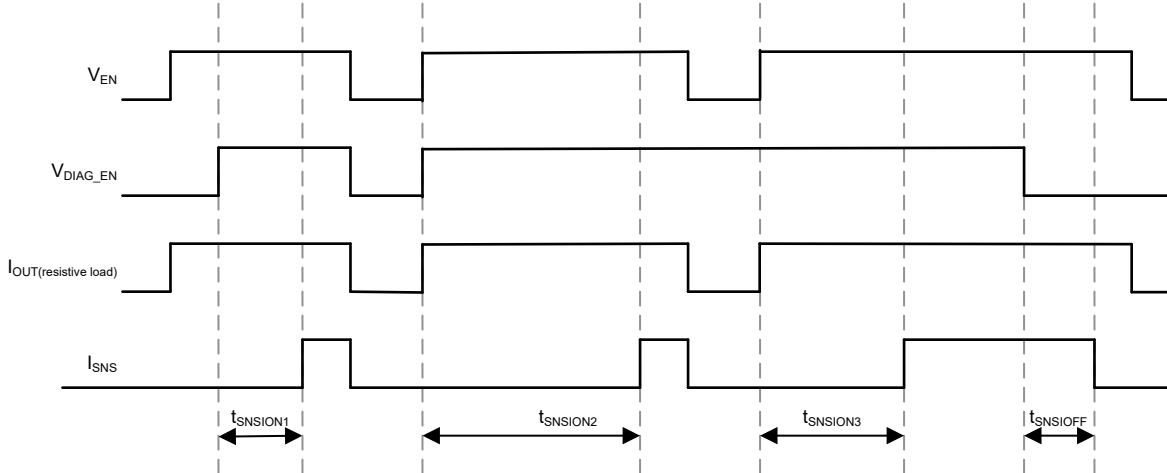


Figure 8-7. SNS Settling Time From EN or DIAG_EN

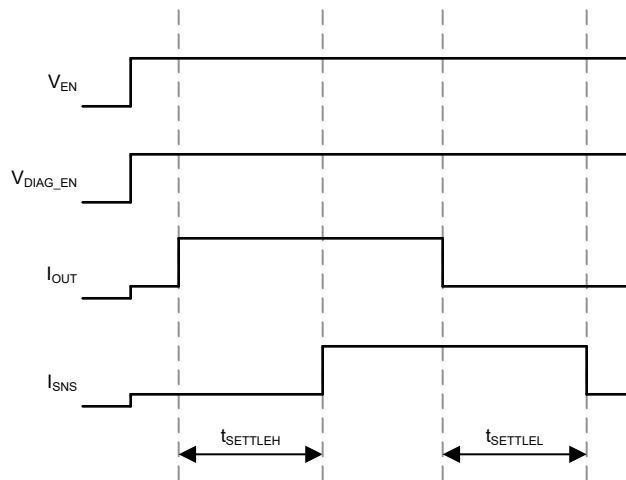


Figure 8-8. SNS Settling Time From Load step

8.3.2.2 SNS Output Filter

Due to the internal architecture, the SNS pin signal has a ripple component at a frequency of approximately 1.6MHz. Based on the R_{SNS} value, appropriate C_{SNS} can be connected on SNS pin to filter out this ripple component and reduce the peak-to-peak ripple of the SNS pin voltage. Table 8-1 shows the typical peak-to-peak ripple voltage values with and without C_{SNS} on SNS pin. The designer can select a C_{SNS} capacitor value based on system requirements. A larger value can provide improved filtering. A smaller value can allow for faster transient response. For example, the 150pF C_{SNS} with 1k Ω R_{SNS} adds 750ns (5RC) to the settling time of SNS voltage.

Table 8-1. SNS Ripple (Typical measurement at $V_{BB} = 13.5V$, $I_{LIM} = OPEN$, $T_A = 25^\circ C$)

R_L (Load resistor)	R_{SNS}	C_{SNS}	PEAK-TO-PEAK RIPPLE WITHOUT C_{SNS} (mV)	PEAK-TO-PEAK RIPPLE WITH C_{SNS} (mV)
10 Ω	1k Ω	150pF	105mV	50mV
2.2 Ω	1k Ω	150pF	157mV	55mV

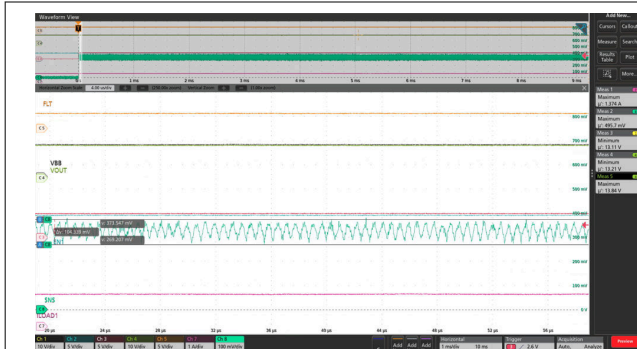


Figure 8-9. SNS Pin Ripple Without C_{SNS} at $V_{BB} = 13.5V$, $I_{LIM} = OPEN$, $R_L = 10\Omega$, $R_{SNS} = 1k\Omega$ and $T_A = 25^\circ C$

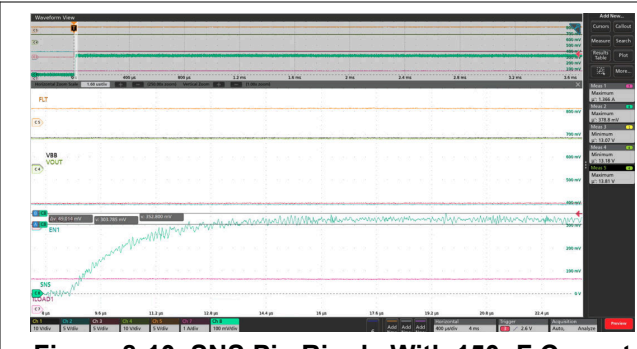


Figure 8-10. SNS Pin Ripple With 150pF C_{SNS} at $V_{BB} = 13.5V$, $I_{LIM} = OPEN$, $R_L = 10\Omega$, $R_{SNS} = 1k\Omega$ and $T_A = 25^\circ C$

8.3.2.3 Multiplexing of Current Sense Across Devices

Figure 8-11 shows SNS pin sharing across two devices using common R_{SNS} resistor. Similarly multiple devices can be configured to share SNS pin. When DIAG_EN is set high, the selected device current sense output can be enabled using associated EN signal, and a current proportional to the load current (I_{LOAD}/K_{SNS}) flows out of the SNS pin through the external sense resistor to ground. This current is reflected as a voltage that can be measured by an MCU's ADC input. When DIAG_EN is set low, the SNS pin is placed in a high-impedance (tri-state) condition. This feature allows multiple TPS1HC04-Q1 devices to share the same sense resistor and ADC input pin, as only one device can drive the SNS pin at any given time.

K_{SNS} is designed such that SNS pin current at maximum rated load current is same across the device family. This allows for devices with different current ratings to be multiplexed by having same R_{SNS} resistor and ADC full scale range.

When implementing current sense multiplexing across devices, the disabled state SNS pin leakage current ($I_{SNSleak_disabled}$) from devices (with DIAG_EN set to low) introduces measurement error when reading the current from an active device. For TPS1HC04-Q1 device, the disabled state SNS pin leakage is very low (typical few nA), allowing higher count of devices to be multiplexed.

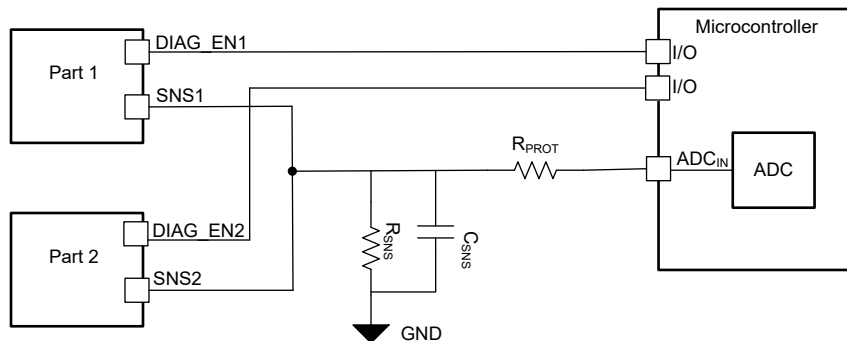


Figure 8-11. SNS Multiplexing Across Multiple Devices

8.3.3 Overcurrent Protection

The TPS1HC04-Q1 provides thermal shutdown and current limiting protection during overcurrent events to protect the internal power MOSFET. These protection functions are enabled when the device is in the active state. The current limit fault gets asserted at about 80% ($I_{CL_FLT_Trip}$) of set current limit value.

8.3.3.1 Adjustable Current Limit

The TPS1HC04-Q1 offers a high accuracy, adjustable current which enables higher reliability and provides protection to the power supply during a short circuit or power up with large capacitance. An adjustable current

limit can also save system costs by reducing PCB traces, connector size, and the capacity of the preceding power stage by setting the current limit at a lower level.

The current limit of the device can be adjusted via an external resistor on the ILIM pin. The device provides ILIM settings with a thermal regulated current limit which adjusts the current limit level based on the relative temperature of the FET and the controller. This avoids fast heating of the FET and delays the trigger of relative thermal shutdown, which enables the device to charge up large capacitors at startup. With ILIM pin shorted to GND, the device current limit can be configured without thermal regulation where the device limits the current at the set ILIM value. [Table 8-2](#) details the different settings that are possible based on the ILIM pin configuration.

Table 8-2. Current Limit Settings Through ILIM Pin

R _{LIM} VALUE on ILIM pin	TYP I _{CL} = K _{CL} / R _{LIM}	THERMAL REGULATION
ILIM = GND or R _{LIM} < 16.67kΩ	Maximum setting of 45A	Disabled
R _{LIM} = 16.67kΩ	45A	Enabled
16.67kΩ < R _{LIM} < 50kΩ	I _{CL} = K _{CL} / R _{LIM}	Enabled
R _{LIM} = 50kΩ	15A	Enabled
ILIM = Open or R _{LIM} > 50kΩ	Minimum setting of 15A	Enabled

The device also offers a fast-trip circuit breaker function which is used when a short-circuit occurs while a channel is enabled which is also known as a hot-short. Once the I_{CB} threshold is reached, the device quickly turns off the channel to protect the internal MOSFET. Additionally, the device provides a current limit foldback function at higher voltages to help protect the internal power MOSFET during high V_{DS} events.

The different overcurrent events that can occur in a system are:

- hot-short
- enable into short
- current overload (slow creep)

A hot-short occurs when the device is enabled and a short-circuit condition is applied to the output of the device. Enabling in to short occurs when there is already a short on the output of the MOSFET and the device is enabled into the short-circuit condition. Current overload or also known as slow creep can occur if there is a slow rising overcurrent event at the output.

The following sections describe how the current limiting with thermal regulation and without thermal regulation work along with the circuit breaker and thermal shutdown functions to help protect against the various overcurrent conditions that can occur.

8.3.3.1.1 Current Limiting With Thermal Regulation

Based on the ILIM setting the device can be configured to limit current with thermal regulation. The thermal regulation works by monitoring the relative temperature of the MOSFET (T_{J,FET}) to the temperature of controller (T_{J,CONTROLLER}) and reducing the current limit based on the relative temperature.

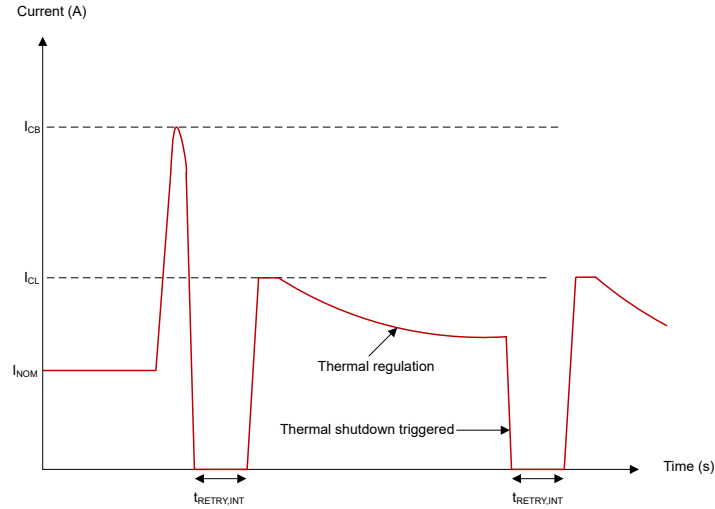


Figure 8-12. On-State Short-Circuit Behavior with Thermal Regulation

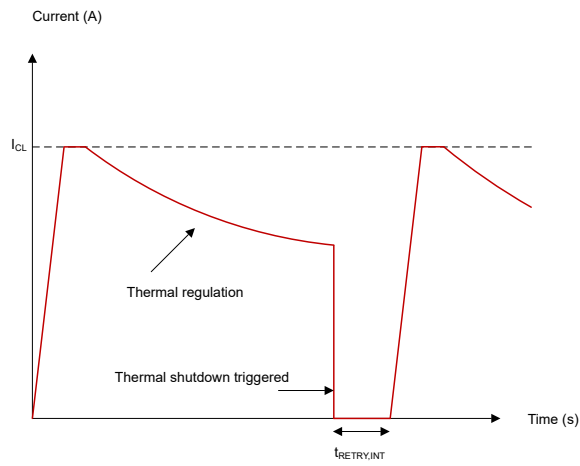


Figure 8-13. Enable Into Short with Thermal Regulation

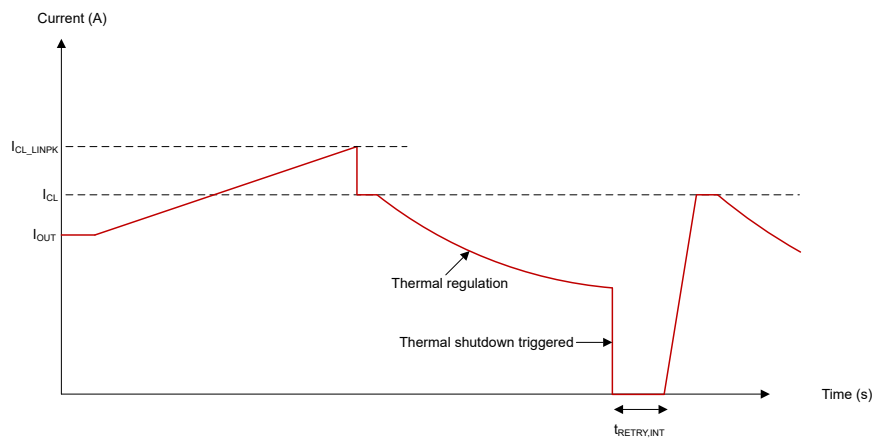


Figure 8-14. Overload Behavior (current creep) with Thermal Regulation

8.3.3.1.2 Current Limiting With No Thermal Regulation

Based on the ILIM setting, the device can be configured to limit current without thermal regulation. The device limits the current based on the setting at the ILIM pin. Applications where this can be used are bulb loads and motor loads with high inrush currents.

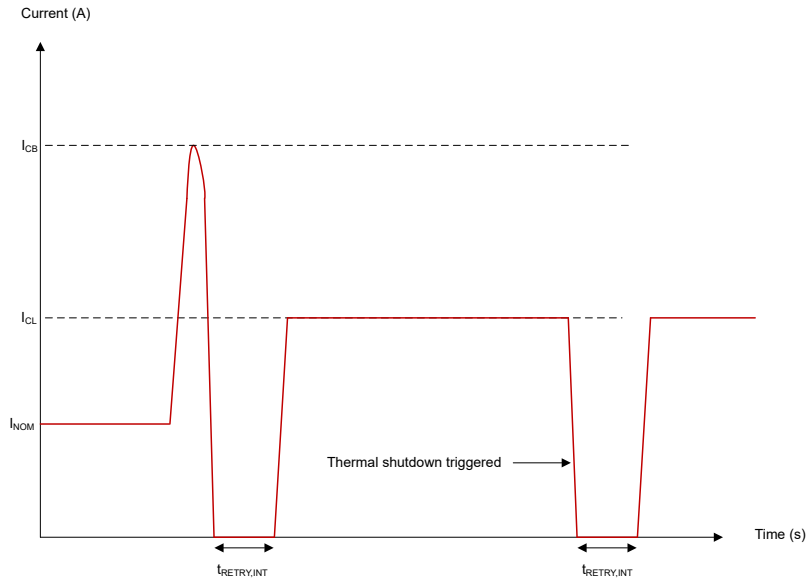


Figure 8-15. On-State Short-Circuit Behavior with No Thermal Regulation

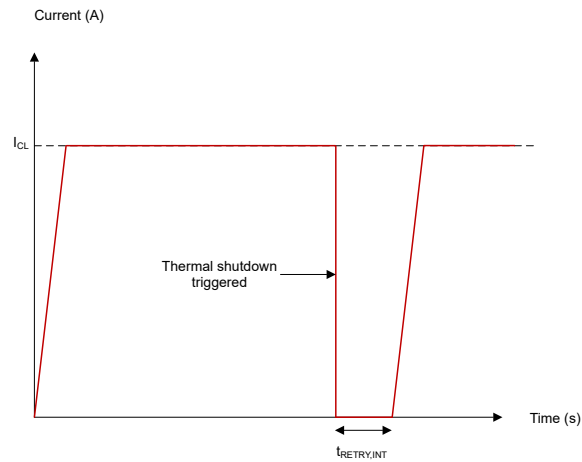


Figure 8-16. Enable Into Short with No Thermal Regulation

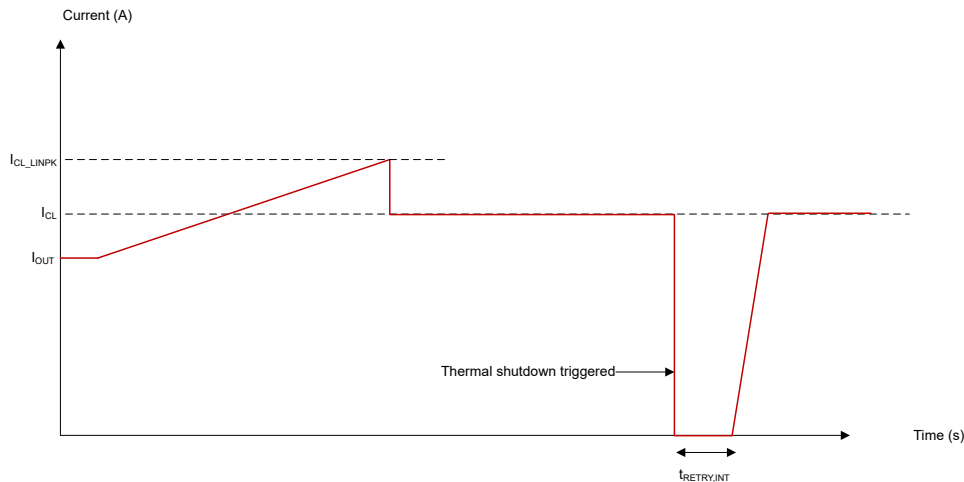


Figure 8-17. Overload Behavior (current creep) with No Thermal Regulation

8.3.3.1.3 Current Limit Foldback

To protect the MOSFET from overcurrent at high V_{DS} voltages the device offers a current limit foldback mechanism for higher current limit. If the V_{BB} voltage is greater than V_{DET1} then the current limit folds back to 1/2 of current limit setting. If the V_{BB} voltage is above V_{DET2} , the current limit folds back 1/3 of current limit setting. Figure 6-21 shows device current limit foldback behavior across V_{BB} voltage.

8.3.3.1.4 Current Limit Accuracy

The adjustable current limit of the device can be set using Equation 3 for valid range of R_{LIM} resistor mentioned in Table 8-2.

$$R_{LIM} = K_{CL} / I_{CL} \quad (3)$$

The accuracy of current limit depends on R_{LIM} resistor tolerance and K_{CL} parameter variation (K_{CL_min} , K_{CL_max}) mentioned in Electrical Characteristics. For example, for 33.2k Ω R_{LIM} resistor with 1% tolerance, the I_{CL} can be calculated as below.

$$I_{CL} (\text{max}) = \text{minimum}((K_{CL_max} / R_{LIM_min}, \text{ where } R_{LIM_min} = 0.99 * R_{LIM}), I_{CB})$$

$$I_{CL} (\text{min}) = K_{CL_min} / R_{LIM_max}, \text{ where } R_{LIM_max} = 1.01 * R_{LIM}$$

For R_{LIM} GND and OPEN case, K_{CL} parameter variation contributes to I_{CL} variation.

The device current limit variation in fold-back state is same as nominal current limit variation and can be determined using above method. Device I_{CB} also folds back similar to I_{CL} across V_{BB} based on V_{DET1} and V_{DET2} thresholds.

8.3.3.2 Thermal Shutdown

The device includes a temperature sensor on the power FET and within the controller portion of the device to monitor the temperature of the FET ($T_{J,FET}$) and the temperature of the controller ($T_{J,CONTROLLER}$). There are two cases that the device considers to be a thermal shutdown fault:

- **Relative thermal shutdown (T_{REL}):** $T_{J,FET} - T_{J,CONTROLLER} > T_{REL}$
- **Absolute thermal shutdown (T_{ABS}):** $T_{J,FET} > T_{ABS}$

If either the above faults occur, the switch is turned off.

8.3.3.2.1 Relative Thermal Shutdown

A relative thermal shutdown event can occur when there is a large peak power event such as a short-to-ground event where the FET temperature ($T_{J,FET}$) quickly rises relative to the controller temperature ($T_{J,CONTROLLER}$). Once the relative temperature ($T_{J,FET} - T_{J,CONTROLLER}$) exceeds T_{REL} the channel is turned off.

8.3.3.2.2 Absolute Thermal Shutdown

An absolute thermal shutdown occurs when the FET temperature ($T_{J,FET}$) rises above T_{ABS} . This can occur when a channel is subjected to long durations of overcurrent such as a permanent short use case. Once the FET temperature ($T_{J,FET}$) exceeds T_{ABS} the channel is turned off.

8.3.4 Retry Protection Mechanism From Thermal Shutdown

When a thermal shutdown occurs, the device shuts off and implements a retry protection mechanism to improve system reliability. Figure 8-19 explains how the device responds depending on the load current and duration of the overcurrent event.

For load current lower than current limit, device enters into infinite thermal shutdown retry cycles phase until the device recovers from the thermal shutdown fault. In this case, the device turn off time depends on cooling time needed with inherent 200 μ s delay.

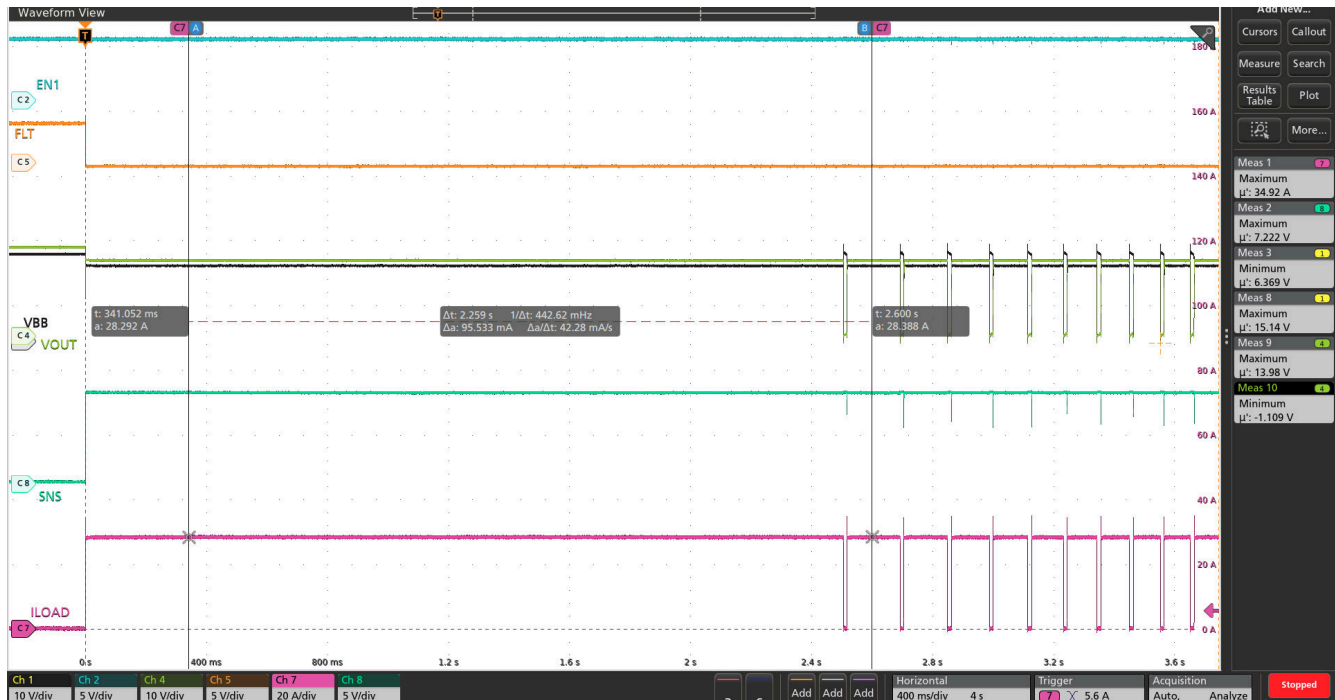


Figure 8-18. Device Enters Into Infinite Thermal Shutdown Retry Phase For Load Current (28A electronic load) Less Than Current Limit ($I_{LIM} = GND$)

For load current higher than current limit, device implements a finite retry cycles phase protection mechanism based on the duration of the overcurrent event, that can trigger when either of the below fault conditions occur:

1. **Absolute thermal shutdown (T_{ABS}):** $T_{J,FET} > T_{ABS}$
2. **Relative thermal shutdown (T_{REL}):** $T_{J,FET} - T_{J,CONTROLLER} > T_{REL}$
3. **Circuit Breaker (I_{CB}):** A fast-trip protection that triggers when current exceeds the I_{CB} threshold during a hot-short condition. This quickly turns off the channel to protect the internal MOSFET.

The finite retry cycles phase protection mechanism has below durations:

1. **Initial Retry Window ($t < t_{RETRY_WINDOW}$):**
 - After I_{CB} or thermal shutdown triggers.
 - Retry attempts occur every t_{RETRY_INT} minimum duration.
 - Each retry can start with I_{CB} peak followed by current limit (I_{CL}) peaks.
2. **Extended Overcurrent Window ($t > t_{RETRY_WINDOW}$):**

- Limited to 6 retry attempts.
- First retry cycle happens with minimum $t_{RETRY,EXTD}/2$ duration.
- Successive 5 retry cycles happen with minimum $t_{RETRY,EXTD}$ duration.
- Current peaks are typically limited to I_{CL} .

3. **Latch-off Condition:**

- After 6 unsuccessful retry attempts.

Table 8-3. Response To Thermal Shutdown

LOAD CURRENT	CONDITIONS		MINIMUM RETRY TIME
$I_{LOAD} < I_{CL}$	-		Infinite retry
$I_{LOAD} > I_{CL}$	$t < t_{RETRY_WINDOW}$		$t_{RETRY,INT} = 160\mu s$ (typical)
	$t > t_{RETRY_WINDOW}$	$n_{RETRY,EXTD} < 6$	$t_{RETRY,EXTD} = 80ms$ (typical)
		$n_{RETRY,EXTD} > 6$	Latch-off

In any of the above retry cases the relevant channel restarts when below "**restart**" conditions are fulfilled.

1. **Temperature Recovery:** the T_{ABS} or T_{REL} to recover below the T_{HYS} level to restart the device.
2. **Retry Window:** For $I_{LOAD} > I_{CL}$, appropriate t_{RETRY_WINDOW} interval must elapse.

In case of $I_{LOAD} > I_{CL}$, if the retry timer has expired and the temperature of T_{ABS} or T_{REL} has not recovered below the T_{HYS} level, the channel does not retry until the temperature falls below the T_{HYS} level. Once a channel latches off due to an extended overcurrent event, the EN pin can be brought from high to low (with minimum pulse duration of about 20us) to reset the \overline{FLT} and SNS signal. The output of the channel then follows the EN pin after the initial toggle from high to low.

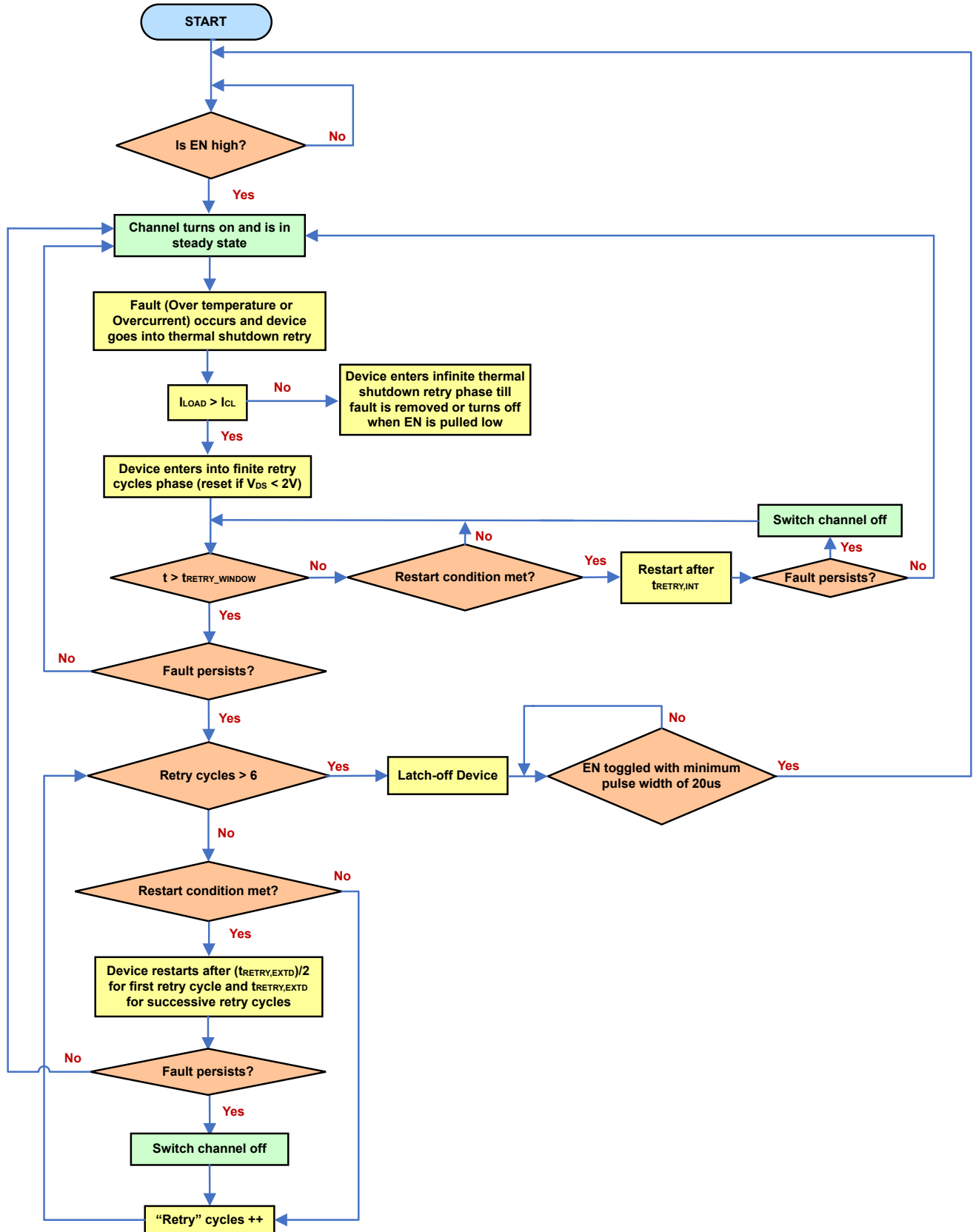


Figure 8-19. Retry Protection Mechanism

The following figures show how the device retries after a hot-short with and without thermal regulation, respectively. When the device experiences a thermal fault and enters the retry cycle, the first current peak in initial retry window reaches I_{CB} threshold, triggering fast trip circuit breaker. Successive current peaks are lower and correspond to set current limit (I_{CL}) value.

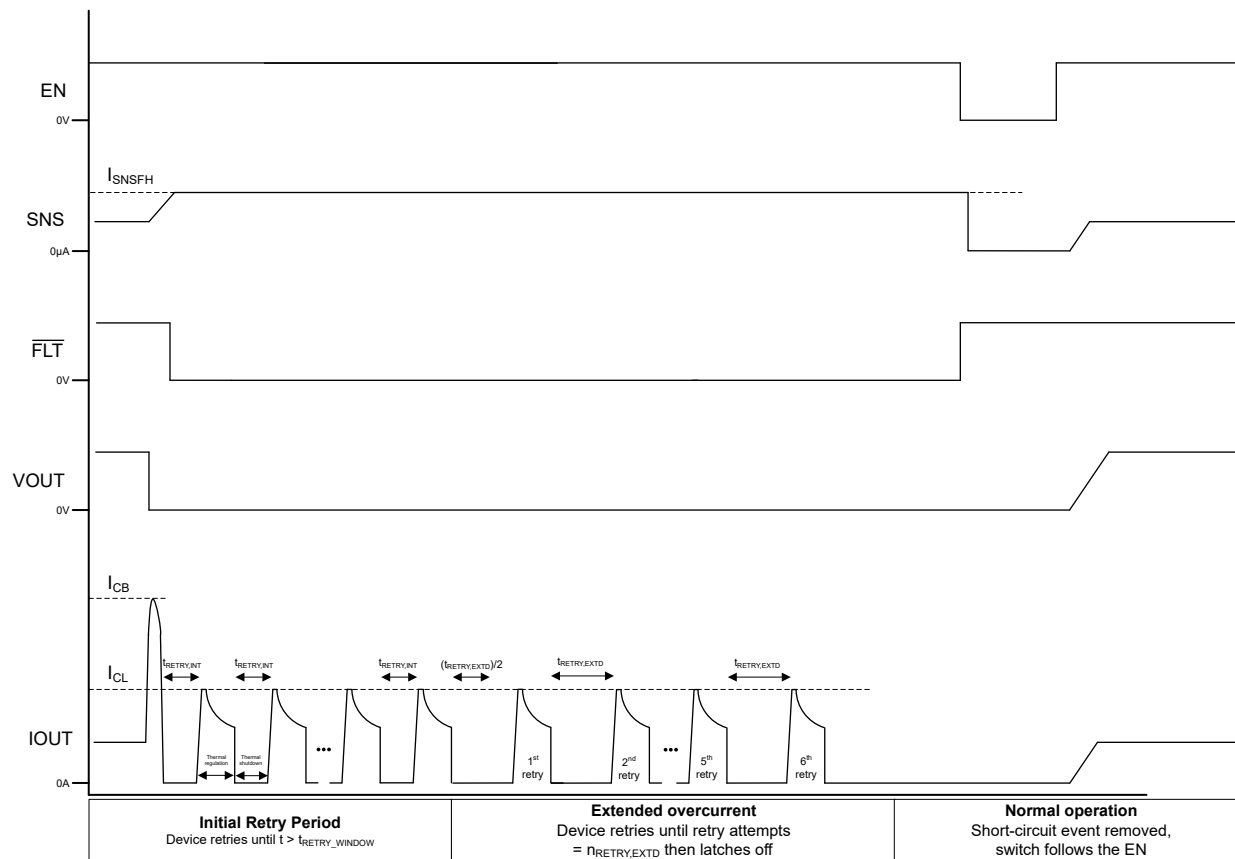


Figure 8-20. Retry Behavior After Hot-Short with Thermal Regulation

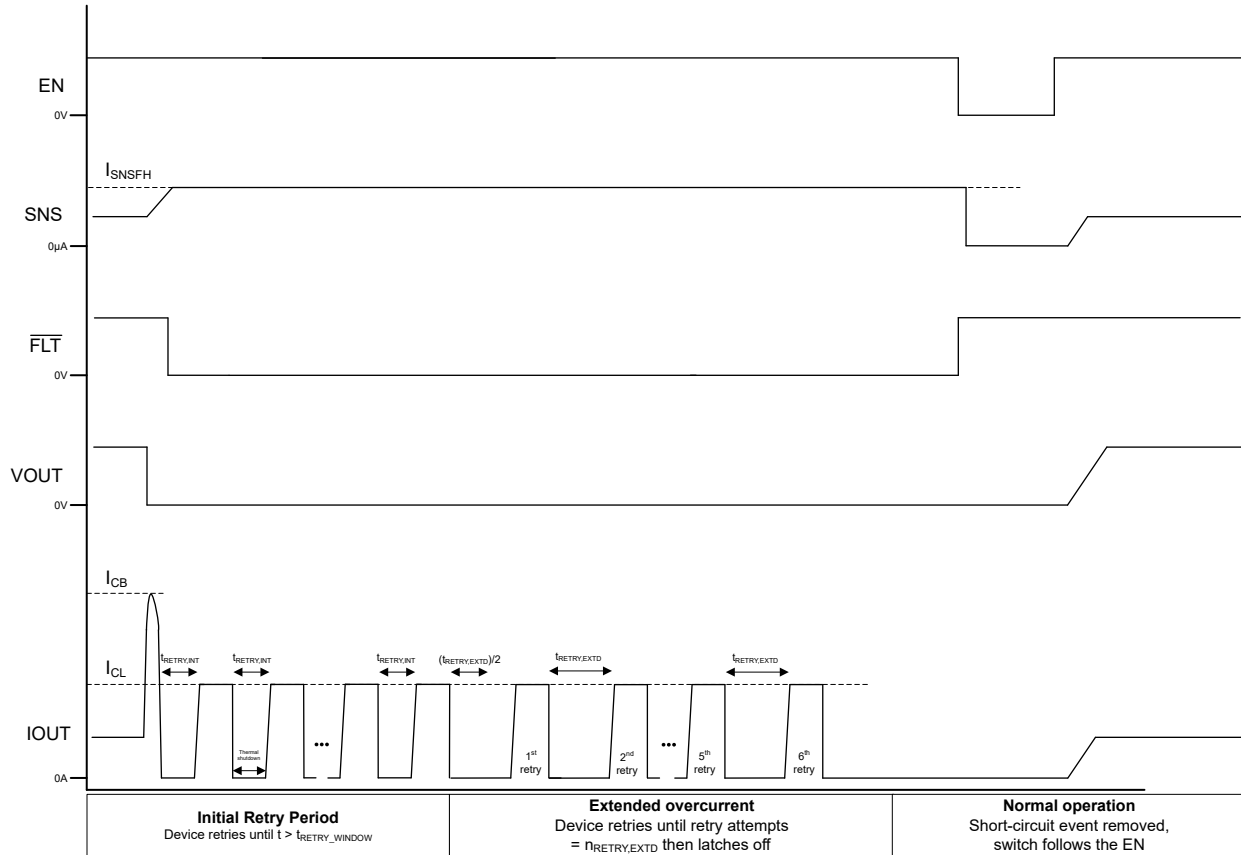


Figure 8-21. Retry Behavior After Hot-Short with No Thermal Regulation

In case the device enters finite retry cycles phase protection mechanism due to overcurrent fault without thermal shutdown fault, the device can stay in thermal regulation in initial retry window and directly enter thermal shutdown retry behavior in extended retry window.

8.3.5 Inductive-Load Switching-Off Clamp

When switching an inductive load off, the inductive reactance tends to pull the output voltage negative. Excessive negative voltage can cause the power FET to break down. To protect the power FET, an internal clamp between drain and source is implemented, namely $V_{DS(\text{clamp})}$.

$$V_{DS(\text{clamp})} = V_{VS} - V_{OUT} \quad (4)$$

During the period of demagnetization (t_{decay}), the power FET is turned on for inductance-energy dissipation. The total energy is dissipated in the high-side switch. Total energy includes the energy of the power supply ($E_{(VS)}$) and the energy of the load ($E_{(\text{load})}$). If resistance is in series with inductance, some of the load energy is dissipated on the resistance.

$$E_{(\text{HSS})} = E_{(VS)} + E_{(\text{load})} = E_{(VS)} + E_{(L)} - E_{(R)} \quad (5)$$

When an inductive load switches off, $E_{(\text{HSS})}$ causes high thermal stressing on the device.. The upper limit of the power dissipation depends on the device intrinsic capacity, ambient temperature, and board dissipation condition.

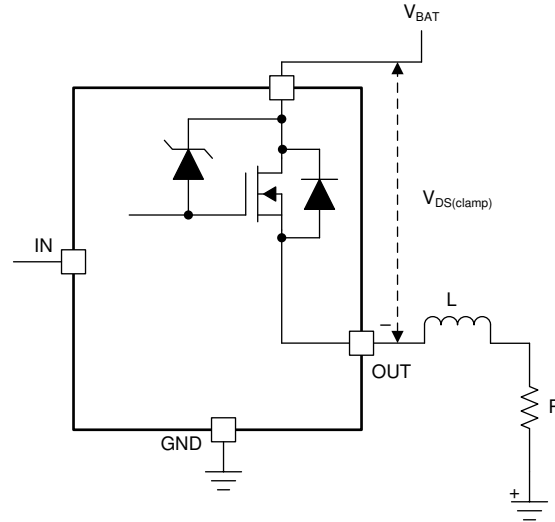


Figure 8-22. Drain-to-Source Clamping Structure

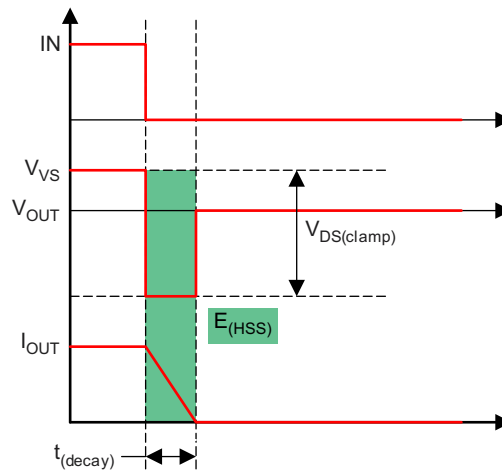


Figure 8-23. Inductive Load Switching-Off Diagram

From the perspective of the high-side switch, $E_{(HSS)}$ equals the integration value during the demagnetization period.

$$E_{(HSS)} = \int_0^{t_{(decay)}} V_{DS(clamp)} \times I_{OUT}(t) dt$$

$$t_{(decay)} = \frac{L}{R} \times \ln \left(\frac{R \times I_{OUT(max)} + |V_{OUT}|}{|V_{OUT}|} \right)$$

$$E_{(HSS)} = L \times \frac{V_{VS} + |V_{OUT}|}{R^2} \times \left[R \times I_{OUT(max)} - |V_{OUT}| \ln \left(\frac{R \times I_{OUT(max)} + |V_{OUT}|}{|V_{OUT}|} \right) \right] \quad (6)$$

When R approximately equals 0, $E_{(HSD)}$ can be given simply as:

$$E_{(HSS)} = \frac{1}{2} \times L \times I_{OUT(max)}^2 \times \frac{V_{VS} + |V_{OUT}|}{|V_{OUT}|} \quad (7)$$

Note that for PWM-controlled inductive loads, adding the external freewheeling circuitry as shown in [Figure 8-24](#) is recommended to protect the device from repetitive power stressing. TVS is used to achieve the fast decay. See [Figure 8-24](#) for more details.

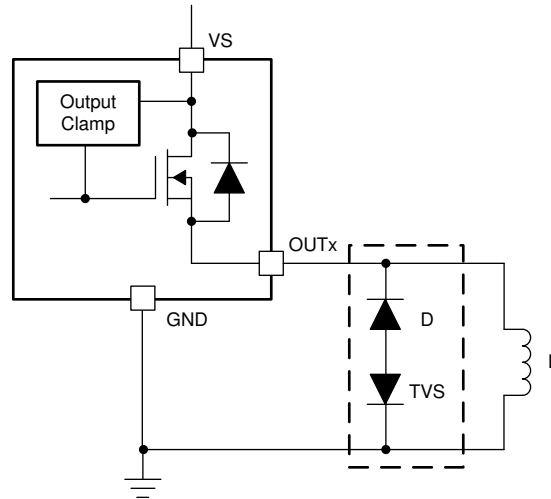


Figure 8-24. Protection with External Circuitry

[Figure 8-25](#) shows the VDS clamp engaging during 5mH inductive load discharge. [Figure 8-26](#) and [Figure 8-27](#) shows maximum energy dissipation capability of the device during inductive load turn off.



Figure 8-25. 5mH Inductive Load Driving (VBB = 13.5V, T_{AMB} = 125°C)

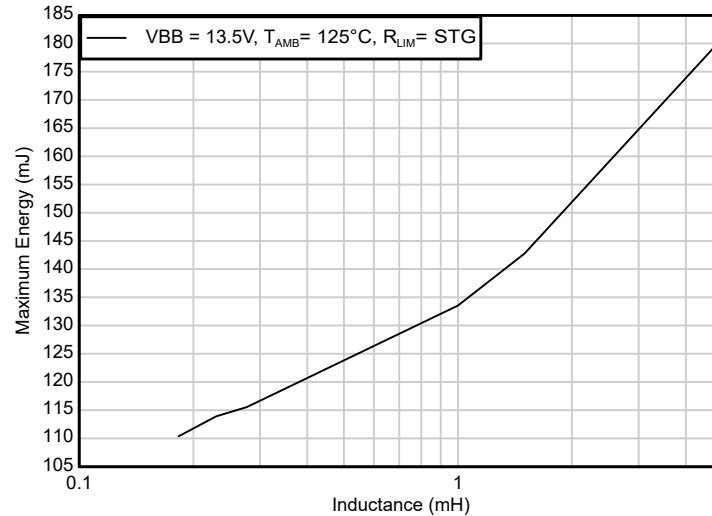


Figure 8-26. Maximum Energy Dissipation for Inductive Switch OFF vs Inductance (single pulse, VBB = 13.5V, T_{AMB} = 125°C)

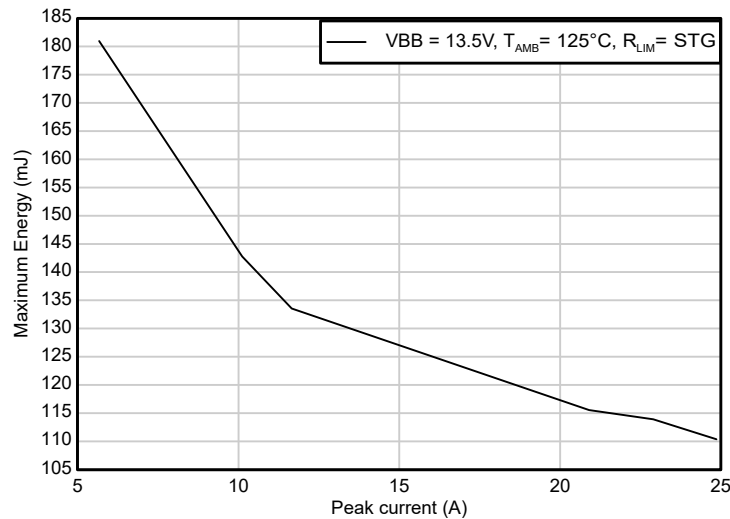


Figure 8-27. Maximum Energy Dissipation for Inductive Switch OFF vs Peak Current (single pulse, VBB = 13.5V, T_{AMB} = 125°C)

8.3.6 Slower Slew Rate Option

The TPS1HC04-Q1 offers device versions (D, B) with slower rising and falling slew rate for automotive seat heater applications. Such applications require that 10%-90% rise and fall times of the PWM currents must stay at or below 80A/msec. The slower slew rate helps reduce electromagnetic interference in the vehicle's electrical system. Without proper slew rate control, the fast switching of current in the seat heater application can cause EMC issues in the system.

8.3.7 Capacitive Load Charging

The TPS1HC04-Q1 incorporates an advanced adjustable current limiting circuit with thermal regulation that significantly improves system reliability by effectively managing inrush currents when charging large capacitive loads. The device also provides protection against current limit and overcurrent faults by turning off the smart high side switch. With no protection, charging a large capacitive load can lead to high inrush currents that pull a supply down, however by using the low thermal regulated current limit device options the capacitive load can be safely charged.

8.3.7.1 Adjustable Current Limiting for Inrush Control

Adjustable current limit feature of the device allows precise control of inrush current during capacitive load charging. By selecting an appropriate external resistor value on the ILIM pin, designers can:

- Tailor the maximum charging current to match specific capacitive load requirements.
- Protect upstream power supplies from excessive current draw during startup.
- Reduce PCB trace width requirements and connector sizing by limiting peak currents.
- Minimize voltage droop on the supply rail during capacitive charging.
- Enable the use of smaller, more cost-effective components throughout the system.

Figure 8-28 and Figure 8-29 compares the 470uF capacitive load charging at same conditions with device configured to maximum (ILIM pin shorted to ground (STG)) and minimum (ILIM pin OPEN) current limit setting. The lower current limit limits the inrush current while charging the capacitive load and provides clean startup without triggering thermal shutdown.

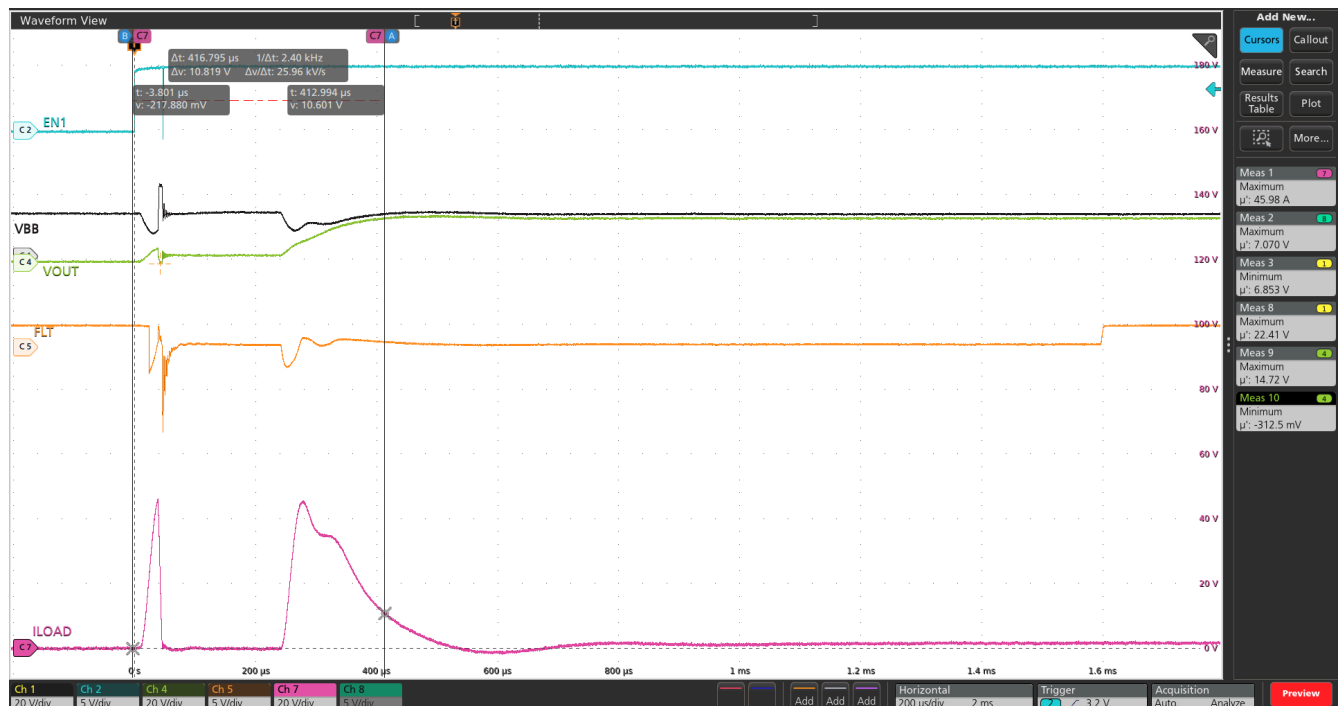


Figure 8-28. 470uF Capacitive Load Charging with TPS1HC04-Q1 Device at 13.5V VBB, ILIM Pin shorted to ground and 125°C Ambient Temperature

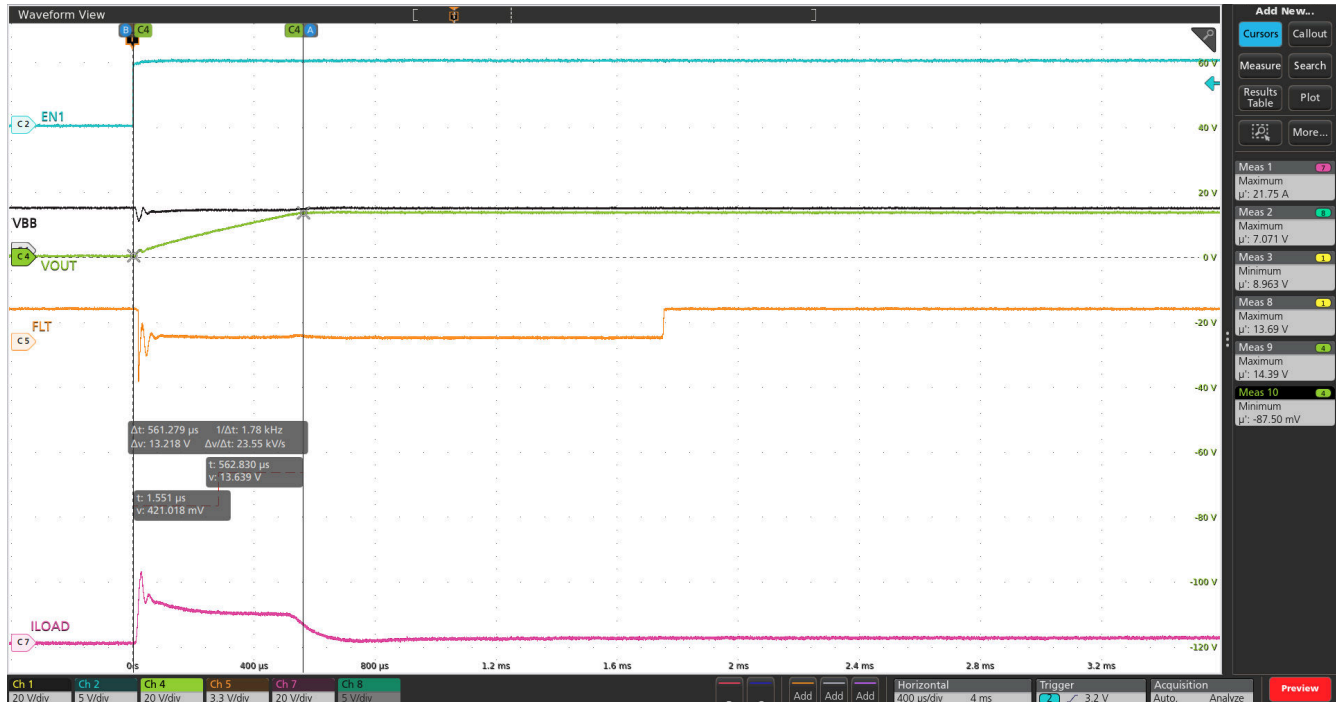


Figure 8-29. 470uF Capacitive Load Charging with TPS1HC04-Q1 Device at 13.5V VBB, ILIM Pin OPEN and 125°C Ambient Temperature

8.3.7.2 Current Limit with Thermal Regulation for Capacitive Loads

When configured with an external resistor on the ILIM pin, the TPS1HC04-Q1 enables thermal-regulated current limiting. The thermal regulation works through a negative feedback mechanism by continuously monitoring the relative temperature of the power FET ($T_{J,FET}$) compared to the controller temperature ($T_{J,CONTROLLER}$). As the temperature difference increases during high-current events, the device automatically reduces the current limit to maintain safe operation while allowing maximum charging current. This feature provides below advantages for capacitive load charging:

- **Expanded Capacitive Load Range:** The thermal-regulated current limiting significantly expands the range of capacitive loads that can be safely charged without triggering thermal shutdown, as shown in [Figure 8-30](#). By dynamically adjusting current based on thermal conditions, the device can handle much larger capacitances than traditional high-side switches.
- **Elimination of Manual Pulsing:** Previously, without thermal regulation of current limit, customers often resorted to manually pulsing switches on and off to charge large capacitive loads. This approach introduced significant noise and EMI concerns into the system. The device thermal regulation eliminates the need for this practice.
- **Prevention of Thermal Runaway:** The thermal regulation implements a negative feedback loop that stabilizes the system during capacitive charging. As temperature rises, current is automatically reduced, preventing the uncontrolled thermal escalation seen in conventional switches.

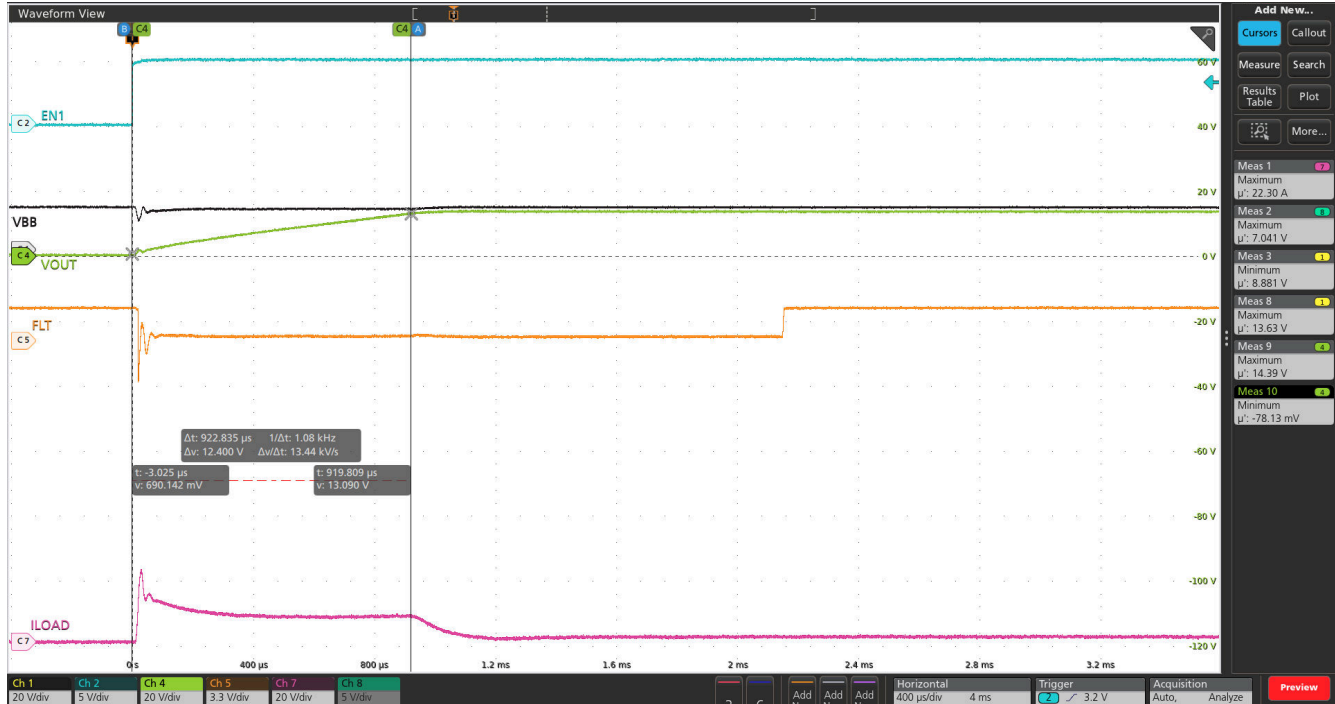


Figure 8-30. 680uF Capacitive Load Charging with TPS1HC04-Q1 Device at 13.5V VBB, ILIM Pin OPEN and 125°C Ambient Temperature

8.3.7.3 Retry Thermal Shutdown Behavior for Capacitive Loads

For large capacitive loads, device can trigger thermal shutdown fault and enter into retry thermal shutdown flow. In this case, the retry protection mechanism (Section 8.3.4) of the device allows load to turn on reliably with multiple retry cycles. For most properly sized capacitive loads, the thermal regulation can prevent reaching thermal shutdown conditions, resulting in smooth capacitive charging without interruption. Figure 8-28 shows capacitive load charging with multiple thermal shutdown retry cycles. This behavior can be acceptable in applications where capacitive load has high enough load impedance connected in parallel, hence not discharging the capacitor significantly when the device is off during thermal shutdown.

8.3.7.4 Impact of DC Load on Capacitive Charging Capability

When designing systems with both capacitive and DC loads on the same channel, it's important to consider the combined thermal impact:

- **Thermal Budget Consumption:** Any DC load connected in parallel with a capacitive load consumes part of the device's thermal budget. The power dissipation from the DC load (I^2R) generates heat that raises the baseline temperature of the power FET.
- **Reduced Capacitive Charging Capability:** With a power dissipation across FET to DC load, the margin between operating temperature and thermal shutdown threshold is reduced. This effectively decreases the maximum capacitance that can be safely charged without triggering thermal shutdown.
- **Accelerated Thermal Shutdown:** The combined heating effect of DC load current and capacitive charging current can accelerate the onset of thermal shutdown. This can cause the device to enter the retry mechanism earlier and more frequently during capacitive charging.
- **Design Considerations:** When both load types must be supported simultaneously:
 - Select a more conservative (higher) R_{LIM} value to reduce the current limit.
 - Provide adequate PCB copper area for improved thermal dissipation.
 - For critical applications, consider using separate channels for DC and capacitive loads.

For more information on driving inductive or capacitive loads, reference TI's [How To Drive Inductive, Capacitive, and Lighting Loads with Smart High Side Switch](#) application report.

8.3.7.5 Device Capability

The table below shows some data for capacitive load charging across device family at $V_{BB} = 18V$, $T_A = 125^\circ C$. Only single channel is enabled for TPS2HC08-Q1 and TPS2HC16-Q1 devices.

Table 8-4. Capacitive Load Charging Results Across Device Family

PART NUMBER	ILIM	CAPACITIVE LOAD	CHARGING TIME (typical)	THERMAL SHUTDOWN TRIGGERED
TPS2HC08-Q1	OPEN	2mF	>10ms	No
	GND	1mF	<10ms	Yes
TPS2HC16-Q1	OPEN	47uF	<10ms	No
	GND	220uF	<10ms	Yes
TPS1HC08-Q1	OPEN	470uF	<10ms	No
	GND	1mF	<10ms	Yes
TPS1HC04-Q1	OPEN	680uF	<10ms	No
	GND	470uF	<10ms	Yes
TPS1HC03-Q1	OPEN	680uF	<10ms	No
	OPEN	1mF	<10ms	Yes

8.3.8 Bulb Charging

Figure 8-31 shows a simple bulb model as a combination of capacitive and resistive elements that define the startup and steady-state characteristics:

- R_{inrush} : The initial cold filament resistance that limits peak inrush current at startup.
- C_{inrush} : Represents the energy storage required for the filament to generate sufficient heat for proper illumination.
- R_{dc} : The steady-state hot filament resistance that determines normal operating current ($V_{battery} / R_{dc}$).

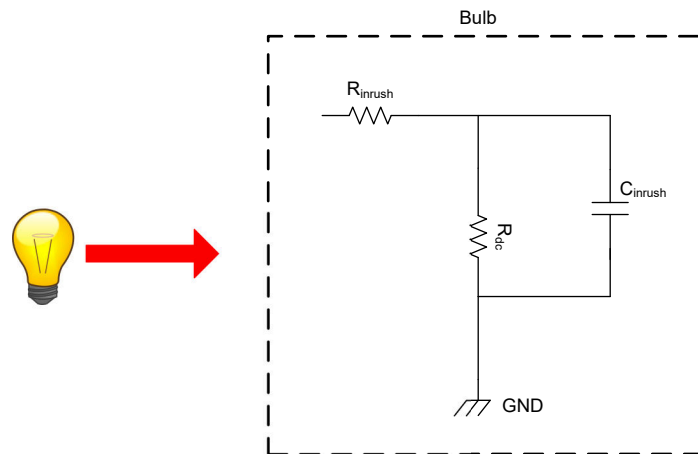


Figure 8-31. Simple Bulb Model

During cold startup, the filament resistance (R_{inrush}) can be 7-10 times lower than the steady-state value (R_{dc}), resulting in substantial inrush currents and need of low R_{ON} (on-resistance) switch.

In real environment, a bulb is introduced to many inductances and resistances when placed in a vehicle. Figure 8-32 shows simplified vehicle architecture model in real environment consisting of below complex electrical network that significantly affects the bulb turn-on behavior and peak current.

- **R_{vehicle}** : The total wire harness and connector resistance in the path from battery to chassis ground excluding $R_{\text{ds,on switch}}$ (R_{ON} of the switch) typically ranges from 45m Ω to 130m Ω in production vehicles. The short and long cable harness length typically makes 50m Ω and 100m Ω of R_{vehicle} respectively.
- **L_{vehicle}** : Wire harness inductance affects current slew rate and turn-on timing.
- **System resistances**: Connector contact resistance and ground path resistance contribute to the overall circuit behavior.

The three primary components that determine peak inrush current during bulb charging are:

- **R_{vehicle}** : Higher vehicle resistance reduces peak current.
- **$R_{\text{ds,on switch}}$** : The switch's on-resistance (R_{ON}) contributes to current limiting.
- **R_{inrush}** : The cold filament resistance of the specific bulb.

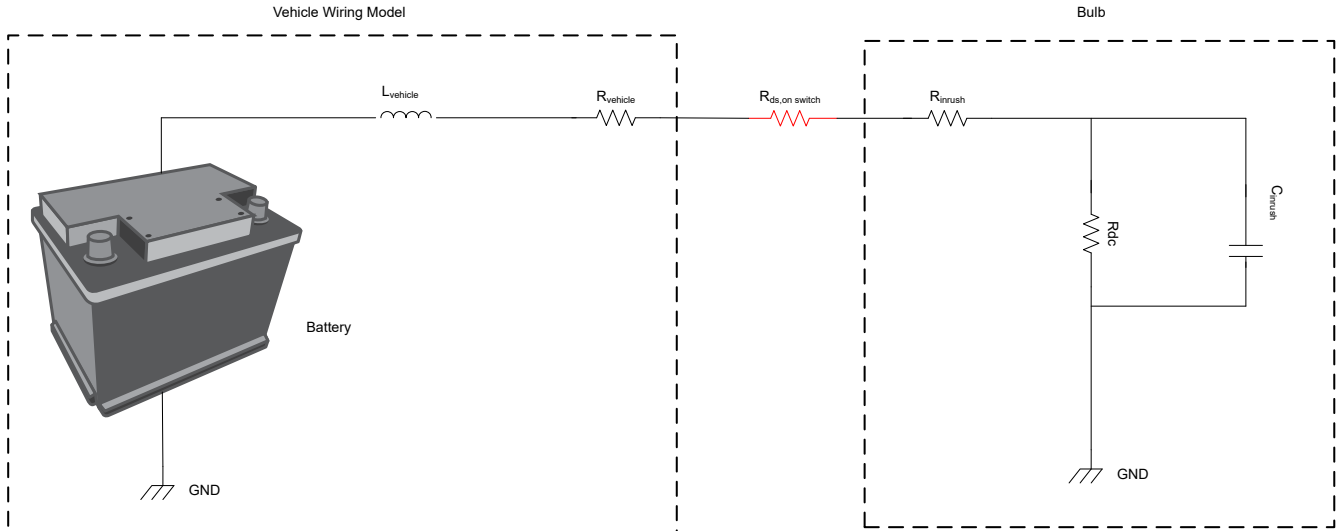


Figure 8-32. Simplified Vehicle Architecture Model

8.3.8.1 Non-Thermal Regulated Mode for Bulb Loads

For bulb loads with high inrush currents, the TPS1HC04-Q1 offers a specialized non-thermal regulated current limit mode that can be enabled by connecting the ILIM pin directly to GND. This mode provides consistent and predictable current limiting behavior regardless of temperature conditions with below device features.

- Maintains a fixed current limit of 45A regardless of temperature.
- Allows the device to handle the high initial current demand.

Figure 8-33 shows the 35W bulb charging behavior of the device in non-thermal regulated current limit mode, set by grounding the ILIM pin. In non-thermal regulated mode, device is able to meet the high inrush current demand of the bulb load and turns on in $< 10\text{ms}$.

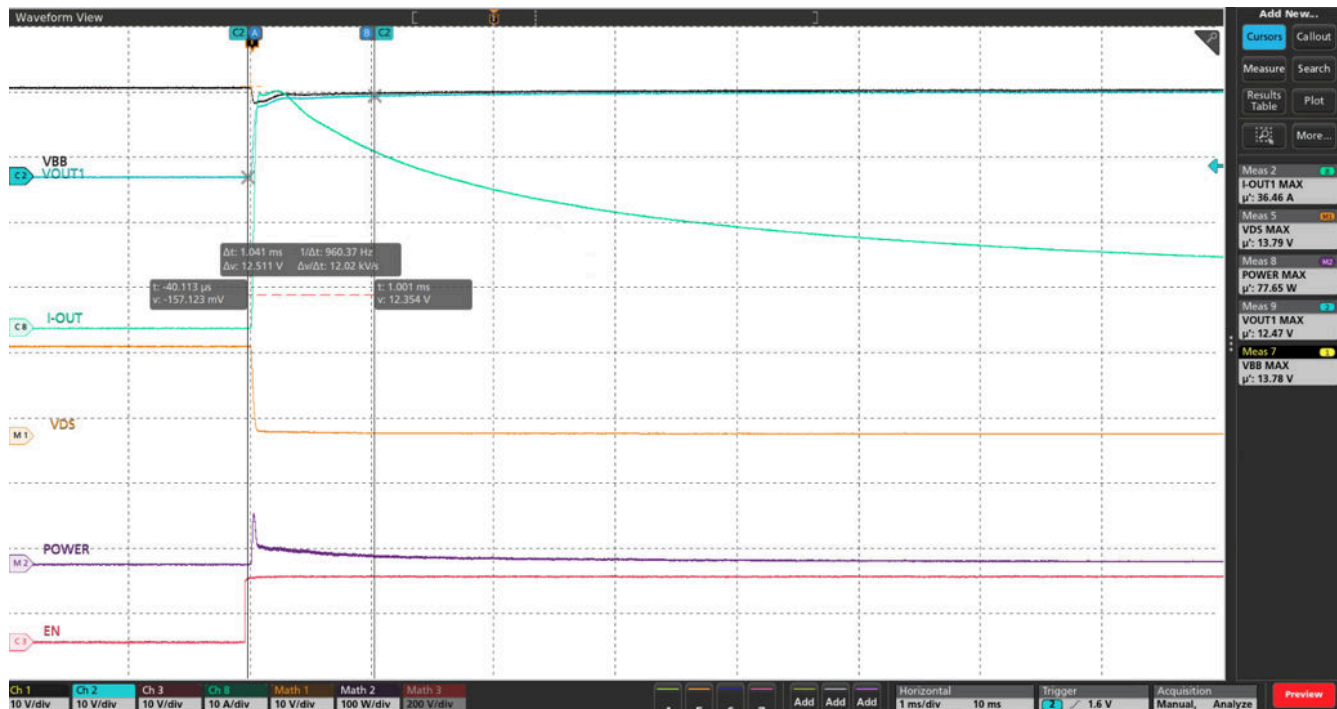


Figure 8-33. 35W Bulb Charging with TPS1HC04-Q1 Single Channel at 13.5V VBB, T_A (device) = 25°C, T_A (bulb) = -40°C, ILIM = GND

8.3.8.2 Thermal Management During Bulb Inrush

For high wattage bulb loads or at cold temperature startup or high VBB voltage, with high inrush current demand, the device employs sophisticated thermal protection mechanisms:

- **Relative Thermal Shutdown**

During high-inrush events, toggling of the switch output can be observed due to the FET heating up rapidly. When this occurs, the device enters a relative thermal shutdown ($T_{J,FET} - T_{J,CONTROLLER} > T_{REL}$) state and auto-recovers from this event within t_{RETRY_INT} . This rapid recovery allows the bulb to continue charging while preventing excessive thermal stress on the device.

- **Absolute Thermal Shutdown**

If the junction temperature continues to rise despite relative thermal protection, an absolute thermal shutdown event occurs when the FET temperature exceeds T_{ABS} . In this case, the switch turns off to protect the device and auto-recovers from this event within t_{RETRY_EXT} once the temperature decreases sufficiently, resuming bulb charging.

The below figure shows the 100W bulb (at cold condition) charging behavior of the device in non-thermal regulated current limit mode, set by grounding the ILIM pin. The device engages in thermal shutdown protection and turns on the bulb after few cycles.

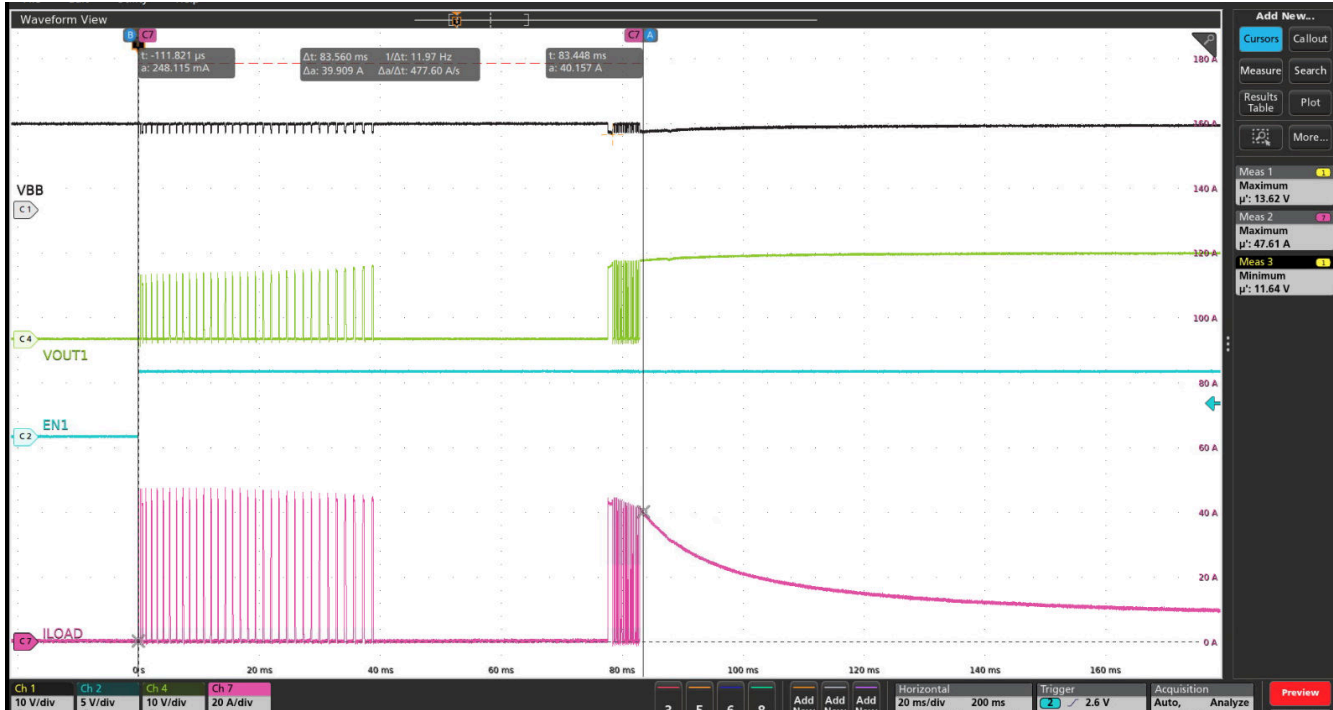


Figure 8-34. 100W Bulb Charging with TPS1HC04-Q1 Single Channel at 13.5V VBB, T_A (device) = 25°C, T_A (bulb) = -40°C, ILIM = GND

8.3.8.3 Device Capability

The table below shows some data for bulb load charging across device family at VBB = 13.5V, T_A = -40°C. Only single channel is enabled for TPS2HC08-Q1 and TPS2HC16-Q1 devices.

Table 8-5. Bulb Load Charging Results Across Device Family (with short cable length, $R_{vehicle}$ = 50mohm)

PART NUMBER	ILIM	BULB LOAD	CHARGING TIME (typical)	THERMAL SHUTDOWN TRIGGERED
TPS2HC08-Q1	GND	35W	<10ms	Yes
TPS2HC16-Q1	GND	27W	>10ms	Yes
TPS1HC04-Q1	GND	35W	<10ms	No
	GND	60W	<10ms	Yes
	GND	100W	>10ms	Yes
TPS1HC03-Q1	GND	4 x 27W (with long cable harness length)	>10ms	Yes
	GND	2 x 27W	<10ms	Yes
	GND	35W	<10ms	No

8.3.9 Fault Detection and Reporting

8.3.9.1 Diagnostic Enable Function

The DIAG_EN pin enables or disables the diagnostic functions. If multiple devices are used, but the ADC resource is limited in the microcontroller, the MCU can use GPIOs to set DIAG_EN high to enable the diagnostics of one device while disabling the diagnostics of the other devices by setting DIAG_EN low. In addition, the device can keep the power consumption to a minimum by setting DIAG_EN and EN low.

Table 8-6. Diagnosis Configuration Table

DIAG_EN	EN	SNS	FLT	PROTECTIONS AND DIAGNOSTICS
L	H	High Impedance	See Table 8-8	SNS disabled, $\overline{\text{FLT}}$ reporting, full protection
	L		High Impedance	Diagnostics disabled, no protection
H	-	See Table 8-8	See Table 8-8	See Table 8-8

8.3.9.2 $\overline{\text{FLT}}$ Reporting

In active state with EN high, the $\overline{\text{FLT}}$ pin is used to monitor the fault condition for the device regardless of DIAG_EN status. In case of off state diagnostics with EN low, the $\overline{\text{FLT}}$ pin monitors the fault condition when DIAG_EN is high. When a fault condition occurs on the device, the $\overline{\text{FLT}}$ pin is pulled down to GND. A 3.3V or 5V external pullup is required to match the supply level of the microcontroller.

8.3.9.3 $\overline{\text{FLT}}$ Timings

The below table shows the $\overline{\text{FLT}}$ pin timings.

Table 8-7. $\overline{\text{FLT}}$ Timings

CONDITION	TIMING
Open load or STB fault to $\overline{\text{FLT}}$ assertion in DIAGNOSTIC state.	See Section 8.3.10.1.2 (t_{OL} , t_{OL1} , t_{OL2})
Any other fault occurrence to $\overline{\text{FLT}}$ assertion	See $t_{\text{FAULT_FLT}}$
Fault clearance to $\overline{\text{FLT}}$ reset	The internal design architecture causes maximum 1ms delay for $\overline{\text{FLT}}$ signal to reset from the fault clearance event.

8.3.9.4 Fault Table

The below table shows the response of the FLT (regardless of DIAG_EN being high) and SNS (with DIAG_EN being high) pins during different conditions.

Table 8-8. Fault Table

CONDITIONS	EN	OUT	CRITERION	SNS (with DIAG_EN high)	FLT (with external pull-up)	BEHAVIOR	FAULT RECOVERY
Normal	L	L	—	High Impedance	H	Normal	—
	H	$V_{\text{BB}} - I_{\text{LOAD}} \times R_{\text{ON}}$	—	$I_{\text{LOAD}} / K_{\text{SNS}}$	H	Normal	—
Overcurrent	H	$V_{\text{BB}} - I_{\text{CL}} \times R_{\text{ON}}$	Current limit triggered	I_{SNSFH}	L	Holds the current at the current limit until thermal shutdown or when the overcurrent event is removed	Auto-retry or latch, see Section 8.3.4
Hot short	H	L	output shorted to ground	I_{SNSFH}	L	Device will immediately shutdown, and reenables into current limit.	Auto-retry or latch, see Section 8.3.4
Enable into permanent short	L to H	L	output shorted to ground	I_{SNSFH}	L	Device will enable into current limit until thermal shutdown.	Auto-retry or latch, see Section 8.3.4

Table 8-8. Fault Table (continued)

CONDITIONS	EN	OUT	CRITERION	SNS (with DIAG_EN high)	FLT (with external pull-up)	BEHAVIOR	FAULT RECOVERY
Open load, short to battery (STB)	L	H	$V_{BB} - V_{OUT} < V_{OL}$	I_{SNSFH}	L (when DIAG_EN is high)	Internal pull-up resistor is active to detect open load fault.	Auto
	H	H		I_{LOAD} / K_{SNS}	H	Normal behavior. User can make judgement based on SNS pin output.	—
Absolute Thermal shutdown	H	—	T_{ABS} triggered	I_{SNSFH}	L	Shuts down when devices hits absolute thermal shutdown.	Auto-retry or latch, see Section 8.3.4
Relative Thermal Shutdown	H	—	T_{REL} triggered	I_{SNSFH}	L	Shuts down when devices hits relative thermal shutdown.	Auto-retry or latch, see Section 8.3.4

8.3.10 Full Diagnostics

8.3.10.1 Open-Load Detection

8.3.10.1.1 Channel On

If a channel is on and the DIAG_EN = Logic High, then the high accuracy current sense of the device can be used to detect open-loads in the on state through an external ADC. Please note there is no detection reported on the \overline{FLT} pin. Determination of an open-load while a channel is on must be made by the user or system.

8.3.10.1.2 Channel Off

Open load detection is available in the off state if DIAG_EN = Logic High. If the channel is off and a load is connected, the output voltage is pulled to $\approx 0V$ by the load. In the case of an open load, the output voltage is close to the supply voltage, $V_{BB} - V_{OUT} < V_{OL}$. The FLT pin goes low to indicate the fault to the MCU, and the SNS pin outputs I_{SNSFH} fault current. There is always a leakage current $I_{OL,OFF}$ present on the output, due to the internal logic control path or external humidity, corrosion, and so forth. Thus, the device implements an internal pullup resistor (R_{PU}) to offset the leakage current. This pullup current must be less than the output load current to avoid false detection in the normal operation mode. To reduce the standby current, the device implements a switch and pullup resistor which is controlled by the DIAG_EN and the EN pin.

There are two settings for the open-load detection delay - 0.4ms (for P and D variants) and 2.4ms (for M and B variants). The 2.4ms open load detection delay represents the delay for the internal pullup (R_{PU}) resistor to engage between V_{BB} and V_{OUT} pins. This allows user to do fast DIAG_EN sequencing (DIAG_EN high pulse < 2.4ms) when SNS pins of multiple devices are tied to common R_{SNS} for MCU current sense reading. In this case, the open load fault will not engage for disabled devices during current sense read.

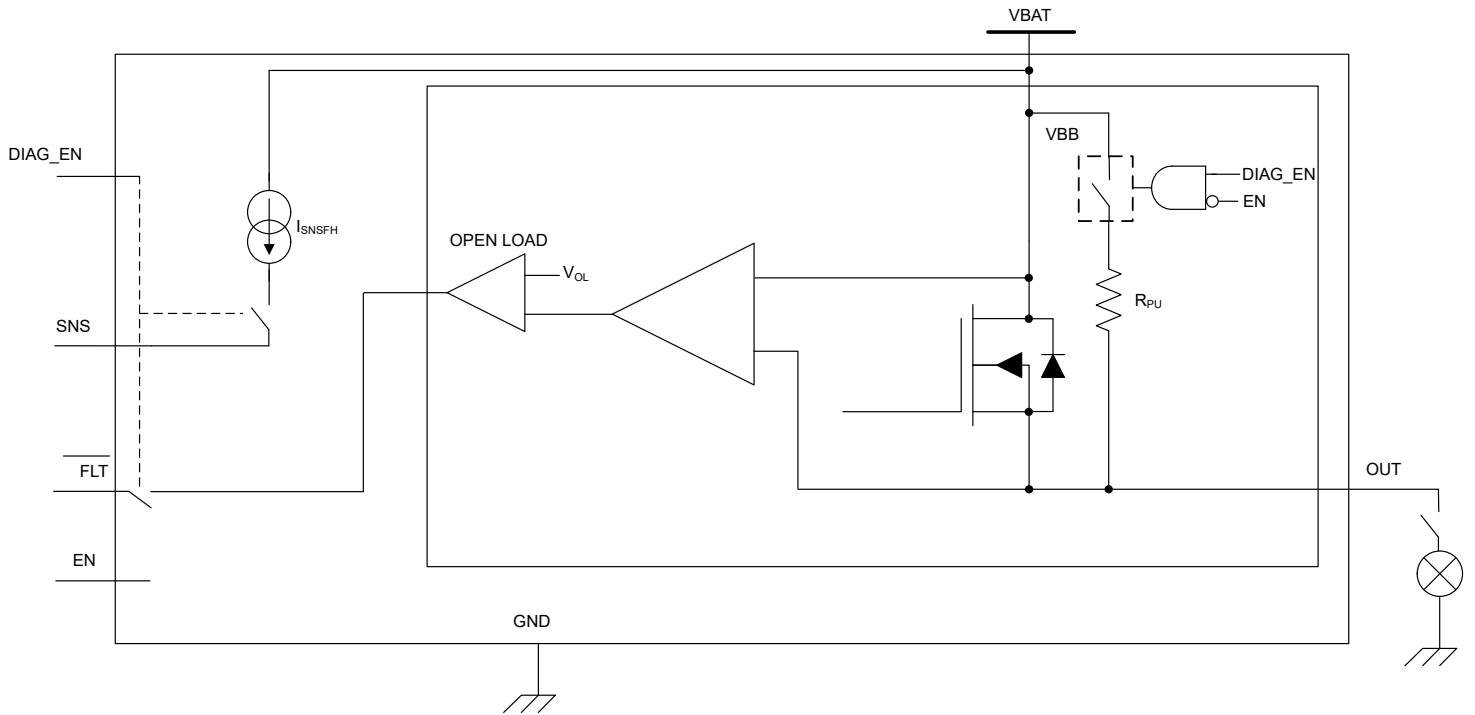
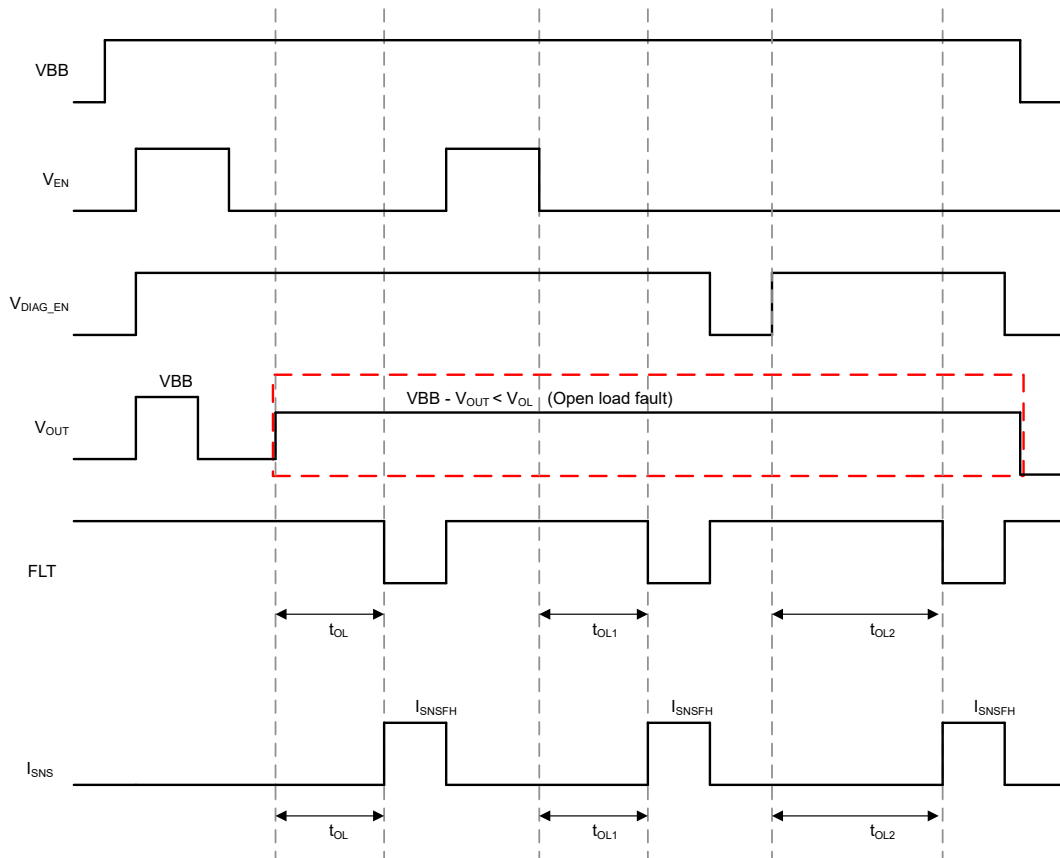


Figure 8-35. Open-Load Detection in Off-State



Note

Rise and fall times of control signals are 100ns. Control signals include: EN and DIAG_EN.

Figure 8-36. Open-load Detection Timing Characteristics

8.3.10.2 Short-to-Battery Detection

Short-to-battery detection has the same detection mechanism and behavior as open-load detection, both in the on-state and off-state. See [Table 8-8](#) for more details.

8.3.10.3 Reverse-Polarity and Battery Protection

Reverse-polarity, commonly referred to as reverse battery, occurs when the ground of the device goes to the battery potential, $V_{GND} = V_{BAT}$, and the supply pin goes to ground, $V_{BB} = 0V$. In this case, if the EN pin has a path to the *ground* plane, then the FET turns on to lower the power dissipation through the main channel and prevent current flow through the body diode. Note that the resistor/diode ground network (if there is not a central blocking diode on the supply) must be present for the device to protect the device during a reverse battery event. The ground protection network will cause the device ground to be at a higher potential than the module ground (and microcontroller ground). This offset needs to be accounted for in logic pins interface between the device and the microcontroller.

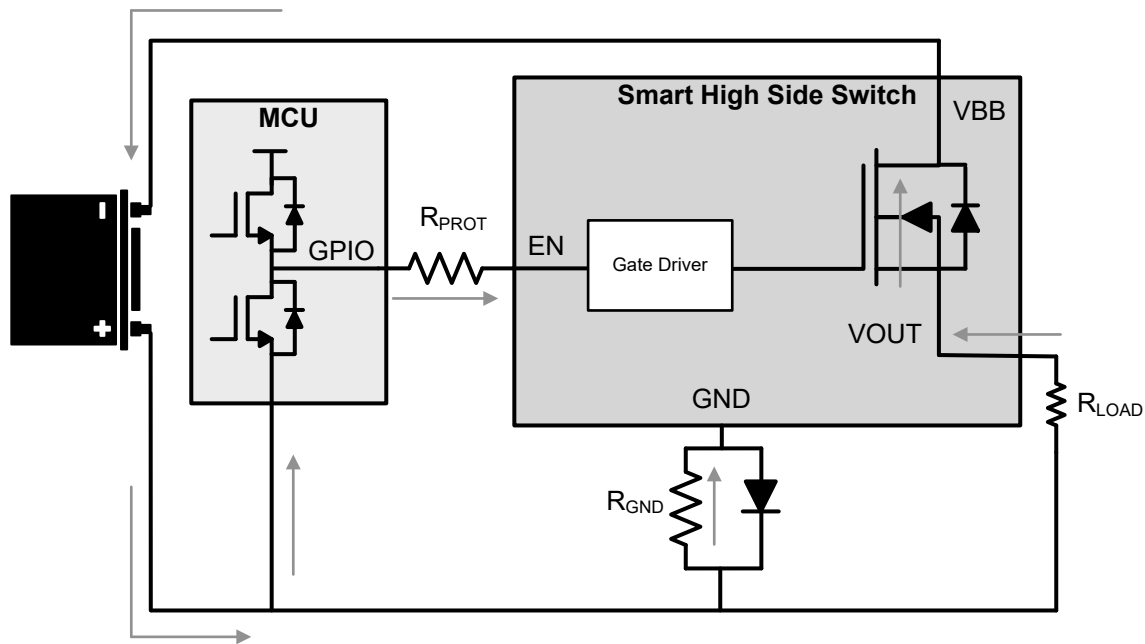


Figure 8-37. Reverse Battery Circuit

For more external protection circuitry information, see [Reverse Current Protection](#).

8.3.11 Full Protections

8.3.11.1 UVLO Protection

The device monitors the supply voltage V_{BB} , to prevent unpredicted behaviors when V_{BB} is too low. When V_{BB} falls down to V_{UVLOF} , the device shuts down. When V_{BB} rises up to V_{UVLOR} , the device turns on.

8.3.11.2 Loss of GND Protection

When loss of GND occurs, output is turned off regardless of whether the enable signal is high or low.

Case 1 (loss of device GND): loss of GND protection is active when the thermal pad (Tab), IC_GND, and current limit ground are one trace connected to the system ground, as shown in [Figure 8-38](#).

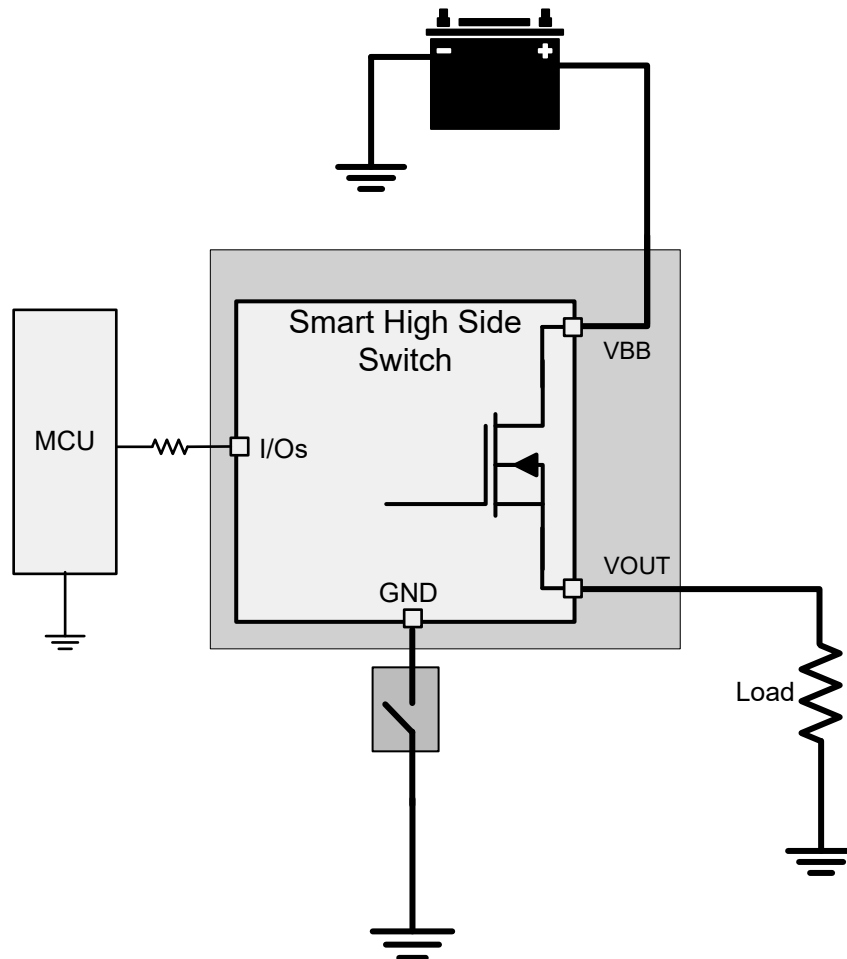


Figure 8-38. Loss of Device GND

Case 2 (loss of module GND): when the whole ECU module GND is lost, protections are also active. At this condition, the load GND remains connected.

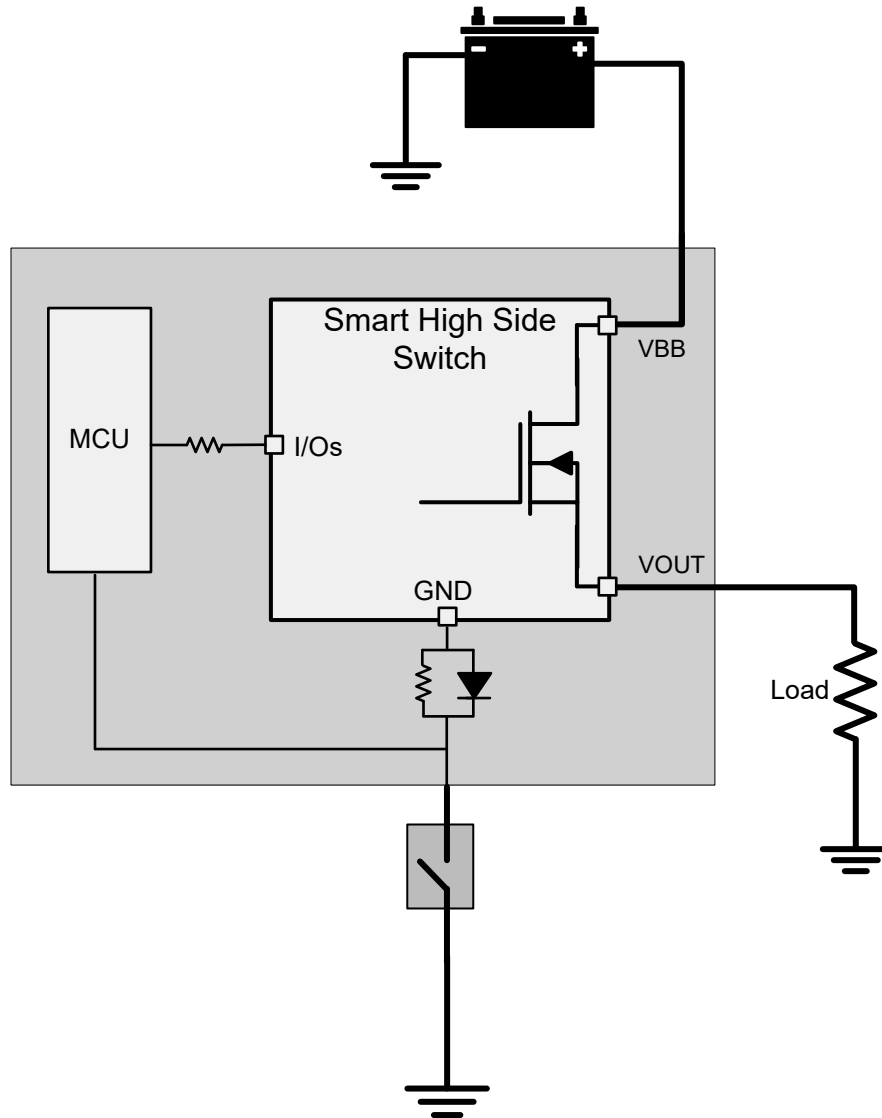


Figure 8-39. Loss of Module GND

8.3.11.3 Loss of Power Supply Protection

When loss of supply occurs, output is turned off regardless of whether the input is high or low. For a resistive or capacitive load, loss of supply protection is easy to achieve due to no more power. The worst case is a charged inductive load. In this case, the current is driven from all of the IOs to maintain the inductance output loop. TI recommends either the MCU serial resistor plus the GND network (diode and resistor in parallel) or external free-wheeling circuitry.

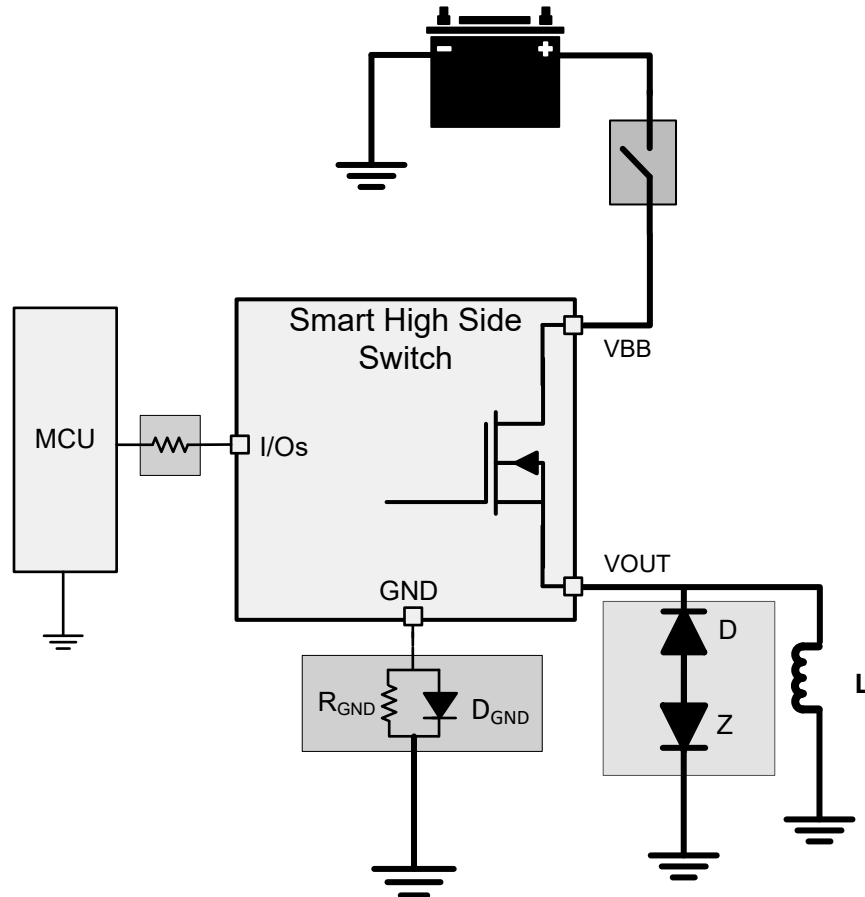


Figure 8-40. Loss of Battery

8.3.11.4 Reverse Current Protection

Method 1: block diode connected with VBB. Both the device and load are protected when in reverse polarity. The blocking diode does not allow any of the current to flow during reverse battery condition.

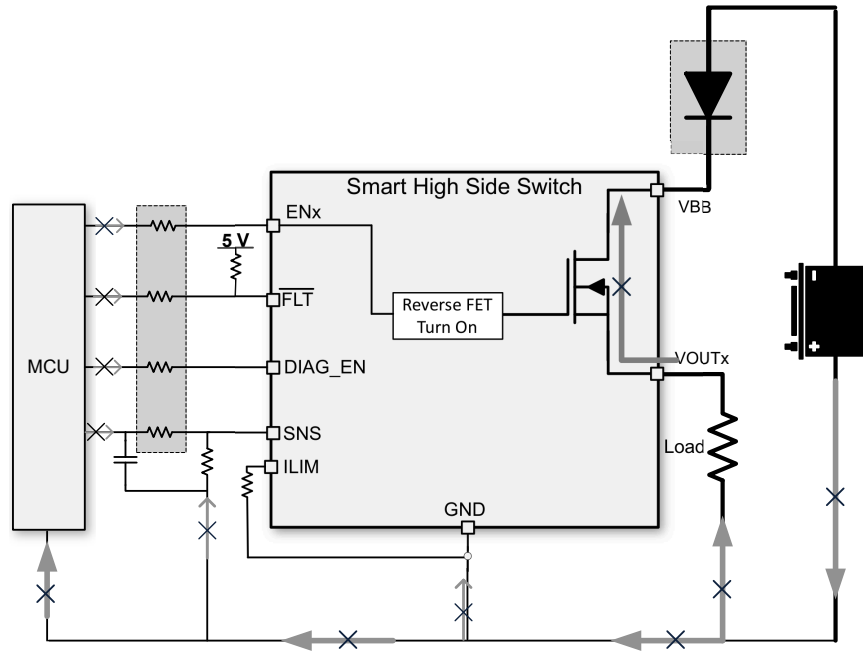


Figure 8-41. Reverse Protection with Block Diode

Method 2 (GND network protection): only the high-side device is protected under this connection. The load reverse current is limited by the impedance of the load. When reverse polarity happens, the continuous reverse current through the power FET must not make the heat build up be greater than the absolute maximum junction temperature. This can be calculated using the $R_{ON(REV)}$ value and the $R_{\theta JA}$ specification. In the reverse battery condition, the FET must come on to lower the power dissipation. This action is achieved through the path from EN to system ground where the positive voltage is being applied. No matter what types of connection are between the device GND and the board GND, if a GND voltage shift happens, verify that the following proper connections for the normal operation:

- Connect the current limit programmable resistor to the device GND.

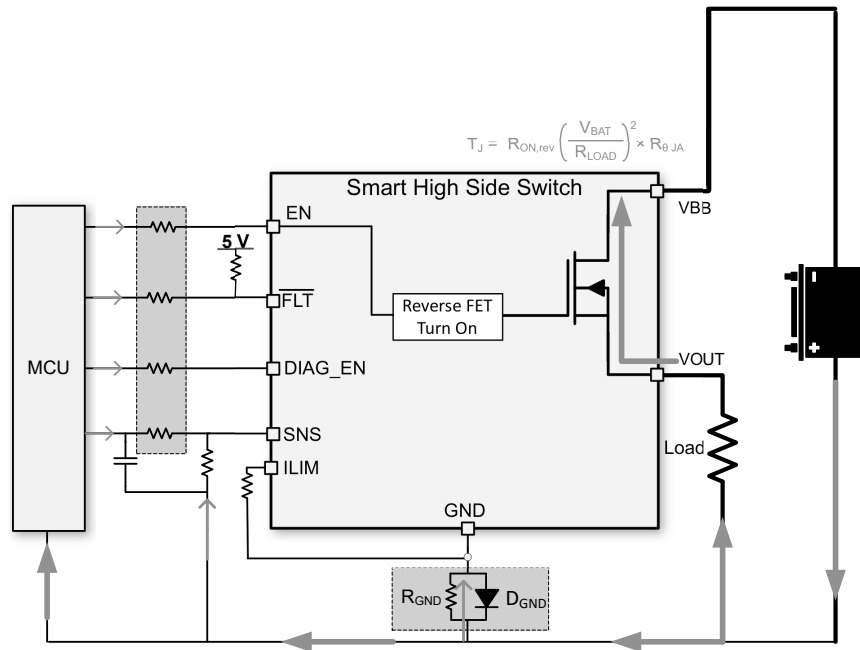


Figure 8-42. Reverse Protection with GND Network

- **Recommendation – resistor and diode in parallel:** a peak negative spike can occur when the inductive load is switching off, which can damage the HSS or the diode. So, TI recommends a resistor in parallel with the diode when driving an inductive load. The recommended selection are a 4.7kΩ resistor in parallel with an $I_F > 100\text{mA}$ diode. If multiple high-side switches are used, the resistor and diode can be shared among devices.
- **Ground Resistor:** The higher resistor value contributes to a better current limit effect when the reverse battery or negative ISO pulses.

$$R_{GND} \geq \frac{(-V_{CC})}{(-I_{GND})} \quad (8)$$

where

- $-V_{CC}$ is the maximum reverse battery voltage (typically -16V).
- $-I_{GND}$ is the maximum reverse current the ground pin can withstand, which is available in the [Absolute Maximum Ratings](#).
- **Ground Diode:** A diode is needed to block the reverse voltage, which also brings a ground shift ($\approx 600\text{mV}$). Additionally, the diode must be $\approx 200\text{V}$ reverse voltage for the ISO 7637 pulse 1 testing so that the diode does not get biased.

8.3.11.5 Protection for MCU I/Os

In many conditions, such as the negative ISO pulse, or the loss of battery with an inductive load, a negative potential on the device GND pin can damage the MCU I/O pins (more likely, the internal circuitry connected to the pins). Therefore, the serial resistors between MCU and HSS are required.

Also, for proper protection against loss of GND, TI recommends 10kΩ resistance for the R_{PROT} resistors.

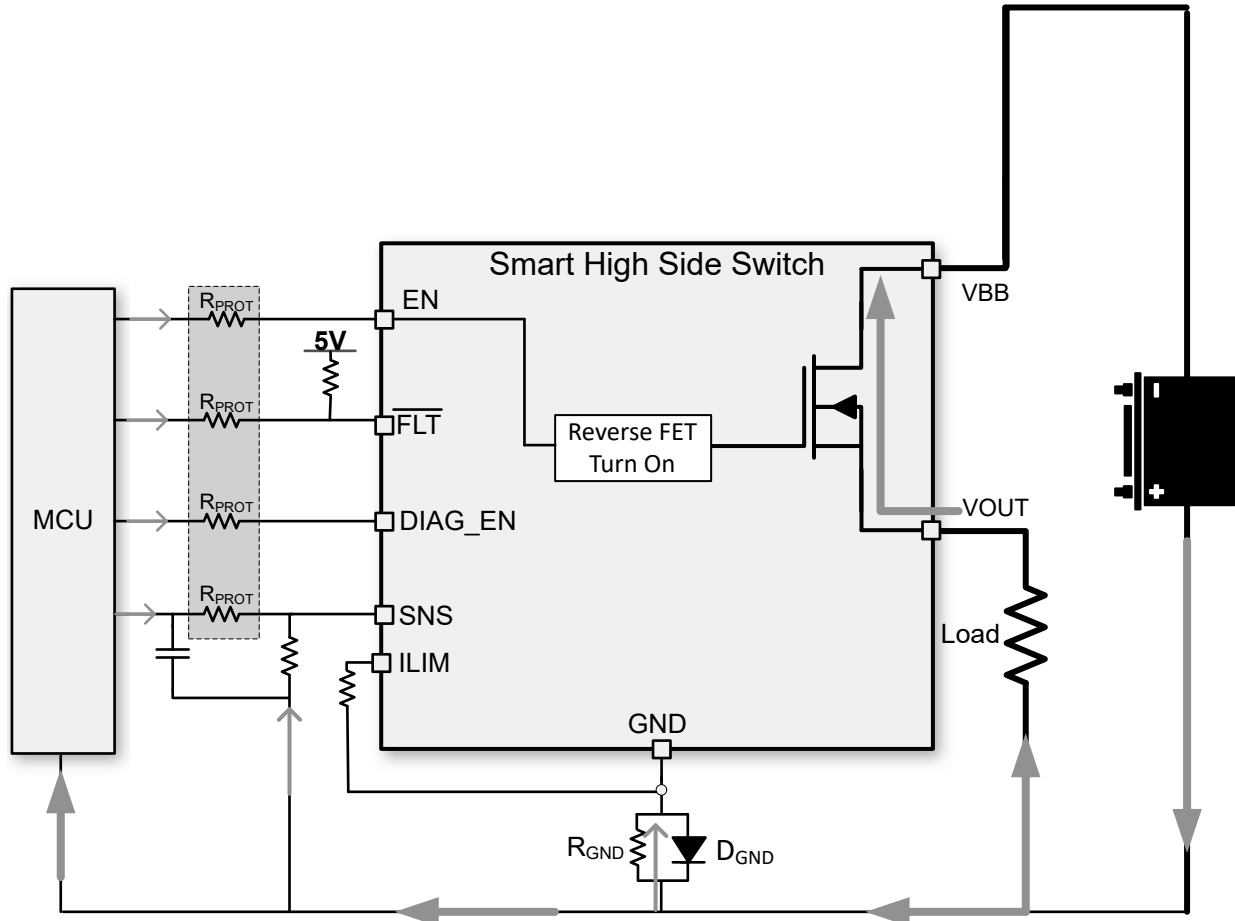


Figure 8-43. MCU I/O Protections

OFF

Device OFF state and occurs when the VBB voltage of the device is below the V_{UVLOF} .

SLEEP

This device state is entered from STANDBY state when the EN pin is pulled low for duration more than t_{STBY} amount of time and VBB is lower than V_{HV_F} . Output is turned off. In the SLEEP state, all blocks inside the device are turned off and the current into the VBB is I_{SLEEP} . From SLEEP, the device can transfer into the ACTIVE state if the EN pin is pulled high, the DIAGNOSTIC state if the DIAG_EN pin, without the EN pin, goes high, or the STANDBY state if VBB is greater than V_{HV_R} .

STANDBY

The device STANDBY state is entered when the EN pin is low. Output is turned off and the DIAG_EN pin is also low but there has not yet been t_{STBY} amount of time. This state is included so that the device output can be modulated using PWM without any of the internal rails being cut off and put to SLEEP state. Once the device has waited t_{STBY} and VBB is less than V_{HV_F} , the device completely shuts down and transitions into SLEEP state. However, if the time is less than t_{STBY} and the EN pin was to go high, the device transitions into ACTIVE state. Similarly if the DIAG_EN goes high, the device transitions into DIAGNOSTIC state.

DIAGNOSTIC

The device DIAGNOSTIC state is entered when EN is low and the DIAG_EN pin is high. Open-load or short-to-battery can be diagnosed in this state. The device signals a \overline{FLT} and the SNS pin outputs I_{SNSFH} current in either an open-load or short-to-battery fault condition.

ACTIVE

The device enters ACTIVE state when the output is on by pulling the EN pin high. In the ACTIVE state, the current limit value is set by the external resistor on the ILIM pin. If the DIAG_EN pin is pulled high while in the ACTIVE state, the SNS pin outputs a proportional current to the load current. Additionally the \overline{FLT} pin reports if there is a fault occurring on any channel. The device can transition out of the ACTIVE state by turning off all of the channels while DIAG_EN is high or low. If the device turns off and DIAG_EN is high, the device transitions into the DIAGNOSTIC state. If the device turns off and the DIAG_EN pin is low, then the device transitions into the STANDBY state.

FAULT

The device FAULT state occurs when the EN pin is high but some event has caused the device to behave differently from normal operation. These fault events include: absolute thermal shutdown, relative thermal shutdown, current limit, open load and short to battery faults. Each of these fault events either directly or eventually shut off the FET to protect the device and system.

9 Application and Implementation

Note

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes, as well as validating and testing their design implementation to confirm system functionality.

9.1 Application Information

The TPS1HC04-Q1 device is capable of driving a wide variety of resistive, inductive, and capacitive loads, including bulbs, LEDs, relays, solenoids, heaters, and sub-modules. Full diagnostics and high-accuracy current-sense features enable intelligent control of the load. An external adjustable current limit improves the reliability of the whole system by clamping the inrush or overload current.

9.2 Typical Application

The following figure shows an example of the external circuitry connections for TPS1HC04-Q1.

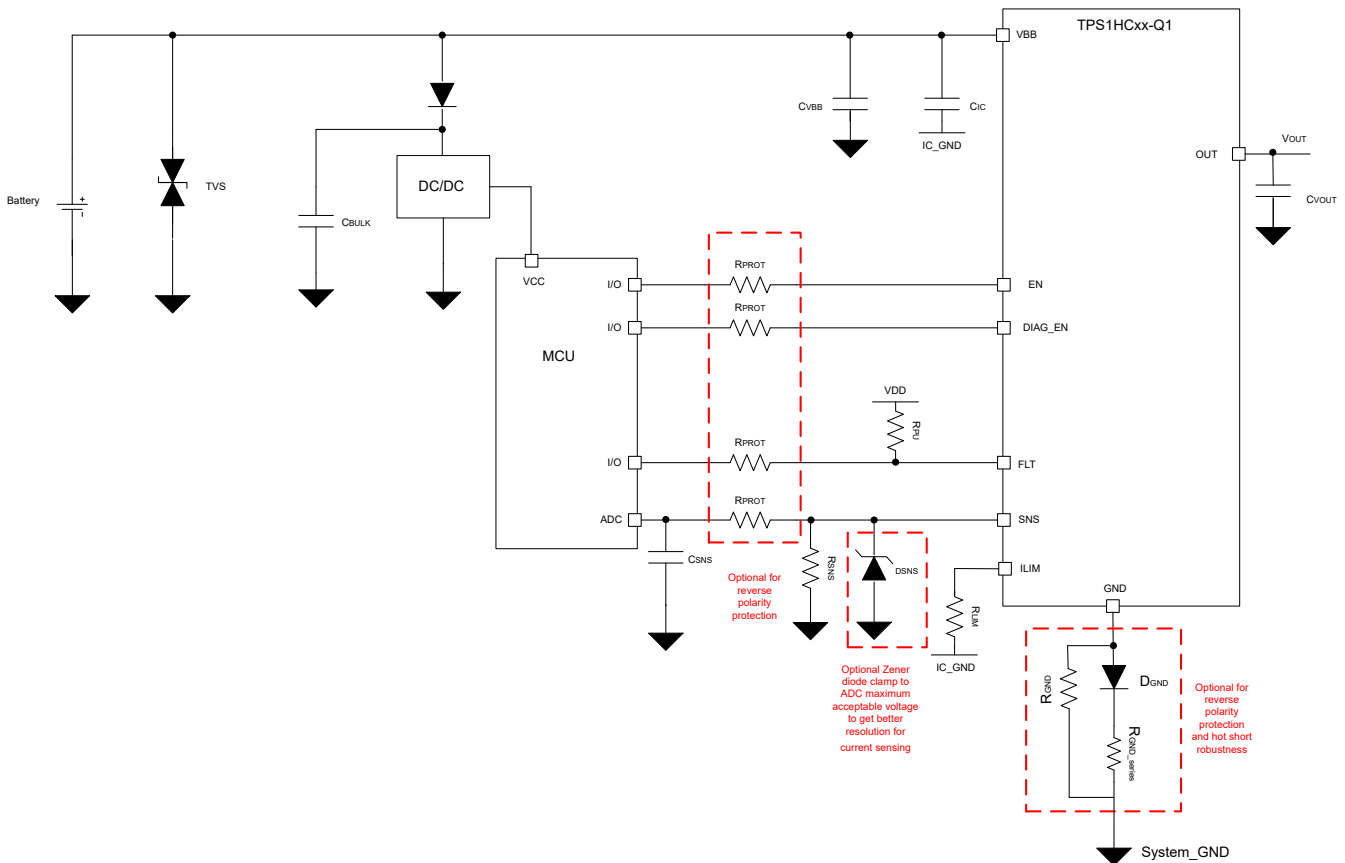


Figure 9-1. Typical Application Diagram

9.2.1 Design Requirements

Table 9-1. Recommended Component Values

COMPONENT	DESCRIPTION	PURPOSE
TVS	SMBJ39CA	Filter voltage transients coming from battery (ISO7637-2)
C_{VBB}	220nF	Better EMI performance
C_{IC}	100nF	Minimal amount of capacitance on input for EMI mitigation

Table 9-1. Recommended Component Values (continued)

COMPONENT	DESCRIPTION	PURPOSE
C _{BULK}	10μF	Help filter voltage transients on the supply rail
R _{PROT}	10kΩ	Protection resistor for microcontroller and device I/O pins
R _{LIM}	Values listed in Section 6.5	Set current limit threshold
R _{SNS}	1kΩ	Translate the sense current into sense voltage
D _{SNS}	SMBJ50A	Clamp SNS pin voltage to ADC maximum acceptable voltage to have improved current sense resolution.
C _{FILTER}	100nF	Coupled with R _{PROT} on the SNS line creates a low pass filter to filter out noise going into the ADC of the MCU
C _{VOUT}	22nF	Improves EMI performance, filtering of voltage transients
R _{PULLUP}	4.7kΩ	Pull up resistor for open-drain pins ($\overline{\text{FLT}}$ and LPM)
R _{GND}	4.7kΩ	Stabilize GND potential during turn-off of inductive load
D _{GND}	BAS21 Diode	Keeps GND close to system ground during normal operation
R _{GND_series}	1Ω	Resistor in series to D _{GND} for hot short robustness.

9.2.2 Detailed Design Procedure

The R_{SNS} resistor value can be calculated using [Equation 1](#) in case of no external component connected on SNS pin and [Equation 2](#) when an external zener diode or resistor divider is connected on SNS pin to clamp SNS pin voltage to ADC maximum acceptable voltage, V_{ADC,max} for better current sense resolution. To achieve better current-sense accuracy, a 1% tolerance or better resistor is preferred.

Table 9-2. Typical Application

PARAMETER	VALUE (no external component connected on SNS pin)	VALUE (external zener diode or resistor divider is connected on SNS)
I _{LOAD,max}	N/A	N/A
I _{LOAD,min}	100mA	100mA
V _{ADC,max}	5V	5V
V _{ADC,min}	5mV	5mV
V _{HR} (needed)	1V	1V
K _{SNS}	3000	3000
K _{CL}	500	500
I _{SNSFH}	7.5mA	7.5mA
V _{HR} (calculated with maximum R _{SNS})	3.33V	-
R _{SNS} (minimum)	150Ω	150Ω
R _{SNS} (maximum)	667Ω	1600Ω

For this application with a zener diode (D_{SNS}) connected on SNS pin, a R_{SNS} value of 1000Ω can be chosen to satisfy the [Equation 2](#) requirements.

In other applications with a higher dynamic current range, either more emphasis can be put on the lower end measurable values which increases R_{SNS}. Likewise, if the higher currents are of more interest the R_{SNS} can be decreased.

To set the adjustable current limit value I_{CL}, use [Equation 9](#) to select the R_{LIM} value.

$$R_{LIM} = K_{CL} / I_{CL} \tag{9}$$

TI recommends R_{PROT} = 10kΩ for 5V MCU IO connections.

9.2.2.1 EMC Transient Disturbances Test

Due to the severe electrical conditions in the automotive environment, immunity capacity against electrical transient disturbances is required, especially for a high side power switch, which is connected directly to the battery. Detailed test requirements are in accordance with the ISO 7637-2:2011 and ISO 16750-2:2010 standards.

Table 9-3. ISO 7637-2:2011(E) in 12V System

TEST ITEM	TEST PULSE SEVERITY LEVEL AND V_s ACCORDINGLY ^{(1) (2)}		PULSE DURATION (t_d)	MINIMUM NUMBER OF PULSES OR TEST TIME	BURST-CYCLE PULSE-REPETITION TIME		INPUT RESISTANCE (Ω) ⁽³⁾	FUNCTION PERFORMANCE STATUS CLASSIFICATION ⁽⁴⁾
	LEVEL	V_s/V			MIN	MAX		
1	III	-112	2ms	500 pulses	0.5s	—	10	Status II
2a	III	55	50 μ s	500 pulses	0.2s	5s	2	Status II
2b	IV	10	0.2s to 2s	10 pulses	0.5s	5s	0 to 0.05	Status II
3a	IV	-220	0.1 μ s	1h	90ms	100ms	50	Status II
3b	IV	150	0.1 μ s	1h	90ms	100ms	50	Status II

- (1) Tested both under input low condition and high condition.
- (2) The pulse 2A voltage is 54V maximum from VBB with respect to ground. A voltage suppressing mechanism must be used to pass Level III. This test was run with an 1 μ F capacitor from VBB to system ground.
- (3) GND pin network is a 4.7k Ω resistor in parallel with a diode BAS21-7-F.
- (4) Status II: The function does not perform as designed during the test, but returns automatically to normal operation after the test.

Table 9-4. ISO 16750-2:2010(E) Load Dump Test B in 12V System

TEST ITEM	TEST PULSE SEVERITY LEVEL AND V_s ACCORDINGLY ^{(1) (2)}		PULSE DURATION (t_d)	MINIMUM NUMBER OF PULSES OR TEST TIME	BURST-CYCLE PULSE-REPETITION TIME	INPUT RESISTANCE (Ω) ⁽³⁾	FUNCTION PERFORMANCE STATUS CLASSIFICATION ^{(4) (5)}
	LEVEL	V_s/V					
Test B		35	40ms to 400ms	5 pulses	60s	0.5 to 4	Status II

- (1) Tested both under input low condition and high condition (DIAG_EN, EN, and VBB are all classified as inputs).
- (2) Considering the worst test condition, the device is tested without any filter capacitors on VBB and VOUT.
- (3) The GND pin network is a 4.7k Ω resistor in parallel with a diode BAS21-7-F.
- (4) Status II: The function does not perform as designed during the test, but returns automatically to normal operation after the test.
- (5) Select a 36V external suppressor.

9.2.3 Transient Thermal Performance

The TPS1HC04-Q1 device can experience different transient conditions that cause large currents to flow for a short duration of time. These may include:

- Inrush current during high capacitive or bulb load charging.
- Fault conditions such as output shorted to ground, triggering overcurrent protection.
- Briefly energizing a inductive load such as motor or solenoid for a limited time, then de-energizing.

In these transient cases, the thermal impedance parameter $Z_{\theta JA}$ denotes the junction-to-ambient thermal performance. The below figure shows the simulated thermal impedance for EVM under natural convection conditions using an FR4 2s2p board. The device (chip + package) was modeled on a 76.2 × 114.3 × 1.5mm board featuring two inner copper layers (two at 70 μ m Cu thickness and two at 35 μ m Cu thickness). Five thermal vias positioned beneath the exposed pad established contact with the first inner copper layer (12mm x 12mm). All simulations were performed at an ambient temperature of 25°C with power dissipation set at 1 W for the channel.

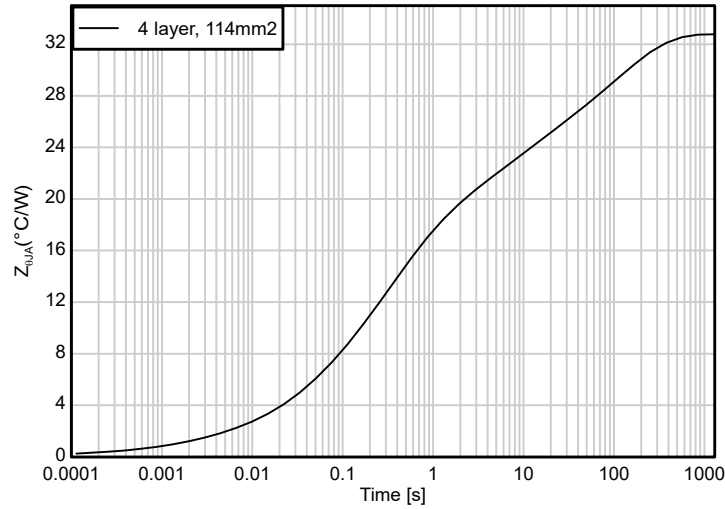
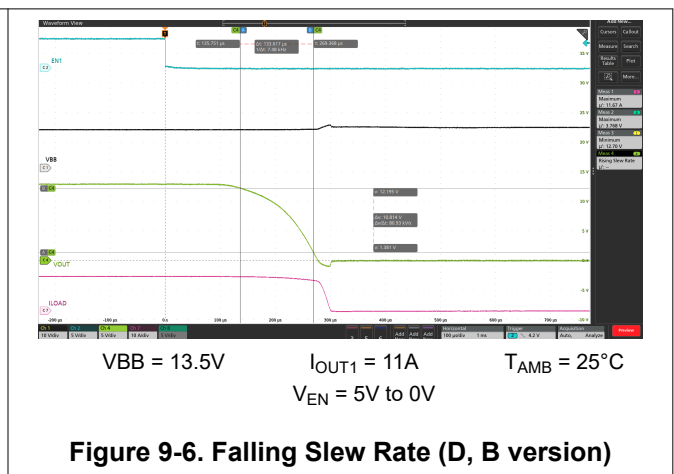
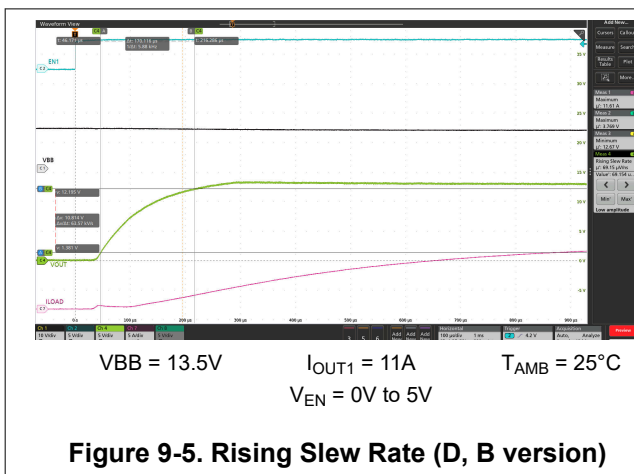
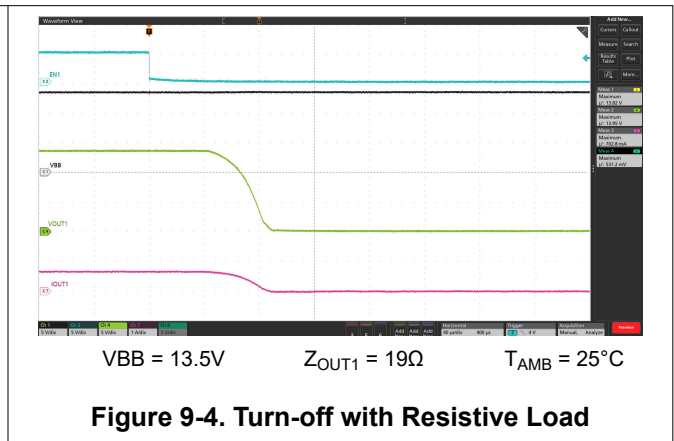
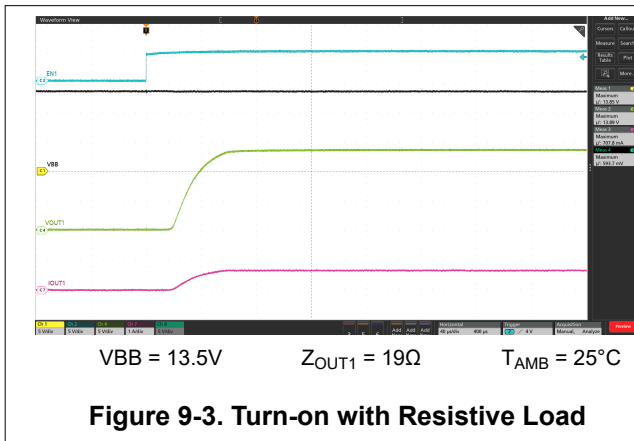
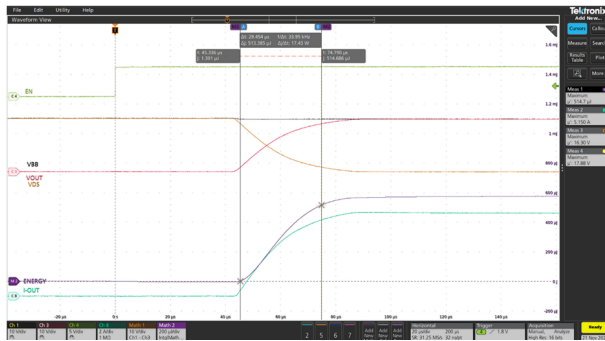


Figure 9-2. $Z_{\theta JA}$ (transient thermal impedance) for EVM 2s2p PCB Layout, 5 Thermal Vias Below Exposed Pad

9.2.4 Application Curves

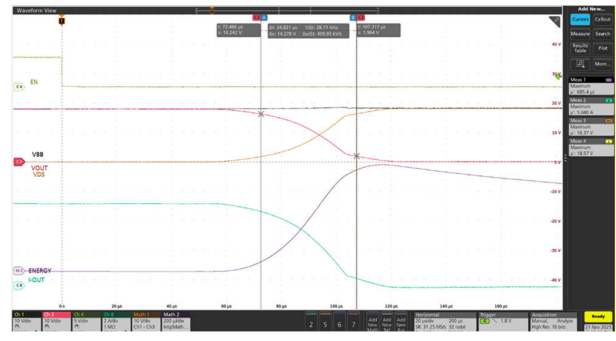
The subscript "1" is sometimes used to refer the device channel in few images below.





VBB = 13.5V I_{OUT1} = 5A T_{AMB} = 25°C
V_{EN} = 0V to 5V

Figure 9-7. Rising Slew Rate (P, M version)



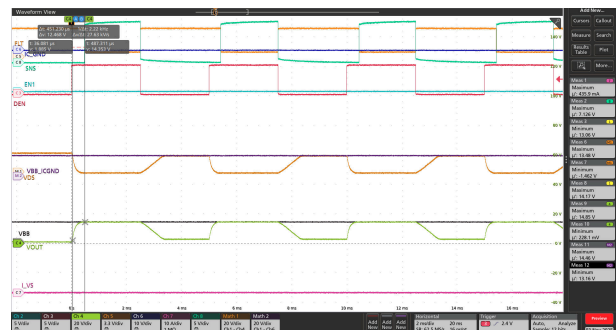
VBB = 13.5V I_{OUT1} = 5A T_{AMB} = 25°C
V_{EN} = 5V to 0V

Figure 9-8. Falling Slew Rate (P, M version)



VBB = 13.5V V_{OUT1} = STG T_{AMB} = 125°C
I_{LIM} = STG V_{EN1} = 5V

Figure 9-9. Device Turn-on Behavior with Output Shorted to GND



VBB = 13.5V V_{OUT} = open load T_{AMB} = 25°C
DIAG_EN = PWM V_{EN1} = 0V
(200Hz)

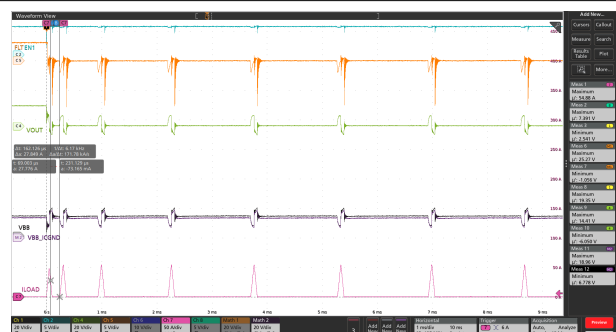
SNS outputs I_{SNSFH} current when DIAG_EN is high and is floating when DIAG_EN is low
FLT = get asserts when DIAG_EN is high

Figure 9-10. Open Load Detection Delay with Open Load Fault on the device (P, D version)



VBB = 13.5V Z_{OUT1} = 1μH + 100mΩ T_{AMB} = 125°C
V_{EN1} = 5V

Figure 9-11. Hot Short (Retry behavior)



VBB = 13.5V Z_{OUT1} = 1μH + 100mΩ T_{AMB} = 25°C
V_{EN1} = 5V

Figure 9-12. Hot Short (Retry behavior) zoomed to initial retry window

9.3 Power Supply Recommendations

The device is qualified for both automotive and industrial applications. The normal power supply connection is a 12V automotive system. The supply voltage must be within the range specified in the [Recommended Operating Conditions](#).

Table 9-5. Voltage Operating Ranges

VBB VOLTAGE RANGE	NOTE
3V to 6V	Extended lower 12V automotive battery operation such as cold crank and start-stop. The device is fully functional and protected but some parametrics such as R_{ON} , current sense accuracy, current limit accuracy and timing parameters can deviate from specifications. Check the individual specifications in the <i>Electrical Characteristics</i> to confirm the voltage range.
6V to 18V	Nominal 12V automotive battery voltage range. All parametric specifications apply and the device is fully functional and protected.
18V to 28V	Extended upper 12V automotive battery operation such as double battery. The device is fully functional and protected (short-circuit protection up to 24V) but some parametrics such as R_{ON} , current sense accuracy, current limit accuracy, and timing parameters can deviate from specifications. Check the individual specifications in the <i>Electrical Characteristics</i> to confirm the voltage range.
35V	Load dump voltage. Device is operational and lets the pulse pass through without being damaged but does not protect against short circuits.

9.4 Layout

9.4.1 Layout Guidelines

To achieve good thermal performance, connect the VBB pad to a large copper pour. On the top PCB layer, the pour can extend beyond the package dimensions as shown in the layout examples below. In addition to this, having a VBB plane on one or more internal PCB layers and/or on the bottom layer is recommended. Vias must connect these planes to the top VBB pour. Connecting the VOUT pad to large copper pours on the board can also help to achieve better thermal performance as the heat can transfer through the internal copper pillars to the large copper pours on the board.

TI recommends that the IO signals that connect to the microcontroller be routed to a via and then through an internal PCB layer.

If used in the design, the C_{IC} capacitor, must be placed as close as possible to the VBB and GND pin of the device. If a ground network is used for reverse battery protection, the C_{IC} capacitor must be connected from the VBB net to the IC_GND net. The C_{VBB} capacitor must be placed close to the VBB pin and connected to system ground to allow for best performance.

The R_{LIM} component must be placed close to the ILIM and GND pin of the device. If a ground network is used for reverse battery protection, the R_{LIM} must be connected from the ILIM pin to the IC_GND net for expected current limit performance.

The FLT and SNS pin traces must be routed far apart (orthogonal or in different layers) to avoid any coupling between the two signals.

The TPS1HC03-Q1 device footprint is compatible with all other devices in the family and can be used for common board design.

9.4.2 Layout Examples

9.4.2.1 Without a GND Network

The below figure shows an example PCB layout without a GND network. TI recommends that the IO signals that connect to the microcontroller be routed to a via and then through an internal PCB layer.

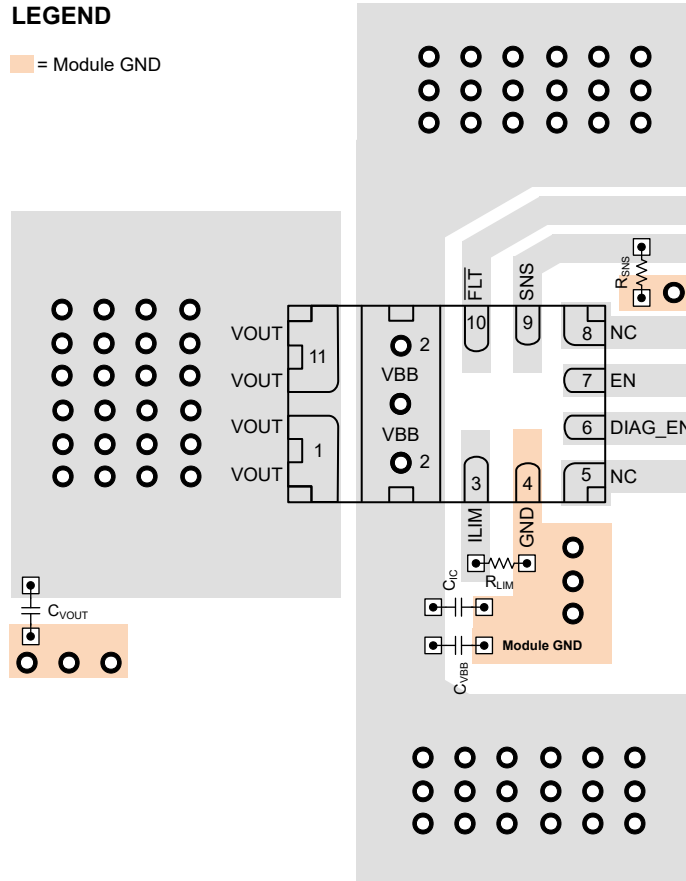


Figure 9-13. Layout Example without a GND Network

9.4.2.2 With a GND Network

The below figure shows an example PCB layout with a GND network. TI recommends that the IO signals that connect to the microcontroller be routed to a via and then through an internal PCB layer.

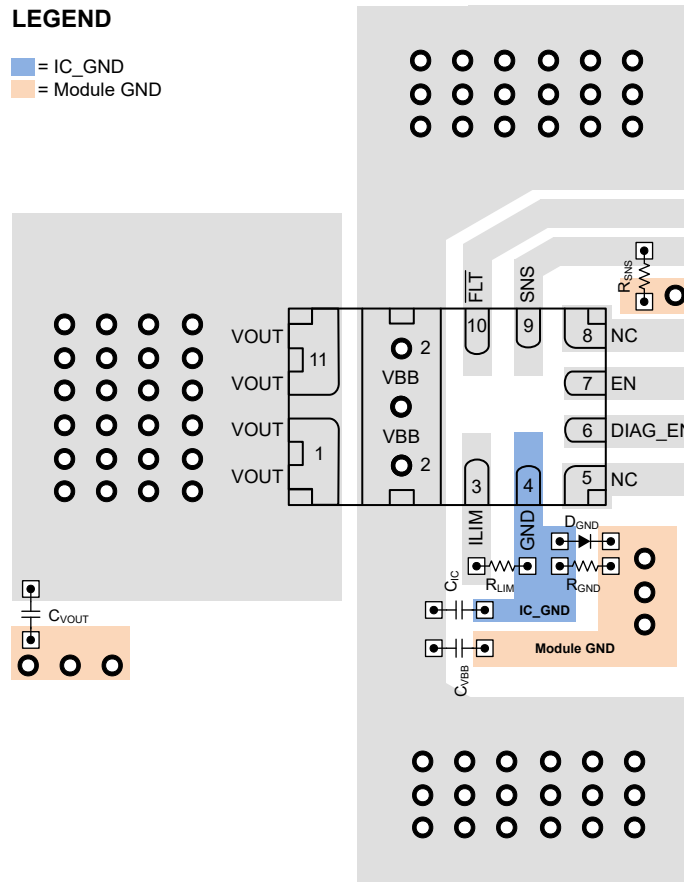


Figure 9-14. Layout Example with a GND Network

9.4.3 Wettable Flank Package

In traditional QFN packages, confirming proper solder connections to PCBs via Automatic Optical Inspection (AOI) is challenging. Exposed copper edges after package sawing are prone to oxidation, making reliable solder wetting difficult. Without a consistent solder fillet, proper solder connections cannot be visually confirmed during inspection.

To mitigate above challenge, wettable flank process employs mechanical and metallurgy-based techniques that enable the sidewall of QFN packages to be wettable to a specified height. This creates an inspectable solder fillet, providing visual confirmation of proper connection and meeting inspection requirements.

Wettable flank can be of three types – Dimple cut, Step cut and Immersion Tin. Dimple cut or step cut options feature visible grooves on package sidewalls, whereas the Immersion Sn approach uses tin plating on the sidewall without requiring physical grooves.

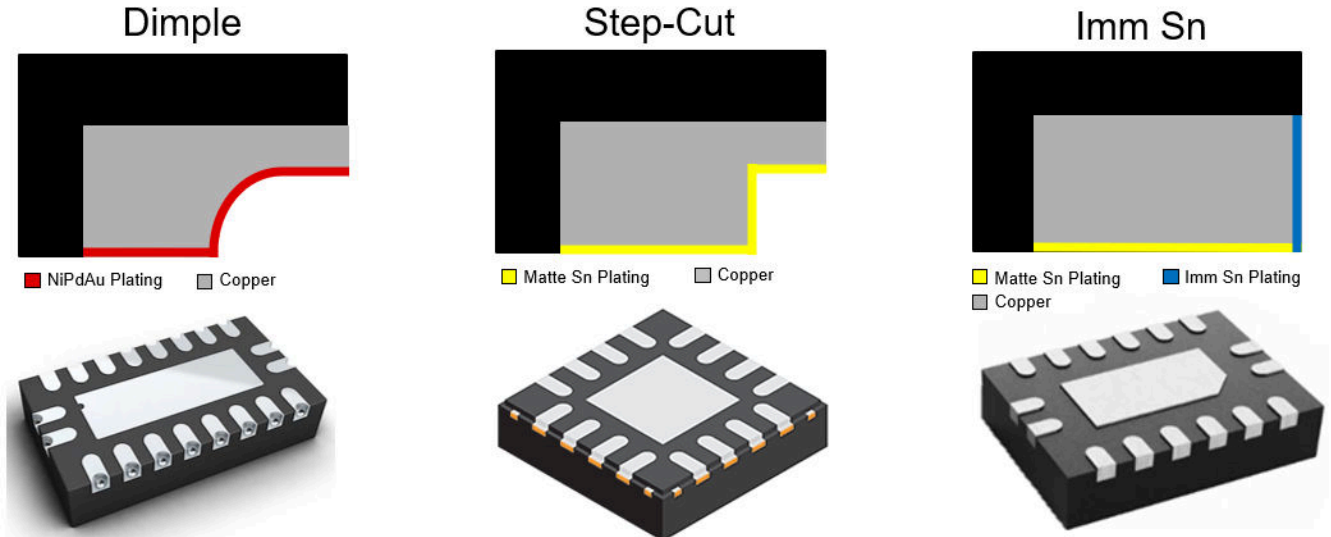


Figure 9-15. Types of Wetable Flank Packages

The VAH package of the TPS1HC04-Q1 uses the Immersion Sn plating option. This implementation meets industry requirements for minimum 100 μ m side-wetting of solder material, making sure reliable connections while allowing for automated optical inspection.

10 Device and Documentation Support

10.1 Third-Party Products Disclaimer

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10.2 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. Click on *Notifications* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

10.3 Support Resources

[TI E2E™ support forums](#) are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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10.4 Trademarks

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10.5 Electrostatic Discharge Caution



This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

10.6 Glossary

[TI Glossary](#) This glossary lists and explains terms, acronyms, and definitions.

11 Revision History

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

DATE	REVISION	NOTES
December 2025	*	Initial Release

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most-current data available for the designated device. This data is subject to change without notice and without revision of this document. For browser-based versions of this data sheet, see the left-hand navigation pane.

PACKAGING INFORMATION

Orderable part number	Status (1)	Material type (2)	Package Pins	Package qty Carrier	RoHS (3)	Lead finish/ Ball material (4)	MSL rating/ Peak reflow (5)	Op temp (°C)	Part marking (6)
TPS1HC04PQVAHRQ1	Active	Production	VQFN-HR (VAH) 11	3000 LARGE T&R	-	SN	Level-2-260C-1 YEAR	-40 to 125	1HC04P

(1) **Status:** For more details on status, see our [product life cycle](#).

(2) **Material type:** When designated, preproduction parts are prototypes/experimental devices, and are not yet approved or released for full production. Testing and final process, including without limitation quality assurance, reliability performance testing, and/or process qualification, may not yet be complete, and this item is subject to further changes or possible discontinuation. If available for ordering, purchases will be subject to an additional waiver at checkout, and are intended for early internal evaluation purposes only. These items are sold without warranties of any kind.

(3) **RoHS values:** Yes, No, RoHS Exempt. See the [TI RoHS Statement](#) for additional information and value definition.

(4) **Lead finish/Ball material:** Parts may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

(5) **MSL rating/Peak reflow:** The moisture sensitivity level ratings and peak solder (reflow) temperatures. In the event that a part has multiple moisture sensitivity ratings, only the lowest level per JEDEC standards is shown. Refer to the shipping label for the actual reflow temperature that will be used to mount the part to the printed circuit board.

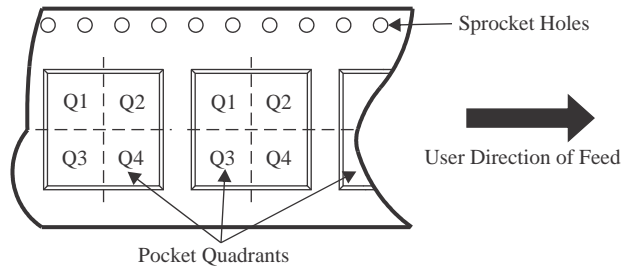
(6) **Part marking:** There may be an additional marking, which relates to the logo, the lot trace code information, or the environmental category of the part.

Multiple part markings will be inside parentheses. Only one part marking contained in parentheses and separated by a "-" will appear on a part. If a line is indented then it is a continuation of the previous line and the two combined represent the entire part marking for that device.

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TAPE AND REEL INFORMATION

QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE


*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
TPS1HC04PQVAHRQ1	VQFN-HR	VAH	11	3000	180.0	12.4	2.5	3.9	1.2	4.0	12.0	Q1

TAPE AND REEL BOX DIMENSIONS


*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
TPS1HC04PQVAHRQ1	VQFN-HR	VAH	11	3000	210.0	185.0	35.0

GENERIC PACKAGE VIEW

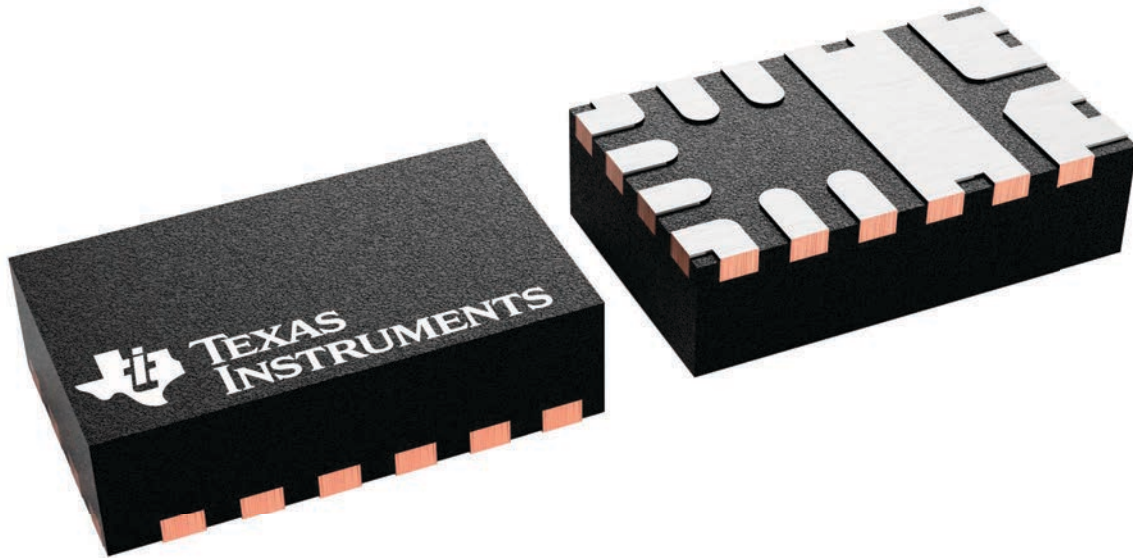
VAH 11

VQFN-HR - 1 mm max height

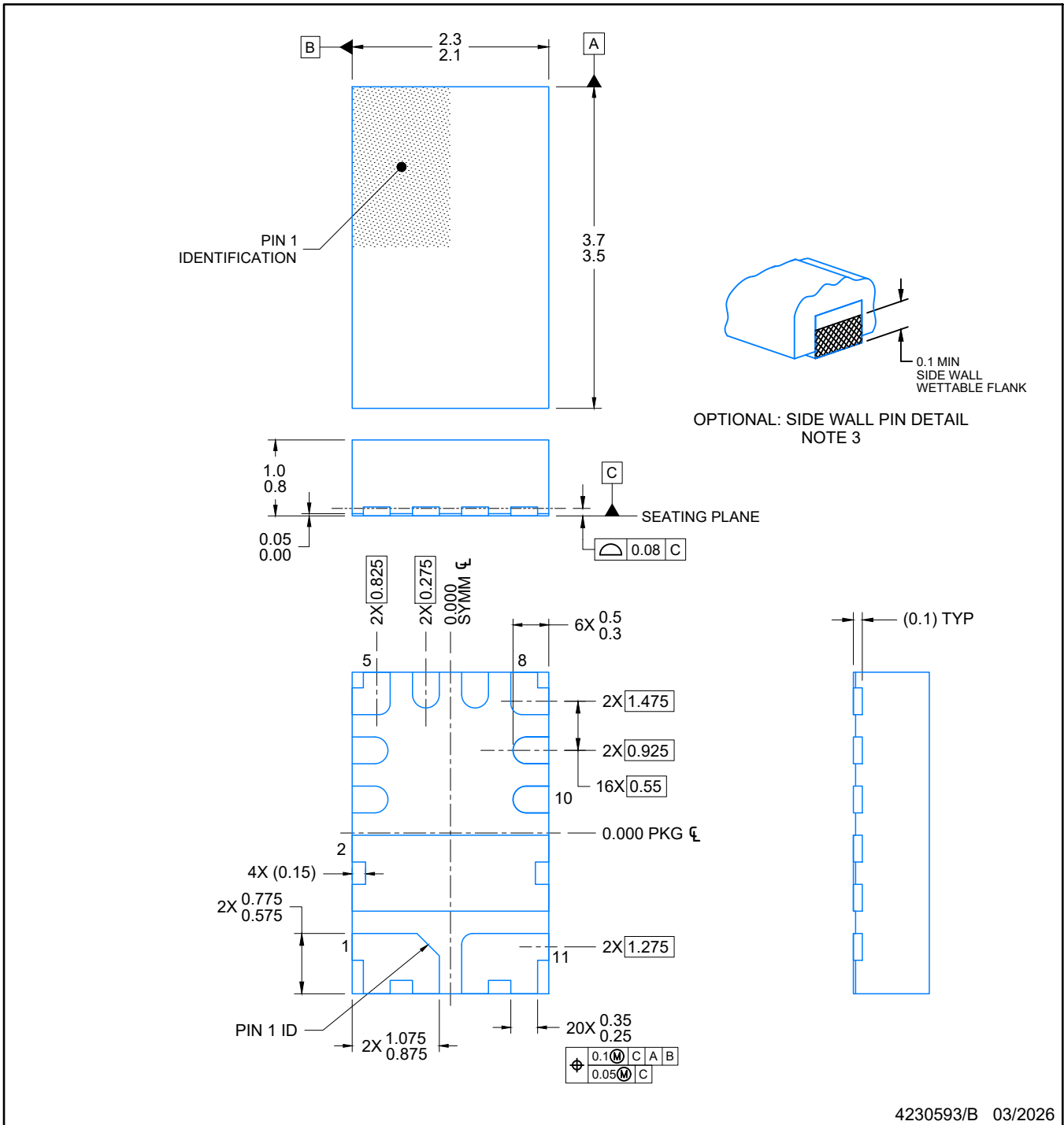
2.2 x 3.6, 0.5 mm pitch

PLASTIC QUAD FLATPACK - NO LEAD

This image is a representation of the package family, actual package may vary.
Refer to the product data sheet for package details.



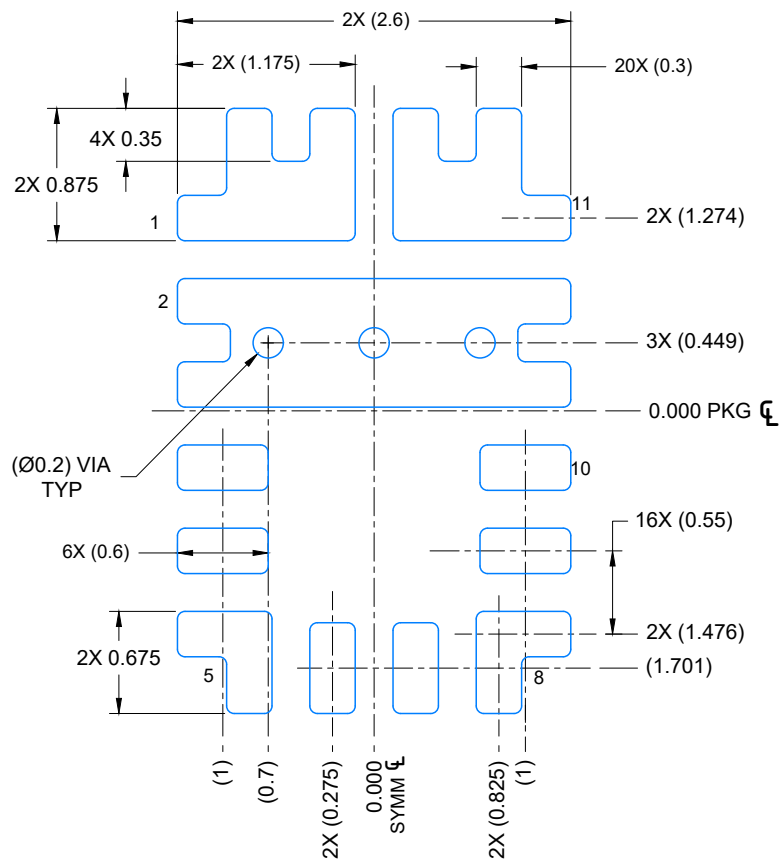
4230955/A



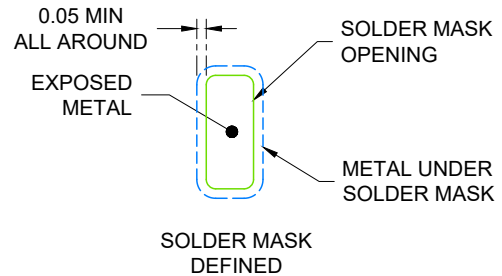
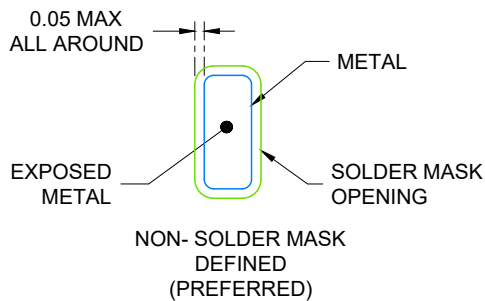
4230593/B 03/2026

NOTES:

1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. Minimum 0.1 mm solder wetting on pin side wall. Available for wettable flank version only.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 20X

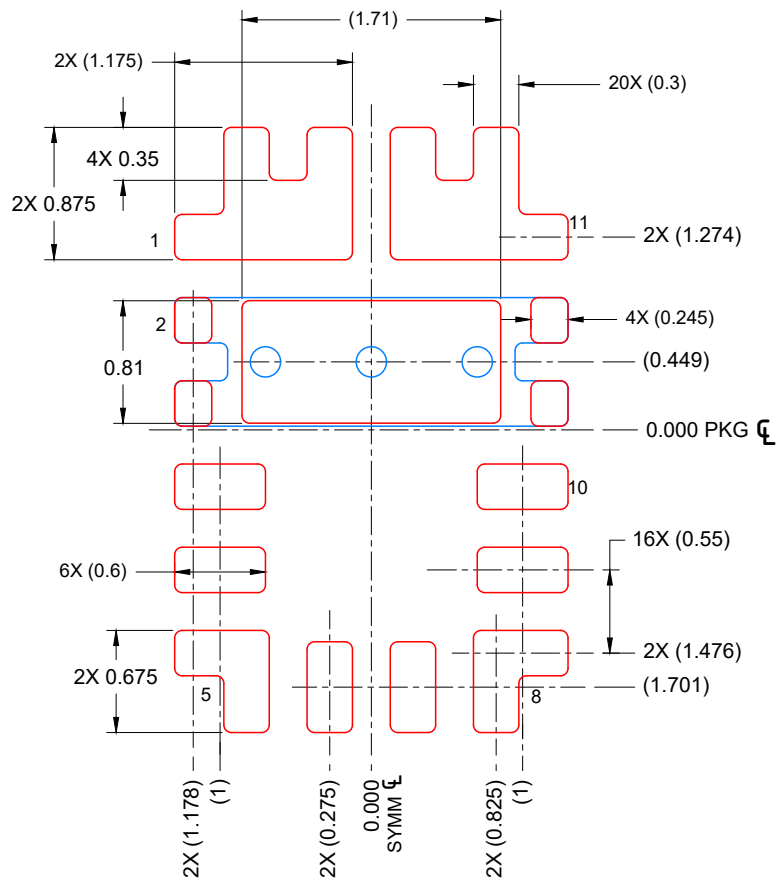


SOLDER MASK DETAILS
NOT TO SCALE

4230593/B 03/2026

NOTES: (continued)

4. For more information, see Texas Instruments literature number SLUA271 (www.ti.com/lit/sluea271).
5. Solder mask tolerances between and around signal pads can vary based on board fabrication site.



SOLDER PASTE EXAMPLE
 BASED ON 0.1 mm THICK STENCIL
 SCALE: 20X

4230593/B 03/2026

NOTES: (continued)

- 6. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.

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